PLatter: On the Feasibility of Building-scale Power Line Backscatter

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Abstract

This paper explores the feasibility of reusing power lines in a large industrial space to enable long-range backscatter communication between a single reader and ultra-low-power backscatter sensors on the walls that are physically not connected to these power lines, but merely in their vicinity. Such a system could significantly improve the data rate and range of backscatter communication with only a single reader installed, by using pre-existing power lines as communication media. We present PLatter, a building-scale backscatter system that allows ultra-low-power backscatter sensors or tags attached to walls with power lines right behind them to communicate with a reader several hundred feet away. PLatter achieves this by inducing and modulating parasitic impedance on power lines with the tag toggling between two loads in specialized patterns. We present a detailed evaluation of both the strengths and weaknesses of PLatter on a large industrial testbed with power lines up to 300 feet long, demonstrating a maximum data rate of 4 Mbps.

1 Introduction

This paper asks "Can we read ultra-low-power sensors in a large industrial or commercial building with a single reader using the power line system?" Given the significant cost associated with retrofitting an industrial building, a wired network for IoT installation is not desirable. On the other hand, long-range wireless networks are either power-hungry (e.g., WiFi or cellular), or support a very low data rate (e.g., LoRa). In this paper, we explore an alternative approach by combining backscatter and power line communication technologies. Backscatter systems [24, 16, 43, 12] are popular for their ultra-low power consumption, suitable for battery-free objects and low-power sensors. However, they are notorious for their short operation range (e.g., a few cm to 10 m). There has been some research on extending the range of backscatter systems [42, 39, 23], but they either work only outdoors and in line-of-sight scenarios, or support a very low data rate. To address these limitations, this paper proposes to use the power line system, an existing framework that pervades nearly all buildings and spreads along the walls to every room, as a *wired-wireless medium* to read backscatter tags attached to the walls, thus enabling long-range, high data rate backscatter with a single reader.

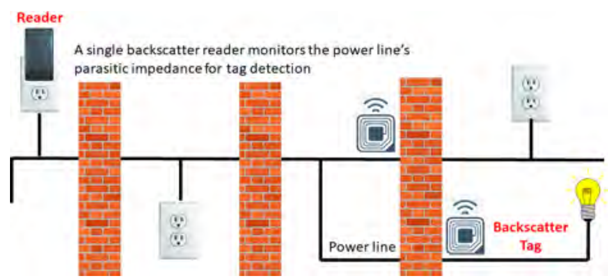


Figure 1: PLatter leverages the pre-existing power line infrastructure to provide long-range backscatter communication between backscatter tags and a single reader.

Consider an industrial IoT context where backscatter sensors, powered by coin-cell batteries, monitor lighting, temperature, or fault conditions, and can be conveniently attached to the closest available walls or ceilings, just a few cm away from the ubiquitous power lines passing behind. A single reader plugged into an outlet can then read their data even when they are way out of the wireless communication range or significantly obstructed. There exists a rich literature in using power lines for communication [10, 45, 6, 41], positioning [31, 48], synchronization [34, 44, 35], sensing [20, 29, 30, 9, 14, 8], or as a source to harvest stray electromagnetic energy [21, 19]. One naive approach is to directly attach the IoT sensors to power outlets and use traditional power line communication. However, this limits the number of sensors and their locations to only a few outlets available in each room. Instead, we leverage existing power lines for backscatter communication by attaching a single reader to the power line and placing ultra-low-power tags any-where along the power cables.

This paper explores the feasibility of such a building-scale backscatter system (Fig. 1), PLatter[1], where the power lines enable a single reader to receive sensory data from multiple ultra-low-power tags that are well beyond its RF communication range. PLatter's design leverages fluctuations in the parasitic impedance induced to the power line system by the backscatter tags as they toggle between two loads. In principle, conductors close to the power lines give rise to parasitic impedance; it is usually unwanted, though unavoidable, for applications where these conductors function by coupling with the power lines [18]. In PLatter, however, we leverage this as a benefit. Specifically, the PLatter reader measures the RF characteristic impedance of the power line by injecting a carrier signal into the power socket. The key enabler here is the terminating impedance mismatch of the power line due to the outlets in other rooms that are either left open or connected to appliances with mismatched impedance. This creates a reflected wave back to the reader. Meanwhile, each tag attached to the walls toggles between two internal impedance values (instead of high-power radio transmission), inducing recurrent patterns of parasitic impedance to the power line. This fluctuation is minute enough to ensure no harm to the normal operation of the power grid, but is readily detectable and decodable by the PLatter reader. Therefore, PLatter tags can function at much lower power because they do not need an active radio front-end. Instead, they only need an antenna with impedance switching capability to couple with the nearest power line.

The core challenge, however, is that the power line cables are designed to deliver AC power signals at 50/60 Hz and significantly suffer from impedance mismatch and signal attenuation in Radio Frequency ranges. A high impedance mismatch between the reader and its power line interface can result in a significantly high reflection coefficient, preventing the carrier signal from entering the grid and impacting communication. In addition, the characteristic impedance of power lines varies depending on cable length and geometry, which complicates the impedance matching circuitry even more. Further, the impedance at the reader interface may change over time as appliances are turned on/off or switch their operating states. This creates a standing wave inside the cables that varies with time, which significantly affects the performance of the backscatter network.

To overcome these challenges, we design an intelligent reader with adaptive frequency and impedance tuning capabilities to actively maintain tag detection. As such, the reader constantly monitors the input impedance of the cable and will accordingly tune the injected carrier frequency or the on-board impedance matching network to discover tags. In addition, PLatter also adapts to new appliances connecting to terminal outlets. The key intuition is that any change in the power line network causes a spike in the characteristic impedance, which is detectable by the reader and can be adapted to.

The second challenge is the design of an ultra-low-power tag that can create detectable parasitic impedance changes in the power line infrastructure. For this, we design a backscatter tag that switches between selected load impedance values to induce a distinct modulation pattern on the parasitic impedance sensed by the reader. We further improve tag detection by applying MAC-layer coding (e.g., PN codes) specifically for larger power line networks (e.g., in a warehouse). This also enables multi-tag detection by leveraging orthogonal codes per tag. Finally, in support of an ultra-low-power tag architecture, we design PLatter as a unidirectional network where data only flows from the tags to the reader. This greatly simplifies the tag circuitry by not requiring any envelope detector, digital signal processing, or decoding module. We show that this design choice reduces the tag power consumption to as low as 5 μW, with which a tag can operate for 12.9 years on a coin-cell CR2032 battery.

