Detecting Battery Cells with Harmonic Radar

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ABSTRACT

Harmonic radar systems have been shown to be an effective method for detecting the presence of electronic devices, even if the devices are powered off. Prior work has focused on detecting specific non-linear electrical components (such as transistors and diodes) that are present in any electronic device. In this paper we show that harmonic radar is also capable of detecting the presence of batteries. We tested a proof-of-concept system on Alkaline, NiMH, Li-ion, and Li-metal batteries. With the exception of Li-metal coin cells, the prototype harmonic radar detected the presence of batteries in our experiments with 100% accuracy.

CCS CONCEPTS

• **Security and privacy** → **Embedded systems security**.

KEYWORDS

Harmonics, Non-linear junction, Detection, Battery

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1 INTRODUCTION

Internet of Things (IoT) devices capture data about their local environment and that data can be used to infer characteristics about nearby people. As the number of deployed devices grows, it will become increasingly difficult for people to know if they are being observed by these devices. This problem is be particularly salient as people become the occupants (perhaps temporarily) of a new space such as a hotel, conference room, or rental unit. In that case, the person may not be aware of all devices present in the environment. In some cases, devices such as hidden cameras may be purposely obscured to escape detection [7]. Conversely in smart environments with dozens or hundreds of deployed devices, it may become extremely difficult for an administrator to maintain the location and status of every device in a space. Ideally a method would exist to quickly and comprehensively locate *all* electronic devices present in an environment. Building on prior research on harmonic radar, this paper takes another step forward to such a solution.

Previous research has shown that harmonic radar systems can detect the presence of electronic devices without the need for device to cooperate with the discovery process, without knowledge of the device's communication protocols (e.g., Wi-Fi or Bluetooth), and works even if the devices are powered off [12]. It works by transmitting a radio frequency (RF) and monitoring for a response at the first harmonic. Electronic devices comprised of components with nonlinear metal junctions such as transistors and diodes will re-radiate the RF at the first harmonic (two times the transmitted frequency), but other items that do not contain these electronic components will not (discussed in more detail in Section 2). Other research has found that devices can be identified based on their harmonic response [13], but that work focused on the physical properties of nonlinear electronic components. In this paper we show that harmonic radar is also able to detect the presence of batteries.

In addition to the security and privacy risks raised by the presence of IoT devices ubiquitously and unobtrusively collecting data, battery cells are a fire hazard in environments such as checked bags in airplanes [5] as well as e-waste recycling plants [10]. Moreover, separating batteries from electronic waste is critical for the correct extraction of precious metals from discarded electronics [15]. Existing methods for detecting batteries in cluttered environments rely on expensive X-ray machines and computationally intense machine-learning techniques [18]. The ability to detect batteries with less expensive equipment and in a more efficient manner becomes increasingly important with the widespread propagation of battery powered IoT devices [14].

In this paper, we make two important **contributions**:

- A theoretical discussion about why a harmonic radar *should* detect batteries
- Laboratory experiments that confirm a harmonic radar *does* detect batteries.

Our work is, to the best of our knowledge, the first to show that harmonic radars are able to detect the presence of batteries.

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2 BACKGROUND: HARMONIC RADAR

Radars are remote detection systems comprised of a transmitter (TX) which propagates an RF wave at a chosen frequency (f_0) and phase (ϕ) as well as a receiver (RX) that is commonly co-located with the transmitter and measures the electromagnetic spectrum at the transmitter's chosen frequency. The RF signal travels through the air from the transmitter and strikes objects present in the environment. A portion of the transmitted energy then reflects off from each object in the radar's line of sight and returns to the receiver. The presence of a signal detected by the receiver at the transmitted frequency indicates a reflection, and therefore, the presence of a object, sometimes called a *target*, in the operating area of the radar. This situation is known as a *linear response*, as the return signal is at the same frequency as the transmitted signal (perhaps altered slightly by the Doppler shift for moving targets).

2.1 Detecting electronic devices

A major challenge in using a radar-like system to detect electronic devices in a cluttered environment such as a home or office is that the vast majority of objects in a typical environment generate a linear response. These linear responses arrive superimposed at the receiver. At best, using radar for electronic device detection and identification requires heavy use of signal-processing techniques to declutter the return signal. In practice, even with strong algorithms it would be challenging to detect and identify the footprint of a small electronic target device amid all the clutter. Moreover, traditional radars detect targets by the reflection from their "enclosure" or outer shell, making it difficult to detect items that might be intentionally hidden (or lost and out of sight).

