# PL-Tags: Detecting Batteryless Tags through the Power Lines in a Building

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**Abstract.** We present a system, called PL-Tags, for detecting the presence of batteryless tags in a building or home through the power lines. The excitation (or interrogation) and detection of these tags occurs wirelessly entirely using the powerline infrastructure in a building. The PL-Tags proof-of-concept consists of a single plug-in module that monitors the power line for the presence of these tags when they are excited. A principal advantage of this approach is that it requires very little additional infrastructure to be added to a space, whereas current solutions like RFID require the deployment of readers and antennas for triggering tags. An additional benefit of PL-Tags is that the tags are wirelessly excited using an existing phenomenon over the power line, namely electrical transient pulses that result from the switching of electrical loads over the power line. We show how these energy rich transients, which occur by simply turning on a light switch, fan, television, *etc.*, excite these tags and how they are detected wirelessly over the power line. We contend that the PL-Tag system is another class of potential batteryfree approaches researchers can use for building pervasive computing applications that require minimal additional infrastructure.

**Keywords:** Ubiquitous computing, Pervasive computing, Tagging, Sensing, Sensors, Power lines, Hardware.

## 1 Introduction and Motivation

Today's computers have seen an astonishing increase in computational and storage capabilities. Battery technology, however, has not followed the same desirable trend. The success of many pervasive and ubiquitous computing systems will be contingent on their self-sustainability. It is neither practical nor desirable to replace hundreds of batteries in large distributed sensor deployments. Scavenging energy available in the environment for use by low-power sensors and electronics offers an ideal solution for many mobile and ubicomp applications.

Motivated by the success of RFID technology, researchers have developed ways to wirelessly transmit energy for the purpose of powering identification tags and sensors

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[15, 20, 25]. The advantages of these batteryless solutions are their potential to be long-lived and their reduction in size requirements. Although these solutions are attractive for future ubicomp applications, they still require the deployment of custom hardware throughout a home or building (antennas and readers in the case of RFID-based systems). In addition, although these solutions may eventually become more cost-effective on an individual unit basis, they are not without some drawbacks. For example, having to install and maintain a collection of readers is time-consuming, and the large number of readers required for coverage of an entire space increases the number of potential failure points.

Inspired by this desire to provide a practical batteryless solution and building on the current trend of leveraging already existing infrastructure [6, 17, 18, 19, 24], we present a proof-of-concept system, called PL-Tags, for detecting the presence of batteryless tags in a building or home through the power lines. The PL-Tag system uses a building's electrical infrastructure to wirelessly trigger and interrogate those tags. The excitation and detection of these tags occurs entirely using the powerline infrastructure. Electrical transient pulses produced by the switching of electrical loads over the power line trigger the tags. These transients occur naturally through the switching of certain electrical loads in a building or home. The power lines naturally radiate these broadband transients as RF energy, which excite the tags, causing them to inductively couple their response back over the power line. A plug-in module that continually monitors the power lines senses the tags' responses.

The PL-Tag system requires only the installation of a single plug-in module that connects to an embedded or personal computer. Unlike RFID, PL-Tags does not require the addition of readers or antennas in the space since the power lines act as the antenna and the plug-in module acts as the reader. In addition, the interrogating signal that excites the tags is a naturally occurring phenomenon found in any electrical system. This opens up the possibility for new interaction where human-initiated electrical events, such as turning on a light or television, cause the interrogation of the tags. Although our current proof-of-concept is limited in its read range (~30-50 cm from the power line), we highlight a new strategy in batteryless sensing and spur interest in this research area.

In this paper, we report the results of a series of experiments to determine the viability of this approach in a variety of settings. We also report the performance results in terms of distance and detection accuracy in a home and office building. Results show that the PL-Tag system can trigger and detect tags up to 30-50 cm from the nearest electrical wiring. Finally, we discuss potential applications, the limitations and potential future improvements for this approach.

## 2 Related Work

Common examples of battery-less systems are those that harvest energy from the environment. Solar power is the most popular and well-known example. Many calculators, landscape lights, and backup power systems use solar energy. Researchers have created a solar-powered node composed of sensors, a processor, an RF transmitter, and solar cells, to collect, process, and forward sensor data to a central wearable device in [3]. They showed the possibilities of energy harvesting through ordinary exposure to sunlight and indoor light for an entire day. Although this solution shows promise in a variety of applications, there may be concerns in dimly lit areas and the sensor may not be enclosed within other objects. Recent research in this area has also targeted temperature differentials [9, 23], low-level mechanical vibrations [1, 2, 14, 26], and other sources of kinetic energy, such as the natural motion of the human body [11, 21, 22].

Tagging systems, such as passive RFID systems, use inductive coupling to remove the need for batteries in the tags. RFID systems consist of an antenna and reader combination that interrogates nearby tags. The MediaCup [7] and commercial projects like electric toothbrushes use inductive coupling to charge a small battery or capacitor for extended use. Other researchers have extended the concept of inductive coupling to remotely charge sensor packs [4]. Researchers have demonstrated wirelessly powering RFID-based sensors using long-range RFID readers [15, 20, 25]. For example, the Wireless Identification and Sensing Platform (WISP) is a passive UHF RFID tag that uses a low-power microcontroller for sensing and communication. More general-purpose wireless power transfer techniques have been demonstrated to power consumer electronic devices [10]. Although these solutions are encouraging for practical ubicomp sensor installations, our focus is to present a different strategy for potentially powering sensors - namely, leveraging an existing infrastructure like the power line as the interrogator. Both approaches have advantages and disadvantages. Thus, specific applications will ultimately dictate the necessary complexity of the additional infrastructure. One can imagine RFID sensors being more appropriate for applications that require the detection of a large number of tags and very high accuracies, where as PL-Tags would be more appropriate for home applications, where there might not be as many tags and costs plays an important role.

