Wireless Electricity Metering of Miscellaneous and Electronic Devices in Buildings

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***Abstract*- Miscellaneous and electronic loads (MELs) consume about 30% of the electricity used in U.S. commercial buildings, but our understanding of their energy use lags the traditional end-uses. A key component of reducing energy use is understanding how devices are used, but few studies have collected field data on the long-term energy used by a large sample of devices due to the difficulty and expense of collecting device-level energy data. This paper describes a wireless MELs metering system and an office building case study where these meters were deployed. Hundreds of miscellaneous and electronic devices where metered for several months. This paper includes key findings on the meters, network and MELs energy use.**

I. INTRODUCTION

Miscellaneous and electronic devices (also known as miscellaneous and electronic loads, or MELs) consume about one-third of the energy used in U.S. buildings, and their energy use is increasing faster than other end-uses [1]. In order to address the growing energy use of MELs, it is important to have empirical, field data on the energy use of these devices to ensure energy efficiency activities are targeted at products that contribute the most to energy use or have the greatest energy savings potential.

The most comprehensive studies of the MELs end-use in the U.S. are based on national surveys of a few thousand residential and commercial buildings, in which monthly, whole-building utility bills are collected. These monthly bills are then statistically disaggregated to estimate end-use energy consumption. In these models, MELs are included in the "Other" end-use, which is a statistical residual that cannot be attributed to one of the traditional end-uses (heating, cooling, lighting, etc.). It is therefore subject to errors due to data collection or model specification in these traditional end-uses.

With the proliferation of MELs over the last 20 years, metering at the individual device level is needed to properly characterize energy use of this equipment. Several studies have been conducted in recent years to fill this gap. In California, MELs metering has been conducted in both residential [2] and commercial [3] buildings. The residential study sampled 50 homes, metering 17 devices per home for a period of one week. Meter readings were collected at one-minute intervals. The commercial building study sampled 47 office buildings, metering 10 devices per building for a period of two weeks. Meter readings were again collected at one-minute intervals. A third study was recently completed in Minnesota. Metering was conducted in about 50 homes, with 16 devices metered per home for a period of one month. Meter readings were collected at six-minute intervals. The data collected through these studies significantly improved the state of knowledge of MELs energy use in U.S. buildings. The main limitation is that the expense of the metering equipment (the last two studies used Watts Up Pro meters, US$200-300 per metering point) limits the number of devices per building that can be metered. Because of the wide diversity of MELs devices found in buildings, it is important to be able to meter a large number of devices per building. Also, the meters all used on-board data storage, which limits the length of the metering period and the frequency of energy measurements.

To address the limitations of these earlier studies, it is important to develop MELs field metering techniques that are more cost-effective and allow more frequent meter readings over longer time periods. The goal of this study was to utilize recent developments in wireless sensor networks to develop a lower-cost, reliable MELs metering system that allowed long-term metering of MELs devices in buildings. We identified that the vast majority of MELs are plug-in devices, and developed system is a wireless plug-in device metering system. This system was tested in several homes and a commercial office building. The hardware, network, and commercial building case study are discussed here.

II. ELECTRICITY METERING WIRELESS SENSOR NETWORK

The wireless power meters used in this study are a research platform developed by the University of California, Berkeley [4] in collaboration with Lawrence Berkeley National Laboratory (LBNL). Called ACme ("AC meter") and shown in Figure 1, these meters provide power readings every ten second and are accurate

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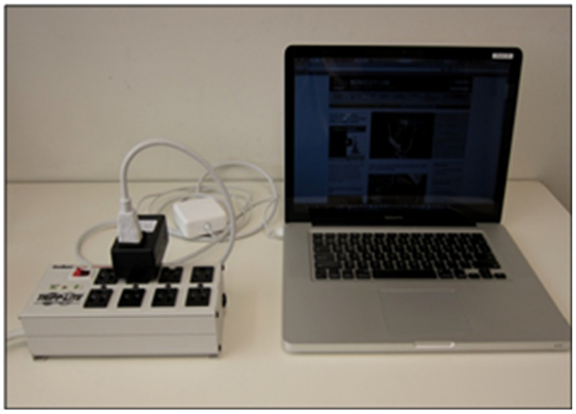

