Demo: PowerBlade
A Low-Profile, True-Power, Plug-Through Energy Meter

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ABSTRACT

We present PowerBlade, the smallest and lowest power AC plug-load meter that measures real, reactive and apparent power, and reports this data, along with cumulative energy consumption, over an industry-standard Bluetooth Low Energy radio. Achieving this design point requires revisiting every aspect of conventional power meters: a new method of acquiring voltage; a non-invasive, planar method of current measurement; an efficient and accurate method of computing power from the voltage and current channels; a radio interface that leverages nearby smart phones to display data and report it to the cloud; and a retro power supply reimagined with vastly lower current draw, allowing extreme miniaturization. PowerBlade occupies a mere 1" by 1" footprint, offers a $^1/_{16}$" profile, draws 52 mW continuously, offers 1.13% error on unity power factor loads in the 2-1200 W range and slightly worse for non-linear and reactive loads, and costs \$11 in modest quantities of about 1000 units. This new design point enables affordable large-scale studies of plug-load energy usage—an area of growing national importance.

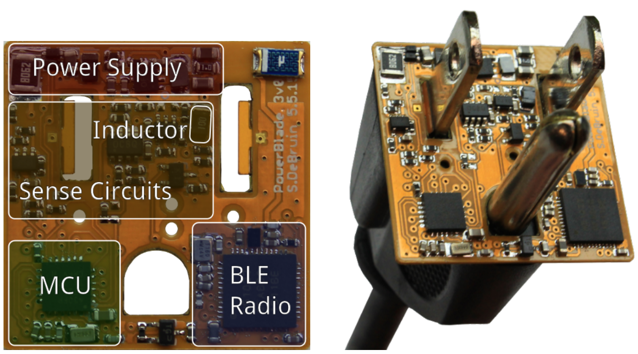

Figure 1: Front and perspective views of PowerBlade, a wireless power meter that measures real, reactive, and apparent power. PowerBlade's low profile and plug-through form factor allow it to sit inconspicuously between a plug and outlet, and its square-inch footprint saves adjacent outlets from being blocked.

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1. INTRODUCTION

Consumers lack the tools and knowledge to actually understand their energy consumption. While the majority of building usage comes from obvious loads such as HVAC, lighting, and appliances, a remaining 20% resides in miscellaneous electrical loads (MELs) [3]. These diverse loads, from televisions and computers to vending machines and ceiling fans, represent the long-tail of electricity use. Understanding the characteristics of these loads requires insight into each device's individual consumption.

In this paper, we present PowerBlade, a new power meter design that achieves a vastly smaller form factor than prior systems. We introduce a new, essentially two-dimensional form factor, that of a plug-through power meter. PowerBlade is only $^1/_{16}$ inch in depth with a 1" by 1" footprint, and metered loads are literally plugged through it and into the outlet as shown in Figure 1. Despite these size limitations, PowerBlade functions as a wireless true power meter, capable of monitoring real, reactive, and apparent power and transmitting this data in real time using Bluetooth Low Energy.

Achieving this profile requires new solutions to previously solved aspects of power meter design. Traditional AC-DC power supplies require substantial volume. Instead, PowerBlade is designed to operate at less than 7 mW average power draw, allowing it to utilize a simpler four-component supply. Traditional current sensing requires breaking the AC path in order to use a sense resistor. PowerBlade non-intrusively detects the magnetic field generated from the current passing through it. A horizontally wire-wound inductor placed parallel to the magnetic field acts as a magnetometer, allowing the current waveform to be monitored in real time.

Despite these limitations, PowerBlade still offers accurate power metering. For resistive loads, like incandescent light bulbs, it remains within 1.13% of the real power measurement. Over a longer term (i.e. hours), errors in the accumulated energy measurements are comparable to popular commercial products.

PowerBlade is smaller and lower power than all previous power meters with a volume of 0.0625 in^3 and a no-load power draw of 52 mW. For comparison, Kill-A-Watt [1], a commercial system, has a volume of 14.0 in^3, and a no-load power draw of 450 mW. Academic prior work, ACme [2], has a volume of 13.7 in^3 and a no-load power draw of 100 mW. By achieving such a small form factor, PowerBlade does not block adjacent outlets, an advantage over all prior work.

We believe that PowerBlade provides a new opportunity for researchers. The plug-through form factor leads to a new way of thinking about deployments. Rather than metering every outlet in a building, PowerBlade is capable of metering every load, following the plug no matter which outlet it connects to. We believe that this will lead to new capabilities for researchers and allow a better understanding of energy consumption.