Alternatives, such as vibration and motion-powered devices, do not require external powering sources, but the harvesters usually result in extra bulk. Physical motion and actuation, which convert kinetic energy to electrical has proven to be successful. MIT's self-powered switch is capable of wirelessly transmitting a static identification number using the power generated from pressing a spring-loaded igniter switch [16]. The flexing of a piezo plate mounted on shoes can produce enough energy to power a simple wireless transmitter [11]. Commercial products like the Faraday Flashlight use continuous physical motion and magnetic induction to power an LED [5]. Hand cranks have also been integrated into small flashlights and radios to produce temporary power. An off-body example of physical actuation is the Electro-Kinetic Road Ramp in the UK, which generates power each time a car drives over its metal plates [2]. This power is stored to run streetlights and traffic signals.

Detecting tagged objects has also been a long studied problem in ubicomp. Traditional examples include static labels (*e.g.*, a barcode or 2-dimensional glyph) that are placed on an object and read or scanned by some form of reader device. Barcode solutions are typically limited to line-of-sight locations of a camera or optical reader. MIT's FindIT Flashlight uses active tags that respond to an incident laser [12]. A modulated laser signal is used to wake-up and interrogate the tags. An indicator light on the tag notifies the user that the desired object has been found.

Previous work has focused on leveraging the existing infrastructure in a home or building to collect signals at a single location, called infrastructure mediated sensing [17]. Researchers have recently begun exploring the use of existing home infrastructure to detect human originated events, such as using the power lines [18, 19, 24]. A single plug-in sensor can classify events, such as the actuation of a light switch, through the analysis of noise, transduced along the power line, from the switching and operation of electrical devices [18]. Other prior work includes the PowerLine Positioning system [19, 24], which uses existing power line infrastructure to do practical localization within a home.

## 3 PL-Tags Approach and System Details

The PL-Tags system consists of wireless tuned passive tags and a power line interface module (seeFigure 4) that is plugged into any electrical outlet in a building or home. The power line interface is attached to a data collection apparatus and a PC that performs the analysis on the electrical signal. Tags are triggered wirelessly by electrical transients naturally produced over the power line from the switching of electrical loads. These transients are radiated as RF energy that is received by the tags. Tags resonate at their tuned frequency and inductively couple over the power line in response to the electrical transients. The powerline interface isolates and detects both the transient pulse and the resulting “ringing” waveform from the coupled tags over the power line. For this initial proof-of-concept, we tuned each tag to a different frequency in order to identify the triggered tag. The broadband nature of the electrical transient facilitates this effect.

### 3.1 Theory of Operation

Electrical transient pulses are short-lived, high-frequency increases in voltage on the power lines (see Figure 1). Some sources of these transients are the result of the arcing contacts in switches and relays, which are caused by the abrupt switching of high current loads and the sudden actuation of motors and other inductive loads [8,13]. These types of transients are usually normal mode (occurring between hot and neutral). In addition, they are both broadband and high in energy across the entire band, with voltage surges exceeding hundreds of volts. Typically, the rise times are on the order of a few microseconds, with the decay times approximately tens to hundreds of microseconds (see Figure 2). The frequency components of the waveform range from a few kHz to over 100 MHz. Peak voltages for typical electrical devices found in a home are hundreds of volts to a few thousand volts. For example, a motor-type load, such as a fan, will create a transient noise pulse when it is first turned on and when it is turned off. In addition, a light switch connected to a 100 W incandescent light or the relay switch on a television will produce an electrical transient pulse.

Patel *et al.* showed an approach that can be used to train on the duration and frequency characteristics of these transient electrical noise pulses to later determine which device has been actuated when a transient is seen on the power line [18]. Depending on the switching mechanism, the load characteristics, and length of the transmission line, these impulses can be very different. Fig. 2 shows the energy distribution of an electrical transient pulse caused by a light switch connected to a 1000 watt load being actuated. Note the rich number of high amplitude frequency components for each pulse and their relative strengths. If we take a different electrical load, such as a television, the resulting electrical transient pulse is different, but there is still considerable energy across a broad portion of the frequency spectrum.

The operating principle of PL-Tags is that the transient surge can be used to wirelessly induce an RC circuit to resonate (*i.e.* near-field effect), and in turn cause the resonator to inductively couple back over the power line. By tuning the resonator to a known frequency that is both within the high energy band of the transient and is not a harmonic of another signal source, such as a radio station, the presence the frequency can be seen over the power line as an exponentially decaying “ringing” waveform (see Figure 3). In this case, the decay rate is related to the resistance between the resonator and the electrical line. Since there may still be potential ambient noise present at the tuned frequency of the resonator, we use the bounds of the electrical transient to help detect the presence of the ringing waveform. Fig. 2 shows an example of a transient with and without the excited resonator. Note the flat tail at the end of the second transient at 180 kHz, which is the ringing.

