Remote Electricity Actuation and Monitoring Mote

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Abstract— **This work presents the design and evaluation of the REAM (Remote Electricity Actuation and Monitoring) node based around the modular Tyndall Mote platform. The REAM node enables the user to remotely actuate power to a mains power extension board while sampling the current, voltage, power and power factor of the attached load. The node contains a current transformer interfaced to an Energy Metering IC which continuously samples current and voltage. These values are periodically read from the part by a PIC24 microcontroller, which calculates the RMS current and voltage, power factor and overall power. The resultant values can then be queried wirelessly employing the Tyndall 802.15.4 compliant wireless module.**

Keywords-Actuation; Energy; Monitoring; Platform; Wireless; Sensor; Network; Buildings

I. INTRODUCTION

Ireland's profile on energy end-use shows that electricity accounts for 18% of energy consumption in the industry sector, 50% in the service sector and 26% in the domestic sector [1]. In terms of mega-watt per hour electricity consumption, the service sector accounts for 40% of the total consumption across sectors. The service sector therefore proves to be the environment where electricity spending is the highest, and, with an estimated 30% waste of electricity consumed in buildings [2], an environment where opportunities for savings are important.

Buildings of the service sector are either commercial or institutional buildings. Examples of service sector employment include government, healthcare, education, banking and retail. These buildings use electricity primarily for space heating, hot water generation, lighting, and powering business equipment and domain-specific machines [1]. In the attempt of reducing electricity consumption in buildings, identifying and monitoring individual sources of electricity consumption is key. It enables the discovery of energy wastage and is an opportunity for better control of inefficient loads in order to improve their efficiency.

Both from an environmental and cost reduction perspective, the need to effectively meter energy consumption and the application need for intelligent plug actuation has been recognized. To increase the efficiency of this smart control of appliances it stands to reason that actuation should not alone rely on human input but also on feedback gathered from ambient sensors. An example of when this would be particularly useful is when completely switching off stand-by appliances (e.g. light, tv, hi-fi), hence avoiding the need to remember to turn on/off these appliances individually. Not surprisingly there has been a proliferation of these devices, both wired and wireless in the last number of years.

The ZEM30 from Episensor [3] falls into the electricity metering category and allows users to collect data from secure, low powered wireless sensor networks and deliver this data to a central location automatically via the internet via their SiCA platform architecture. Similarly, there are products available from The Energy Detective [4] or Owl [5] which use CT clips to monitor power and wirelessly transmit data to either home computers or simple LCD displays. However, the TED-5000 series from The Energy Detective have Google PowerMeter embedded while 3rd party apps for e.g the iPhone are also available.

On the plug actuator side, there are a number of simple and low cost plug actuators such as the Bye-Bye standard power saver [6] and Stand-by Buster [7] which can switch up to 13A and are used as remote controls to turn on/off appliances. No interaction is possible with surrounding wireless sensors and only actuation is possible, no metering. Commercially available products which provide both energy monitoring and actuation capabilities in a plug or strip are limited but include the Plogg [8] from Energy Optimizers Limited and the EnergyHub Socket from Energy Hub[9].

Research activities in this area have included the MIT Plug [10]. The Plug is a functional power strip with sensing, networking, and computing abilities. It provides apparent power measurements through a current transformer and uses an ADC for direct sampling. Power can be sensed and switched on/off at any of the 4 sockets on the strip. As with most sensor nodes, the Plug has a microcontroller and wireless transceiver. However, the Plug also contains embedded sensors including microphone and phototransistor and an expansion port that allows the addition of extra sensors where required.

The ACme plug [11] was developed as part of the Berkeley Wireless AC Meter/Switch project. ACme uses the ADE7753 energy monitor chip for energy and power measurements, the SHARP solid-state relay for power switching, and the Berkeley EPIC wireless module for communication and has primarily been used for high-fidelity monitoring of electrical usage in buildings [12]. Ruzzelli, Schoofs et al have used a combination