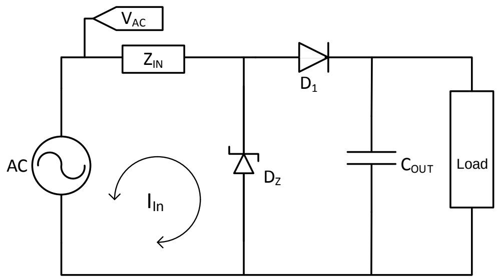

Figure 2: Zener regulated, half wave rectified power supply. Z_{IN}, either a resistor or capacitor, is used to the drop the line voltage. D_1 is a rectifying diode. C_{OUT} stores charge between each positive half cycle of the AC wave. The maximum voltage exposed to the load is the zener voltage of D_Z. This power supply design achieves an exteremely small form factor because it does not need to dissipate much power (for the resistive design) or store much charge (for the capacitive design) when the load is sufficiently low power.

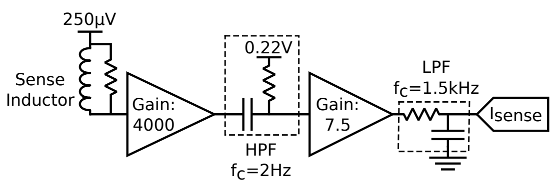

Figure 3: Current sensing circuit. A horizontally wire-wound inductor acting as a magnetometer senses the current waveform. The signal is amplified and filtered before the resulting I_{SENSE} is measured by the ADC on the MSP430.

2. OVERVIEW

In order to function as a power meter, PowerBlade has to overcome several challenges unique to its form factor. The first challenge is contact with the AC plugs. Since PowerBlade does not plug into the outlet itself, it must tap in at the device plugged through it. The PCB is designed with flexible tabs extending into the plug hole that bend and contact the load prongs.

The second challenge is the design of the power supply. While many ICs exist for AC-DC power conversion, all require large-volume components that do not meet our volume constraints. Figure 2 shows the power supply design for PowerBlade. Populating Z_{IN} with a resistor minimizes the volume required by the power supply, but introduces a static power draw of 45 mW above the 7 mW required for the MSP430 microcontroller and the nRF51822 radio to operate.

Finally, the solution for current sensing is shown in Figure 3. Using a horizontally wound inductor to sense current creates a magnetometer called a search coil [4]. Importantly, the voltage output from the coil is proportional to the change in current over time, rather than the current itself. PowerBlade integrates the signal in software after sampling it in order to recover the current waveform. The integrated current is multiplied by the sampled voltage in order to calculate power at a rate of 42 samples per AC cycle (2.52 kHz).

In order to transmit the data to users, the microcontroller transfers its power measurements over UART to a Bluetooth Low Energy radio. The radio transmits the data in broadcast advertisements, with updated measurements once per second.

To determine the accuracy of PowerBlade, we compare its measurements to a professionally calibrated benchtop power meter. Resistive loads with a unity power factor, such as incandescent lights, exhibit a sinusoidal current waveform in-phase with voltage. To evaluate PowerBlade's accuracy in this simple but common case,

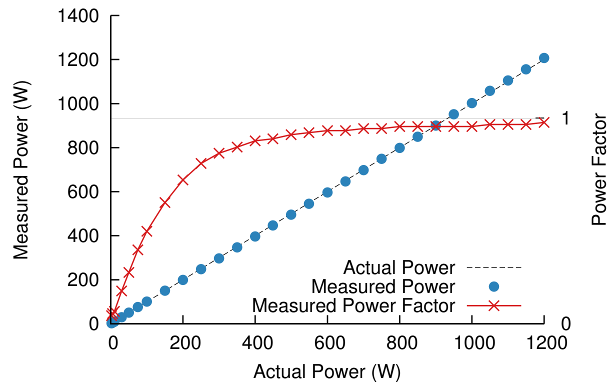

Figure 4: Metering accuracy for a variable resistive (power factor = 1) load: measured power vs actual power as well as measured power factor. The reported real power tracks accurately with ground truth. The minimum AC load for accurate metering is 2 W, and over the range from 2 W to 1200 W the accuracy in real power is 1.13%. PowerBlade's metering and reporting system is accurate over a range of resistive loads.

we use a programmable AC load with a fixed unity power factor and variable wattage. Figure 4 shows the end-to-end accuracy for a resistive load.

A video demonstrating PowerBlade and describing the design of the system is available online at https://youtu.be/oNUXhCDnHoE.

3. DEMONSTRATION

We will demonstrate PowerBlade transmitting real-time power data. In order to avoid possible issues with international AC standards, we will bring a converter that will supply 120 V at 60 Hz. We have several example loads available across a range of wattages and power factors. A smartphone application will read the measurements from PowerBlade in real time and display them to the participants. We will provide a smartphone, but the application will also be available to be installed on users' personal devices.

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