The onset of the transient is used to determine the noise floor of the power line right before the onset of the pulse and the end of the transient is used to mark where the ringing waveform should occur. Tuning each PL-Tag resonator to a different frequency that is not a harmonic of another is a simple way to differentiate between tags. We can imagine extending this concept to directly harvesting the power and implementing a low-power load modulation scheme or a DTMF-based scheme for identifying the tags, but our intent with this work was simply to demonstrate the concept. However, the frequency-differentiation approach could be sufficient for applications that only require a small number of tags. Also, note that because PL-Tags relies on the near-field effect, coupling occurs only over short distances (tens of centimeters), with actual distance being dependent on the strength of the transient.

For devices that produce continuous noise, they are still bounded by some transient phenomena, but also exhibit electrical noise during their powered operation. For this class of noise, we are interested in the bounding transients although certain inductive loads might provide continuous energy sources during their operation. For this paper, we only look at these electrical transients.

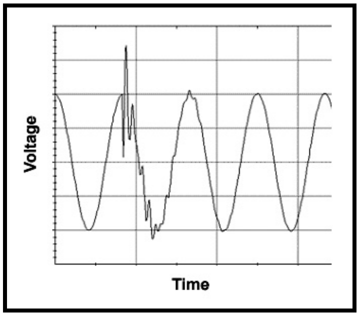


**Fig. 1.** Example of an electrical transient voltage spike

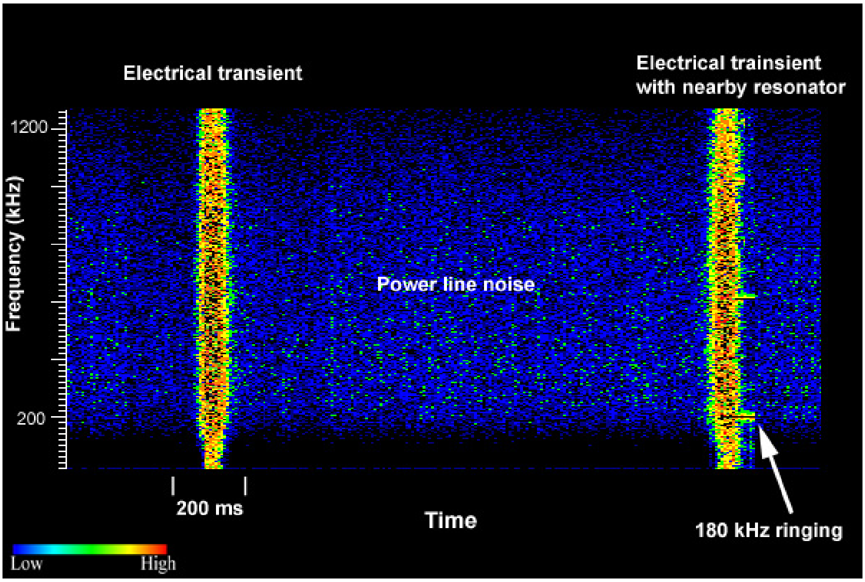


**Fig. 2.** Frequency spectrum of transients with and without a 180 kHz resonator placed near the power line. The second transient shows the ringing at the 180 kHz at the end of the transient.

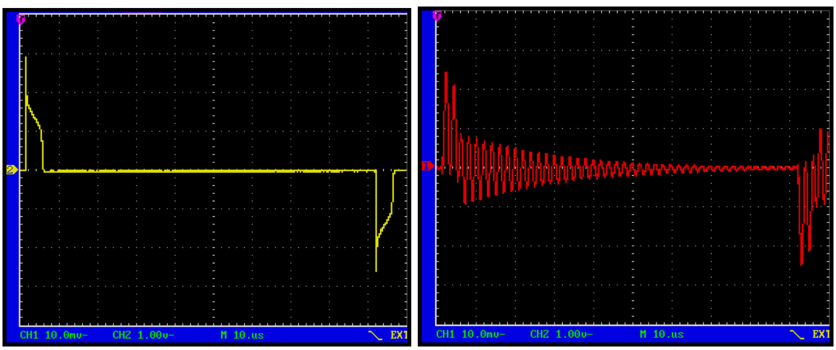

**Fig. 3.** Zoomed in view of a transient pulse (left) inducing the ringing waveform (right) of a tuned resonator

Finally, it is interesting to look at the practicality of using the transients as the "triggering" source from a regulatory point of view. In the United States, the Federal Communications Commission (FCC) sets guidelines as to how much electrical noise AC-powered electronic devices can conduct back onto the power line (Part 15 section of the FCC regulations). Device-generated noise at frequencies between 150 kHz-30 MHz cannot exceed certain limits. Regulatory agencies in other countries set similar guidelines on electronic devices. However, this mainly applies to continuous noise output of electronic devices, such as those that have solid state switching power supplies. Controlling high power electrical transients is a more challenging task and is

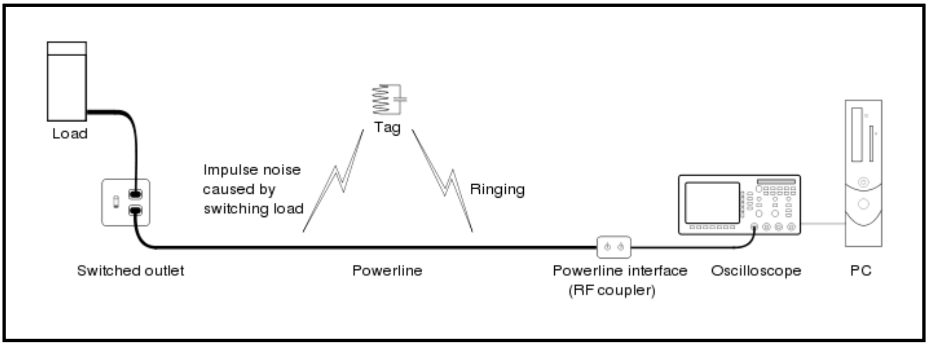


**Fig. 4.** Overview and high-level diagram of the PL-Tag system

often not directly regulated. The generation of electrical transients extends beyond the control of an individual device such as a light switch or television. It is the result of the electrical load of other devices on the power line and the transmission lines themselves. Regulatory agencies usually require sensitive electronic devices to implement proper transient filters within their own devices (IEC 61000-4-4). Thus, there is value in using this naturally occurring phenomenon for interrogating at power levels that may not be allowed by certain regulatory agencies.

