The Tiny Agent- Wireless Sensor Networks
Controlling Energy Resources

Glenn Platt\textsuperscript{1}, Joshua Wall\textsuperscript{1}, Philip Valencia\textsuperscript{2}, John K. Ward\textsuperscript{1}
\textsuperscript{1}CSIRO Division of Energy Technology, PO Box 330, Newcastle NSW 2300, Australia
\textsuperscript{2}CSIRO ICT Autonomous Systems Laboratory, PO Box 883, Kenmore QLD 4069, Australia
Email: \{glenn.platt, josh.wall, philip.valencia, john.k.ward\}@csiro.au

Abstract—CSIRO is using wireless sensor network technology to deploy “tiny agents”, working as autonomous controllers for individual pieces of electrical load/generation equipment in a distributed energy system. The tiny agent concept is a novel application of wireless sensor networks, providing the benefits of multi-agent systems science in a cheap, mobile, and highly distributable platform. However, the performance constraints inherent to wireless sensor networks mean the real-world realization of a tiny agent system is a significant challenge. This article details our work on tiny agents. We include a brief review of multi-agent system benefits, and then discuss the challenges inherent to the tiny agent concept. We also detail our applications work in applying wireless sensor network technology to operate as tiny agents, with a focus on intelligent heating, ventilation and air-conditioning control.

Index Terms—Demand Response, Distributed Energy, Multi-Agent Systems, Wireless Sensor Networks

I. INTRODUCTION

CSIRO has had significant experience applying wireless sensor network (WSN) technology in real-world deployments as part of our work with distributed energy, an exciting field of research designed to change the way electricity networks operate. Until recently, we have used WSN hardware in the relatively traditional role of distributed sensors. We are now working on a novel application of WSNs as agents for the intelligent control of energy resources, including heating, ventilation, and air-conditioning (HVAC) systems.

CSIRO is working on the decentralized control of groups of energy resources, as we believe such an approach has significant advantages over the more traditional centralized control systems currently used in electricity networks [1]. In particular, our technology revolves around the application of multi-agent systems research, from disciplines including machine learning and complex systems science, to the management of large energy devices. In essence, entities in the electricity network (such as HVAC systems or small electricity generators) are represented and managed by agents, where an agent gathers data, makes decisions, and takes actions on behalf of a certain entity. A collection of agents is able to achieve quite complex outcomes, often displaying behaviour that would not be possible from one single agent— a system-wide behaviour emerges from the network of individual devices. The agent concept in general, and the science of multi-agent systems in particular, is a very complex and diverse field. Entire books have been dedicated to the area of multi-agent systems science, and the reader is directed to examples such as [2] for a more comprehensive review of this area.

In using multi-agent systems techniques for managing energy resources, our general approach is to deploy an agent for each individual (significant) load or generator in the electricity network. In a domestic situation, individual agents may be associated with devices such as an air-conditioner, hot water heater, washing machine or dishwasher; and these agents can then collaborate to minimize the energy consumption of a house.

Basic requirements of an agent, physically located at a distributed energy device, are a method for interacting with and controlling the device, a computing ability enabling the agent to manage the requirements of the local device, and communications ability so the agent can interact with other agents in the multi-agent system.

Until recently, our applications of WSN hardware have been relatively traditional— sending data back to a distributed energy agent for collation and further processing. For example, we often use WSNs for integrating electricity demand management techniques with HVAC systems, where WSNs can be used to provide high-granularity sensor data such as temperature and occupancy; are relatively cheap, and easily deployed.

Having already realized the benefits of a decentralized approach to controlling significant electricity loads and generators, we are now working on further decentralizing our management and control system, pushing the application of agents to lower levels of the electricity network. We are working on the deployment of tiny agents, where the functionality of wireless sensor network hardware is extended from a sensor-centric behaviour, to implementing the role of distributed, intelligent control agents. In this concept, a wireless sensor based tiny agent is responsible for controlling one particular, discrete device, based on inputs from the surrounding environment. Example applications of a tiny agent may include:
Control of air-conditioner or HVAC system devices such as building management systems (BMS), variable speed drive (VSD) fans, variable air volume (VAV) dampers, and chiller/heater system components; based on inputs such as the occupancy and temperature of a room, and the maximum desired cost of electricity to run the air-conditioning plant. Multiple tiny agents would be used in a typical office building HVAC system.