We show the feasibility of PLatter with custom backscatter tags at 13.56 MHz, which are compliant to FCC regulations and safety measures, and two USRP N210 software-defined radios emulating a mono-static full-duplex reader with custom PCB front-end that enables dynamic impedance tuning and notch filters to safely connect the reader to active power lines. We deployed PLatter in an industrial environment with more than 952 m^2 floor space, along with up to 300 feet (91 meters) power cables in various geometries (Sec. 8.2), in non-line-of-sight (NLoS) and dynamic scenarios (Sec. 8.4), and with active power (Sec. 8.6). We show that PLatter enables ultra-low-power backscatter communication that achieves up to 4 Mbps data rate while only consuming 5 μW power at the tag.

Contributions: Our core technical contributions are:

- A building-scale backscatter communication system leveraging the power line infrastructure to achieve up to 4 Mbps data rate over 300 feet power cables.
- A novel parasitic impedance modulation scheme by varying the parasitic impedance that a PLatter tag induces on power cables through near-field coupling.
- A detailed evaluation of an intelligent reader architecture with dynamic impedance tuning and frequency selection capabilities for power cables with arbitrary shapes and connected appliances.

Limitations: In this paper, we focus on extensively evaluating the feasibility of backscatter communication through the power line system. However, there are many

[1] PLatter: Power Line Backscatter

different factors that can affect the performance of the system, which require extensive follow-up exploration. For example, while PLatter tags can be read through long cables, the wireless medium between the tag and the surface of the cable is still limited to a few tens of centimeters, limiting the tag placement only on walls and ceiling along the power cables. Sec. 9 further elaborates on the limitations and future research directions.

2 Background and Related Work

While the power lines inside homes and buildings are primarily designed to carry high voltage 50/60 Hz AC signals for power distribution, they can also be used to communicate data at higher frequencies by acting as a transmission line, a transmitting antenna, or a receiver. According to basic electromagnetic theory, a time-varying current in a wire will produce an associated time-varying electromagnetic field around the wire. Since the power lines in a building are essentially a collection of wires, they can be potentially used as antennas. Using power lines as RF antennas has been explored in various contexts since the 1920s [17]. Several works describe various forms of a line cord antenna [25, 46, 44], whereby a receiver is coupled to the power line to receive high-powered broadcasts from TV or radio stations. Power lines have also been examined as transmitting antennas to either distribute AM radio broadcast signals over the main power distribution grid, known as carrier current [11], or as intentional radiators for cordless phone system transmitter or in-home video distribution [37].

This paper explores the feasibility of enabling long-range ultra-low-power backscatter communication using power line infrastructure by measuring the parasitic impedance induced by nearby backscatter tags. The rest of this section elaborates on other related work in both the power line and backscatter contexts.

Power Line as a Transmission Line: In a Power Line Communication (PLC) network, both transmitters and receivers are connected directly to the power line and communicate their data directly over the line. This has been widely used in home automation tasks, leading to protocols such as X10 [3], Insteon [1], and HomePlug [45]. Smart metering is currently a leading application for these systems. Today, high data rate PLC is a commercial reality known as broadband over power lines (BLP), and BLP modems can be purchased for various home or office applications with OFDM PHY layer and CSMA/CA MAC layer protocols.

Power Line as a Transmitting Antenna: Carrier current [11] is a popular method from the 1970s that uses the power lines as transmitting antennas for low-power AM broadcasts. A carrier current system can cover an entire building or even a group of buildings at low transmission power, which makes it ideal for localized radio such as college and high school radio stations. Power Line Positioning (PLP) is another technology that uses power lines in a building to track the location of small sensors throughout the home [36, 32], or detect the presence of objects, people, and their activities [20, 29, 30]. Both of these technologies rely on lower radio frequencies (e.g., 300 kHz to 20 MHz) for best performance. Similarly, leaky feeder systems [26] use a coax cable running along the tunnels, underground mines, or railways for emitting and receiving radio waves, functioning as extended antennas. However, the cable is specifically designed for radiating, with slots cut into the outer shielding. PLatter purely relies on existing power line infrastructure in any building to read backscatter tags.

Power Line as a Receiving Antenna: Early research on power line position systems demonstrated that both AM and VHF FM radio broadcasts can be also heard and demodulated by the power line as a receiving antenna [13]. SNUPI [10] and more recent follow-up work [37] have also shown a uni-directional communication network from wireless sensors to base stations attached to home power lines. However, the sensors are still actively transmitting high-power wireless signals, which are then sensed by the receiver attached to the power line. In contrast, PLatter allows the tags to be ultra-low-power by eliminating the need for an active radio front-end.

Wireless Backscatter Communication: Traditional backscatter networks such as RFID [43] and NFC [12] rely on energy harvesting from a carrier wave to power battery-free tags, which then send sensory data to the reader. However, a majority of these networks are limited to either a short range (< 10 m) or a low data rate. Recent work on LoRa [39, 23] and WiFi backscatter [7, 47] target these challenges by either using LoRa-compliant chirp signals to extend the range, or more complex modulation techniques such as OFDM to improve the data rate. However, some of these backscatter systems still assume a separate power source in the near proximity of the tags or are limited to line-of-sight scenarios to achieve long-range communication. NetScatter [23] is the closest wireless backscatter network that provides multi-room coverage by using chirp spread spectrum coding, but at the exchange of a reduced data rate of 100-150 kbps.

In contrast to this rich prior work, PLatter explores the feasibility of a building-scale backscatter communication with up to 4 Mbps data rate using the power line infrastructure already available in every building.

FCC Rules and Regulations: Power line communication and carrier-current systems are generally considered as "Restricted Radiation Devices" under Part 15 of volume 11 in FCC rules and regulations, which specifies the

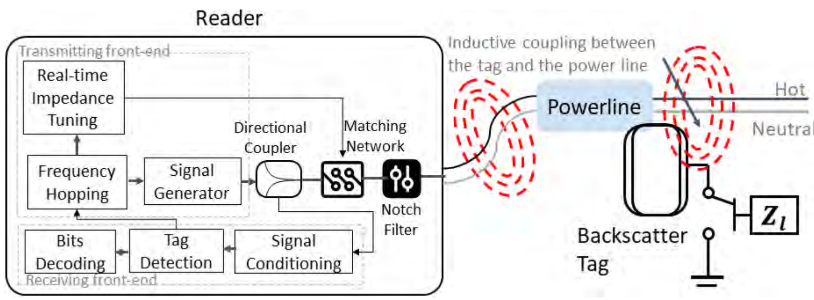


Figure 2: PLatter Overview

maximum electric field strength that an EM radiator is allowed to emit. To comply with these regulations, PLatter is specifically designed as unidirectional and is only relying on the induced parasitic impedance; hence the tags are not designed to emit wireless radiation. In addition, the EM field strength meter shows compliant readings around the cables as PLatter reader injects carrier signals. Our current implementation exploits the unlicensed ISM band at 13.56 MHz, which also makes PLatter compatible with NFC systems.