Harmonic radars work differently from linear radars. They leverage the *nonlinear response* generated from electronic devices by setting the RX frequency to nf_0, where n is a positive integer greater than one and f_0 is the transmitted frequency. The reflected power of the harmonic has an inverse relationship with its associated integer (lower values of n provide higher received power, higher values of n provide lower received power); hence, the work presented in this paper (and other papers [8]) exclusively uses the first harmonic where $n = 2$ and the RX frequency is $2f_0$.

Digital memory and computation, even for simple devices like embedded systems, rely on semiconductors and other components that reflect RF signals nonlinearly. Perez et al. showed that harmonic radar systems are able to *detect* these devices [12] and to *identify* them with high accuracy [13].

2.2 Detecting batteries

Harmonic radar can suffer from a problem: corrosion on targets can lead to false detection. Specifically, metal oxides such as rust also have a nonlinear RF behavior [4]. This "problem", however, suggests an avenue for remotely detecting batteries. Commercially available battery cells contain metal oxides in the cathodes [9, 16, 19]. We wondered if this battery composition and its resulting nonlinear oxides would lead to detection by a harmonic radar.

Exploring the research literature, we see the nonlinear behavior of Lithium-Ion batteries was examined by Harting et al. [3]. In their work, the authors estimate the "state-of-health" of the batteries by applying a high-amplitude sinusoidal input signal through a wire

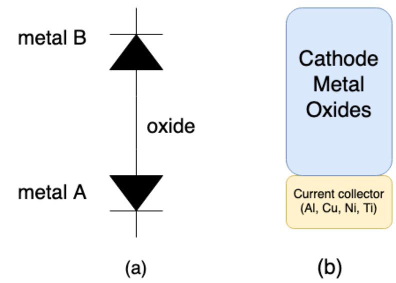


Figure 1: (a) Metal-Oxide-Metal (MOM) equivalent circuit. Adapted from Ida et al. [4]. (b) MOM junction found in battery cathodes.

connected directly to the battery system. They measure changes in the sinusoidal output voltage over time and estimate the loss capacity fade due to loss of active material. Other research discusses the nonlinear behavior of Lithium-Ion batteries in the context of their electrochemical reactions during charge and discharge [3, 6].

Prior research, however, always connected the batteries over a wire and leveraged the non-linear responses of batteries' chemical processes; hence, the frequencies studied are limited to those associated with the chemical reactions.

The metal-oxide-metal junction created by corrosion can be modeled by the equivalent circuit shown in Figure 1(a) [4]. The junction between a battery cell's cathode and the current collector follow a similar structure, as depicted in Figure 1(b); hence, it is reasonable to model a battery cell's cathode-collector boundary with the equivalent circuit in Figure 1(a), and expect harmonic responses comparable to corroded metals. Thus, a harmonic radar can be used to *remotely* detect the presence of batteries using RF by levering the batteries' physical structure.

We explored battery detection using a harmonic radar to detect four different types of batteries: Alkaline, NiMH, Li-ion, and Li-metal. With the exception of Li-metal batteries, in our experiments, the prototype harmonic radar detected the presence of batteries commonly found in household electronics with 100% accuracy.

3 METHODS

In this section we describe our experimental setup and our test batteries.

3.1 Experimental setup

The design of our harmonic radar system is based on the setup proposed by Perez et al. for detecting electronic devices [11]. A minor, but important, difference is the addition of a reflection-less filter, which attenuates more effectively the system's generated harmonics. We next describe our radar's components.

3.2 Hardware

Figure 3 illustrates the block diagram of our experimental setup. The system can be divided into two high-level blocks: transmitter (TX) and receiver (RX). The TX block is comprised of a Signal-Hound VSG60A capable of generating signals between 50 MHz and 6 GHz. A MiniCircuits SLP-2950+ low pass filter blocks harmonics

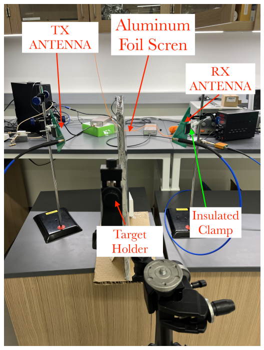


Figure 2: Experiment setup.

