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Communicating Power Supplies: Bringing the Internet to the Ubiquitous Energy Gateways of Electronic Devices

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***Abstract*—Saving energy in buildings is often hampered by the lack of detailed information about what is using the energy, how much it is using, and how to automatically and remotely control devices. The problem is especially acute for the large number of small, energy-using devices that are present in both residential and commercial buildings. Most of these products use a switching ac to dc power supply to operate electronic and other internal components. We describe a "communicating power supply" (CPS) to enable the communication of energy and control information between the device and a building management system or other central entities. We developed a proof-of-concept system of Internet-connected CPSs and demonstrated both energy reporting and control utilizing a custom, cloud-based information clearing house. If CPS technology became widespread in devices, a combination of automated and human interactive solutions would enable high levels of energy savings.**

***Index Terms*—Energy efficiency, energy management, energy reporting, green buildings, switched-mode power supply.**

I. Introduction

IDENTIFYING and reducing energy waste is challenging when there is limited information about which devices are using how much energy. With the proliferation of smaller energy-using devices in residential and commercial buildings (i.e., plug loads), the number of individual devices and their aggregate energy use is increasing. In homes and commercial buildings, plug loads represent 30% of the total electricity use [1], [2]. Moreover, the amount of electricity used by plug loads is growing faster than any other load category in both sectors [3]. A large fraction of these loads are electronics, and electronic devices present a unique and excellent opportunity to leverage the Internet of Things (IoT) for understanding and reducing energy use.

Electronic devices are among the first everyday devices to be connected to the Internet, so that they can benefit from Internet-based content. Televisions (TVs) and game consoles now come standard with networking capability, and these devices, along with traditionally networked devices such as computers, are driving much of the increase in building energy use. Nowadays, these devices do not have a built-in capability to measure and report their energy use or receive control input over the network. As a result, they cannot participate in systems to improve whole building energy use or integrate fully with renewable energy sources or the electricity grid. Network connectivity is critical for these tasks and serves as one driver for the IoT. Electricity metering is important for understanding energy efficiency tradeoffs and advanced methods of grid and renewable energy integration, but metering has proven expensive and complicated thus far [1].

We introduce the concept of the communicating power supply (CPS) that adds electricity metering, computation, and communication to electronic devices, and we also demonstrate example applications that can be performed with this infrastructure in place. We propose to add metering by utilizing the properties of the ubiquitous ac to dc switching power supplies that are present as a part of every electronic device. These power supplies switch voltage and current through a transformer at rates between 1 and 100 kHz depending on the input voltage and power requirements, and measuring these variables allows us to cheaply measure the power being handled by the power supply. Adding the basic measurement capabilities to a power supply costs $0.10, and adding the microprocessor and communications (if they do not already exist for other applications) adds modestly to the overall device cost. These very low costs place electricity metering and reporting in the reach of very cheap devices such as compact fluorescent or light-emitting diode (LED) light bulbs and battery chargers. Appliances that primarily use power through motors or resistive heating are not candidates for this technology nowadays, but these devices will likely move to variable speed drive and variable speed heat pump-based systems in the future [4]. Variable speed systems use the same sort of switching power supply making these more advanced and efficient systems candidates for the proposed technology. Due to the extremely low cost and ease of integration with existing technology, energy awareness is a clear application that can help drive the adoption of IoT concepts across many device types.

This paper introduces the CPS and presents an example implementation of a CPS ecosystem. In Section II, we discuss the overall concept. Section III contains a survey of related work on energy aware devices as well as on communicating energy information on local area networks (LANs) and the Internet. Section IV contains a detailed review of our proof-of-concept demonstration and sample applications. In Section V, we

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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provide a perspective on the widespread deployment of this technology from a consumer, energy policy, and energy efficiency standpoint.

II. System Concept

Reducing the energy use of plug loads becomes increasingly important, as the number of electronic devices grows and the end uses in buildings become more efficient. However, nowadays solutions for saving energy are based on either long-term energy policy methods or transitional technologies that do not perform as consumers expect or desire. Reducing the energy use of plug loads has been most effective through voluntary energy efficiency programs such as the U.S. EPA's Energy Star program or via mandatory national energy efficiency standards. Unfortunately, these processes have trouble keeping pace with the rapid advance of technology. Despite this challenge, significant energy has been saved through these programs [5].

