A Wireless Sensor Network Based Green Marketplace for Electrical Appliances

Danny Hughes, Ka Lok Man
Computer Science and Software Engineering
Xi'an Jiatong-Liverpool University
Suzhou, Jiangsu Province,
People's Republic of China
daniel.hughes@xjtlu.edu.cn

Kevin Lee
Dieter Schwarz Chair of Business Administration and E-Business and E-Government,
University of Mannheim,
Mannheim, Germany.
lee@bwl.uni-mannheim.de

Jo Ueyama
Department of Computer Science
University of São Paulo
Rua Arlindo Béttio 1000,
Sao Paulo,
SP, Brasil.
joueyama@usp.br

***Abstract*— Wireless sensor and actuator networks are a promising tool to support energy monitoring and conservation. However, to date, research in this area has focused upon supporting infrastructure managers, while failing to consider the important role of appliance manufacturers in conserving energy. This paper presents an architectural vision for conserving energy that respects the divergent interests of infrastructure managers and appliance manufacturers. From the manufacturer's perspective, the system will provide feedback on the performance of appliances after deployment, along with a new mechanism to reach potential customers. From the infrastructure manager's perspective the system reifies appliance energy consumption data, while providing intelligent suggestions on appliance purchases. In concert, we argue that these features will provide significant energy and cost savings.**

Keywords- Wireless Sensor Networks, Energy Conservation

I. INTRODUCTION

Energy conservation is a critical world-wide problem, which has a particularly significant impact on developing countries such as China, where keeping up with the growing demand for energy has necessitated a costly and environmentally damaging expansion of power generation facilities [1]. Improving the energy efficiency of electrical appliances has long been recognized as a critical problem that must be addressed in order to reduce energy consumption and thus ease its associated financial and environmental costs. While replacing legacy appliances with more energy-efficient devices has the potential to reduce energy consumption, it is often financially infeasible for organizations to replace all legacy devices. This paper argues that Wireless Sensor and Actuator Networks (WSAN) have the potential to improve the energy efficiency of legacy appliances, while allowing infrastructure managers to more effectively target green purchases.

Wireless Sensor and Actuator Networks (WSAN) [4] are composed of small-form factor embedded computers equipped with low-cost sensors that communicate using low power radio technologies. WSAN are a promising platform for providing fine-grained monitoring and control of electrical appliances via a common *infrastructure management interface*. Continuous and fine-grained monitoring of appliance power consumption allows for the identification of appliances that require maintenance. Power consumption data can also be used by infrastructure managers to better understand patterns of appliance use in their organization. Critically, a WSAN infrastructure also allows managers to effectively control appliances that may be geographically distributed from a common *infrastructure management interface*.

The availability of fine-grained usage data for electrical appliances also offers a new opportunity for appliance manufacturers to reach potential customers. Appliance manufacturers may provide a detailed 'power profile' for the appliances they sell, which can be compared to the performance of legacy devices via the *infrastructure management interface* to allow infrastructure managers in selecting the most critical and effective green purchases.

The remainder of this paper is structured as follows: Section II discusses related work in the field of WSN-based power monitoring. Section III presents our vision for an end-to-end energy conservation architecture. Section IV presents a case study of this architecture. Section V discusses avenues for future work. Finally, section VI concludes.

II. RELATED WORK

Dutta et al. [2] introduce a simple hardware and software design for cost-effective monitoring of the energy consumption of devices that use switching-regulator type power supplies. The proposed architecture consists of a simple hardware interface to a standard WSAN 'mote' platform [3] and associated analysis software for the TinyOS operating system [4]. This platform infers power consumption based upon the relationship between current-load and the frequency of switching in the power regulator. The resulting system demonstrates low overhead and high accuracy. However, the approach advocated by Dutta et al. does not provide a generic solution for monitoring the power consumption of legacy appliances as (i) not all appliances use a switching-regulator power supply and (ii) retrofitting legacy devices with the required hardware would be cost-prohibitive for large infrastructures which may house thousands of legacy appliances.