Intelligent control of relatively small loads within a house- where a tiny agent would be associated with loads such as the hot water system, pool pump and refrigerator- each agent controlling its associated load, whilst the network of agents collaborate together to achieve a given household energy goal.

As per the general agent concept, individual tiny agents collaborate together and can achieve quite complex outcomes, such as maximizing the efficiency of a HVAC system, or minimizing total running costs in response to instantaneous energy price fluctuations.

 Whilst design features of WSN hardware such as its low cost, ease of deployment, robust communications and low power consumption mean it is well suited to implementation as tiny agents, the tiny agent concept embodies a significant paradigm shift for the application of such hardware. Challenges here include the application of multi-agent system science to ensure reliable behaviour of the system of tiny agents, interfacing to energy loads and generators, data aggregation/fusion, and ensuring network security. Importantly, many of the well known techniques in the relevant research disciplines are not easily applicable to wireless sensor network hardware- they assume relatively powerful computing and communications platforms, and were not designed to consider the significant constraints inherent to wireless sensor networks.

Recognizing such challenges, we remain confident that the price, performance and deployment benefits of WSN technology mean the tiny agent concept is well-suited to the intelligent control of energy resources, and have invested a significant amount of time in this area. This article builds upon our previous conference paper in this area [3], giving further information on our hardware implementation of tiny agents, and detailing the results of a recent CSIRO technology trial of tiny agents used for intelligent HVAC control.

II. INTELLIGENT HVAC CONTROL

It is common in commercial buildings to condition the temperature of multiple spaces or rooms with a single HVAC system and controller. Whilst typical HVAC systems use wired sensors for transmitting information such as room temperature and humidity back to the central controller, such installations are quite expensive. As such, typical HVAC installations often have a limited number of sensors located in a subset of the rooms being controlled. This method of deployment erroneously assumes every room is the same temperature as the room containing the temperature sensor. The resulting energy-inefficient control decisions often cause unnecessary heating or cooling, and occupant discomfort. WSN technology alleviates the costs associated with
conventional wired sensors and controller hardware, offering an opportunity to install multiple WSN devices deployed as autonomous agents for both the sensing of the HVAC system environment, and control of HVAC system devices. Figure 1 illustrates how CSIRO is using tiny agents for intelligent HVAC control, where individual agents control a particular room, zone or building, with a unified goal of energy efficiency and occupancy comfort.

One of the benefits of our HVAC control technology is the ability of the tiny agent system to participate in demand side energy management programmes. Demand side energy programmes aim to improve the efficiency and performance of the electricity distribution network through better control of loads and generators on the “demand side” of the network. Importantly, by participating in these programmes that improve the network as a whole, individual users will be financially rewarded—by reduced tariffs, or payment schemes that pay a user to take a particular action with their load. Considering HVAC systems, demand side benefits are available from more optimal load control—fundamentally, in an HVAC system it is possible to reduce electrical consumption by trading off human comfort against the cost of operation of the HVAC plant. Alternatively, it may be possible to simply shift electrical consumption, preserving human comfort, by pre-cooling or pre-heating the offices in advance of an electricity price spike, and then allowing the office temperature to drift gradually during a high price period, thereby minimising electricity consumption during expensive periods.

Importantly, for optimal performance when subscribed to a demand management programme, we believe the HVAC management system should be dynamic and intelligent, responding to changing events, and considering a variety of external factors such as occupancy, human comfort, electricity price, and weather forecast. This application requires high-granularity data from a variety of sources, hardware that can be easily retrofitted to existing buildings, and a control technique that is dynamic and robust. Our tiny agent is well suited to this application, and is detailed further in the following sections.

III. IMPLEMENTATION ISSUES

Whilst we are confident there are a number of benefits to the tiny agent concept, as shown in figure 2, there are many challenges also. To address these issues, CSIRO is working on customized hardware solutions, low power application-specific communications protocols and security techniques for application in our tiny agents.