Recently, a new type of power control for plug loads has entered the market. These commercially available products for monitoring and controlling miscellaneous electronics (MELS) are installed in between the device and the plug. This plug-through approach has the advantage of flexibility with regards to the devices monitored and/or controlled. One major downside to this approach is the loss of native controls such as remotes, switches, or other interfaces. For example, if one of these devices is installed in between a lamp and a plug, the actual lamp switch must always be turned "ON" in order for the relay in the outlet control to function. This approach replaces the native interface, with whatever interface is associated with the control device—something that may not always be desired by the user. Users expect devices to retain their native user interface, and keeping track of which control method is currently active leads to frustration and rejection of the control technology [6]. A second drawback is that the plug-through devices are not permanently assigned to a specific device, making the identity of the device being metered and controlled open to question.

Our CPS concept measures the energy use of the device it is powering, reports the energy use and device's identity over a network to a central entity, and receives control information from users or other devices via the same central entity. At the same time, the user is still able to control power state directly using legacy interfaces on the product, so that the existing, native controls are retained. This concept is shown in Fig. 1, where three electronic devices are powered by CPSs. The power supplies convert the main's ac power to the dc power used by the device, measure energy use, and report these data to a local or cloud-based web service. The web service aggregates this information, receives network-based control requests from users or energy management applications, and passes control information back to the CPS devices. The CPS devices pass these controls along to the device of interest, and the devices change power state accordingly. The device remains connected to power the entire time and all native controls on the device continue to function. Energy data are reported at regular intervals or as requested by the central entity.

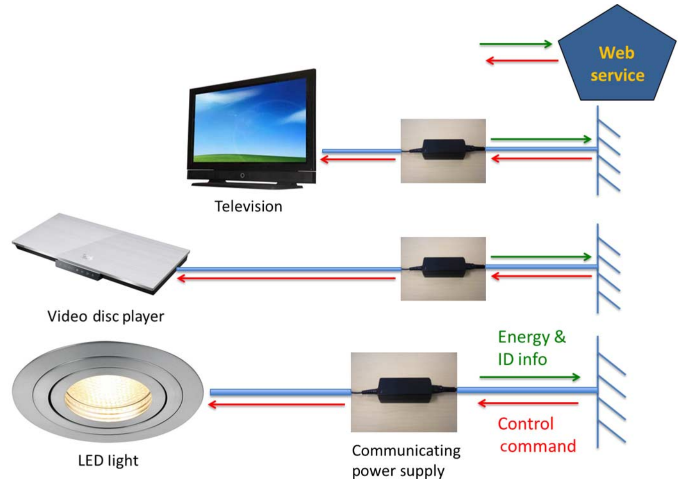

Fig. 1. System concept showing three devices with CPSs that report energy data to a web service and pass control information directly to the device.

The key difference between CPS technology and existing solutions is as follows:

1) The CPS is integrated into the power supply (either internal or external to the device), has knowledge of the unique device and device type under control, and is sold as a part of the product rather than as an aftermarket add-on. This enables higher market penetration.
2) The high level of integration reduces the cost of monitoring and control to levels far below those possible with aftermarket, add-on devices.
3) The CPS allows devices to retain all of their native controls and local user interfaces and do not require users to adapt to multiple, conflicting types of control.

III. Related Work

Measuring and controlling the energy use of devices have seen a great deal of attention in recent years, and there has been activity in the academic literature, the consumer market, and among standard organizations. In this section, we review the existing solutions for measuring and reporting the energy use of devices over a network.

A. Energy Aware Consumer Products

There are three categories of existing systems for reporting the energy of plug load devices over the Internet: large smart home appliances, plug-level energy monitors, and nonintrusive load monitoring (NILM). In addition, there is a "middleware" that facilitates network communication from the plug load energy monitor to the central entity.

Major appliance manufacturers offer product lines of smart home appliances that can be connected to Wi-Fi and can be monitored and controlled from a computer or mobile device. These are mostly large appliances, such as washers, dryers, refrigerators, and dishwashers. The appliances are high-end models in terms of cost and possess features that may not be desired or needed by a homeowner who is only interested in the addition of energy reporting capabilities.