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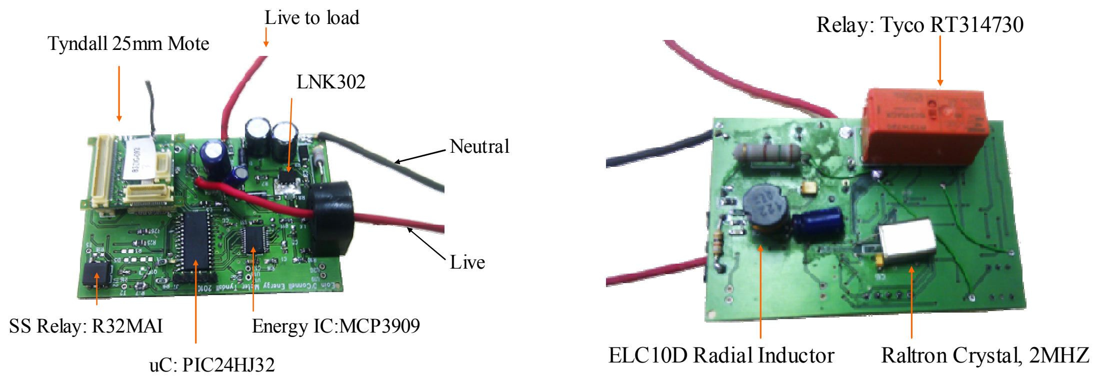

Figure 1. Labeled REAM plug layer top and bottom

of Episensor energy meters, ACme plugs and motes to demonstrate real-time recognition and profiling of appliances using the RECAP appliance load monitoring system in addition to automated electricity data annotation [13, 14]. Bauer et al [15] also investigated appliance recognition using power consumption as part of their research into the monitoring of activities of daily life in the home. The iSensor uses a 0-10A current transformer and a Jennic ZigBee microcontroller. A number of research institutes are enabling their research into energy profiling/consumption, home automation, smart homes and the Internet of Things by using Ploggs including Fraunhofer FIT [16], University of Bath/TU Delft [17] and the University of Southampton [18].

II. REAM NODE

The REAM board enables a user to remotely turn off and on power to a mains power extension board and sample the current, voltage, power and power factor of the attached load The power measurement and control is performed by a device consisting of five primary components: current-to-voltage conversion, energy metering, mains power supply, microcontroller with radio, and solid state AC relay and mechanical relay, as shown in Fig. 1. The plug layer contains a current transformer interfaced to a Microchip MCP3909 Energy Metering IC which samples the current and voltage. These values are periodically read from the part by the PIC24 microcontroller. The PIC24 calculates the RMS current and voltage, the power factor and power. These values can then be queried by the Tyndall microcontroller layer. The PIC24 is connected to a solid state relay which it can toggle. This toggles a larger mechanical relay which switches off or on power to a load. Fig.2 shows a picture of a REAM node.

A. Mains Power Supply

Classically in such applications where space is an issue, resistive or capacitive dropper type circuits are used to provide a low voltage non-isolated DC output from a high-voltage AC source. These type of circuits tend to be hugely inefficient because the DC current flowing at the output also flows through the high voltage AC lines entering the circuit. To overcome these issues and provide a more efficient high voltage AC-DC converter, a different topology was used, which also conforms to the space restrictions of such an application. The new design replaces the classical resistive or capacitive dropper element with a circuit which boasts efficiencies of up to 70%. The design is based around Power Integrations new Link Switch TN family of semiconductors specially designed for this application. The particular family chosen for this design is the LNK304 [19] family and the circuit can be constructed entirely using surface mount components. The LNK304 can supply up to 120mA at up to 12V..

B. REAM Hardware

To achieve accurate measurements it is necessary in energy metering devices to oversample the 50-60Hz AC input signals. For that reason a 16-bit processor from Microchip operating at 64MHz (32 MIPS) was chosen. All calculations are done using floating point precision and 2nd order digital IIR (Infinite Impulse Response) filters were implemented on both current and voltage channels. The PIC24HJ32GP302 [20] samples the current and voltage channels via the MCP3909 at approximately 10 KHz. The filtered values are averaged over a period of 0.5s and all of the necessary measurements are updated such as RMS Voltage, RMS Current, Real Power, Apparent Power, Reactive Power, Power Factor and accumulated energy in kWh.

The MCP3909 [21] from Microchip provides an SPI interface through which the PIC24HJ32GP302 attains current and voltage samples. The voltage sense mechanism used in this circuit used a simple voltage divider to reduce the 230V AC input down to 600mV. The current sense side of the circuit uses a basic current transformer to provide a voltage proportional to the AC current which is flowing at 230V. A current transformer was chosen because it dissipates almost zero energy from the mains AC supply and provides a very linear output from mA up to 15A

The user can also actuate the plugs remotely; actuation is achieved through the use of an opto-isolated ultra low-power solid state relay which drives a 230V AC relay. This AC powered relay ultimately switches the load on and off. This provides a high level of isolation from the high voltage AC lines.