A. CSIRO’s Fleck Wireless Sensor Node

To address some of the shortcomings of commercially available WSN platforms, CSIRO’s Autonomous Systems Lab [4] has developed the Fleck™ wireless sensor device. Recognizing the variety of potential applications of WSN hardware, Flecks are designed to be a durable, yet versatile device capable of sensing, computation, actuation and wireless communications. Consisting of a low power CPU with additional off-chip flash memory and advanced radio transceiver, each Fleck also has connections for customized sensor/actuator boards including interfaces for video or audio digital signal processing (DSP), global positioning system (GPS) with up to 1GB MMC storage, strain gauge, water quality, inertial, soil moisture, motor control, and optical communications applications. Features of the CSIRO Fleck are listed in Table 1, and a photo of the unit in figure 3.

One of the implementation challenges of using WSN hardware for tiny agents is the additional power consumption involved in this application. Essentially, tiny agents are required to operate at a relatively high microprocessor and sensor duty cycle, to maintain optimal awareness of, and control over, their

![Figure 2. The benefits and challenges of the tiny agent concept.](image-url)
environment. Further, the sensors we commonly apply in our work, such as long-range passive infrared (PIR) occupancy sensors, often have relatively high power consumption. Considering these factors, CSIRO is using techniques such as energy-wise radio duty cycling, energy scavenging from photo-voltaic power supplies, optimal software scheduling, and low current draw sleep modes to optimize energy consumption and pro-long battery life.

### B. Energy-Aware Communications Protocol

As well as hardware design, we have also spent a significant amount of time designing energy efficient communications protocols for use in our tiny agents network. An advantage of “in-network” computation, where actuation is based on locally sensed data, is that the communications topology is scalable unlike the more common “back-to-base” techniques. Back-to-base WSNs are inherently non-scalable since the entire network data aggregates to flow through the node closest to the base. As the number of nodes increases, the required bandwidth eventually exceeds the “last hop” node’s capabilities and the performance of the network is subsequently degraded. Achieving local range, reliable, low power communications in an ad hoc network with a shared communications medium is possible, however no easy task. Furthermore, back-to-base reporting of debug information and base-to-all code dissemination is often desired and needs be considered when designing or choosing a communications strategy.

We achieved scalable, low power communications by designing a slotted time-division multiple access (TDMA) approach and using local flooding for the tiny agents’ local point-to-point and point-to-many communications. As with most WSNs, the easiest way to achieve dramatic power savings is to reduce idle listening (i.e. to turn the radio off when no one is transmitting). This implies duty cycling the radio duty and can result in the difference between a network running for a day or for a year. Obviously such savings are desired, however radio duty cycling introduces a scheduling requirement since nodes need to know when to be listening and when to send. Often this is achieved through additional packets with protocols for exchanging schedules and bidding for resources. Many other tradeoffs such as latency, scalability and reliability also need to be considered and so it is not surprising that this has been the subject of much research in the sensor network community [5].

Our approach achieves scheduling through synchronization rather than explicit schedule protocols. Each node periodically samples sensors, performs logic, transmits packets and performs duty-cycled listening for packets. We refer to this sequence of states as a cycle. All

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**TABLE I**

<table>
<thead>
<tr>
<th>Feature name</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Radio range</td>
<td>Up to 1300 m</td>
</tr>
<tr>
<td>Radio data rate</td>
<td>100 kbps</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>3.3 – 8 V</td>
</tr>
<tr>
<td>Sleep mode current draw</td>
<td>&lt; 30 µA</td>
</tr>
<tr>
<td>Solar charging circuitry</td>
<td>Yes (Super-capacitor/NiMH)</td>
</tr>
<tr>
<td>Daughter board interface</td>
<td>Yes</td>
</tr>
<tr>
<td>On-board temperature sensor</td>
<td>Yes</td>
</tr>
<tr>
<td>Screw terminals</td>
<td>4 x digital I/O, 3 x analog input</td>
</tr>
<tr>
<td>Flash memory</td>
<td>1 MB (upgradeable to 4 MB)</td>
</tr>
<tr>
<td>On-board communications ports</td>
<td>RS-232</td>
</tr>
<tr>
<td>TinyOS compatible</td>
<td>Yes</td>
</tr>
</tbody>
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**Figure 3**: A CSIRO Fleck™ for indoor environments

**Figure 4**: Energy-wise radio duty cycling.
nodes share the same cycle period—indeed the nodes are synchronized. However, within a local neighbourhood, nodes are out of phase and hence so are their transmissions, thereby achieving TDMA. This improves the medium access control aspect of our system since it reduces packet collisions arising from the “hidden terminal problem” [6]—an issue often neglected in many medium access control (MAC) algorithms to the detriment of performance in real world deployments.