Plug-level energy monitors offer monitoring and control capabilities at the wall outlet, as an independent power strip, or at the circuit breaker panel. These relatively expensive plug adapters are used to monitor each end-use device, and many brands are commercially available. The devices typically communicate over a wireless network and a user dashboard is provided on a computer or a mobile device. It costs about $50 per end use for plug-level adapters and could be more than $1000 to monitor the important devices in a single home when including gateway hardware and control software. In addition to high initial cost, these devices have several important drawbacks. First, they must be individually installed and programmed. If the device is moved, or additional devices are plugged in, then the identification and control aspects are lost. Second, many of the products rely on proprietary communication protocols, which lead to incompatibilities and legacy networks. Thus, they are adequate for short-term or limited operation but not suited for a permanent, scalable system.

An alternative to plug-level energy monitors are NILM systems. NILM systems consist of one energy meter to monitor whole house energy consumption and use signal processing to disaggregate the individual end-use loads. Multiple groups have published algorithms to optimize the disaggregation analysis [7]–[14]. This technique is still largely a research effort, with groups investigating various techniques to disaggregate end-use loads via methods such as machine learning. There are currently no commercially available products on the market. This technique works well for large (over 150 W) loads that operate in discrete levels (e.g., ON/OFF and high/medium/low), but does not work as well for low-powered loads or loads with large number of variable states, such as the dishwasher or electric stove. For nonintrusive monitoring, electric loads should be physically present within a residence and must vary in energy consumption. For example, the energy consumption of an electric stove not consuming electricity or permanently ON will not be recognized, as any load must change power consumption within the monitoring period of time to be identified. Loads must also change power consumption in discrete levels. Continuously varying loads such as dimmer switches on lights or adjustable speed drives on motors may not be suitable for monitoring without implementing rather expensive feature detectors. Multiple sources of inaccuracy arise from heterogeneity in meters, load profiles, and appliance types (category, make, size, and manufacturer). Low-power consumer appliances, such as MELS, exhibit similar power consumption characteristics making the recognition task even more challenging. NILM still does not achieve the same level of accuracy as direct metering at the end use.

A research effort that complements device-level energy monitoring is open source "middleware" [15]. These are software and hardware infrastructure that facilitate communication between the end-use monitor and the central entity. The embedded systems are programmed to gather data from the energy monitor and communicate this information over the network layer to the data server. A user dashboard would be located on a mobile device or PC, which allows control and monitoring via the data server. Together, the CPS and middleware would both be necessary to implement the complete energy reporting system.

B. Protocols for Energy Reporting and Control

Protocols or formats for energy reporting have proliferated in recent years. Some are meant for LAN use such as the Zigbee Smart Energy Profile (SEP), whereas others are largely intended for use over the Internet (e.g., GreenButton and OpenADR 2.0b). The former category protocols are nominally designed to operate with low-power wireless devices that support small packet sizes and the later protocols prize human readability over compactness. The type of network connection used may limit the selection of reporting protocol. The CPS system is primarily concerned with transferring data inside a LAN, and it makes sense that at least some devices will have simple, low-power networking capabilities rather than more capable Wi-Fi or Ethernet connections. There is no reason, however, that all CPS devices need to use the same network interface or even the same data format for transmission. The CPS ecosystem can accommodate both broadband and lower-speed connections between the devices and the network. This section provides a brief overview of some popular and emerging standards for sharing energy data to highlight the advantages and disadvantages for energy reporting.

Zigbee SEP version 1.x and 2.0 are intended for low-power devices using IEEE 802.15.4 radios. SEP 2.0 can be used over other network links that support IPv6 in addition to IEEE 802.15.4 links. SEP 1.x was optimized for the very short packet lengths available in the 802.15.4 standard, but there are a variety of interoperability problems with the 1.x versions. SEP 2.0 was designed to operate over IPv6 using an HTTP interface, and this makes the use of 802.15.4 more challenging due to the short packet lengths, long latencies, and the complexity of packet segmentation.

OpenADR 2.0b and GreenButton Connect are XML standards for exchanging energy data between utilities, consumers, and third-party energy service providers. Unlike Zigbee SEP, they were designed to pass over high-bandwidth network connections, and typical file sizes are measured in tens of kilobytes. This makes passing data in this format very difficult using low-power networks. It is likely that these standards will continue to see use in their respective application areas, but they are not likely to be useful for LAN communication using resource constrained devices.