3 PLatter Design

In contrast to typical backscatter systems, PLatter leverages the existing power line infrastructure to increase the communication range between ultra-low-power tags and a single reader. Attached to an outlet, the reader continuously measures the characteristic impedance of the power line and looks for variations in parasitic impedance to detect and decode the tags' data. To minimize power consumption and network complexity, PLatter is designed to be unidirectional from the tags to the reader for upstreaming sensory data to the reader. Therefore, the tags perform modulation whenever sensory data needs to be sent, independent from the reader operation. Meanwhile, the reader performs real-time impedance tuning and frequency adjustment to adapt to network changes. Fig. 2 shows an overview of PLatter.

Designing Reader's Transmission: The reader's signal is not only subject to attenuation and noise, but also susceptible to appliances being turned on/off. In addition, it experiences frequency-selective fading due to the standing waves. To mitigate these, PLatter adopts an adaptive reader design that continuously monitors network changes by measuring the input impedance. It hops towards a favorable frequency if the current carrier signal is heavily attenuated, or performs real-time impedance tuning with an impedance matching network at its interface to the power line network. Sec. 4 elaborates our design.

Tag Design and Data Decoding: Sec. 5 details the tag hardware, its modulation scheme, and a decoding pipeline. PLatter's modulation scheme leverages the fact that electromagnetic fields of high-frequency injected signals into power lines couple with other nearby conductors. Hence, as long as the carrier signal traverses the power line (reader's task in Sec. 4), one can enable long-range backscatter via the power line by coupling with ultra-low-power tags along the power line. Sec. 5 elaborates this modulation scheme and further shows how PLatter achieves robust and efficient tag detection and decoding with low-cost and low-power tag circuitry.

4 Designing Reader's Transmission

In this section, we first describe PLatter's power line backscatter channel model (Sec. 4.1) and the choice of frequency band of operation (Sec. 4.2). We then detail two key reader designs: (1) adaptive frequency hopping (Sec. 4.3); (2) real-time impedance tuning (Sec. 4.4).

4.1 Power Line Backscatter Model

In PLatter, the carrier signal from the reader propagates through electric wires and various discrete components such as transformers. Part of the signal attenuates, while the remaining energy gets reflected in the case of impedance mismatch at the termination. The end result is a standing wave that operates on the wire. This wave is further modulated due to the presence of backscatter tags as it switches between different impedance values, modulating the wiring system's overall impedance.

Power Line Channels are Frequency-selective: A natural property of the standing wave created on the wire is that it has several nulls whose locations are dependent on frequency. To see this in practice, Fig. 3 illustrates the attenuation in typical NM-B 14/2 power cables of different lengths (25, 50, and 100 feet). A single tone (0-1 GHz) is injected into the cable and the reflection characteristic (S11) is measured while the other end of the cable is left open for minimal terminating loss. We see that the attenuation increases with both frequency and cable length. In addition, the non-linear behavior of the cable at certain frequencies is due to impedance mismatch, which leads to standing waves, or high reflection at the entrance of the cable.

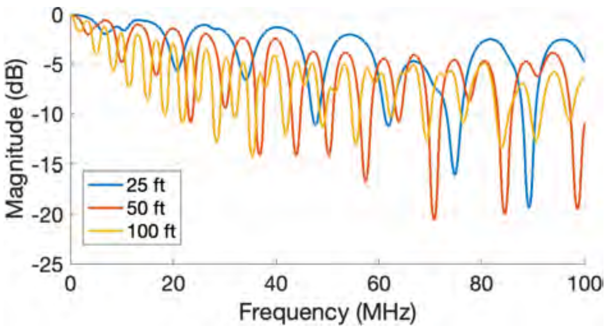


Figure 3: Reflection characteristics (S11) of cables with different lengths demonstrate the standing wave effect and attenuation trend as frequency and cable length vary.

Time-Varying Channels: The power line channel has been widely studied. Much like a traditional wireless channel, it also exhibits multipath effects due to the superposition of various signal paths. We refer the reader to [27] for a detailed channel model. Two points are worth noting: (1) appliances can greatly influence the power line channel both by injecting high-frequency noise and changing the system's overall impedance; (2) some elements, such as a charged transformer, may cause periodic time-variations in power line channels [28]. These, if any, fall around the order of *ms* and can simply be avoided by modulating signals of the order of μs.

Why can the reader sense tags' modulation? To understand how the tag modulation is detectable, we refer to Ampere's law [22], where a magnetic field is generated by a group of closely bundled wires and the current flowing through them. For the power line infrastructure, the hot and neutral wires carry currents in the opposite direction, canceling the magnetic field generated by the 50/60 Hz AC signal. It is, however, possible to create an electromagnetic field when injecting a higher frequency signal (e.g., for the purpose of impedance measurements). In this case, the power line can be crudely visualized as a gigantic coil, causing near-field inductive coupling with a secondary coil (e.g., the backscatter tag), as shown in Fig. 2. For modulation, the tag alternates the load on its coil and creates a varying parasitic impedance that can be detected by the reader (more details in Sec. 5).

4.2 Choosing Frequency of Operation

Given the mono-static setup of PLatter's reader, we first study the reflection behavior of multiple power lines across a wide range of frequencies between 0-100 MHz, shown in Fig. 3. While we observe a gradual increase in the amount of signal attenuation with length and frequency, the attenuation at 10-20 MHz is comparatively small across different lengths of cables, with reasonable sizes of (coupling) antennas. This allows the reader to receive a reflected signal for the purpose of computing

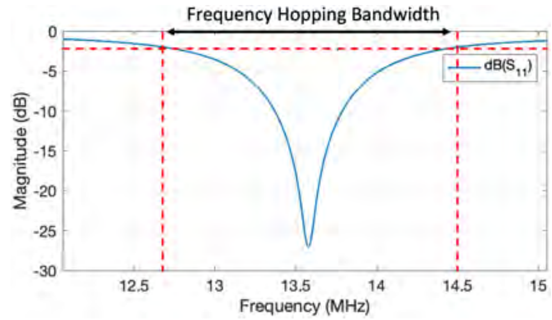


Figure 4: A typical NFC antenna resonates at center frequency 13.56 MHz and minimum of 50% antenna delivery for a $\sim$ 2 MHz bandwidth.

impedance. Among the frequencies below 20 MHz, we choose to design PLatter in the unlicensed ISM band of 13.56 MHz. This makes PLatter inherently compatible with NFC in terms of tag antenna design.

To select the operating bandwidth, we need the tag antenna to resonate well over the entire bandwidth, so that it can effectively induce the desired parasitic impedance variations for data transfer. To examine this, we select an off-the-shelf NFC antenna [2] with a center frequency of 13.56 MHz. As shown in Fig. 4, the antenna has a highly narrow beam, but we can still expect about 50% of delivered power on frequencies between 12.5 MHz and 14.5 MHz (i.e., reflection powers below -2.92 db). Therefore, we select this bandwidth for frequency hopping with potential steps of every 500 kHz.