Data transmission is confined to a window of time known as a slot. In fact, the whole cycle is divided equally into slots. The slot duration is based on the expected maximum number of packets to be sent within one cycle. This slot duration is pre-calculated and is the same for all nodes across the network. The slot state however can change and is defined by the state of the radio for a given slot. Possible states are transmitting (radio in transmit mode), scanning (radio in receive mode), sampling sensors (radio off) or unassigned (radio off) as shown in figure 4. The periodicity of the transmissions means that neighbouring nodes should predictably transmit in the same slot in every cycle. The first two or more slots are reserved for sampling and transmitting with the remaining slots initially either scanning or unassigned. The scanning slots are arranged in a contiguous block known as the scanning window which helps reduce thrashing of the radio. The number of slots in the scanning window is determined by the expected number of neighbours, the acceptable latency of discovering new neighbours and the desired power savings (i.e. duty cycle). If a packet is received during a scanning slot it is changed to an assigned slot and it will listen for packets from that neighbour in subsequent cycles. If no packets are received during a scanning slot, the slot will be return to the unassigned slot in the next cycle. The number of slots that were not assigned within the scanning window will be used to shift the scanning window to other slots in the next cycle to discover new neighbours. The state of slots may vary from cycle to cycle, however the total number of slots where the radio is on and total number where the radio is off will remain constant across all cycles. This achieves a constant radio duty cycle and is convenient for calculations of network longevity. Over a number of cycles, nodes eventually synchronize their assigned slots to the neighbouring transmissions and have their radios off at other times. This results in very low radio duty cycling of < 1%, and significant power savings. Although this approach is scalable and useful for our purpose, it is not well suited or scalable for back-to-base reporting. Currently we ensure the local flood reaches the base node so that we can achieve both local and back-to-base communications. This is not ideal however, and our research is continuing in this area.

C. Application Aware Communications

CSIRO’s latest work in WSN communication protocols involves research into application-aware, energy-wise MAC and network layer multi-hop routing mechanisms, designed using a cross-layer approach to adapt to application-specific sensing and actuation requirements. As the requirements of sensing and actuation functions in a distributed energy system vary in regards to parameters such as frequency, delivery time and reliability, we are looking at ways to dynamically adapt the underlying communications protocols to ensure application objectives are met while optimizing network performance and energy usage.

CSIRO’s MAC layer protocol, called A²-MAC [7], is an application adaptive MAC protocol for WSNs. It is based around a hybrid TDMA (slotted) scheme where a time-frame is divided into separate signalling and scheduled data transmission phases. During the smaller signalling phase, nodes access the channel using a contention-based mechanism, with the access of the scheduled-data phase governed by a time-division scheduling algorithm. As duty-cycle control can be more easily designed with a TDMA based MAC scheme, this split-phase hybrid approach enables optimal channel efficiency and energy consumption, while facilitating the ad hoc nature of WSNs and tiny agents. A²-MAC employs a loosely distributed synchronization scheme where synchronization information is exchanged with a defined neighbourhood during the signalling phase. Loss of synchronization in A²-MAC is also alleviated by making the scheduled data slot much larger than clock drifts.

In addition to application-aware MAC protocols, CSIRO is tailoring multi-hop routing routines for efficient packet delivery amidst vastly different sensing and actuation requirements. Called ISRED (Integrating Sensing and Routing for Efficient Delivery) [8], CSIRO’s multi-hop protocol has been designed following guidelines set out in the Sensornet Protocol architecture [9], and includes enhanced routing services designed to perform efficient, reliable sensing and actuation functions. The choice of routing protocols is heavily application dependent. In proactive routing, routes are computed automatically and periodically, which works best for regular data collection application such as environmental monitoring. In reactive routing, routes are discovered on-demand when traffic must be delivered to an unknown destination, which works best for sporadic actuation and control type functions. ISRED uses the best of both worlds in that it dynamically configures routing parameters, such as the routing beacon interval $T_b$, to ensure reliable and energy-efficient communications specific to the target application.