The Internet Engineering Task Force (IETF) Energy Management (eman) Working Group is developing a framework [16] for energy management of devices and device components within or connected to communication networks that are based on Simple Network Management Protocol (SNMP). The devices can then be monitored and controlled if the appropriate management information base (MIB) is used to interact with the device. The framework primarily addresses energy object identification and monitoring of the energy state of the object. Although typically more compact than XML-based schemas, SNMP is still not as compact as a binary representation of information. This limits the applicability of the eman approach to constrained network devices. The Consumer Electronics Association (CEA) and the Electric Power Research Institute (EPRI) announced a new standard [17] that defines a modular communications interface (MCI) for appliances based on the Universal Smart Network Access Port (USNAP) concept. The standard specifies "details of the mechanical, electrical, and logical characteristics of a socket interface that allows communication devices," defined as universal communication modules (UCMs), "to be separated from

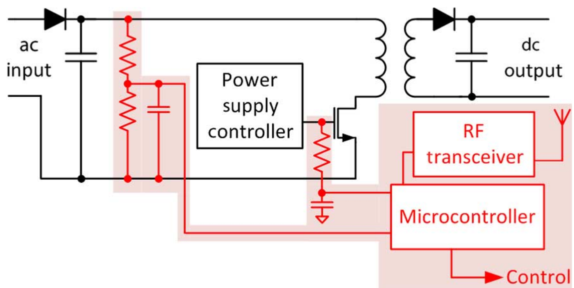

Fig. 2. Simplified schematic of a CPS where shaded components are added for a complete CPS and unshaded components are part of the original power supply design.

end devices” such as smart meters, communication nodes, and other smart grid devices. This is an emerging standard, but the interface to the MCI is a simple serial interface and the networking is handled by the MCI. Although this is attractive for low-cost devices, use of an MCI requires a relatively expensive add-on for network access, and this limits the ability of a CPS to participate in network activities. There is no specific energy reporting standard or scheme for MCI at this time, but other standards and protocols can be supported by specific MCIs. USNAP also has implicit mechanical standards which limit miniaturization and cost reductions.

IV. Proof-of-Concept Demonstration

The CPSs allow unobtrusive power monitoring and control. To illustrate the CPS concept, we rapidly prototyped a network connected CPS and implemented the technology with three standard electronic devices. In this section, we explain the principles of operation, the software and hardware implementation, and example energy-saving applications.

A. Principles of Operation

The CPS consists of a series of components. First, there is the power supply, which efficiently converts the incoming ac power to dc power. We add components that enable us to measure the power converted by the power supply, and we use a microprocessor to manage these measurements and handle the networking aspects of communication. A radio frequency (RF) transceiver handles the physical aspect of communication.

The ac to dc switching power supplies switch the input current through a magnetic device at high speed in order to maintain a stable output voltage while efficiently converting input power to output power. Power supplies modulate the duty cycle of the switching to control the current in the magnetic element, and this controls the available power at the output. They use the output voltage and/or current as feedback signals to the controller, so that the correct duty cycle can be used to maintain the output within a set of specifications. Modern power supplies must do this at high efficiency even at low-output powers, and they must consume virtually no power in the no-load condition. In order for this to be possible, power supplies modulate both the duty cycle and the frequency of the switching to minimize wasted energy and maximize overall performance [18]. The duty cycle can be used as a proxy for the power passing through the supply for a given input voltage. Fig. 2 shows a simplified schematic of a CPS without the feedback shown and with added components and connections shaded. Fig. 3 shows sample outputs (logically inverted) from the switching node on the power supply. The controller output that controls the switching action of the power supply is low-pass filtered and digitized by a microcontroller. The microcontroller also measures the value of the input voltage. These two values are applied to a lookup table with interpolation to map duty cycle and voltage to a power level. Fig. 4 shows an example calibration curve with measured duty cycle on the independent axis and input power to the supply on the y-axis for a fixed input voltage. There is a clear one-to-one mapping between duty cycle and input power, but the curve is piecewise linear. This occurs because at higher power outputs, the frequency is at the maximum value with only duty cycle changing. This represents the continuous conduction portion of the power supply operation, whereas the rest of the operational range has an increased efficiency due to discontinuous current in the transformer. Fig. 5 shows how the duty cycle output changes over differing input voltage. It is important to measure input voltage