4.3 PLatter's Frequency Hopping Design

The core challenge in designing PLatter is the potential standing wave effects due to the impedance mismatch between the power line and the reader, which create deep nulls at certain positions along the cable. The key intuition that PLatter leverages is the frequency-selective behavior of the power line. Specifically, while one frequency can cause a deep null at certain location along the cable, the effect could be completely reversed at a slightly different frequency. An example of this is shown in Fig. 5, where we see more than 5 dB improvement in the tag SNR by slightly shifting the frequency of the carrier signal. However, it is critical to find the best carrier frequency quickly for high data rate communication. Thus, PLatter leverages the continuous and locally convex behavior of the power line across frequencies (as in Fig. 5) and defines a Stochastic Hill-Climbing algorithm with random initial points. At every iteration, the reader measures the SNR of the reflected signal and searches for the tag reflection (explained in Sec. 5.3). It then adjusts the carrier frequency and continues this operation until no improvement on the tag SNR can be found.

Another requirement of this frequency hopping algorithm is a mechanism to quickly and reliably detect

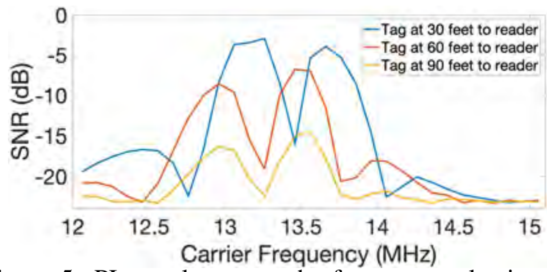


Figure 5: PLatter leverages the frequency-selective behavior of the power lines to improve the tag SNR by intelligently shifting the frequency of the carrier signal.

whether there is an active tag present. To achieve this, we design each tag to perform a known modulation in the form of a physical layer preamble before sending data. This preamble is defined as a sequence of periodically switching between two impedance values for a fixed time, which appears as a square wave with a switching frequency of $f_p = 1/T_p$. This can be easily detected in the frequency domain with a simple FFT. This way, the reader can quickly hop between frequencies and search for active tags, then fix on a frequency to receive data.

4.4 Real-time Impedance Tuning

One of the essential requirements of PLatter to work is an impedance matching network between the reader and the power line so that the carrier signal can enter the power line network and get reflected back (at other ends of the cable; e.g., an open outlet). While different matching network architectures are proposed for traditional Power Line Communication (PLC) systems [15, 38, 40], PLatter's backscatter setup necessitates a different architecture. In a completely wired setup like PLC, where both the transmitter and receiver are connected to the power line, impedance matching is required at both of them, incurring much higher noise [44]. PLatter, instead, relies on a mono-static reader setup in which the matching network is shared between the transmitting and receiving radio chains of the reader (Fig. 2). However, the time-varying channel conditions (Sec. 4.1) remain a challenge in designing such a matching network. In addition, a new scalability challenge arises as the characteristic impedance of the power lines in different buildings may be drastically different depending on the geometry and layout of the building.

PLatter addresses these challenges by performing real-time impedance measurement and tuning. It continuously monitors network changes due to appliances being turned on/off and accordingly adjusts the matching network. The key enabler here is that PLatter does not necessarily require a perfect matching, since it only relies on the variations of parasitic impedance to decode tags' data. Hence, approximate impedance matching is

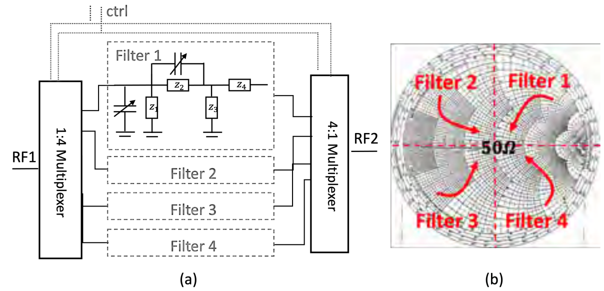


Figure 6: PLatter's modular matching network design that provides real-time impedance tuning by inferring channel conditions and adapting accordingly.

sufficient as long as the reader obtains sufficient reflected signal power. This greatly reduces the technical difficulty of PLatter – it would be much easier to design a tunable matching network that targets approximate rather than precise tuning to 50 Ω for example.

As such, we design a tunable matching network (Fig. 6 (a)) with four sets of analog filters, each constructed as a series of two cascaded L networks. These filters can be selectively populated to form different circuit structures (e.g., L-shape or π-shape). In addition, they also include programmable and digitally tunable capacitors. The circuit structures and corresponding components (R, L, or C values) are carefully selected such that each network can cover roughly a quadrant of the input impedance viewed in the Smith Chart (Fig. 6 (b)). With this, PLatter can coarsely match any input impedance encountered in our experiments, which enables tag detection and decoding.

5 Tag Design and Data Decoding

In this section, we describe PLatter tag's data modulation scheme (Sec. 5.1), its hardware (Sec. 5.2), the corresponding detection and decoding pipeline (Sec. 5.3), and scalability to multiple tags (Sec. 5.4).

5.1 Tag Data Modulation

Similar to other inductive coupling based backscatter tags (e.g., NFC), our primary design requirement for PLatter's tag is to ensure sufficient coupling with the power line when they are in close proximity. The tag must then modulate its digital signals onto power lines. On one hand, frequency modulation (FM), seen in many traditional PLC deployments, provides enhanced robustness but the data rate is relatively low (e.g., tens of kbps at most). On the other hand, phase modulation (PM) or amplitude modulation (AM), commonly used in backscatter systems, are easier and cheaper to implement but are less robust. PLatter's design choice is to perform what we call *Parasitic Impedance Amplitude Modulation* as a variation of Amplitude Shift Keying (ASK). The

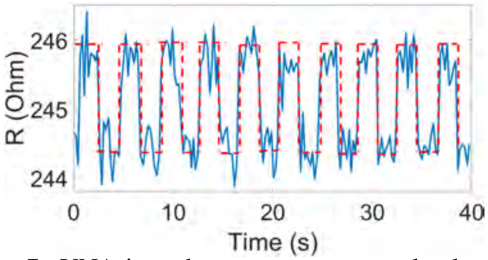


Figure 7: VNA impedance measurement clearly shows the tag placed at 8 cm away from the middle of a 100-ft cable modulating the parasitic impedance.

power of parasitic impedance is a function of the tag's reflection coefficient as

$$\Gamma = \frac{Z_T + Z*_A}{Z_A - Z_T} \tag{1}$$

where Z_A is the power line characteristic impedance and Z_T is the impedance of the tag terminal. To achieve the highest variation in parasitic impedance, we choose to switch between short and open with expected nominal 0 Ω and infinity impedance values.