In our latest tiny agents, the radio used in the Fleck consumes over 500 times more energy than the microcontroller and remaining circuitry. Efficiency is achieved in ISRED by piggy-backing sensing data onto the routing beacons, therefore aiming to minimize radio
transmission. After a data sensing event, instead of immediate transmission, the data will be passed to the routing components, and awaits the next available beacon transmission for delivery. Greater efficiency is also achieved when the sensing interval \( T_s < T_r \), as sensing data is able to be concatenated together and transmitted within a single burst subject to packet length constraints.

To test the communications protocol described in the previous two sections, we deployed a total of 30 tiny agents, distributed throughout several floors of a multi-story commercial office building, with a single floor dimension of 40 x 46m. The tiny agent sensor suite consisted of air temperature, humidity, human occupancy, and damper position sensors. The radio duty cycling protocol presented in section B was used for sensing and actuation purposes, configured with a cycle period of 5 minutes, and up to a 3-hop routing path. For the specified sensor suite and deployment environment, the radio duty cycling protocol was able to achieve an average of 93.4% packet transmission reliability, with each tiny agent consuming 31µAh per cycle.

D. Tiny Agent Security

Considering the overall tiny agent concept, wireless sensor network devices are used to both monitor the surrounding environment, and control energy resources. Due to the sensitive nature of data gathered, and the ability of tiny agents to control and actuate critical devices, information must only be made available to authorised parties (authentication) and be protected from modification (data integrity) or disclosure (privacy) in transit. If these requirements are jeopardised, an adversary could obtain abnormal readings or influence the system, with undesirable consequences.

It is evident from current wireless communication systems that encryption is the most widely used form of security. The goal of encryption is to make transmitted data illegible to anyone other then those that possess the secret (key) to decrypt it- usually an authorised party. Some of the most common security suites in use today include transport layer security (TLS) [10], secure shell (SSH) [11], and internet protocol security (IPSec) [12]. Our challenge is that often the protocols used by these schemes are computationally expensive, and/or energy-intensive, and are therefore beyond the capabilities of current resource-constrained wireless sensor network devices.

Considering the core techniques that make up security suites such as those above, two well-known cryptographic techniques are the symmetric and public key security schemes. Given the hardware constraints of wireless sensor networks, implementing either of these schemes on a tiny agent is a difficult challenge, and CSIRO has spent a considerable amount of time investigating the deployment of these schemes using wireless sensor network hardware.

1) Symmetric key cryptography for tiny agents

A number of parties are working on security considerations for wireless sensor networks, the most well-known work being based on traditional encryption techniques, referred to as symmetric key schemes. These schemes involve the use of a common shared private key, to both encrypt and decrypt data. Two popular cryptography schemes widely considered by the wireless sensor network community include TinySec [13], a link-layer mechanism included as part of the TinyOS operating system, and the Advanced Encryption Standard (AES) based suite of protocols included in the IEEE standard 802.15.4 [14].

TinySec is a software-based security mechanism implemented at the communication protocol suite’s link layer, supporting message integrity and authentication with message authentication codes, confidentiality with encryption, and access control using shared keys. TinySec encryption uses symmetric key infrastructure based on an 80-bit symmetric encryption algorithm (cipher).

The IEEE 802.15.4 specification outlines a set of link-layer security suites based on the AES standard [15]. Unlike TinySec, the 802.15.4 AES is implemented using dedicated hardware, thus providing computational and resource advantages over a software implementation. The security services offered by 802.15.4 include access control, message integrity, and message confidentiality. The 802.15.4 security specification also offers a limited pair-wise keying mechanism, where each pair of nodes share a different key, thus providing greater robustness in the event of a single key being compromised.