### 3.2 Experimental Apparatus Details

The experimental setup consisted of a plug-in power line interface module, an electrical transient pulse generator, and prototypes of PL-Tags tuned at different resonant frequencies (see Figure 4). The plug-in power line interface was custom hardware consisting of two filtered outputs (see Figure 5). The first was a bandpass-filtered output with a passband of 100 Hz to 250 kHz. The second output was bandpass-filtered with a 100 kHz to 50 MHz passband. Both filtered outputs incorporated a 60 Hz notch filter in front of their bandpass filters to remove the AC power frequency and increase the effective dynamic range of the sampled data.

The outputs of the powerline interface were connected to a multi-input 2.5 GHz oscilloscope with a PC interface, which allowed us to capture and transfer signal traces for post processing. Although most of our analysis can be performed in real-time, this method allowed for flexibility during the experimentation. The device produced 14-bit resolution samples with a sampling rate of 40 GS/sec.

The tags consisted of very minimal hardware in which each tag had a tuned LC circuit (see Figure 6 and Figure 7). The simplicity is encouraging from a size and cost point of view. Each tag was equipped with an adjustable capacitor for tuning and a custom wound antenna. We used both a signal generator connected to a transmission antenna and our transient pulse generator to tune the antenna to the desired frequency. For our experiments, we built three different tags. Two of the tags incorporated an air core antenna design, tuned at 135 kHz and 180 kHz. The third was a ferrite rod-based antenna tuned at 135 kHz (see Figure 7). For additional experimentation, we also built a full wave rectifier circuit and loaded it down with a 10k resistor to measure the actual voltage transfer from the transient pulses (see Figure 6).

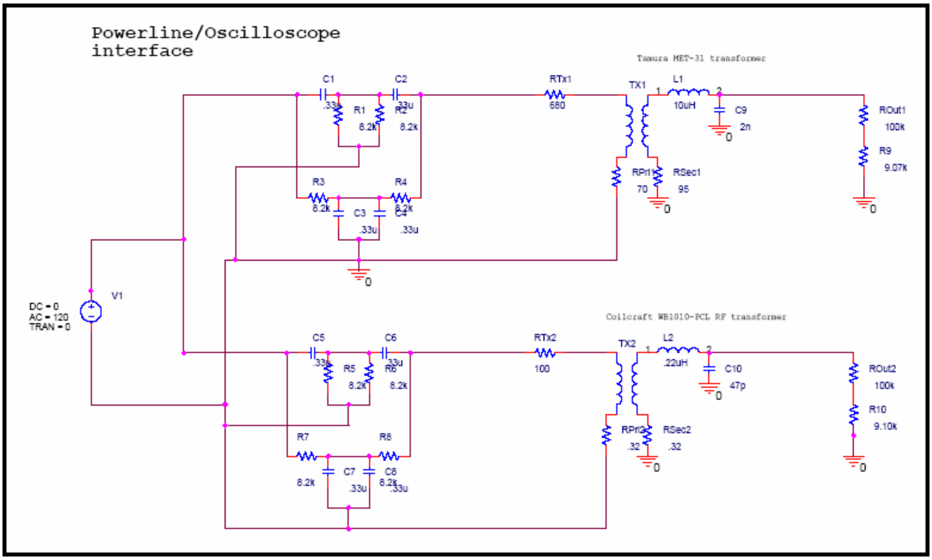


**Fig. 5.** The schematic of our powerline interface device used in detecting the transients and the presence of a PL-Tag

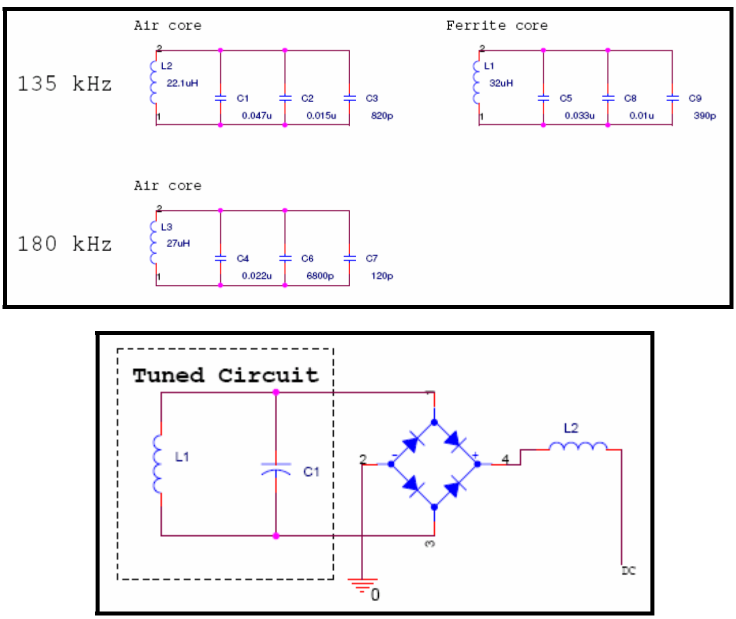


**Fig. 6.** Top: Schematic for the LC resonators used for the tags. Bottom: Setup for measuring the power being coupled to the tag in response to the electrical transients