Figure 2. REAM node in enclosure with attached extension board and plug

1) The Modular Tyndall Mote: The Tyndall prototyping system has been developed to address a wide array of scenarios in the Wireless Sensor Network (WSN) application space. A highly modular approach to design has been adopted negating the need to replace the mote infrastructure should a change in wireless technology, sensing capabilities or power supply be required [22, 23].

In addition the embedded intelligence within the system can provide the necessary filtering and processing algorithms to enable autonomous operation, adaptive sampling regimes based on sensory input and data filtering using readily available embedded C or TinyOS code libraries. For the REAM node, the Tyndall mote communicates with the PIC24 via SPI. The mote sends the PIC a command word. The command provided to send these is called PIC_command and accepts an unsigned 8bit integer. The sensor layer used is the Tyndall Pervasive Monitoring Layer [24] which includes a variety of typical sensors on board which provide useful data within the AAL environment including temperature, humidity, light levels, vibration, orientation and presence. Each REAM node contains a Tyndall 25mm microcontroller and radio layer with an Atmega1281 microcontroller and a 2.4GHz EM2420 radio and hence can use the existing networking capabilities of the motes. Each node runs TinyOS 2.1.1. and can also be individually addressed. This allows for individual actuation and control of the reporting period.

A comprehensive cross-platform graphical user interface for control and debug was developed in Java. This uses the Java SDK supplied with TinyOS. This allows: Remote Calibration, Remote Actuation, Wireless reporting of power, current, voltage, power factor and energy usage, Graphing of the received data and Storage of the received data to a MySQL database:

C. Preliminary Testing

Functional testing of the REAM plugs involved testing the accuracy of the energy metering against a calibrated Archmeter PA310 power meter[25], testing the remote actuation capability of the devices and measuring the latency between a command sent from the microcontroller to switch on/off a load and when the AC supplied to the plug load changes. For the functional testing an Input Voltage (Mains) of 230-240 was used and current was tested in the range of 0-10A. A number of different loads were then placed on the REAM plug after calibration and accurately measured. These are summarized in Table I. All tests were carried out with an Archmeter PA310 power meter as a reference. Tests were carried out with a sampling period of 1 second.

TABLE I. LOADS USED FOR TESTING FUNCTIONALITY AND CALIBRATION

Load	Current	Power	Power Factor
Resistor config 2	0.93A	214W	1
Resistor config 1	0.71A	200W	1
Analog Oscilloscope	0.34A	70W	0.88
Heat Gun (Medium)	3.46A	890W	0.99
Heat Gun (Full)	7A	1.8kW	0.99

The power profile of a laptop, a HP Compaq dc9700, was then measured with stress steps of 30 seconds as follows:
1: 100% load, full load on 4 cores
2: 25% load, full load on 1 core, 3 idle
3: 50% load, full load on 2 cores, 2 idle
4: 75% load, full load on 3 cores, 1 idle
The results are shown in Fig. 3. The spikes after the 3rd step correspond to FireFox loading.

1) Actuation Latency Timing: The latency involved in mains power actuation associated with the node was also investigated. The time taken for the microcontroller on the node to toggle the AC supplied to the plug load was measured. The times recorded denote the time between the change in the output control pin of the micocontroller to the relay circuitary and the change in the AC supplied to the load. For the tests a divided down form of the AC output was observed on an oscilloscope.

Table II summarises these tests listing the test configuration, whether there was a load or not, the state of the relay and the minimum and maximum latencies. Test configuration1 involves probing the Output Pin on the REAM PIC24 microcontroller to the relay control circuit and the AC output at load. Test configuration 2 toggles when the basestation (Tyndall mote) receives a message from the PC to send command to the REAM node while the AC output at load is again probed. The time recorded takes into account the basestation to node RF communications and the delay in the relay circuit.