Figure 1 ACme node (left in power strip) measuring laptop power

to the greater of 0.5W or 2% of reading for over 80% of measurements. The ACme system consists of three tiers: the ACme node which provides a metering interface to a single AC outlet, a network fabric for data relay, and application software that collects the power and energy data, stores it in a database, and provides various data processing functions. The architecture used in the commercial building is summarized in Figure 2.

Figure 3 shows the electronics contained inside an ACme node. Each ACme integrates an MSP430 microcontroller, an IEEE802.15.4 RF transceiver, power supply and a dedicated energy metering IC to provide real and apparent power measurements. A Hall effect sensor is used to measure the current passing through the meter. Due to the small size and use of commodity parts, the production cost of the ACme system in small volume is approximately $65. It is expected the cost (including programing and calibration) would be approximately $20 in volumes of 10k devices. The power draw of an ACme node is 0.4W which is dominated by the quiescent power of the power supply.

The network tier provides UDP transport over an IPv6 wireless and wired network. The meters are connected together and to wireless network edge routers using a 6LowPAN wireless mesh network. The edge routers are connected via Ethernet to a wired backhaul network using an IPv6 tunnel. Routing in the wireless mesh is handled using the Hydro routing protocol [5], a previously developed and well tested predecessor to the in-development IETF RPL protocol. Nodes automatically

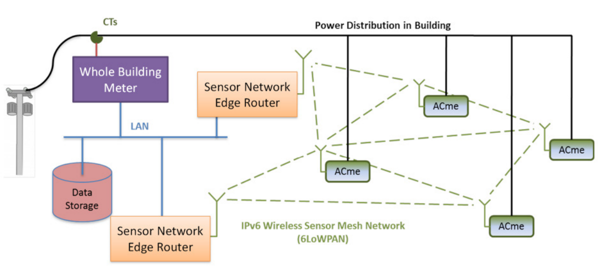

Figure 2 Schematic of Metering Network

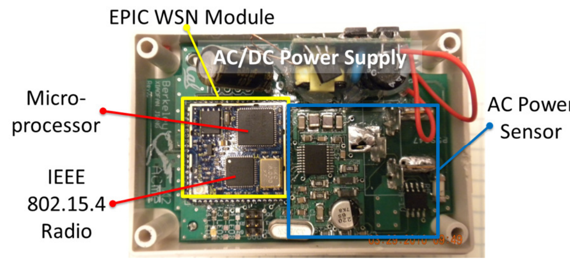

Figure 3 Interior of an ACme node

join the IPv6 subnet after being plugged in, and begin interactions with the application layer. A simple flood based method of time synchronization is used to provide local time stamping of data packets at the meter.

The application tier receives data from the IPv6 tunnel, provides basic integrity checking, and stores the readings. Data are stored in both a MySQL database and dumped to a remote file for data reliability. A simple web application is used for visualization. This tier also provides complete backup services, daily network status updates, and additional diagnostic information.

A key enabling aspect of this system is the use of configuration rather than re-programming in the system firmware. Many system parameters can be changed over the network without reprogramming, and this has enabled us to work around minor bugs and update parameters such as meter sample rate or calibration without creating a new image in over a year. Reprogramming hundreds of meters by unscrewing the case and using a wired programmer is not a reasonable solution, and simple over-the-air configuration served this network well.

III. Commercial Building Deployment

The commercial study building, an office building located on the LBNL campus, is a 1960s era facility largely used as a traditional office space. It has a total floor area of 90k square feet. Approximately 450 occupants in six departments are located on four floors and a basement. The building has individual offices, cube farms, conference rooms, break rooms, a computer training facility, server closets, and network equipment.