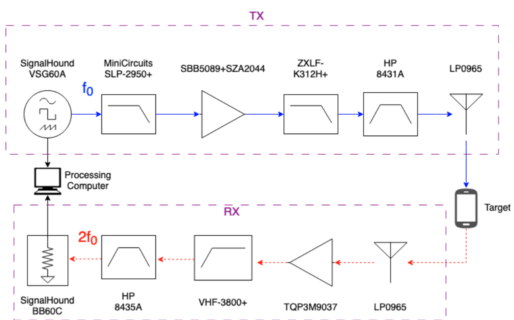


Figure 3: Block Diagram Harmonic Radar Architecture.

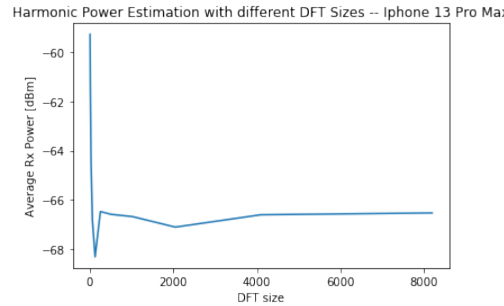


Figure 4: Average RX power estimated with different DFT window sizes. Target: iPhone 13 Pro Max.

produced by the signal generator. A SBB5089+SZA2044 power amplifier module with a 40 dB gain increases the signal's amplitude. A MiniCircuits ZXLF-K312H+ low pass reflection-less filter and a HP 8431A bandpass filter attenuate harmonics produced by the power amplifier. The RX block is comprised of a TQP3M9037 LNA for amplification of the received signal. A MiniCircuits VHF-3800+ high-pass filter and a HP 8435A band-pass filter attenuate any scattering at the transmitted (fundamental) frequency. A SignalHound BB60C spectrum analyzer collects the received signal. Each TX and RX block includes a LP0965 Log Periodic directional antenna for wireless transmission, and a BNC cable is used to connect the trigger channels of both blocks for synchronization.

In the spirit of using only off-the-shelf and relatively cheap components, the system described here cannot fully eliminate the harmonics generated by the TX amplifier, leading to unintentional transmissions (mostly from the coupling of the TX and RX antennas). To avoid the unintended emissions from masking the weaker responses from actual nonlinear targets, we place an aluminum foil screen between the antennas as shown in Figure 2.

3.3 Signal acquisition and processing

We use the terms "capture" or "measurements" to denote data obtained in the following manner:

- Set TX carrier frequency to f_0 and power level to -20 dBm.
- Set RX carrier frequency to $2f_0$ and maximum receive power level to 0 dBm.
- Place target on a tripod in the radar's line-of-sight.
- Set TX to emit a 0.6 ms Continuous Wave (CW) pulse, pull the trigger channel "high" until transmission ends, and set RX to capture twice as long (1.2 ms) to avoid missing the pulse.
- Apply flat-top window to RX-captured IQ data and calculate a Discrete Fourier Transform (DFT).

Additionally, we report the signal strengths for all harmonic responses by averaging the power spectrum over 10 "captures". We selected the TX power level (-20 dBm) so any unintended harmonic emissions were kept below the noise floor, as determined by the reference signals (see Figure 6). We selected the length of the transmitted pulse experimentally to minimize the acquisition time and raw data size; a major problem with this optimization is that the API to communicate with the spectrum analyzer did not allow us extract information about the trigger directly (i.e., when the trigger channel is pulled "high"). Triggers in the SignalHound BB60C are stored in a memory region with a one-to-one correspondence to the IQ buffer; trigger information is represented as binary states (one if trigger channel is "high", zero if "low"). For every data transfer we had to examine the trigger array to find the location of the transmitted pulse in the IQ buffer. Transferring the whole IQ buffer (around 0.6 seconds/100 MB worth of data) guarantees the presence of a trigger, but has the cost of examining large arrays of data for each capture. Continuous transfers of smaller portions of the IQ buffer result in faster trigger lookups but multiple transfers maybe needed to find the location of the pulse. To make the system efficient it was necessary to craft a pulse large enough that only a few "mid-size" reads are required to find the trigger, but small enough that the memory occupied is not a constraint.