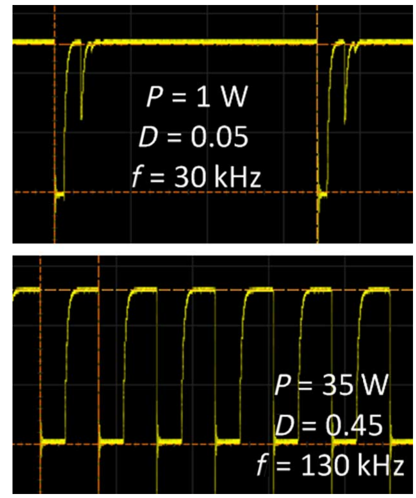

Fig. 3. Oscilloscope traces of logically inverted power supply switching signals for two-load conditions showing how duty cycle and frequency change with load power.

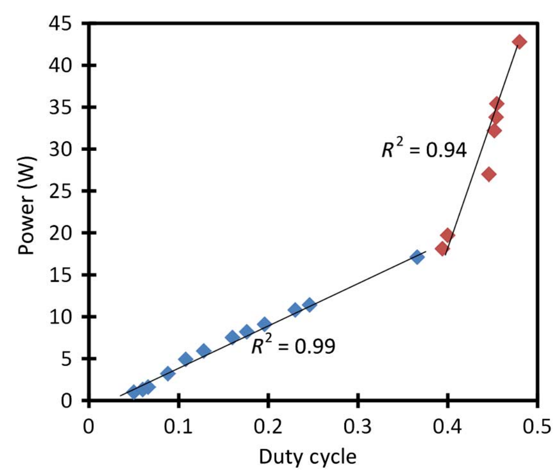

Fig. 4. Example calibration curve for a fixed input voltage mapping duty cycle to power.

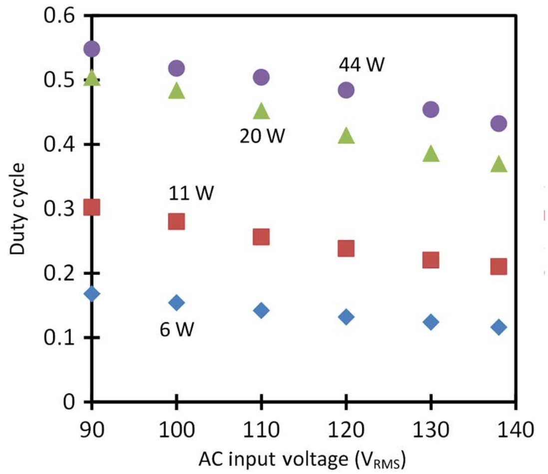

Fig. 5. Example calibration curve showing the effect of varying input voltage on duty cycle.

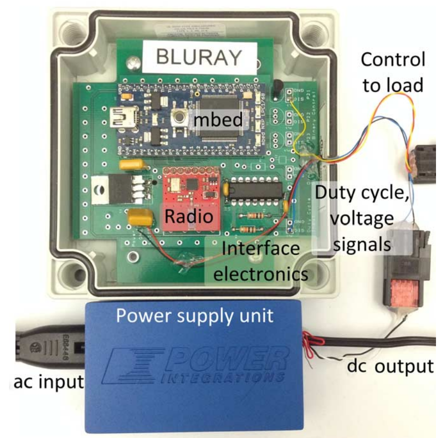

Fig. 6. Photograph of a prototype CPS. In Fig. 2, the microcontroller is the ARM mbed, and the unshaded components make up the power supply unit. Wired connections between sub-units are also shown.

mostly to determine system operating voltage (e.g., 100, 120, or 220 V) rather than the exact voltage value due to the low slope of these curves, but accounting for voltage is nonetheless important.

The wireless networking we perform is simple yet robust under the circumstances of our demonstration. We reviewed existing networking stacks available and found that they were not easy to port to our prototyping platform or had reliability issues in environments with heavy levels of spectral congestion. We opted for a simple, frequency-agile, star network. The entire network communicates with a central hub at regular intervals and changes carrier frequency when communication becomes unreliable. Nodes search for the carrier frequency currently in use if communication is broken.