A. *Building Device Inventory*

We conducted a full inventory of the MELs devices in the office building. It is not practical to do this in a larger building, but we wanted a full inventory to enable the evaluation of sampling methods where only small portions of the building would be inventoried. Due to the diversity of devices, a standardized system of identifying and recording MELs is essential for inventory and energy data analysis. Nordman and Sanchez [6] developed a taxonomy of MELs, and we updated this taxonomy to include new device types available today. Inventory data were collected via direct computer entry in the field into an auto-completion enabled spreadsheet. This ensured accurate and consistent inventory data. Approximately 5000 devices were inventoried in the office building.

B. *Meter Deployment*

Given the number of devices in our study building, metering all these devices would be time and cost prohibitive, and not all data generated would provide useful insights. We installed 455 ACme devices—about a 9% sampling rate—for over 6 months to capture usage patterns and long term variations. The selection of an appropriate sampling method is driven by the multi-fold purpose of our energy data collection and analysis:

- Measure power consumption of MELs and capture the different power states;
- Derive usage patterns of MELs;
- Study usage correlations between devices;
- Provide a large survey of power and energy measurements of individual devices in actual use.

We used a staged, stratified random sampling approach to select devices for metering. Devices were divided into stages by department housed in the building (to ease organization issues), and stratified by device type to meet our data collection objectives listed above. This stratification is essential because a simple random sample would result in metering a large number of uninteresting devices (e.g. computer speakers) without capturing enough interesting devices (e.g. computers, displays). The 455 metered devices are spread throughout the building, and no care taken to ensure good network connectivity. A total of 7 (roughly two per floor) edge routers (devices that connect the wireless mesh network to wired Ethernet) were deployed in convenient locations throughout the building. All 455 meters formed a single mesh network providing reliable communication with many possible data sinks to the wired LAN.

IV. METHODOLOGICAL FINDINGS

We accumulated extensive lessons learned and experience from the metering activities that will be useful in future meter and network development as well as future field studies. These lessons learned fall into two categories: hardware or network related and field method related. The hardware and network findings will be discussed here.

- Small, wireless meters enable the sort of study needed to answer key MELs energy use questions.
- Although the network provided global time synchronization, the accuracy proved to be worse than 10s at times. The needed time synchronization at the meter is better than 1s to provide the capability to correlate usage between nearby devices and correct for dropped network packets.
- Network connectivity, either wireless or wired, is not available 100% of the time. To ensure as much of the metered data reach the data store, local data storage in the meter and the edge router is needed to deal with network interruptions.
- Due to the network protocol used and the nature of the RF transceivers (IEEE 802.15.4 compliant), a limited amount of data could be received by each edge router. Approximately 50 meters could be reasonably serviced (a data rate at the edge router of 3kbps including data and network overhead). Additional edge routers were used to ensure this rough guideline was met.
- A 15A in-line fuse was included in the meters for over-current protection, but this fuse occasionally failed at lower current. This caused frustration for device users and was not needed because the building circuit breakers provided this protection already.
- On occasion meters dropped off the network and needed to be reset to rejoin. This required unplugging the meter and was impossible on some devices (e.g. servers). An external reset that did not cut power to the load would have solved this problem.

V. ENERGY DATA BASED FINDINGS

The data collected have provided significant insight into the energy use of MELs in the study building. The data collection enabled evaluation of required meter sample rate, metering period, estimates of annual energy use, evaluation of the time devices spend in each power mode and more.

