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# Energy Management for Intelligent Buildings

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## 1. Introduction

The increasing availability and affordability of wireless building and home automation networks has increased interest in residential and commercial building energy management. This interest has been coupled with an increased awareness of the environmental impact of energy generation and usage. Residential appliances and equipment account for 30% of all energy consumption in OECD countries and indirectly contribute to 12% of energy generation related carbon dioxide (CO<sub>2</sub>) emissions (International Energy Agency, 2003). The International Energy Association also predicts that electricity usage for residential appliances would grow by 12% between 2000 and 2010, eventually reaching 25% by 2020. These figures highlight the importance of managing energy use in order to improve stewardship of the environment. They also hint at the potential gains that are available through smart consumption strategies targeted at residential and commercial buildings. The challenge is how to achieve this objective without negatively impacting people's standard of living or their productivity.

The three primary purposes of building energy management are the reduction/management of building energy use; the reduction of electricity bills while increasing occupant comfort and productivity; and the improvement of environmental stewardship without adversely affecting standards of living.

Building energy management systems provide a centralized platform for managing building energy usage. They detect and eliminate waste, and enable the efficient use electricity resources. The use of widely dispersed sensors enables the monitoring of ambient temperature, lighting, room occupancy and other inputs required for efficient management of climate control (heating, ventilation and air conditioning), security and lighting systems. Lighting and HVAC account for 50% of commercial and 40% of residential building electricity expenditure respectively, indicating that efficiency improvements in these two areas can significantly reduce energy expenditure. These savings can be made through two avenues: the first is through the use of energy-efficient lighting and HVAC systems; and the second is through the deployment of energy management systems which utilize real time price information to schedule loads to minimize energy bills. The latter scheme requires an intelligent power grid or smart grid which can provide bidirectional data flows between customers and utility companies.

The smart grid is characterized by the incorporation of intelligence and bidirectional flows of information and electricity throughout the power grid. These enhancements promise to revolutionize the grid by enabling customers to not only consume but also supply power.

Utilities will be able to provide customers with real time pricing (RTP) information and enable their active participation in demand response (DR) programs to reduce peak electricity demand. The smart grid will also facilitate greater incorporation of renewable energy sources such as wind and solar energy, resulting in a cleaner power grid.

The smart grid must however, be allied with smart consumption in order to realize its full potential. The extension of the smart grid into the home via smart meters, home automation networks (HAN's) and advanced metering infrastructure (AMI) enables the provision of real-time pricing information and other services to consumers. This facilitates services such as residential DR. DR is the modification of user electricity consumption patterns due to price variations or incentives from the utility, and its objective is to reward behaviour which reduces energy utilization during peak pricing periods. Smart grid DR provides a means of stretching current power infrastructure and delaying the need to build new power plants. It also reduces the rate of greenhouse gas emission by limiting the need for costly and dirty coal-fired peaker plants.

In this work, we focus on two of the largest electricity consumers in buildings – appliances and lighting. Efficient management of these two load categories will result in substantial savings in electricity expenditure and energy use. In order to achieve the three energy management goals discussed above, we require insight into appliance usage patterns and individual appliance energy use. This is achieved by means of distributed and single-point sensing schemes. We therefore survey the various approaches and detail their advantages and disadvantages. We also survey intelligent lighting schemes which utilize networked ambient intelligence to balance energy conservation with occupant comfort. The combination of appliance energy monitoring and control, with intelligent lighting can result in energy savings greater than 15% in residences alone.

We begin by defining intelligent buildings and discuss building and home automation networks, as they provide the framework for intelligent environments. We then discuss appliance energy management and follow this with intelligent lighting control. We conclude with a discussion of the privacy and security threats that must be addressed in smart environments in order to guarantee widespread adoption of these technologies.

## 2. Intelligent buildings

The Intelligent Building Institute defines an intelligent building as: “... one that provides a productive and cost-effective environment through optimization of its four basic elements – structure, systems, services and management – and the interrelationships between them. Intelligent buildings help building owners, property managers and occupants realise their goals in the area of cost, energy management, comfort, convenience, safety, long term flexibility and marketability.” (Caffrey 1985). These buildings are characterized by three features (Wong et al.,2005):

- Automated control
- The incorporation of occupant preferences and feedback
- Learning ability (performance adjustment based on environmental and occupant changes)

Such environments are distinguished by a tight coupling of HVAC, security, lighting, and fire protection systems. They are sensor rich and produce large amounts of data which can be analysed to predict occupant behaviour and detect equipment faults. They can automatically sense, infer and act in order to balance user comfort and energy efficiency

(Paradiso et al., 2011), a concept also known as ambient intelligence or pervasive computing.