B. Hardware Implementation

The purpose of our demonstration was twofold: to demonstrate the CPS concept and highlight the advantages of rapid prototyping, as it relates to the IoT. We selected off-the-shelf hardware that had open-source software libraries available when possible. The only system components that were specially prepared were the power supply modules and the circuit boards that contained various interface components. The power supplies were built by Power Integrations, a company that designs power supply controller chips, and these power supplies had the switching output and input voltages available as extra wires fed out of the power supply. These changes add almost nothing to the cost of the power supply because the signals are available outside the controller chip already. We selected ARM mbed for development, and used the NXP LPC1768 microcontroller board. The processor is more than capable for this project–and selected as the complexity of networking and application is considered too much to be implemented on an 8-bit device as efficiently. ARM mbed also employs software abstraction that allows us to target other ARM Cortex-based platforms with the same code. This will enable easy migration to cost-reduced parts for production. The mbed community also has extensive software libraries, and we leveraged these libraries to minimize development time. The Nordic nRF21L01 transceiver we selected has a well-developed publicly available library in the mbed community, which we used as the basis for our network. We designed a printed circuit board that contained the associated interface components, so that our microcontroller could read values from the power supply and provide control inputs to the connected devices. A photograph of a single prototype CPS including the power supply, the processor module, the radio module, and ancillary components is shown in Fig. 6, and this fully implements Fig. 2. Wires run from the CPS to the device under control, so that the device natively carries out power commands issued by the CPS.

Providing control to the connected products required basic understanding of the product's existing user interface. Device ON–OFF operation is often controlled via a button press (such as a TV power button). The CPS emulated button presses using a MOSFET transistor in parallel with the user-controlled switch. In the case where an analog signal for control was needed, we used a digital-to-analog converter on the microcontroller and an op-amp to drive the required signal. When fully integrated into the product, integrating with the existing interface is easily accomplished as part of the design process.

The overall hardware design occurred rapidly. We breadboarded the components and tested for functionality. We immediately designed a circuit board that contained the appropriate connections and had it fabricated. Within 2 weeks, we had our final hardware platform, which was robust enough for days of operation on a trade show floor.

C. System Demonstration Architecture

We implemented our CPS technology in an LED lamp, Blu-ray player, and a TV. The lamp, Blu-ray player, and TV were power monitored in real time, and the resulting data were uploaded to the Internet immediately after measurement. The energy use information was displayed on a cloud-based dashboard, which also allowed a user to control each device. The user dashboard provides intuitive energy-use information and control of each connected device. Each device also retained the use of its native control interface (e.g., remote for the TV and Blu-ray, and dimmer switch for the LED lamp), allowing the user to seamless switch between web-based and direct-device controls.

Fig. 7 shows an overview of the system used in the demonstration. The mbed devices with radios served as the brains of the

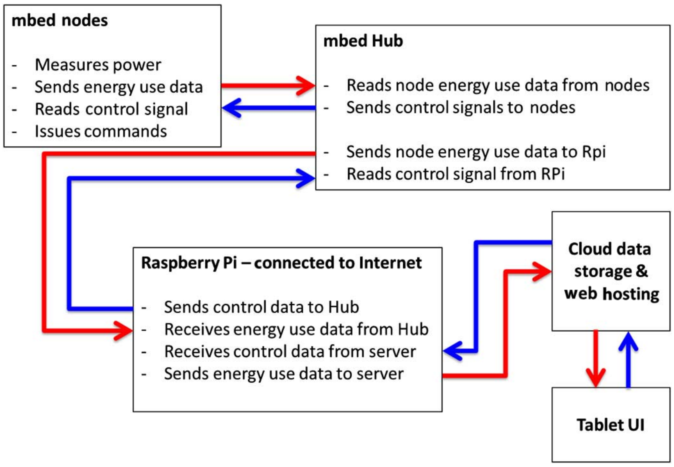

Fig. 7. Functional diagram showing components and communication links of demonstration system. There are multiple mbed nodes and one hub in the network.