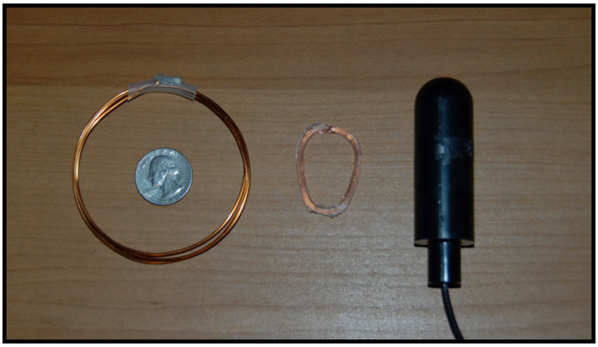

**Fig. 7.** Example PL-Tags. We experimented with both open air coil and ferrite rod antenna designs.

For the software components of our system, we built a C++ application to sample the digital oscilloscope and perform a Fast Fourier Transform (FFT) on the recorded signal. The application allowed us to visualize the entire spectrum and produce the plots presented in this paper. In addition, the application also detected the transient pulses for the recorded signal. We used a simple sliding window algorithm to look for abrupt changes in the input line noise using a threshold value determined through experimentation. The threshold was proportional to the difference between the FFT of the power line noise before the transient and during the transient noise pulse. The sliding window for the transient detector used 1-microsecond samples, which was averaged from the data acquired after performing the FFT on data collected from the powerline interface hardware. Each sample consisted of frequency components and its associated amplitude values in a vector form. Each vector consists of amplitude values for frequency intervals ranging between 50 kHz and 5 MHz. Then a simple Euclidean distance between the previous vector and the current window's vector was computed. When the distance first exceeded a predetermined threshold value, the start of the transient is marked. The window continues to slide until there is another drastic change in the Euclidean distance (the end of the transient), thus allowing us to find the bounding times of the transient.

After having isolated the transient, we inspected the FFT during the onset of the transient and the end of the transient for the known frequency response of the tuned tags. Using the difference between the amplitudes at that frequency, we determined whether a tag is present in the space. In our case, we used a 10% increase in the peak-to-peak voltage at the centered frequency as an indicator for tag being present. Because our experiments were in a quasi-controlled space, this was sufficient for our detection scheme. A future implementation would involve searching over the end of the transient to find the ringing waveforms. If the decay rate and length of the decay is know, those features can also be used in finding the signal (more details in Section 5).

### 3.3 Creating the Transients

We built a portable test apparatus that would reliably and consistently produce an electrical transient noise pulse generated by standard electrical devices found in a building (see Figure 8). Although we could have use almost any device connected to the power line, our apparatus allowed us the flexibility to move the test equipment around. We could have used a signal generator connected to a linear amp to produce similar high-powered noise pulse. However, we wanted to take care to try to match the transient characteristics of standard devices.

The transient generator consisted of a self-contained galvanized gang box with 2 grounded electrical outlets and a 120 V 20A light switch. There was a power cable, which plugged into any electrical outlet power the gang box. The two electrical outlets on the box allowed us to apply various loads in generating the transients. We experimented with a variety of different resistive loads, such as a standard 200 watt light, 1000 watt flood lights, and a space heater to confirm its operation.

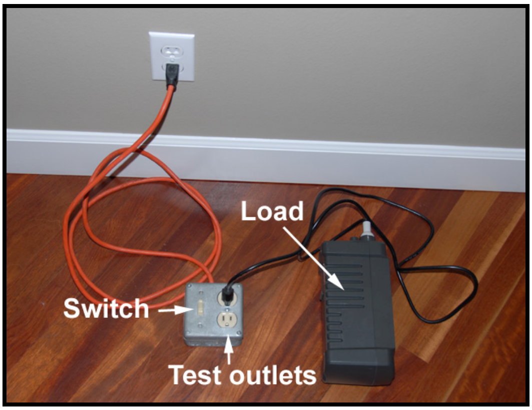


**Fig. 8.** Experimental electrical transient noise generator box. The gang box includes a switch connected to test outlets where the loads are plugged in.

## 4 Feasibility and Performance Results

In this section, we discuss a collection of experiments conducted to determine the feasibility of our transient triggered resonator approach. We attempt to address the following important questions of the approach, including (1) what types of devices generate the necessary electrical transient pulses for this approach, (2) what is the response of the tuned circuit to the electrical transient pulses, and (3) how well can the ringing waveform be detected over the power line?

### 4.1 Transient Generators

Table 1 shows the various household devices used during our experiments to explore the devices that would produce a transient impulse capable of triggering a PL-Tag. The table shows the devices that produced a discernable ringing waveform at the powerline interface module. For these experiments, a PL-Tag was placed approximately a few centimeters from where the device was actuated and the receiver module was plugged in the outlet in the same or nearby room. We found that most loads that drew under 1 A of current did produce detectable transients, but the ringing waveform was not present with our test equipment. A different weak signal detection approach may help discern the signal over the noise. This is what accounts for devices like the microwave door and refrigerator door not being able excite the PL-Tags. We expect other low-power loads would exhibit the same problem. In addition, some microcontroller-based appliances may not directly produce a transient pulse until an internal relay is switched. However, most high current loads like an oven or dryer and inductive loads like an exhaust fan produced enough power to allow us to observe the ringing waveform of the resonator at the powerline interface. We also observed that transients from an inductive load such as a motor create a very strong kickback spike when the load is turned off.