CSIRO has implemented an alternative symmetric key scheme, designed to address limitations of both TinySec and 802.15.4 schemes. With a hardware based encryption scheme deemed unsuitable as it required significant modification of our Fleck devices, we have worked on developing a security scheme based entirely on software, with key components of the algorithm implemented in assembly code to maximize the performance of the system. The symmetric algorithm used in our tiny agents is a variant of RC5 [16], a symmetric block cipher where the algorithm is applied to a given number of bits at once. Investigating the performance of our implementation, we’ve found that a tiny agent can encrypt 2 blocks of data (128 bits) in approximately 0.6ms. This is significantly faster than a software implementation of the AES algorithm on our tiny agents, which takes around 12ms to encrypt 128 bits.

2) Public key cryptography for tiny agents

One of the risks with symmetric key security schemes is key compromise- an unwanted third party obtaining the key to the cipher. Public key cryptography is a different form of cryptography that uses multiple keys, one public and one private, to securely redistribute shared secret keys throughout a network. This effectively mitigates the
risk of key compromise. For public key cryptography to work, there has to be a mathematical relationship between the public and private keys that is elementary to compute in a forward direction but exceptionally difficult in reverse. Due to the intensive mathematical operations required to generate a key pair, public key techniques have long been thought inappropriate for resource constrained devices such as tiny agents. This perception is primarily driven by experiments involving RSA, today’s dominant public key algorithm, as used by the SSL protocol throughout the Internet. Challenging the negative opinions previously mentioned, CSIRO is investigating an increasingly popular technique for public key cryptography on our tiny agents, called Elliptic Curve Cryptography (ECC), that that offers an equivalent security level to RSA, but with significantly smaller key sizes. For example, the report in [17] shows that, as tabulated in table II, a 163-bit key ECC implementation has an equivalent security to a 1024-bit RSA key, but, due to its size, the 163-bit key is significantly less computationally expensive.

Whilst it has significant cryptography performance benefits, ECC remains a difficult technique to implement efficiently on resource constrained tiny agents. Since an ECC algorithm can cycle through hundreds of iterations in order to generate a public key, any slight inefficiency can result in dramatic performance reductions, and thus we are constantly optimizing the efficiency of our ECC implementation. CSIRO’s current ECC implementation involves the use of a projected coordinate system, where expensive inversion functions are avoided by using more multiplication operations. Through experiments with our tiny agent hardware, we have shown that this combination of smart algorithm selection and coding can yield an ECC implementation capable of generating a 163-bit public key on a tiny agent within 3.4 seconds, as detailed in table II.

### Table II. ECC Key Generation Times.

<table>
<thead>
<tr>
<th>ECC key size</th>
<th>Generation time (s)</th>
<th>Equivalent RSA key size</th>
</tr>
</thead>
<tbody>
<tr>
<td>163-bit</td>
<td>3.4</td>
<td>1024-bit</td>
</tr>
<tr>
<td>131-bit</td>
<td>2.0</td>
<td>704-bit</td>
</tr>
<tr>
<td>113-bit</td>
<td>1.4</td>
<td>512-bit</td>
</tr>
</tbody>
</table>

IV. TECHNOLOGY TRIAL

In previous work [3], we showed the basic opportunities available for tiny agent control of an HVAC system, when electricity price varies significantly, in a typical office building. Whilst this work identified some basic opportunities, it was clear further investigations were needed to further explore the issues involved with the proposed HVAC control techniques.

Thus, a second experiment was completed in a standard office building, comprising eleven floors and a total floor area of around 10555m². For this trial, a shift in electricity demand was obtained by directly modifying the temperature setpoints of all zones throughout the building. The building automation system was upgraded to allow this to be performed remotely and in response to external stimuli – for example a price peak in the Australian national electricity market. Trials were particularly targeted at hot days (around 35°C) during which times the electricity network is stressed and hence representative of the conditions under which a change in electricity demand is typically requested.

A variety of experiments were conducted throughout the trial. Focusing on one particular experiment, which was representative of the others, in figure 5 results can be seen for a ‘load reduction with pre-cool’ experiment. The figure shows the building setpoint temperature, two zone temperatures and the total HVAC power consumption. This experiment was conducted on Jan 3rd, 2007, which had a peak ambient temperature of 32.8°C and consisted of:

- Starting the HVAC system at 8am with a 22.5°C setpoint (this is normal);
- 2 hour building pre-cool from 11:45am to 1:45pm with 21°C setpoint;
- 2.5hr demand reduction event from 1:45pm to 4:15pm with 24°C setpoint; and
- Reverting to the normal 22.5°C setpoint until the system shut down at 6pm.