In data processing, the DFT window is the most important design parameter. Harmonic radar detection is heavily dependent on changes of received power, so we applied a flat-top window, known to produce more accurate amplitude estimates [17], before computing the transform with the FFT algorithm. Although the received peak power is not dependent on the pulse length, the power estimated from the DFT is affected by the DFT window length. Using measurements taken on a very responsive nonlinear target (an iPhone 13 Pro Max), we tested different window sizes. As shown in Figure 4, the power estimate plateaus at a 4000-point window; thus,

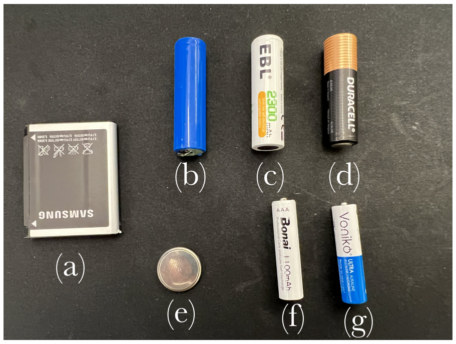


Figure 5: Batteries tested: (a) Samsung Nexus S Li-Ion, (b) Li-Ion 1865, (c) NiMH AA, (d) Alkaline AA, (e) CR20233 coin cell, (f) NiMH AAA, (g) Alkaline AAA.

we chose the closest power of two[1] (i.e., 4096 points) for the DFT window size. For peak detection, we simply chose the maximum value in a bin. This method was simple, fast, and accurate. This simple method may result in an incorrect frequency bin selection (i.e., the maximum peak may not always be at the same bin); since the frequency is known beforehand, it is only necessary to look at the neighboring bins within the spectrum analyzer and signal generator errors. Our spectrum analyzer and signal generator both have a reported error[2] of 2.0 ppm, which results in around 7 KHz of uncertainty from the set frequencies: 2.3 GHz (TX) and 4.6 GHz (RX). In the worst-case scenario, with maximum uncertainty in both generator and analyzer, there can be 14 KHz uncertainty in the DFT center frequency; with the selected DFT size (4096), the frequency resolution is 9.8 KHz;[3] hence, we only need to look at three bins to find the maximum peak, that of the center frequency (bin 0) as well as the two closest neighbors (bin -1 and bin 1).

3.4 Targets tested

We tested both battery and non-battery targets. We tested the non-battery targets to ensure that the harmonic radar was not unintentionally detecting a linear response.

Non-battery targets. To differentiate batteries from other objects, we used three non-battery target configurations: a background response with no objects present, a cardboard box representing a non-reflective object, and an aluminum foil coated box representing a highly reflective object. This test served to quantify the environmental and system generated noise without a target device. Because these reference items do not contain nonlinear junctions, we expected them to display no nonlinear response. In Section 4 we see that is indeed the case, confirming the harmonic radar system works as anticipated.

Battery targets. We tested four battery types commonly found in consumer electronics shown in Figure 5: alkaline, nickel-metal hydride (NiMH), Lithium-ion (Li-Ion), and Lithium-metal.

[1]The FFT algorithm takes advantage of symmetries that result from windows whose size is a power of 2.
[2]1.0 ppm/year with around 2 years of use.
[3]We conducted all experiments at 40 MHz, the maximum acquisition rate of our hardware.

3.5 Experiments

We placed each target item in the radar's line-of-sight at a fixed distance of 35 cm from both TX and RX antennas. We took ten measurements with f_0=2.3 GHz. Perez et al. showed that the harmonic response of consumer electronics is maximal in the region around 2.4 GHz due to the operational frequency range of the target devices [12]. We follow this approach, but selected f_0=2.3 GHz in our experiments to avoid any potential Wi-Fi or Bluetooth interference.

Existing device detection mechanisms based on harmonic radar technology are dependent on differences between the background environment (e.g., no target device present) and the signal received from a target device [1, 2, 12]. In this work we defined 'detection' to mean that observed response was at least 3 dB higher (i.e., double the power) than the background environment. This threshold represents the worst-case detection scenario.

Additionally, we tested a range of values for f_0, from 2.0 GHz to 2.8 GHz in 5 MHz increments, to see whether the choice was significant.[4] This experiment led to a total of 160 signal-strength values across the range, each obtained by averaging 10 repetitions.

4 RESULTS

In this section we discuss the results of our experiments. We found that the harmonic radar did not falsely detect the non-battery targets, and successfully detected each battery type except for the tiny CR20233 coin-cell battery.