The 1 A load was borderline - in most of the cases it created a detectable signal, however, the signal was only detectable when the plug-in module was located close to the tag location (about 1-2 meters).

**Table 1.** Examples of devices that produced electrical transients capable of causing a PL-Tag to resonate and being able to be detected off the power line

| Devices Observed | Transient Produced Detectable Resonating Signal |
|---|---|
| 100 W Incandescent light and wall switch | Y |
| Microwave door light | N |
| Oven light/door | Y |
| Electric stove | Y |
| Refrigerator door | N |
| Electric Oven | Y |
| Bathroom exhaust fan | Y |
| Ceiling fan | Y |
| Garage door opener | Y |
| Dryer | Y |
| Dishwasher | Y |
| Refrigerator compressor | Y |
| Lights via a dimmer wall switch | Y |
| Garbage disposal | Y |
| Drill | Y |
| Microwave Oven | Y |
| Television (CRT, plasma, or LCD) | Y |

### 4.2 Antenna Response of Tuned Tags

Figure 9 shows the frequency response of the tuned resonator in response to an electrical transient 30 cm from the power line for the 180 kHz tag. The peak indicates the resonate frequency of the tag. Clearly, there is noise across the entire band from the transient, but the response is strong enough to resonate and be detected at the receiver module depending on the distance of the tags to the power line and the distance to the module. Between the air core and ferrite rod antenna design, no one design stood out to be significantly better than the other. Thus, we conducted most of our experiments with the air core, because of its more compact size.

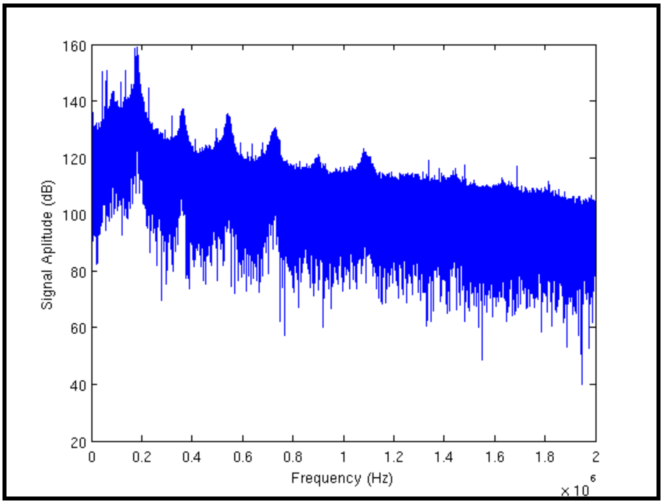


**Fig. 9.** Frequency response of a 180 kHz tuned resonator excited by an electrical transient. Note the peak at the resonate frequency

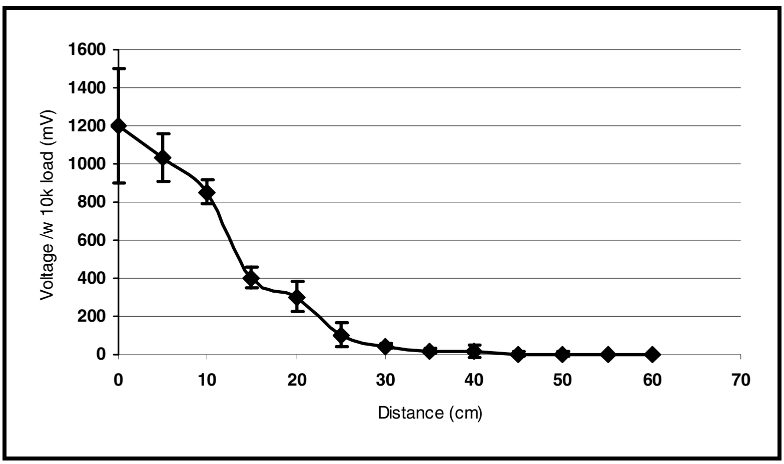


**Fig. 10.** Voltage across tuned tag loaded down with a 10k ohm load at various distances from the power line

In Fig. 10, we show the voltage induced off the PL-Tag when run through a Schottky-based full wave rectifier and a 10k ohm load. Readings were taken at increasing distances and there is a quick drop off as the tag moves beyond 30 cm from the closest power line. Although these are very short-lived responses from the transient pulse, there might be some hope of actually harvesting power for potential onboard processing with a new antenna design and using very low noise components.

### 4.3 Tag Identification over the Power Lines

In order to stay with a batteryless tag, we use a simple inductively coupling approach to detect the presence of the tag. Each tag is assumed to be tuned at a different frequency and the presence of the tag is determined by searching the frequency space for the appropriate ringing tags at the end of an electrical transient pulse. We used this simple approach to demonstrate the proof-of-concept, but could imagine extending it incorporate a low-power modulation scheme.