The meter sample rate (the time between average power readings reported by the meter) must be high enough to meet study objectives but low enough to reduce the amount of data passing over the network. In this study identifying the time spent in power modes was a key goal. In studies where simply annual energy estimates are desired, the meter sample period can be very long. In our case, the sample period must be significantly shorter than the dynamics to be characterized. We found that 1-minute data provided the required resolution while slower sample rates resulting in a reduction in accuracy. This was verified by estimating the time in power mode for hundreds of devices using different sample rates and looking for accuracy degradation. To see how this occurs, Figure 4 shows the time series power curve of a LCD

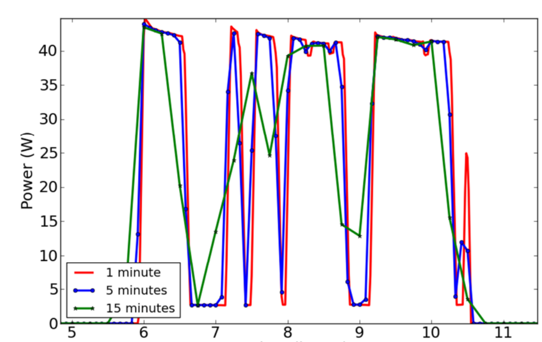

Figure 4 Time series of LCD monitor power

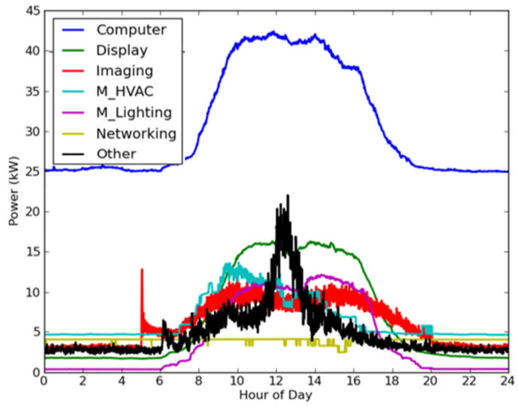

Figure 5 Average weekday load shape for key device categories.

computer display with data resampled at various rates.

Figure 5 shows the average weekday load shape for different device categories based on our random sample and projected to the entire building. The sum of these represents about 40% of the building electricity over a 3 month period (in which there was no air conditioning use). Out of this 40%, 50% is used by computers, and 10% each by imaging equipment, displays, and miscellaneous HVAC (e.g. space heaters, desk fans). Task lighting used 7%, network equipment used 6% and the remaining 7% was used by all other MELs device types in the building. It is estimated that improved use of computer power management could save 60% of the computer total (12% of the building total) energy, and timer controlled plug strips could save 6% of the building total (when applied to devices other than computers, network equipment and refrigerators).

Figure 6 shows the fraction of time desktop computers spent in the "on" power mode during the 6 months of this study. Note the two distinct peaks representing devices with no power management (on nearly 100% of the time) and well power managed devices (on approximately 20% of the time). Increasing the acceptance of power management could save significant energy.

VI. Conclusions

As efficiency improvements in the traditional end uses become more and more successful, MELs continue to increase their share of energy use in buildings. To develop effective strategies to reduce MELs energy use, large-scale data collection is needed to understand the areas of improvement available. We developed and demonstrated power meters with wireless mesh-networking technology,

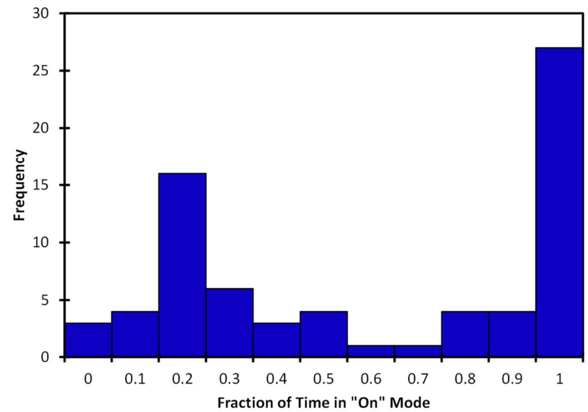

Figure 6 Histogram showing time in the "on" mode for the 73 desktop computers metered.

and devices like these enable the cost-effective data collection needed. The relatively high measurement accuracy and sampling frequency permit new types of analysis, such as accurate power-mode identification.

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