Sentilla provide a range of WSAN products designed to monitor power consumption in data centers [5]. The Sentilla power monitoring architecture is based upon a measure-analyze-act cycle, which supports data center managers in incrementally reducing the power consumption of their infrastructure. While Sentilla provides an integrated solution energy conservation, their solution is tightly focused upon data center scenarios and is not applicable to other kinds of electrical appliances.

There are a number of approaches to managing the power consumption of nodes in a WSAN network for devices with a limited power source such as solar cells [7], or for motes which depend on battery power [6] alone. Such work is highly complementary to that proposed in this paper, as any WSAN that is deployed to support energy conservation should itself impose minimal additional overhead due to the energy consumed by the sensor nodes themselves.

In contrast to the related work discussed in this section, the approach we propose for monitoring power consumption is generic and can be applied to any electrical appliance without the need to modify the appliance itself. Furthermore, the power monitoring systems discussed above are targeted only at infrastructure managers and do not provide support for appliance manufacturers, which has hindered their uptake.

III. AN END-TO-END ARCHITECTURE FOR ENERGY CONSERVATION

This section provides an overview of an end-to-end architecture that is designed to support WSAN-based energy monitoring and conservation. To achieve significant energy conservation, appliance manufacturers, infrastructure managers and appliance users must *all* be engaged. The enabling technology for this vision must be low-cost, easy-to-use and be sufficiently adaptable as to provide support for a wide variety of electrical appliances. The remainder of this section discusses each of these issues in detail.

A. Stakeholder Roles

We have identified three primary stakeholders in the proposed energy management infrastructure: (*i.*) infrastructure managers, (*ii.*) appliance manufacturers and (*iv.*) appliance users.

The ***infrastructure manager*** has responsibility for maintaining all appliances within a piece of infrastructure such as: a retail complex, office building or university. The primary goal of the infrastructure manager is to minimize the financial cost incurred due to the power consumption of appliances in their infrastructure. In order for infrastructure managers to participate fully in the proposed system, it should significantly reduce the cost of running their devices. Furthermore, energy management equipment must be simple to deploy, reliable and should not interfere with other equipment in the infrastructure.

The primary concern of ***appliance manufacturers*** is to maximize their profit by selling as many appliances as possible. Manufacturers may also wish to monitor the reliability and performance of their devices in the field to inform the design of future appliances. In order for manufacturers to participate fully in the proposed system, it is critical that the architecture provide a mechanism through which they can sell more appliances.

The primary concern of ***appliance users*** is that the appliances they use provide the best possible experience. The additional energy management features we provide should thus give additional benefit to appliance user without requiring additional training or hindering the use of the appliance. In small infrastructures, the *infrastructure manager* and *appliance user* may be the same individual (e.g. a home owner).

B. Sensor Network Based Energy Monitoring

The stakeholder requirements outlined in the previous section may be mapped onto technical features of the proposed WSAN infrastructure as follows.

- **Low price-point:** there may be thousands of appliances contained within a single infrastructure and thus the sensor nodes that compose the WSAN should be as cheap as possible.
- **Low-power overhead**: the nodes which compose the WSAN should consume minimal power, and thus maximize cost savings for infrastructure managers.
- **Reliability:** due to the safety-critical nature of many appliances, the system must be reliable.
- **Integration of manufacturer data:** the system will allow manufacturers to submit appliance power profiles, which will be used by infrastructure managers to select *optimum* green purchases.

An overview of the proposed system architecture is illustrated in Figure 1. A description of each system element follows.