For the tag identification experiments, we used our transient generator box connected to an inductive load (a 15-amp power drill) and a resistive load (a 500-watt light). We used both of these loads to generate transients in different locations around a home and office building to determine how accurately we could detect the ringing response of the tags over the power line. We used our transient detection application (see Section 3) to determine the absence or presence of the tags. Figure 11 shows the results of the experiment at various locations using the two different transient generators. We report the read accuracy (the percentage of time the tag was detected) as various read distances. We controlled both the distance between the tag and the electrical system as well as the distance between the tag and the power line interface module. With the powerline interface a fixed 2 meters away, the maximum read distance for the tag was about 40-50 cm, but at very low detection accuracies. The usable range appears to be about 30-40 cm away from the closest electrical wiring. Also, the closer the plug-in module is installed the higher the detection rate. With the tag 20 cm from the power line, the farthest the module could be installed for our proof-of-concept was about 4 meters. Reliable distances at which tags could be detected were in the 2-3m range. Moving to a higher resonate frequency would help with longer read ranges. However, there is a limit, because as we get higher on the frequency band the shorter the ringing waveform will last (faster decay rate) after the end of the transient. This tradeoff needs to be explored in more detail for extending the range of this system. The false positive rate was quite low in our experiments, because of the quasi-controlled nature of the space. However, of the approximately 120 total read cycles, we had 8 unintentional triggers. Most of these occurred in the office building, where other loads were being actuated that were not under our direct control (HVAC system and motion-powered lights). Although we did not experience these, another potential false triggers could result from lightning strikes.

The results also indicate a slight difference in the read accuracies based on the kind of load generating the electrical transient pulse. We would have expected the greater load (the 500-watt light) to produce better results, but it turns out the lower powered inductive load performed better in this case. Possible reasons for this might be that the continuous noise generated by the device contributed a better chance for the tag to be detected or the noise pulse generated by the drill is considerably wider than that of the resistive load.

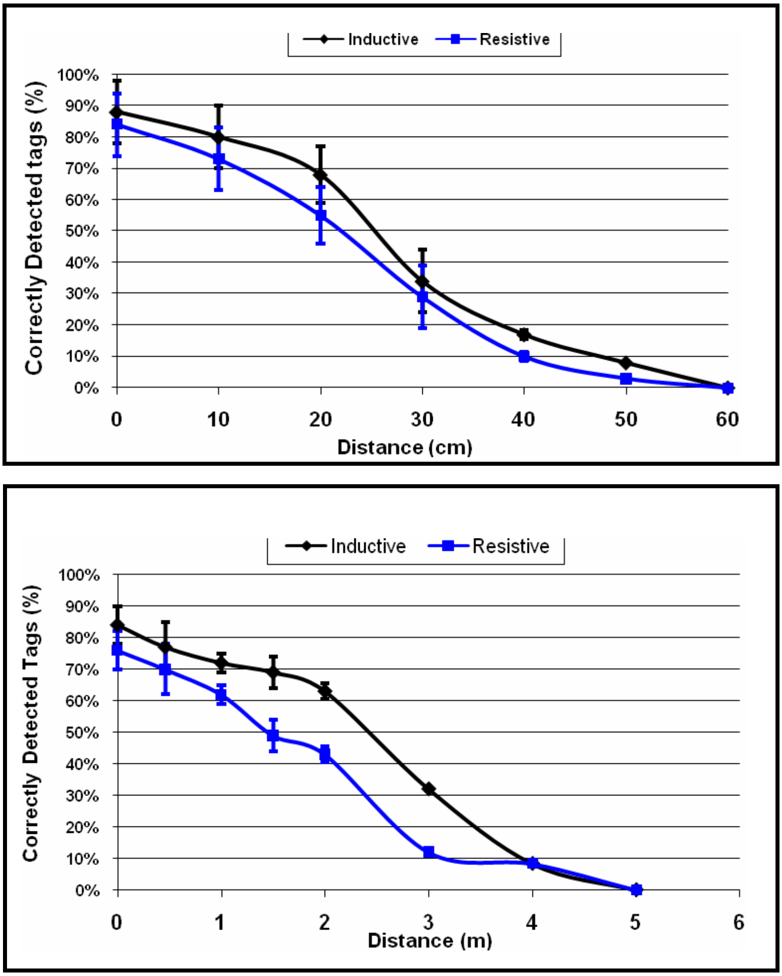


**Fig. 11.** Average read accuracy of PL-Tags at various locations in a home and commercial office buildings using transients created with an inductive and resistive load. Top: This graph shows the accuracy rate (the percentage of successful detections by the receiver module) for various distance of the tag from a electrical wiring. The position of the receiver module was a fix location 2 meters along the power line from the tag (same room). Bottom: This graph shows the accuracy rate of a tag located at a fixed 20 cm from the electrical wiring, but varying the distance of the plug-in receiver module. The distance is an estimate of the electrical wiring distance between the module and the closes wiring to the tag.

## 5 Discussion and Future Work

The results of a batteryless tag powered by a transient impulse are encouraging. However, there is still a significant amount of future work that remains. The current detection range is 30-50cm. Despite the short range, there are still some applications and usage scenarios in which this might be feasible. The first is for finding lost items, where tagged items can be queried by a portable device that a person plugs in the wall (similar to our transient generator) or by the nearest electrical device that could generate a strong enough transient pulse. Another use of this approach is the ability to identify who actuated an electrical device in the space if people were to wear the tags as a bracelet. More specifically, the approach shown in [18] would be used to determine which device was actuated and then using the approach outlined in this paper to determine the identity of tag. This would be useful for smart home applications, where the identity of the person using the device would be useful information. In addition, this approach could also be used to determine who uses what electronic devices for energy monitoring applications.