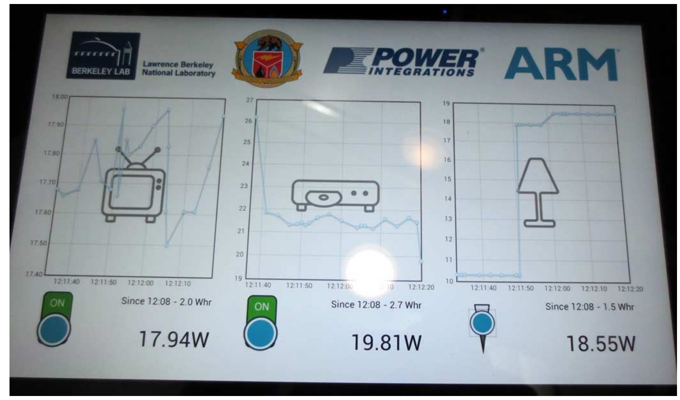

Fig. 8. Photograph of the tablet screen showing real-time power values and control options for the devices using a CPS.

CPS and as the network hub. The hub connected to a local server implemented on a Raspberry Pi, an ARM-based embedded Linux computer, and this server handled interactions with our web service running in the cloud. This section details the functions and interactions of each of these system components.

The mbed-based nodes are integrated with the power supplies of the Blu-ray player, TV, and lamp. Each node measures the device's power consumption and sends that information to the control entity. This information also allows the device's power state to be inferred by the server. In addition, these nodes receive inputs from the control hub and relay those signals to the devices. All communication between the nodes and the hub was wireless. The network hub was also an mbed-based device that controlled network traffic. The hub receives energy-use information from the nodes and sends control information to the CPSs integrated with the devices. A process on both the hub and the nodes ensures that all CPSs are active and connected to the network. If a network interrupt is detected, the hub signals all nodes to change wireless frequencies. The hub relays the node energy-consumption information and cloud-based controls between the local server and the CPS devices.

The local server served as the Internet gateway for the local network hub device. It is not technically necessary for the local server to be a component in this configuration. It is possible to connect the mbed to the Internet and, in turn, make each component in this system based primarily on the mbed platform. However, because of the ease with which Linux could be configured to communicate with both the mbed hub and the Internet-based data reporting system, it was included in our demonstration for the sake of simplicity, in keeping with our rapid prototyping approach. Its inclusion also illustrates how multiple rapid prototyping platforms can easily be configured to communicate over common interfaces.

We adopted a cloud-based data storage and web hosting solution [19] where our data were uploaded and archived. The server archives energy consumption data and allows the user to access and display these data. This same server sends the control signals to the local server. The server can be configured to send controls automatically, only send controls based on direct user inputs, or some combination of the two. Fig. 8 shows the tablet computer display with power traces of the three devices and the control interfaces.

We used a tablet computer to interact with the cloud-based server and allow the user to view energy use information, and control the devices via the Internet. This system shows power consumption (real time and cumulative) for each device and allowed people to control each of the devices with touch buttons and observe the changes in power on the screen.

Our rapid prototyping approach allowed us to go from concept to working prototype in approximately 3 weeks with only two employees and low hardware and development-related expenses. This represents significant gains when compared to the typical prototyping timeline, and it allows for creativity and revision during development as unanticipated problems arise.

D. Energy-Saving Applications and Behaviors

Using readily available hardware and a minimum of software development, we demonstrated the potential of unobtrusive load monitoring and control in a CPS. Our demonstration scratched the surface in terms of intelligent device behaviors that could be implemented with this type of setup. Our server detected when the user had turned OFF the TV (using either the tablet or remote) and sent a control signal to the Blu-ray player to turn it OFF, as well. In addition, when the Blu-ray player was turned ON, the server sent a control signal to the TV to switch it ON.

These behaviors add value for the user and present energy-savings opportunities without introducing inconvenience. Networks of CPSs could be built incrementally, with opportunities for intelligent behaviors, and corresponding energy savings increasing, as the network grows. The largest opportunities for both increased energy efficiency and user benefits can be found in the ability of these devices to respond to one another, or to other measurement and control devices such as smart thermostats.