Pervasive computing is the networking of everyday devices, objects and materials using embedded computers equipped with networking, sensing and actuation capabilities. As networked embedded computers reduce in size and cost, they will proliferate at even greater rates. This development, combined with smaller and cheaper sensors and actuators, will result in the availability of networked processing power in smaller and smaller packages. The result is the permeation of pervasive computing into homes, offices, factories, automobiles, airplanes and every area that humans occupy.

Intelligent embedded agents are software programs which run on embedded computers and mimic some of the attributes associated with intelligence – they reason, plan and learn from occupant behaviour. This intelligence is useful as it reduces the burden and complexity of managing and programming large numbers of agents; it enables the agents to adapt to changing occupant needs or environments; and it frees occupants from requiring in-depth understanding of the system or having to make complex decisions (Callaghan et al., 2009). This is because the agents filter the information received by sensing and observation of building occupants, and make decisions or inferences about what the occupants are trying to achieve. This frees building occupants to concentrate on more productive or important tasks. The benefits of these systems include environmentally friendly buildings; increased occupant comfort, health, security and quality of life; and significant increases in energy efficiency.

The intelligence and sensing capabilities required to support such environments are provided by wireless sensor and actuator networks (WSAN's). WSANs consist of large numbers of tiny, networked sensor or actuator-equipped, power-constrained wireless devices with limited amount of memory and processing power. These devices are the building blocks for the modern day building and home automation networks which we discuss below.

## **2.1 Building automation and home automation networks**

Building automation systems provide centralized management of climate control, lighting, and security systems in order to improve energy efficiency and occupant comfort. These systems reduce energy waste and costs, while boosting occupant productivity (A. C. W. Wong & So, 1997; Kastner et al., 2005). They also facilitate or remote building management as well as improved occupant safety and security (Gill et al., 2009; Newman & Morris, 1994).

Building automation systems have a hierarchical structure consisting of field, automation and management layers (Kastner et al., 2005b) as shown in figure 1. The field layer comprises of temperature, humidity, light level, and room occupancy sensors. The actuators are made up of automated blinds, light switches, flow valves etc. The automation layer consists of direct digital controllers (DDC's) which provide precise automated control of building processes using digital devices (Newman & Morris, 1994), while the management layer provides centralized management of the entire system. It provides a view of the whole building, facilitating centralized control, data collection and analysis.

A primary function of building automation systems is energy management. This goal is achieved by means of schemes such as the duty-cycling of loads to conserve energy; peak load management to regulate total power consumption during peak hours; scheduled start/stop of building HVAC systems at the beginning and end of each day; and real time control of building systems in response to occupancy detection (Merz et al., 2009). The use of BAS' has enabled buildings to dynamically respond to current weather conditions, room

occupancy, time of day and various other inputs, resulting in significant reductions in building energy usage.