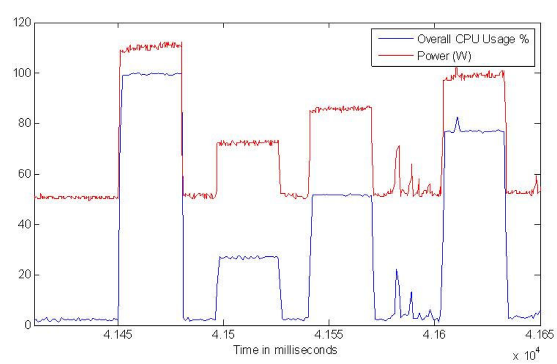

Figure 3. Power profile of HP Compaq dc9700

TABLE II. ACTUATION LATENCY MEASUREMENTS

Test Config	Load	Relay State	Minimum Latency	Maximum Latency
1	No load	On -> Off	8ms	10.8ms
1	~1A	On -> Off	9ms	11ms
1	~1A	Off -> On	7ms	10ms
2	~1A	On -> Off	14.6ms	15.8ms
2	~1A	Off -> On	13.6ms	15ms

These tests show that the plug can be actuated in a reasonable amount of time, in under 20ms in a point to point scenario. Most of the delay is caused by switching time of the mechanical relay as shown in the first tests. Given the low frequency at which the loads are expected to be switched off and on, hours or days apart, this latency will have little effect on the overall power consumption..

III. LOAD ACTUATION FOR ENERGY SAVING IN BUILDINGS

Initial experiments have been conducted to show the energy gains that can potentially be achieved from networking the REAM node to a wireless sensor network, when applied to space heating in buildings. Thanks to the embodiment of both computing resources and a wireless layer onto the REAM node, wireless sensor nodes deployed within a given space have the capability to sense environment changes and communicate them directly to the REAM node for triggering power actuation of heating loads. Such smart environments, where heating loads are automatically switched on and off depending on space occupancy, contrasts with typical deployments where load actuation is decoupled from environment sensing. Indeed, wireless sensor nodes generally report ambient data to a network controller, and applications make use of that data to control the various loads via load actuators. Such approach, preferred in environments where decision-making requires a combination of heterogeneous streams of data and additional processing power, is not efficient in smaller-scale deployments, where direct reporting and actuation is shown to be sufficient. The REAM node allows for all communication architectures to be envisioned, including a fully localized approach. Indeed, placing a sensor layer onto the REAM node would even remove the need for a wireless sensor network to sense the environment, as the node could sense and process sensor data, and derive itself whether the heating load needs to be switched off. Although the following results are specific to our deployment and space usage pattern, they serve as a starting point for further experimentation with the plug actuator and ambient sensors in large-scale buildings

A. Deployment

A space, as illustrated in Fig. 4 has been instrumented for power monitoring/actuation and environment monitoring, using the following equipment.

- A WinterWarm WRC15 electric heater [26], consuming a power or 1.5kW as per the specifications, plugged through the REAM plug actuator to measure its power consumption and to control its power state;
- One Tyndall mote deployed to monitor the space occupancy using a passive infrared (PIR) sensor [24].

The living room of a shared apartment consisting of four people has been chosen for the experiment. Such a space shares similarities with typical building spaces, in that many people get in and out with little initiative in controlling the heating carefully over the day.

B. Preliminary results

Fig. 5 plots the current drawn by the electrical heater against the space occupancy, over a couple of evening hours. The occupancy data only reports periods where individuals remained within the space, and not when they passed through. The heater, regulated by the thermostat, is active at regular intervals for similar duration, showing that the presence of people within the room does not affect the amount of heat that is delivered. More importantly, the data shows periods when steady temperature is maintained whereas the space is unoccupied - see after 20:10, and will stay as such until somebody manually turns off the heater, which may or may not happen. Such situation is very common to public spaces and common areas, where nobody takes the responsibility to regulate heating as they don't feel responsible and as other people may enter the room at a later stage. Energy gains can therefore be easily achieved with an automated and intelligent control of the heat delivery, based on input from the space

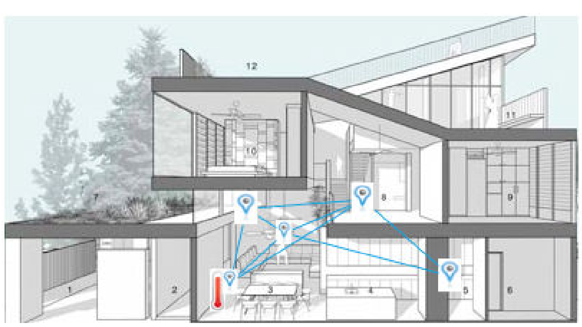

Figure 4. Deployment of sensor nodes for both ambient and electricity monitoring

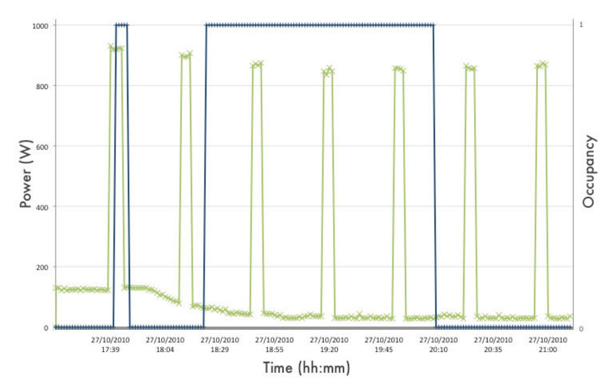

Figure 5. Space occupancy against electric load activity, illustrating periods of unnecessary heating