As a preliminary study, we deployed a 100-ft cable, one end terminated with a Vector Network Analyzer (VNA) and the other left open (SMA open cap). We placed a tag at the middle (i.e., 50 feet away from the VNA) with a distance of 8 cm to the cable. The tag is set to switch between short and open loads with a very slow rate (every 2 sec). As shown in Fig. 7, the impedance measurements clearly capture the tag's modulation. Yet, we should also note the small scale of changes (i.e., parasitic impedance) compared to the absolute value of the cable's characteristic impedance.

In addition, to improve the SNR that a tag experiences at different locations along the cable, PLatter also implements channel coding to effectively pull up the SNR. We choose traditional convolution coding due to its simplicity to implement and a wide range of coding gain-coding rate choices. The gain will be implicitly shown in Sec. 8 where we evaluate PLatter's data rate performance.

5.2 Tag Hardware Design

To achieve ultra-low power consumption at the tag with a high data rate, PLatter exploits a unique hardware design. First, we shift most of the system complexity to the reader with a minimal architecture at the tag. For example, with uni-directional communication from the tag to the reader, we do not need any envelop detector, decoding component, or synchronization module. It is entirely the reader's task to detect active tags and decode their data. Then, to achieve a high data rate, we leverage high-speed SPDT RF switches with nanosecond switching rate, controlled by a low-power microcontroller (Fig. 8 (a)). As such, the tag can easily support orders of Mbps data rate with parasitic impedance amplitude modulation. Fig. 8 (b) shows its dev-kit prototype.

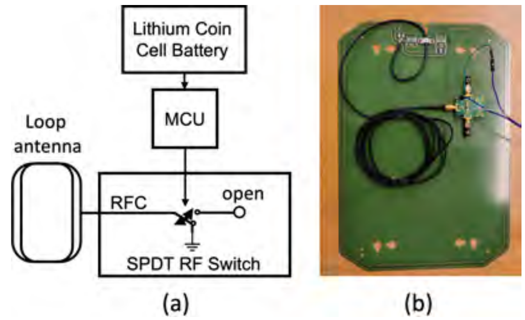


Figure 8: Minimal architecture of a PLatter tag allows ultra-low power consumption.

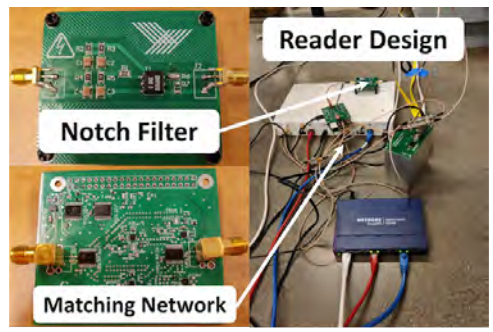


Figure 9: PLatter's reader consists of a 60 Hz notch filter and a matching network that tunes impedance live.

5.3 Tag Detection and Decoding

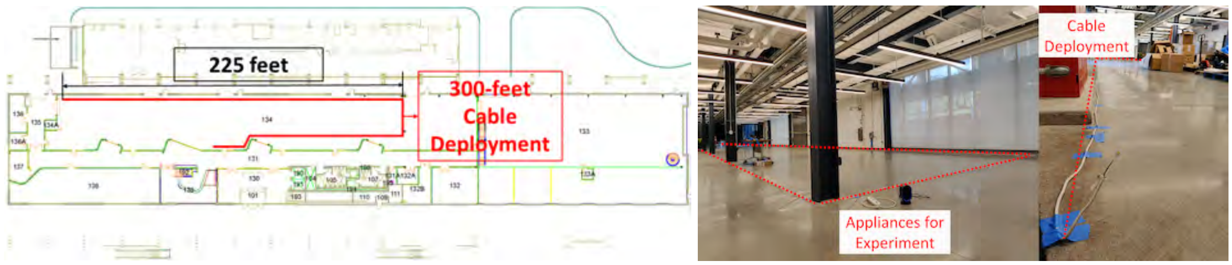
Next, we describe how the PLatter reader extracts the modulated parasitic impedance from the reflected signal. Our decoding algorithm works in two main steps: (1) signal conditioning to remove sudden variations and noises in the measurements; (2) decoding the backscattered bits.

Signal Conditioning: The goal is to remove high-frequency temporal variations in the measurements due to background noise or sudden impedance changes caused by connected appliances. We measure a moving average from the channel measurements that is defined based on the upper bound of the networks' data rate. In addition, if the measurement contains colored noise (as seen in Sec. 8.6), PLatter adopts further denoising.

Decoding Bits: PLatter applies simple thresholding on the output of the previous step. Specifically, if the channel measurement is above the threshold, the backscattered bit is considered as a ”1”, and a ”0” otherwise.

5.4 Scaling to Multiple Tags

In PLatter's design, multiple tags may send data to the reader simultaneously. While many existing medium access control protocols can be implemented for PLatter's



(a). Deployment layout. (b). Testbed photos.

Figure 10: PLatter is evaluated in an industrial environment with up to 300 feet power cables.

power line backscatter network (e.g., ALOHA, TDMA, or CSMA/CD), we leverage PN code assigned to each tag. This enables concurrent communication while keeping the tag circuitry simple and ultra-low-power. In addition, it eliminates the need for a bi-directional link and any sort of synchronization. To achieve this, PLatter incorporates a shift register holding a PN code before the RF front-end. The code length corresponds to the maximum number of concurrent tags that the system needs to support, which is configured prior to deployment accordingly. As an example, a 63-bit PN code requires a 6-bit shift register and supports 63 concurrent tags.

6 Implementation

Reader Front-end: The PLatter reader, shown in Fig. 9, consists of two USRP N210s with BasicTX/BasicRX daughterboards, synchronized to the same clock. They are connected with a directional coupler to emulate a full-duplex reader, which is controlled by shell and C/C++ scripts running on an ASUS 8G RAM 64-bit laptop with Ubuntu 16.04. The reader adaptively selects a frequency between 12.56 MHz and 14.56 MHz and transmits a carrier tone. This signal first travels through the tunable matching network, which is controlled by the laptop and provides four candidate channels, then enters the power line network to capture tags' signal. The reflected signal from the power line first enters the 60 Hz notch filter, then gets captured by the reader with a sampling rate of 25 Msps and processed offline in MATLAB. The notch filter effectively removes active grid noises to guarantee a proper dynamic range of the received signal and protects the reader from severe damage.