Another application is to detect the absence of a tagged item, such as item missing off of a night stand. PL-Tags can also be used to detect if a tagged book was removed from a shelf or if a tagged medicine bottle was removed from a cabinet (assuming the bookshelf is against the wall and there is electrical wiring near the cabinet). One can also imagine a homeowner simply running an extension cord near places of interest to extend the coverage of the PL-Tag system. The limited or short read range could be used as an advantage when trying to localize where the tag may be located in the environment.

Despite the current limitations of the PL-Tags proof-of-concept, the advantage of this approach is the use of an existing infrastructure that is already available in the space. In addition, a unique aspect of this approach is that the exciter is also a naturally occurring phenomenon over the power line. Thus, we can have applications where human-initiated electrical events can be used to query the tags in the space. For example, we constructed a simple door micro-mechanical open/close sensor that is excited by the nearby wall switch. The micro-switch switches between two different capacitors causing the tag to resonate at one of the two different frequencies depending on the state of the contact switch. The power line interface detects the state of the switch, which can in turn trigger a secondary action (notifying the person).

We acknowledge that the 30-50 cm range limits the number of applications, but extending the range to even 1m would substantially increase the application space. Part of this limitation is because of the near-field nature of the system. Exploring far-field effects by trying to harvest the coupled energy from the transients is a potential way of extending the range. However, we believe the detection range can be extended to 1m by designing a new antenna and employing a weak signal detection scheme for the receiver (similar to those used in powerline communication systems).

Our current approach used minimum components to reduce the complexity, but we can improve the performance by building a tag that has a sharply defined resonate frequency. In particular, one strategy to be considered is to maximize the resonator's Q by using teflon insulated wire and high-Q capacitors and producing the highest practical L/C ratio. The antenna can be enclosed (not necessarily encased) by low-dielectric-constant plastic like ABS or teflon in order to keep some distance between the antenna and other nearby components and objects.

With the current proof-of-concept, our read distance along the power line is also fairly short (3-4 meters). Part of the problem is that the near-field effect has a sharp drop off. So, the use of wavelet transforms instead of a traditional FFT could also be used to help identify the ringing waveform and potentially increase the detection accuracy of weaker signals, which would also help increase the tag read range. A better solution is to employ a weak signal detection scheme. This would work by passing the received signal through two filters. The first filter would be matched to the tag frequency and the second filter at a slightly higher or lower non-tag frequency and then the decay envelopes of the filters would be compared. With no tag present, both envelopes will be similar. With a tag signal, the first filter's envelope will decay more slowly than the second filter's envelope. The filters can be implemented in a DSP chip as autocorrelation filters, where a delayed version of the signal is multiplied by itself, causing reinforcement at a frequency determined by the delay time. This will increase sensitivity at the expense of "smearing" the decay envelopes. A Duffing oscillator will be more sensitive than autocorrelation, however its reference (internal driving) frequency must exactly match the tag frequency.

Although we did not measure it directly, we also found orientation to cause variations in the read accuracy, thus for all the experiments we took care to keep the tag orientation consistent. RFID and other inductively coupled techniques have similar problems. Although the main goal of this paper was to leverage already existing systems, it would be interesting to investigate how we might built a custom transient generator that would “shape” the most effective signal to increase the read distance. A signal can deliberately be generated to excite the tags instead of using transients. Another solution would be to install multiple plug-in modules throughout a home or building that would “repeat” the detection of a tag to other modules. In this case, we would be leveraging the power lines both for interrogating the tags and for communicating back to a central module. Although adding more modules increases the amount of hardware required in the deployment, we believe the potential cost effectiveness and ease of installation are still advantageous.

For simplicity, we mainly focused on a single tag in read range at any given time. However, we did conduct experiments with two tags being inductively coupled simultaneously and were able to identify both of them (Fig. 2 actually shows two ringing waveforms from two different tags). Obviously, in practice there would be many tags that would have to be read simultaneously. This also argues for a modulation scheme or frequency shift keying, which is the focus of our future work. A simple strategy is to chirp the tag. A tag built with capacitors makes a single frequency pulse, where as tags constructed with varactor diodes produce a broader range of sharp frequencies pulses. At the receiver end, the detected chirp will exhibit a decrease in the frequency with time. The chirping may enable decomposing multiple tags appearing in the environment. Another approach is to use a DTMF-like approach with two- or three-frequency tags with frequencies widely spaced to prevent coupling between the coils. Crystals can be used to stabilize a tag's frequency output (by placing the crystal in series with the inductor and capacitor). Finally, another low-power strategy is to use an amplitude modulation. For example, some backscatter RFID tags use a FET across the LC circuit to amplitude modulate the output. PL-Tags can accomplish this by using micropower oscillator chips that would drive the FET.

## 6 Conclusion

We presented a system, called PL-Tags, for detecting the presence of batteryless tags in a building or home through the power lines. The excitation (or interrogation) and detection of these tags occurs entirely using the powerline infrastructure in a building. The PL-Tags system consists of a single plug-in module that monitors the power line for presence of these tags when they are excited. Although the results of this approach are still preliminary, the primary advantage of this approach is that it requires very little additional infrastructure to be added to home or building. An interesting additional benefit of PL-Tags is that the tags are excited using electrical transient pulses that result from the switching of electrical loads over the power line, which is an existing phenomenon over the power line. We showed how these energy rich transients, which occur by simply turning on a light switch, fan, television, *etc*, can excite these tags and be detected over the power line. This approach highlights another class of batteryfree sensing approaches that leverage already ubiquitous infrastructure in a building, and we intend to expand interest in this line of research. We also discussed potential new ways of improving the performance of this approach and increasing the tag detection range.

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