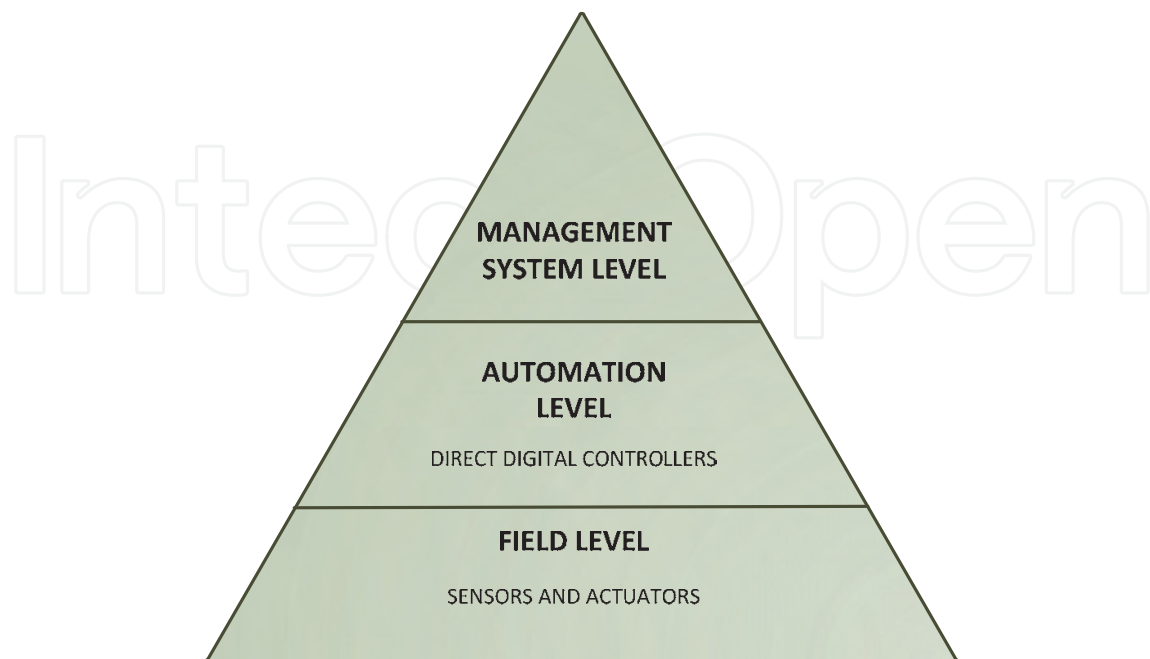


Fig. 1. Building automation system hierarchy (Kastner et al., 2005a)

Sensors and actuators are an integral part of home and building automation networks. These devices serve as the eyes, ears, hands and feet of the system. Unfortunately, wiring costs frequently exceed the cost of sensors (Gutierrez, 2004), so the availability of low-cost wireless communication schemes such as Zigbee (Zigbee Alliance, 2008) enables cost effective and rapid deployment of wireless sensors and actuators throughout a building. Wireless nodes also provide flexibility, easy re-deployment and reconfiguration, all of which are very important features for commercial buildings as they are often re-partitioned and modified to meet differing occupant requirements.

Wireless sensor and actuator networks (WSAN) are defined as a group of sensors and actuators connected by wireless medium to perform distributed sensing and actuation tasks (Dengler et al., 2007). These sensors tend to have the following features: battery powered; low-cost; low-energy consumption; short range communication facilities; limited sensing and computation capabilities. Actuators tend to have greater capabilities than sensing nodes and are often mains-powered, thereby reducing their power and processing constraints. WSANs can observe their physical environment, process sensed data, make decisions based on observations, and utilize their actuators to take appropriate action.

HAN's comprise of smart appliances which can communicate with one another or a Home Energy Controller (HEC) to enable residents to automatically monitor and control home lighting, safety and security systems, and manage home energy usage. The widespread availability of low-cost wireless technologies such as Zigbee has accelerated the deployment of HAN's by facilitating the addition of communication capabilities to household appliances. Figure 2 shows a typical HAN architecture.

Smart appliances are home appliances which combine embedded computing, sensing and communication capabilities to enable intelligent decision-making. Sensing capabilities

enable these devices to measure and report their energy consumption to the HEC, while their actuation abilities enable them to respond to commands from the HEC. These commands can be simple on/off signals, or a DR command to operate in energy saving mode. Their communication capabilities also enable them to report their current operating state to the HEC, which then determines their level of participation in any DR activities. For example delaying the current operation of a washer in the middle of a wash cycle may result in the use of more energy than if it is allowed to finish its operation.

Smart appliances support DR signals in one of two ways. They can operate in energy saving modes when electricity prices are high, or they can delay their operation till prices drop below a specified threshold. Examples include smart dishwashers which can receive DR signals and delay wash cycles till off-peak periods; Microwave ovens which automatically reduce their power levels during peak periods or refrigerators which can delay their defrost cycle till off-peak periods (“GE ‘Smart’ Appliances). Legacy devices such as water heaters, pool pumps or lighting fixtures which do not contain embedded controllers or communication abilities of their own can be controlled via smart plugs. Smart plugs are intelligent power outlets with measurement and communication capabilities which enable device energy monitoring and remote device shut off. We have discussed the architecture required for appliance management and now proceed to show how this architecture can be leveraged to manage building energy use.