Tag Hardware: The PLatter tag (Fig. 9) consists of a minimal hardware, in which an antenna is connected to a 3-port HMC284AMS8G SPDT RF switch [5]. The antenna is a two-loop coil fabricated on PCB and tuned to a center frequency of 13.56 MHz. The other two ports of the RF switch are terminated with short and open SMA caps, resp. The switch is then controlled with either Raspberry Pi for benchmark experiments or MSP430FR5994 MCU [4] for power analysis. The entire tag circuitry is designed in favor of low cost and power consumption, with a nominal 50 Ω impedance and all the required impedance matching shifted to the reader side.

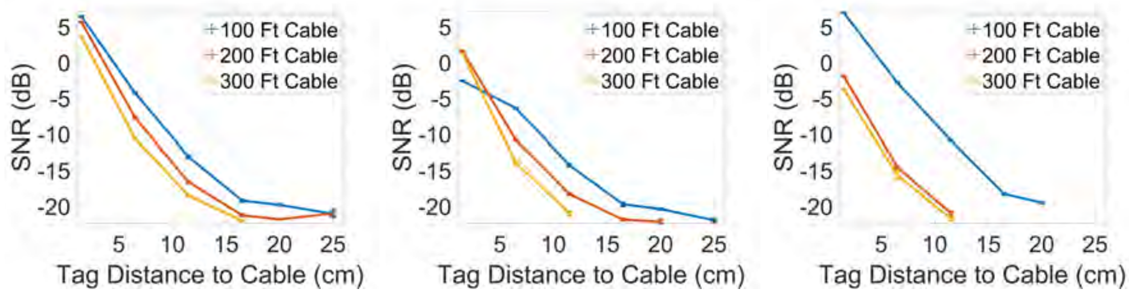
Tag Power Consumption: One of our key design challenges was to minimize tag energy consumption. We pair the RF switch with a MSP430FR5994 MCU. In the active state of transmitting information, PLatter uses 4.95 μW of power; otherwise, the MCU remains in an ultra-low-power sleeping mode (LPM4) (1.05 μW) with an internal low-power, low-frequency oscillator running. Assuming the tag sends 100 packets per day, 20 bytes each at a speed of 1 Mbps, we achieve a daily expenditure of 403.7 mJ. If paired with a small form-factor 3V CR2032 lithium coin cell (235 mAh), we predict that a tag could offer operation for 12.9 years, assuming an efficiency of 75% and no battery self-discharge.

7 Evaluation

Experimental Setup: We deployed multiple NM-B 14/2 cables with different lengths between 25 and 300 feet in an industrial warehouse (formerly, a steel mill) designed to serve as a smart manufacturing testbed (10250 sq. ft.). Fig. 10(a) shows the cable layout, and Fig. 10(b) is taken in the experimental space. Both ends of the cables have SMA connectors soldered for easier connectivity. For safety and controllability, in most of our experiments, the cables do not carry active AC power (i.e., static), except in our active power test (Sec. 8.6), where we instead use the building's existing power grid. Yet, we always have the 60 Hz notch filter in the circuit to ensure consistency.

Evaluation Metrics: We examine and report two main performance metrics: (1) SNR in dB, which reflects the signal strength a tag can enjoy at a certain location; it does not account for any gains from coding and software denoising. (2) Achievable data rate in bit-per-second (bps), which generally coincides with the trend of SNR while implicitly including gains from coding and denoising. Mean values across experiments are reported and error bars denote standard deviation.

Baselines: We do not depict the comparison between PLatter and an active near-field (NFC-based) over-the-



(a). Tag at the start of a cable. (b). Tag at the middle of a cable. (c). Tag at the end of a cable.

Figure 11: PLatter's SNR performance when a PLatter tag is placed at the (a) beginning (b) middle (c) end of cables of different lengths (100 feet, 200 feet, and 300 feet).

air transmission system with an equivalent power given the very short range of NFC tags (a few cms). We note that a far-field equivalent at 13.56 MHz would require a huge antenna (the wavelength is 22 m) that is impractical for an indoor space. However, we do evaluate the effectiveness of PLatter's matching circuit in Sec. 8.3 and we show PLatter achieves a maximum data rate comparable with other backscatter systems.

8 Results

We perform a thorough evaluation of PLatter where we examine multiple factors that impact PLatter's performance – cable length and geometry, tag position, electrical appliances connected, separating material between a tag and the cable, and active power.

8.1 Cable Length and Tag Position

Method: In this section, we evaluate PLatter's SNR and data rate with a single PLatter tag, and we vary three system variables: (1) total cable length; (2) tag's position w.r.t. the reader, i.e., the cable length between the tag and the start of the cable; (3) tag's distance to the cable, i.e., the closest distance between the tag and the cable along the cable's normal direction. The cable is always terminated with the reader at one end and an SMA open cap at the other, emulating an open power outlet.

Result: Fig. 11 shows PLatter's SNR performance at three different tag positions along the cable (beginning, middle, and towards the end). We see that as the tag moves farther away from the cable, the SNR decreases due to weaker inductive coupling; the SNR also drops as the total cable length increases due to higher signal attenuation inside the cable and weaker reflection received by the reader. Comparing across multiple figures, we observe a higher SNR when the tag is placed close to the beginning of the cable, since the carrier signal gets modulated before it experiences severe attenuation. Based on our observation: (1) a tag can be detected when SNR is as low as -21 dB; (2) a tag can be detected and decoded between -16.5 dB and -21 dB but it suffers from a low data rate; (3) a tag's maximum data rate is around 1 Mbps when SNR is around -9.7 dB and increases to 4 Mbps when the SNR is as high as 5 dB.

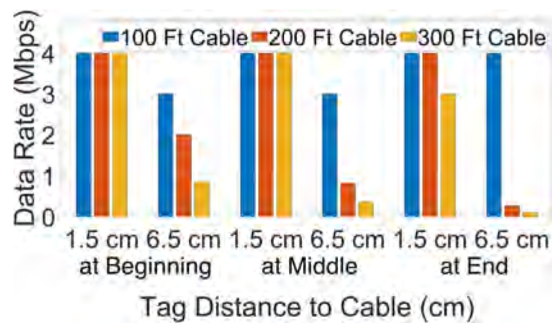


Figure 12: PLatter's end-to-end data rate performance when a PLatter tag is placed at the beginning, middle, and end of cables with different distances to the cables.

Fig. 12 shows PLatter's data rate performance with 6 different configurations – 2 tag distances (1.5 and 6.5 cm) and 3 tag positions (beginning, middle, and end). The overall trend closely follows Fig. 11. Specifically, a tag at a favorable location can modulate at the maximum data rate; otherwise, it adds more redundancy to its data and paces down. In our experiments, an SNR lower than -16.5 dB leads to zero data rate because the tag signal can no longer be decoded; yet, there is still a chance for the reader to detect its presence. Overall, the maximum data rate PLatter can provide is 4 Mbps; this is comparable to the best backscatter-based state-of-the-art [7], yet achieved with a reader farther away from the tag (300 ft) by reusing power lines as a communication medium.