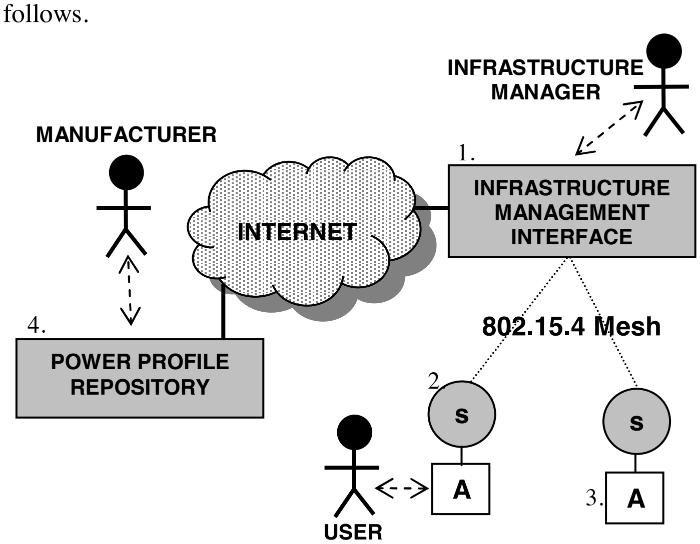

Figure 1: Energy Monitoring Architecture

Figure 1 illustrates the overall architecture of the proposed end-to-end energy management system. Each element referenced in figure 1 is described below:

1. Infrastructure Management Interface: the infrastructure management interface provides an overview of the energy consumption of all appliances within the managed infrastructure. Along with allowing the *infrastructure manager* to view the current energy consumption of all appliances, the management interface will allow the infrastructure manager to compare the current performance of appliances with their ideal performance, as described by the manufacturer provided *power-profile*. In addition, the infrastructure management interface will allow the *infrastructure manager* to compare the performance of legacy appliances to other devices available in the 'green market place'. This allows infrastructure managers to conserve power by planning optimum green purchases, while providing a new method for manufacturers to reach customers. In terms of supporting software, we envisage that the management interface will offer a standard web services interface to the appliance profile repository (4) and an easy-to-use user-interface. The manager may also choose to allow 3rd parties access to appliance power consumption data to support additional services. For example the infrastructure manager may allow maintenance companies access to real-time data, in order to identify aging devices in need of repair. Alternatively, an infrastructure manager may allow their electricity provider access to their power consumption data so that they can suggest more cost-effective pricing plans.

2. Wireless Sensor and Actuator Nodes: the nodes which compose the WSAN will follow a classic low-power mote design such as [3]. Nodes will communicate using a low power 802.15.4 mesh network and power-saving communication protocols. In realizing such a platform, we will build on our previous work in building low-power, adaptable mote platforms [11].

3. Appliance Monitoring: In order to provide generic monitoring of appliances, each mote will be equipped with an AC current sensor to monitor the power consumption of the attached appliance and a relay actuator to activate or deactivate the attached appliance. WSAN sensor nodes should be small enough that they can be unobtrusively installed between each appliance and the electrical outlet, or in the case of permanently installed appliances, by installation in power supply cable. Thus integration with the WSAN requires no modifications to the appliances themselves.

4. Power Profile Repository: The power profile repository provides a global resource for storing and accessing power profiles. Each power profile is provided by the relevant *appliance manufacturer* and describes the power consumption of the associated appliances. Each device will be assigned a location in a global device ontology, allowing managers to compare the power consumption of functionally equivalent devices side-by-side using the *infrastructure management interface*.

C. Appliance Power Profile

An appliance power profile has two key components. The first is an entry in a device description ontolology, which will be realized using a standard ontology descrption language such as OWL [10]. Each appliance power profile also contains a description of the ideal and worst-case power consumption of the associated device for each stage of its usage cycle. This data, together with the device ontology is used by the *infrastructure management* interface to automatically suggest the most optimal replacements for legacy devices in terms of both functionality and power profile.

D. Gathering Contextual Data

In order to better understand the context in which a device is being used, a range of additional sensors will be used. Contextual sensors may monitor many factors. For example: to detect whether a room is occupied or empty, to detect whether the doors and windows are open or closed or to monitor common environmental conditions such as heat and light levels. Section IV explores how these contextual factors can be monitored using a range of low-cost sensors in a real-world case study.