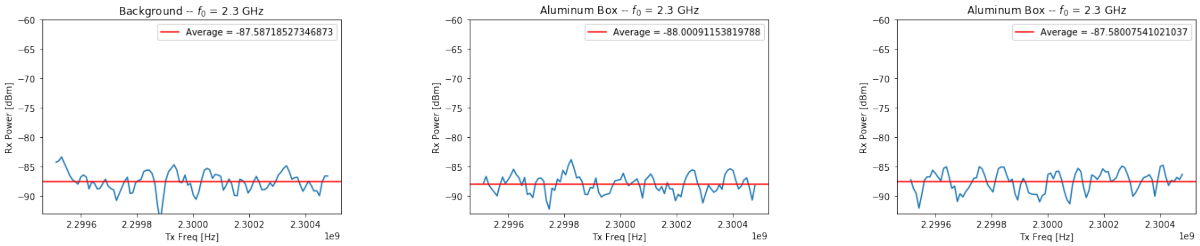
4.1 Non-battery targets

Figure 6 summarizes the measured average RX power for the reference signals discussed in Section 3.4 when f_0 is set to 2.3 GHz. The noise floor of the system is estimated to be -87.6 ± 1.7 dBm as shown by the background capture in Figure 6a. Additionally, the cardboard and aluminum responses, Figure 6b and Figure 6c respectively, serve as a reliability indicator for the chosen frequency and power settings as well as the correct operation of the radar overall. One of the major sources of error for harmonic radars is the reflection of "leaked" energy at $2f_0$ generated by the nonlinear components in the circuit. The fact that both references are within the expected deviation from the average background (e.g., they did not have a harmonic response) confirmed the harmonic radar was working as intended.

4.2 Battery targets at a fixed frequency

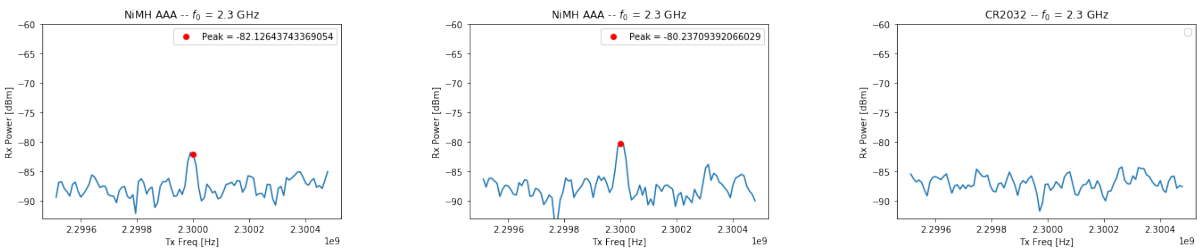
Figure 7 shows that the harmonic radar easily detected the batteries in our testbed using the 3 dBm threshold, except for the CR2032 coin cell. We speculate this result was likely due to the battery's small size. The results are summarized in Table 1. We notice the larger the battery (e.g., AA vs. AAA), the higher the average response. For example, the NiMH AA battery had an average response of -80.0 dBm, but the AAA form factor only had an average response of -82.1 dBm. Recall that due to decibel's nonlinear scale, 3 dBm is a half power point, suggesting the difference of 2.1 dBm may be significant. We intend to examine this characteristic in future work.

[4]Our specific hardware limited our f_0 to the range [2.1GHz, 2.7GHz] using a 200 MHz buffer (100 MHz before and 100 MHZ after).

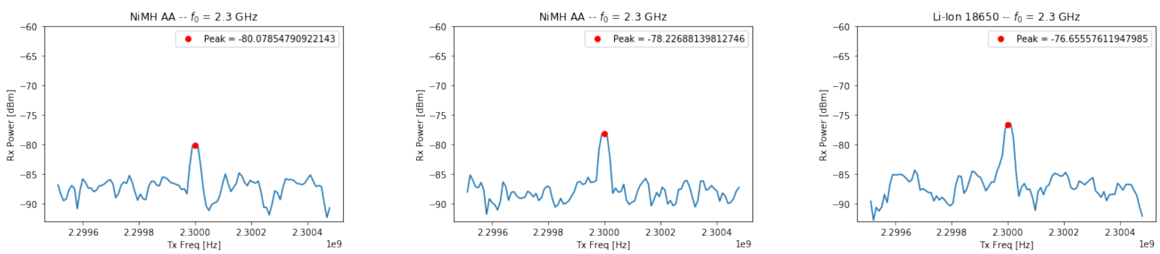


(a) Background Measurement **(b) Cardboard Box Measurement** **(c) Aluminum Box Measurement**

Figure 6: Harmonic response of reference signals. TX frequency set 2.3 GHz and RX frequency set to 4.6 GHz.