From Sec. 8.2 on, we fix the total cable length to be 100 ft and choose a representative subset of tag locations to better demonstrate the influences from other factors.

8.2 Cable Geometry

Method: In this section, we examine three different cable geometries with a total length of 100 ft (two 25-ft ca-

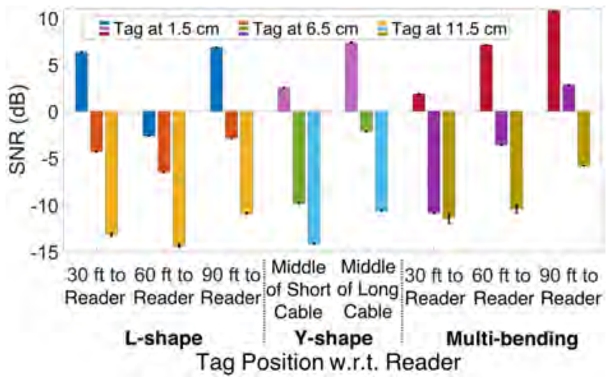
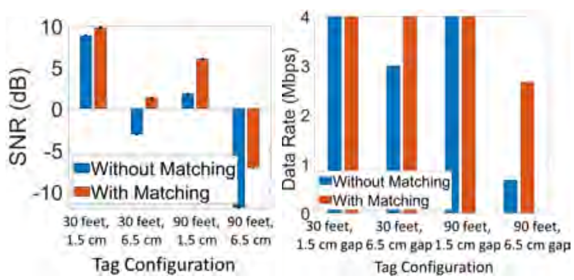


Figure 13: The tag SNR varies as the cable geometry changes, yet PLatter can operate normally in all cases.



(a). SNR (b). Data Rate

Figure 14: Effectiveness of PLatter's Matching Circuit

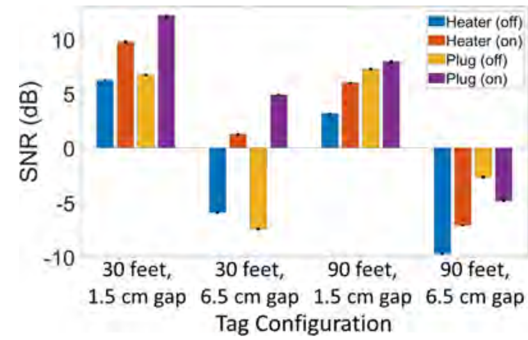


Figure 15: The tag SNR varies slightly as an appliance's internal circuit changes, and PLatter can adapt coordingly with its matching network.

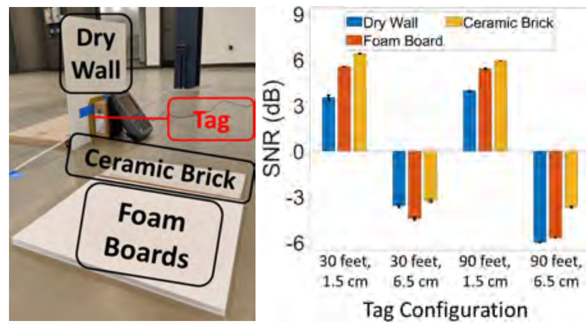


Figure 16: PLatter with different materials.

bles and one 50-ft cable). Specifically, we consider three configurations: (1) L-shape connection forms a long 100-ft cable with a corner point at the middle (50 ft); (2) Y-shape connection has one splitter to form two branches (a 50-ft cable (long) connected with two 25-ft (short) branches); (3) Multi-bending connection has a number of bending points along the cable.

Result: Fig. 13 shows PLatter's SNR performance under different cable geometries at representative locations. Despite minor variations in SNR, we verify that PLatter continues to operate under different practical cable geometries, including at the branches of the Y shape.

8.3 Impact of Electrical Appliances

Method: In this section, we examine both the effectiveness of our matching network and the impact of electrical appliances. We choose two multi-state appliances: (1) a desktop heater (on/off) as a representative of appliances that turn electrical power to heat; (2) a surge protector (on/off) commonly used in daily life. They change the overall impedance of the power line, and PLatter is expected to adaptively tune its matching network. To connect an appliance to our cable, we use a custom-designed SMA-to-plug converter. We use a single 100-ft cable and choose a representative subset of tag locations. Note that only in this experiment, we include SNR values that were measured when PLatter's matching network was off.

Result: We show the effectiveness of the matching network in Fig. 14 by attaching a heater (on) to the cable. We see an overall SNR improvement across different tag configurations, though the actual amount may vary. The impact of appliances is shown in Fig. 15. The reported numbers have included gains from the matching network. In general, for a certain tag configuration, the SNR tends to be higher when the appliance is on (i.e., its internal circuit is connected); even when the appliance is off, with the matching network PLatter still manages to maintain a reasonable SNR and hence data rate.

8.4 Influence of Separating Material

Method: We evaluate the impact of different wall materials between the tag and the power line. Specifically, we consider 3 common materials: dry wall, foam board, and ceramic brick (Fig. 16), with their thickness of around 1.3 cm (1/2 inch). Again, we use a single 100-ft cable and stick to a representative subset of tag locations.

Result: Fig. 16 shows that PLatter's performance slightly varies as we change the separating material; in general, the dry wall panel tends to introduce more attenuation, but PLatter can still maintain a favorable SNR that is way higher than the decoding threshold.

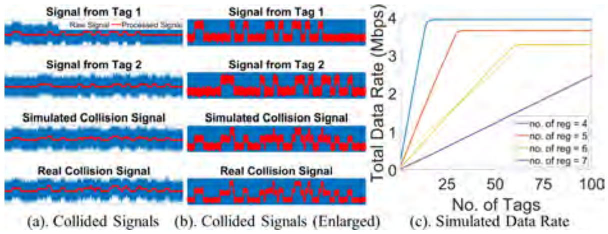


Figure 17: PLatter uses a simulation route to examine the collective data rate in a multi-tag scenario.

8.5 Multiple Tags

Method: In this section, we explore PLatter's performance with multiple tags. First, we verify that signals from multiple tags add up as expected by placing two tags along a 100-ft cable at 30 feet and 90 feet, respectively, with a distance of 1.5 cm to the cable. The tags periodically transmit a specific bit sequence and the reader receives their colliding signal for further analysis. Next, to evaluate the scalability of PLatter in multi-tag scenarios, we conduct a trace-driven simulation of collisions from 1 to 150 tags. We use the simulation route to carefully and exhaustively model various relative timing offsets between tag transmissions to study their overall impact. Our study is informed by actual signals collected from 3 tags placed at 30, 60, and 90 feet from the reader, and for each position, we include both 1.5 and 6.5 cm as their potential distance to the cable. We then engineer a collision in software under different timing conditions and calculate the total data rate across all tags.