E. Modelling Sensor and Actuator Behaviour

At the ***low-power mote level***, in order to manage the heterogeneity of monitored appliances, we intend to adopt a lightweight-component based middleware suitable for execution on embedded devices. Specifically, our approach will be based on Lancaster's OpenCOM model [8]. OpenCOM is a generic component model for building reconfigurable systems that may be tailored for various application domains. This brings with it two critical benefits:

- ***Costs:*** The employment of a consistent tool can lower the software costs that are required when purchasing a variety of technologies for a wide range of sensors. This is particularly beneficial in sensor networks as there exists a high heterogeneity in this domain
- ***Skill transference:*** The utilization of different technologies to build applications for each target device and applicability does not allow transference of skills across different tools. Skill sets and areas of expertise are rarely transferable when relying on different technologies. A generic approach promotes skill transference as developers use a single consistent tool for development.

OpenCOM itself is constructed upon a minimal and policy free microkernel that is capable of deploying required functionalities at runtime. The generic approach of OpenCOM fosters code reusability as developers may reuse existing components and/or processes. For our prototype implementation, we will adopt the OpenCOM-based Lorien Operating System, which provides all of the benefits of OpenCOM, while running natively on embedded WSAN hardware [8].

At the ***gateway level***, and above a component-based software engineering approach is followed based upon our previous work in this field on LooCI, the Loosely coupled component Infrastructure [13]. LooCI components use a novel event-based binding model that allows developers to model rich component interactions, while providing support for easy interception and re-wiring through the use of an event-bus abstraction. LooCI also provides support for advanced features like distributed garbage collection and generic fault tolerance. OpenCOM and LooCI components integrate effectively to provide advanced, reconfigurable middleware features together with fine-grained adaptation of system functionality.

IV. CASE STUDY

As previously discussed, China's power shortage is one of the most critical problems facing the country. Despite major public initiatives [14], power wastage due to the unnecessary operation of legacy appliances such as air conditioners and lighting is still surprisingly common in large organizations. The presence of energy-inefficient legacy devices also remains a key problem [1].

In order to demonstrate the applicability of the ideas presented in this paper, a case study is used which attempts to realize real-world power savings in a large Chinese organization: Xi'an Jiaotong-Liverpool University (XJTLU) in Suzhou, China. In order to effectively demonstrate the potential of the green marketplace approach, the initial focus is on subset of the XJTLU infrastructure and a subset of appliance types. Specifically the focus is on a single floor of a XJTLU building and the monitored appliances are lighting and air conditioning appliances.

The XJTLU floor on which we will conduct this case study consists of 20 staff offices, 5 lecture rooms with the capacity of 50 persons and 2 lecture rooms with the capacity of 200 persons. The infrastructure manager is in charge of ensuring that the facilities are available reliably for the lecturers and students of XJTLU as well as minimizing power consumption within the infrastructure.

Mote-based sensors and actuators are used as the energy monitoring and actuator nodes. The OpenCOM micro-kernel is used as the base of the sensor software on the motes. Customized OpenCOM components are then installed on each Mote depending on what appliance it will be connected to. Motes that will monitor energy usage only will only host a single energy-monitoring component. Motes that also can enact actions using actuators will host additional components.

The deployed motes communicate using a low power 802.15.4 wireless network. Each Mote hosts a LooCI component that can directly communicate with the OpenCOM sensor and actuator components via the LooCI event bus.

These WASN motes are connected to each lighting unit and air conditioning device in the XJTLU infrastructure. Along with the power consumption data for each device, a number of other factors will be monitored as follows:

- ***State of doors and windows*:** simple switch sensors will be used to gather data on whether doors and windows are closed, or open. Air conditioning will be judged to be ineffective and thus unnecessary if doors or windows are open.
- ***Room occupancy*:** a mixture sensors are used to assess whether a room is occupied or not. This includes low-cost Passive Infra Red (PIR) sensors that detect body heat and digital cameras, which can be used to monitor a broad spectrum of factors. Where appropriate, image analysis algorithms together with digital cameras may also be used.
- ***Light levels:*** using simple light sensors to assess whether the light level in each lecture theatre is being kept within acceptable, defined bounds.
- ***Temperature levels:*** low cost temperature sensors are used to identify situations where rooms are being cooled to unnecessarily low temperatures, or heated to unnecessarily high temperatures.