occupancy. PIR sensors have been used in this deployment, but simple binary reasoning on lighting state, sufficient for concluding the occupancy of small-scale spaces, to more complex reasoning on various streams of data for larger-scale space occupancy, may be adopted.

Measuring the time taken to bring a space back to its comfort temperature is the next step, to conclude whether switching off the heater intermittently as soon as the space is unoccupied would degrade the user comfort, and would effectively save energy. Experiments have been conducted to measure the influence of powering off the heater. Results are presented in Fig. 5.

This measurement shows two important insights: (a) in normal operation, the thermostat triggers the electric heater at regular intervals of 18 minutes, but for a continuously decreasing duration. Experimented on in morning time, this observation contrasts with results obtained at nighttime, as shown in Fig. 5, where the heater activity duration was constant - more experimentation will be done to evaluate whether this change downward is linked to changes in daylight; and (b) warming up the space back to the comfort temperature results as expected in a lengthier heater activity as compared to the normal one. Three parameters therefore need to be evaluated and balanced prior to making any decision for regulating heating loads with systems such as the REAM node:

- Power savings by keeping the electric load off;
- Power waste from bringing the space back to its comfort temperature;
- Time taken to bring the space back to its comfort temperature.

The calculation of such trade-off is unique to each specific deployment, as the three parameters will have different values for each space, with the values changing over the day.

Fig. 6 shows that for our setup the interval at which the heater is activated is 19 minutes, for a duration down to 3 minutes for the last occurrence. After a break of 38 minutes, equal to twice the thermostat interval duration, the heater was switched on again, and it took 6 minutes to reach the comfort temperature. Switching off the load has therefore prevented a

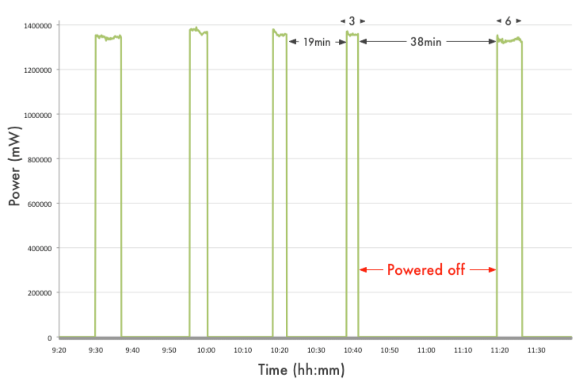

Figure 6. Illustration of the time taken by the heater to reach its optimum temperature after various off durations

3-min activity that would have happened after 19 minutes - power saving, but has generated an extra 3-min activity on start up - power wastage. No energy gains have been achieved, and the comfort of the room occupant may actually have been degraded. However, 30 minutes seems to be in our setup the edge timing value from which energy gains can be achieved, as any pause in heating longer than 30 minutes will generate power savings.

The difficulty of intelligent power control lies in the fact a regulating system cannot know in advance whether a space will remain unoccupied for a sufficient time to achieve energy gains by switching off loads. For this reason, in addition to calibrating a system with the three aforementioned parameters, future work will aim at using pattern recognition techniques to identify recurring patterns in the way a space is used, e.g. morning, lunchtime and evening activity. Decision-making will be optimised to power off loads only at times when there is a high probability to have a space unoccupied for a long period.

IV. Conclusions And Future Work

The REAM node enables intelligent actuation of electric loads based on input received from applications located on wireless sensor nodes or PC-class controllers. The capability to be networked within a wireless sensor network, the computational resources available on the node to protect sensitive data, as well as the monitoring and actuation of electric loads prove to be an enabler for a building optimised energy-efficient solution. Following promising results on energy saving within building spaces via load actuation, immediate work will aim at deploying REAM nodes and Tyndall sensor nodes in spaces with various occupation patterns, in order to investigate decision-making algorithms towards energy-efficient control of space heating.

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