(a) NiMH AAA **(b) Alkaline AAA** **(c) CR2032**



(d) NiMH AA **(e) Alkaline AA** **(f) Li-Ion 18650**

Figure 7: Harmonic response of standalone battery cells. TX frequency set 2.3 GHz and RX frequency set to 4.6 GHz.

Table 1: Battery types and harmonic response. Each battery is easily over the 3 dBm threshold, except for CR2032 coin cell batteries.

Battery Type	Response (dBm)	Difference
Background	-87.6	0.0
NiMH AAA	-82.1	5.5
Alkaline AAA	-80.2	7.4
CR20233	**-86.1**	**1.5**
NiMH AA	-80.0	7.6
Alkaline AA	-78.2	9.4
Li-Ion 18650	-76.6	11.0
Nexus S Li-Ion	-80.6	7.0

4.3 Exploring options for f_0

Figure 8 depicts the results of our experiments with a range of f_0 values, for three batteries (Alkaline AA, NiMH AA, Li-Ion 18650). The batteries we studied, including those not shown in Figure 8, do not show much difference in response across the tested frequencies. Small differences in power can be observed throughout the spectrum; such differences, however, cannot be used to distinguish battery types and form factors since they can be easily counteracted by changing the relative distance between battery cells and the radar's antennas. Moreover, the selection of frequency f_0, at least in the range of our hardware, made little difference in detecting the presence of our test batteries.

5 DISCUSSION & LIMITATIONS

The results presented in this paper demonstrate that existing harmonic radar systems are capable of detecting the presence of battery cells. This may become handy in situations where batteries, on their own, represent a security threat – such as checked bags containing Li-Ion batteries in airplanes, or situations where batteries might need to be detected amid other "linear clutter" such as in recycling

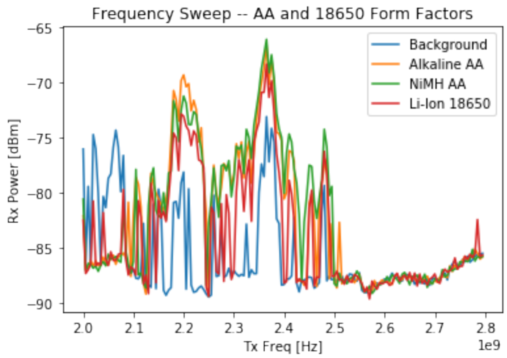


Figure 8: Frequency response for f_0= 2.0-2.8 GHz, for three batteries: NiMH AA, Alkaline AA, Li-Ion 186650. Note that the radar's operational region is 2.0-2.8 GHz.

plants. Nevertheless, the system presented in this work suffers from limitations that we intend to explore further, as follows.

Frequency selection: we explored a range of frequencies f_0 as determined by the capabilities of our harmonic radar hardware. Although these frequencies seem suitable for the detection of consumer-grade electronics, it may be worth exploring a wider range.

Maximum detection range: Previous work shows that harmonic-radar systems are effective at distances up to 2 meters for electronics [11]. We expect a similar range limitation with batteries given the resemblance of their RX traces. The radar's range is dependent on the target's radar cross section and the material covering it, aspects we will consider in future studies.

Multiple Targets: Nonlinear junctions in electronic devices (i.e., transistors) have a measurable harmonic response [1, 2, 11]. Although our results show that batteries, by themselves, produce a measurable harmonic response, we have not tested the ability of the system to detect batteries installed in electronics. The presence of nonlinear components in electronics may affect the overall harmonic response. Moreover, the prototype system has not yet been tested with multiple batteries; differentiating multiple targets with a harmonic radar is an open question.

6 CONCLUSION

In this paper, we characterize the nonlinear behavior of battery cells by drawing parallels between their physical structure to that of rust in metal, which is known to have nonlinear behavior. We also show that their presence can be detected using existing harmonic radars designed for the detection of electronic devices. We studied the harmonic response of four commercially available battery types (Alkaline, NiMH, Li-Ion, Li-metal) under semi-controlled conditions. Our findings shed light on the unexplored area of wireless battery detection, and prompt future investigations on more efficient ways to detect batteries using this technology.

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