In this case, there was a peak load reduction of 35%, and average load reduction of 15%, and a total energy saving of 127kWh.

One key observation from these results is that the pre-cool is ineffective when the air-conditioning chillers are already running at full capacity prior to the pre-cool - as is likely to often occur on hot days when load reductions are required. In this case, the pre-cool only serves to redistribute the cooling between zones, providing additional cooling to some, while consequently taking it away from others and resulting in some zone temperature increases. This effect can be seen with the two zone temperatures (T_{Zone22} and T_{Zone42}) in figure 5.

Another significant conclusion from these results is that building power consumption can not be adequately assessed based on aggregate temperature data obtained from basic zone measurements – it is important that data be intelligently integrated in order to successfully predict behaviour. As an example, it can be seen in figure 5 that the air-conditioning chillers start to pick up load at around 2:30pm specifically to meet the cooling demands of those individual zones whose temperatures increased during the pre-cool. This behaviour could not have been predicted based on simple temperature measurements as currently used in typical HVAC installations - some advanced form
of high-granularity data collection and analysis is needed.

Whilst the results in figure 2 show that changing the HVAC operating state by varying setpoint can reduce energy consumption, they also show the problems encountered with such a fairly basic strategy—in short, whilst the global outcome (energy reduction) may be positive with low overall cost, the cost in individual zones can be quite high—some zones suffering fairly extreme temperature excursions. This is an excellent example of the need for a high-granularity sensing and control system such as our tiny agents—if a tiny agent is associated with the individual rooms of an HVAC system, not only does this provide highly detailed data that can facilitate better predictions of the results of a demand management action, it also provides a flexible low-level control system. In such a control system, the climate in a particular room is managed locally by the tiny agent, where a variety of localised data can be considered in a highly scalable way, without the processing and communications issues associated with a traditional centralised technique. With the availability of better data, and more localised control, the tiny agents can negotiate amongst themselves to achieve a desired demand response, whilst still avoiding the negative characteristics listed in the above points. This area is future work for our project.

V. CONCLUSION

Whilst improved energy management procedures and technologies are of massive interest around the world, we’ve shown in this paper that concepts such as demand management of air-conditioning systems cannot work without flexible, dynamic low-level control systems. CSIRO is working on the concept of tiny agents for the intelligent control of HVAC systems and distributed energy applications, where distributed WSN devices are used to autonomously control individual electrical generators or loads, in a completely decentralized fashion. Such a concept is a significant paradigm shift in the application of wireless sensor network devices, and involves a number of significant challenges. Most of these challenges are related to the application of modern techniques such as agent-based computing and encryption methods to the very constrained hardware environment inherent to wireless sensor networks. When used for intelligent control of HVAC systems, tiny agents facilitate high-granularity sensor data, and autonomous distributed control, resulting in optimal end-use efficiency and HVAC system integration into distributed energy networks.

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REFERENCES


Glenn Platt. Having completed a PhD in telecommunications and worked for a variety of companies from engineering consultancies to Nokia Mobile Phones, Glenn now works as a project leader for CSIRO’s Division of Energy Technology. There, he runs a research programme focussing on applying innovative information and communications technology to improving the way we distribute and utilise energy.

Joshua Wall. With bachelor degrees in engineering and computer science, Josh is a research engineer at CSIRO’s Division of Energy Technology. In addition to his research interests including intelligent HVAC control and wireless sensor and actuator networks, he is currently completing a PhD in Telecommunications.

Philip Valencia. With bachelor’s degrees in engineering (electronic) and IT, Phil is a research engineer at CSIRO’s Autonomous Systems Laboratory. Phil works on the deployment of environmental sensor networks with the ASL team, researching various machine learning, multi-agent systems and complex systems problems. In 2006 Philip began his PhD studies with the Australian Centre for Complex Systems.