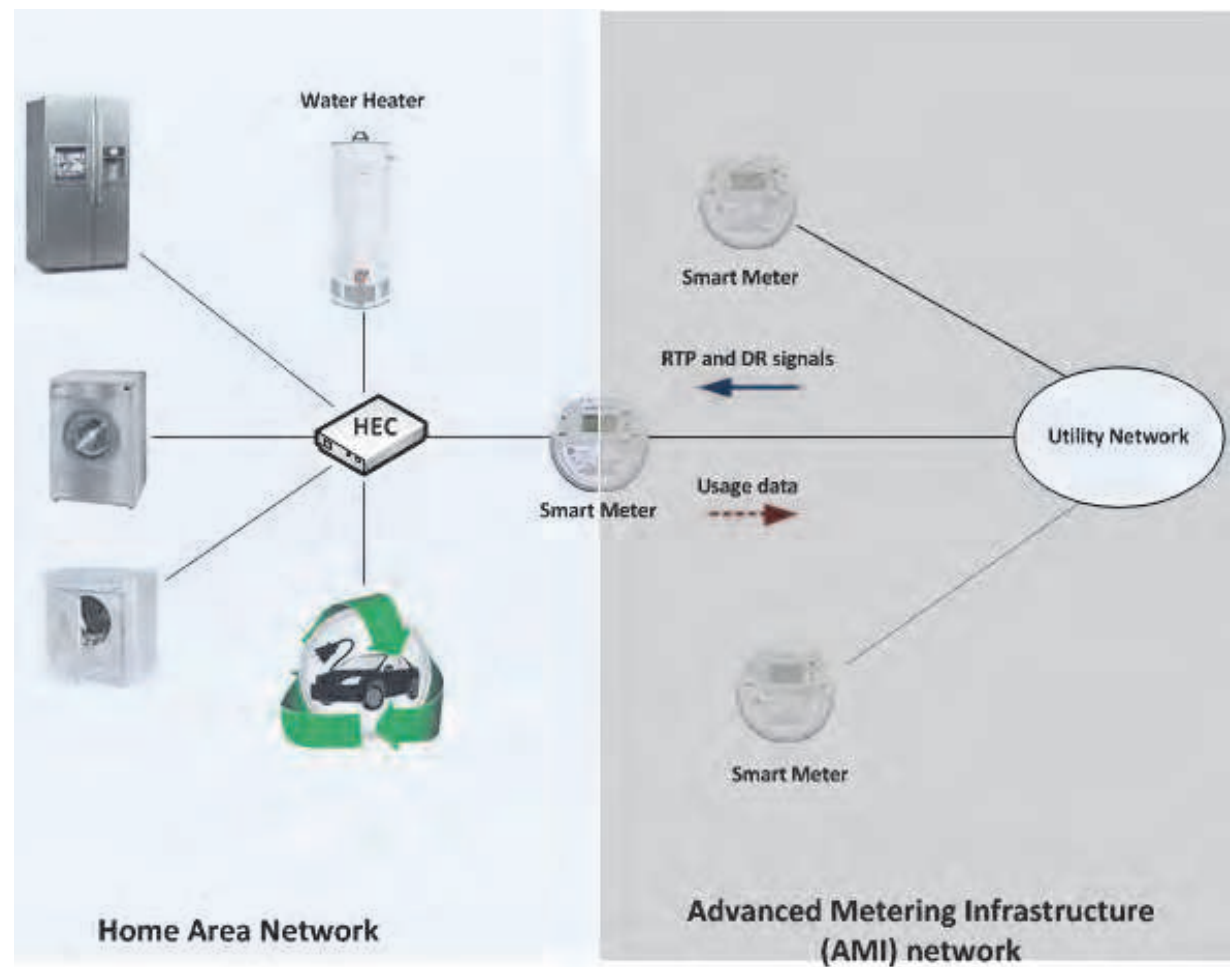


Fig. 2. Home automation network

3. Appliance management

Visibility into load or appliance energy usage is essential for energy-efficient management of building loads. Froehlich et al (Froehlich et al., 2011) note that the greatest reductions in energy usage are made when users are provided with disaggregated energy use data for each appliance, rather than just aggregate energy use data. Therefore in order to determine appropriate energy management strategies, building managers and residents require knowledge of their largest loads, peak usage times and their usage patterns. Energy-efficient appliance management requires energy sensing/measurement, appliance control, and data analysis (recommendations and predictions based on energy usage patterns). In this section we discuss appliance energy consumption, the various energy sensing schemes and conclude with a discussion of how these schemes can be incorporated into the next generation of smart meters.

3.1 Appliance energy consumption

Residential and commercial electricity usage accounts for 75% of US electricity consumption (US Department of Energy, 2009). As can be seen in figure 3a, all appliances (excluding refrigerators) and lighting account for 60% of residential energy usage. The primary electrical loads in commercial buildings are lighting and cooling, which comprise almost 50% of all electricity usage (figure 3b and 3c) and the bulk of commercial electricity bills. It is estimated that a 10-15% reduction in residential electricity use will result in energy savings of 200 billion kWh, equivalent to the output of 16 nuclear power plants (Froehlich et al., 2011). These statistics demonstrate the importance of appliance energy management, along with the potential savings that can be achieved by means of energy efficiency schemes.