A. Power Saving through Monitoring and Control

As previously discussed, the framework allows the power usage of appliances to be monitored and changes enacted using actuators. In the XJTLU case study discussed here the power usage due to lighting and air-conditioning systems can be monitored and appliances remotely deactivated they are considered unnecessary or are using too much power.

In the case of an air-conditioner, the appliance is considered to be unnecessarily active when it is on and the doors or windows are open. The operation of the air conditioning appliances can be altered if light sensors or room occupancy sensors indicate the room has not been used for a time.

In the case of lighting appliances, light-bulbs can be considered to be unnecessarily active when they are on and the light level is too high. The system supports global system control (i.e. manually switching off the lights/air conditioners remotely), as well as the setting of power policies that automatically activate or deactivate appliances based upon pre-configured contextual data. As with air-conditioning units, the operation of lighting appliances can be altered if room occupancy sensors indicate the room has not been used for a time.

B. Power Saving through a Green-Marketplace

As previously stated, by analyzing the way in which monitored appliances are used and comparing this to the power profiles uploaded by partner manufacturers, the system will automatically suggest the most critical devices to replace in order to reduce infrastructure energy costs.

In the case of lighting, it is relatively easy to replace light bulbs with more energy efficient alternatives. However this process is expensive for a large infrastructure. With sensors deployed throughout the infrastructure monitoring all lighting appliances it is possible to determine which will benefit from being replaced first. For example, an LED light bulb can last up to 100,000 hours compared to 8,000 for compact fluorescent light bulb and uses only 2 to10 watts of electricity – less than 1/3 of that consumed by a standard fluorescent bulb. However, LED light bulbs have a significantly higher purchase price, so not all fluorescent bulbs should be replaced at the same time.

By comparing the usage patterns of currently deployed fluorescent bulbs in the infrastructure to the power profile of currently available alternatives, such as LED bulbs it is possible to determine the potential benefits with certainty.

C. Power Saving through Better Maintainance

As mentioned previously, the proposed system will generate automatic alerts where the power consumption of an appliance deviates significantly from the power consumption specified in its power profile. This allows infrastructure managers to identify devices that are ageing and in need of maintenance, thus reducing power consumption and safety risks that arise due to poorly maintained devices.

Looking at the case study appliances. In lighting appliances, a change in the power usage of the appliance is a reliable indicator that a bulb needs to be changed. For air conditioning appliances, a change in power usage might indicate a serious fault that would need to be dealt with promptly.

V. FUTURE WORK

In the near-term the future work will focus upon realizing an initial prototype of the system described here and evaluating it using the case-study evaluation described in section IV. Based upon this case study the system will be refined whilst using the data it produces to inform energy conservation at XJTLU. On the technical front, the work will proceed along three key fronts:

- Development of a generic language and ontology for describing the functionality and power profiles of appliances.
- Realization of an integrated hardware and software sensor and actuator platform, including the development of customizable sensing functionality and resilient, delay tolerant networking approaches.
- Development of algorithms to analyze device performance and suggest energy saving green purchases based upon data from the appliance profile repository.

In the longer term, electronics companies and businesses will be engaged in order to establish a significant pool of power-profiles and test-cases.

VI. CONCLUSIONS

This paper has presented a high-level system architecture designed to promote energy conservation through the use of wireless sensor and actuator technologies and better integration between appliance manufacturers, infrastructure managers and appliance users. We have proposed a well-defined case-study through which the principles of this system can be assessed. It is our hope that by realizing this architecture we can provide a significant and effective new platform for energy conservation.

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