E. Comparison to Related Work

The primary advantage of the CPS concept over related work is that the CPS is a commodity device that is sold as a part of the products of interest. This commoditization results in low costs, market scalability, and the ability to be deployed widely. The tight coupling between the CPS and the product means that all configurations can be done in the factory, removing some of the complexities related to configuration for end users.

The ability to use native controls in addition to the dashboard interface is one distinguishing feature of the CPS. The hardware represents only an *additional* layer of functionality instead of a replacement for the controls with which the user is familiar. Our integrated solution complements the controls with which the user is already familiar while adding a seamless additional layer of energy reporting and internet connectivity. When the device (e.g., TV) is plugged in, our hardware is immediately functional with no additional configuration necessary. This approach removes the burden of choosing between native and remote controls. The user can also choose to utilize only the energy monitoring capabilities of the system without using web-based controls if they desire.

Because the CPS is part of the product, the identity of the product (both product type and unique identity) can be configured in the CPS at the factory. This ensures that devices and their available behaviors can be shared with building energy management and automation systems without the user manually configuring the device type and identity for every device of interest. The identity will stay with the product even if the product moves, because the power supply is a part of the device. Even external power supplies are rarely used with devices other than the one intended.

By integrating the monitoring and control hardware into the device, consumers face a low burden when adopting devices that can monitor and control miscellaneous devices and electronics. Adding power measurement capability, if a microprocessor is already available, is as simple as adding a few passive components (see Fig. 2) for a total price increase of less than USD 0.10. Adding a simple microprocessor and control capability in the power supply is approximately USD 0.15. Adding networking depends on the network stack chosen and can be free when using an existing network connection. A low-cost IEEE 802.15.4 radio costs about $1 including the radio chip and passives, and other network technologies tend to cost somewhat more. Integrating this hardware into pre-existing devices is inherently more cost-effective than currently available products installed in between the plug and the device. Integrated hardware is an important step in changing this technology from something used on the small scale by highly motivated, energy-conscious hobbyists to wider adoption by the average consumer.

V. Policy and Energy Implications

The CPS enables both energy savings and improved energy policy. The CPS is able to report energy, power state, and unique identity to a central entity, so that energy service providers or consumers can be made aware of device state and energy use. Informing services and people about energy use helps, but if the services are able to provide actionable information to people or issue controls back to the devices, significant energy savings is possible. Devices are ON and unused as often as they are ON and used [17]. Nowadays, most devices have very low sleep power, so almost all of the energy is used in the ON or idle state. Therefore, a fraction close to 50% of the total energy used by products is wasted while the device is in the idle (unused) state. CPS technology has the potential to reduce this wasted energy without impacting the services provided to consumers. Plug load research in commercial buildings suggests that simple timer-based control of currently non-networked plug loads would save 6% of commercial building energy use [20]. More advanced control options would be possible with CPS, and it is likely that the widespread deployment of CPS technology has an energy-savings potential of 5%–10% of total building sector energy use.

If new devices were able to report energy use to a central entity, entirely new policy options would be possible. Currently, policy makers develop an energy test procedure that tries to mimic real-world conditions, so that the energy use of a product can be compared to the energy use of similar products. There is no way to be sure that the test procedure is a fair comparison or that it represents reality. CPS technology would allow low-cost field verification of comparative energy performance of devices and provide concrete data by which to develop test procedures. Enrolling devices in a study on energy use would be as simple as recruiting a consumer and setting some software settings, rather than specifically installing and maintaining equipment at consumer sites. In-the-field validation of test procedures and policy actions is extremely valuable, but the cost of such studies is high. The CPS technology can reduce these costs dramatically, and these studies will drive higher levels of energy efficiency in products.

VI. Conclusion

We presented an Internet-connected system of CPSs that enables improved energy awareness of devices and users. We believe that CPS technology is the future of energy monitoring for plug loads, and that all energy-using devices will one day be aware of their identity and share energy information over IP networks. The CPS concept we have shown here demonstrates that this concept is valid at reasonable price points even for quite low-cost devices. Energy awareness enables new sets of interactive energy-saving behaviors where devices control their power state to meet user needs while minimizing energy use. Unlike existing technologies, CPS devices are integrated into the product to provide native controls and automatically include product identity information. The low cost, reduced configuration burden, and tight coupling with the powered product make CPSs an excellent application of IoT concepts.

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