Result: Fig. 17(a) and (b) show that signals from multiple tags add up with each other as expected. Even though the raw received signals (shown in blue) are quite noisy due to background noise, PLatter can still successfully detect the tags by correlating each tag's PN-code. In principle, PLatter only relies on the variations of parasitic impedance, not absolute impedance values. Fig. 17(c) shows the simulated data rate for multiple PLatter tags. It should be noted that the length of PN code and shift register at each tag is defined by the network size (i.e., the maximum number of concurrent tags supported by the system). This imposes a trade-off between the maximum collective data rate and the number of tags, where the maximum total data rate drops down slightly as the number of registers increases.

8.6 Response on Active Power Lines

Method: In this section, we evaluate PLatter with an active power grid in an industrial environment. We connect one end of a 25-ft cable to our reader, with the 60 Hz notch filter and matching circuit in series, and plug the other end into a surge protector, which is further connected to the active power outlet on the wall of the building. This forms a large active power grid with an estimated total length of more than 500 m; the building was operating normally with a variety of appliances running on the power grid. The reader is powered by a portable battery pack and protected by another surge protector. A single PLatter tag is put at three different positions along the 25-ft cable with a fixed distance of 1.5 cm to the cable, and we carry out 15 independent measurements for each case, creating a total of 45 experiments.

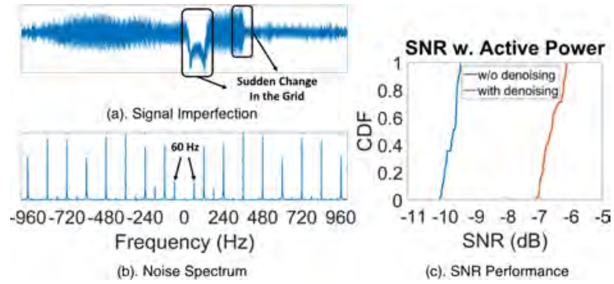


Figure 18: Both sudden signal imperfections and periodic harmonics have been observed in the active grid; PLatter's corresponding denoising technique greatly helps to improve the SNR.

Note that the cable geometry here is completely different from those in Sec. 8.1-Sec. 8.5; meanwhile, it was infeasible to shut down the whole grid to collect static experimental data in this building. Hence, static test results (when PLatter is connected to the whole building's grid but without active power) are not included here.

Result: We first analyze the noise introduced by the active grid. Fig. 18(a) shows a representative trace of the signal in time domain with an obvious imperfection in the middle. This kind of sudden noise has been observed multiple times throughout the experiment and it does not have a fixed pattern. Meanwhile, we have also observed periodic noise components resulting from the 60 Hz AC signal. Fig. 18(b) shows the frequency spectrum of the periodic noise components. The first pair of peaks correspond to the 60 Hz bin, and we see multiple higher-order harmonics. While our notch filter significantly suppresses 60 Hz and its neighboring frequencies so that they would not damage the reader, the residual harmonic noise is still large enough to be detected by the reader. To deal with both kinds of noise, PLatter denoises in software processing to pull up the SNR. Note that this specific denoising is not present in Sec. 8.1-Sec. 8.5.

Fig. 18(c) shows the SNR observed in multiple trials along the cable. The tag was placed at different positions but its distance to the cable was fixed (1.5 cm). In this CDF plot, we see that in average PLatter's denoising technique brings 3-4 dB boost in SNR, although the actual improvement varies slightly along the cable. This makes it easier for the PLatter reader to decode the tag signal and has the potential to be further improved by using more advanced notch filters proposed in the power line communication literature [33]. We admit that the SNR after boosting is still not within the most ideal range; yet, this can be mitigated with channel coding where we add redundancy into the transmitted data (as mentioned in Sec. 5). The experiment shows a positive sign of implementing PLatter in real-world settings with complex power grid conditions, albeit with lower data rate and range.

9 Discussion and Limitation

While PLatter takes a big step toward enabling building-scale backscatter communication using power line systems, there are still some open questions and a few avenues for future improvements.

Tag Proximity to Cables: PLatter requires the tag to be sufficiently proximate to the cables behind walls (within a few tens of cms – Sec. 8.1). While this may restrict the locations where PLatter tags can be deployed, such a solution is still desirable in intrinsically safe environments by just lying a passive cable in the environment for sensor communications. In addition, this requires the knowledge of power line locations behind the wall, which can be addressed by using stud finders during the sensor deployment. In our future work, we plan to study other modulation mechanisms at the tag to improve the tag detection rate at larger distances from the cable.

Variability in Performance: Based on our observation, PLatter's performance and range are highly dependent on several factors, specifically cable geometry, tag position (w.r.t. reader), distance to the cables, and active power variations. While PLatter can automatically adapt to these changes, it may experience performance drops and failure in highly dynamic setups.

Uni-directional Communication: PLatter in its present form is uni-directional from the tag to the reader. We believe that in principle, modulating information in the reverse direction while keeping low-cost and low-power is possible, and we leave this for future work.

Tag Scalability: While PLatter provides a proof of concept for multi-tag backscatter communication, the overall data rate of the network can be enhanced using MAC protocols such as TDMA or slotted ALOHA with minimum collisions. New backscatter MAC protocols like NetScatter [23], with power line time synchronization mechanisms [34] enabled, can further improve PLatter's overall performance; integrating them with PLatter is one interesting part of our future work.

Impact of Parasitic Impedance on Connected Appliances: Although large parasitic impedance can be generally problematic at high frequencies since it might sharply change voltages or currents, the amount of parasitic impedance induced by PLatter tags is negligible as the tag is completely passive in a sense that it has no active radio front-end and hence no radiation.

Electrical Wiring Complexity: In addition to controlled experiments, PLatter has been evaluated in an industrial manufacturing building, where the power grid was operating actively (Sec. 8.6), which provides the feasibility of backscatter communication using power line systems. However, we acknowledge that electrical wiring in some buildings can be complex with various hardware components in the line, which has long been a challenge in power line communication research.

10 Conclusion

This paper presents PLatter, a system that allows ultra-low-power backscatter tags attached to walls to communicate with a reader several hundreds of feet away. PLatter achieves this by using the existing power lines behind the walls as a communication medium, without physically being connected to them. To achieve this, PLatter modulates parasitic impedance on the power line system, which allows data to be recovered at a high rate at a single centralized reader through a large indoor facility. We present a detailed proof-of-concept evaluation of PLatter, exploring its strengths and weaknesses in a large indoor industrial testbed. While this paper broadly explores the concept of power line backscatter, our future work hopes to stress test the system at scale in diverse environments and explore higher-layer protocol designs.

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