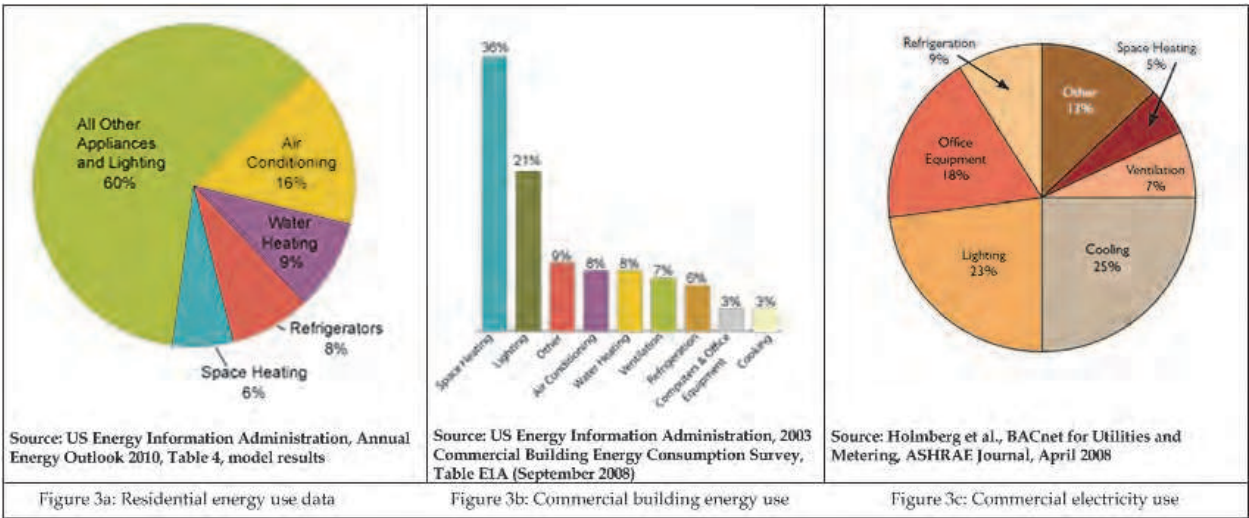


Fig. 3. Residential and Commercial energy usage data

3.2 Energy sensing, measurement and control

As earlier discussed, visibility or feedback into energy use is the first step for energy management. Energy usage measurement schemes fall into two classes – direct or distributed sensing and single point sensing schemes. The choice of schemes used is a function of system cost, the size of the system to be measured and ease of installation.

### 3.2.1 Distributed or direct sensing

This is the most accurate scheme for obtaining disaggregated appliance energy use data. Each of the sensed devices is connected to the mains through a smart plug or sensor which measures appliance energy usage. The smart plug either displays device energy usage directly or it transmits readings to a central controller. An important feature of these devices is the ability to control attached appliances and switch them on or off. Examples include the University of California, Berkeley's Acme (Jiang et al., 2009) and the Plogg ("Plogg Smart Meter Plug,). The features of these devices are:

- Highly accurate measurements
- Simple device tagging/identification
- The ability to control the sensed device
- Requires the deployment of a large number of nodes
- High system and installation cost

### 3.2.2 Single point sensing

Single point sensing addresses the cost and convenience issues associated with distributed sensing schemes. In this method, disaggregated energy use data is obtained from a single point in the household or building. This provides a cost-effective and easily deployed solution with fewer points of failure than a distributed solution. It is especially attractive in large building and commercial environments where a large number of devices are to be sensed. This scheme is known as non-intrusive load monitoring (NILM) or non-intrusive appliance load monitoring (NALM). Aggregate power measurements are monitored and are converted into feature vectors that can be used to disaggregate individual devices by identifying signatures unique to each monitored device.

Single-point sensing involves feature extraction, event detection (e.g. device turn on/off) and event classification. The features of this scheme are:

- Lower cost and easier installation
- No device control
- Training required to identify/tag
- Some schemes can only sense appliance activity but not measure energy use

This sensing scheme can be divided into two classes – low and high sampling frequency methods, with the sampling frequency requirements being a function of the selected feature vector components. The shorter the duration of the events we are trying to detect, the higher the sampling frequency requirements. Low-sampling frequency schemes are cheap and simple, making them ideal for residential environments with a small number of high-power loads. On the other hand, high-sampling frequency schemes provide greater versatility in detecting and disaggregating loads, but this comes at the price of higher system cost and computational complexity.

#### 3.2.2.1 Low-sampling frequency schemes

The first NALM scheme was developed by Hart et al in the late 1980's (Hart, 1992). It utilizes aggregate complex power (i.e. real and reactive power) to identify step changes in a real vs. reactive power (P-Q) space.

Hart classified loads into 3 groups in order of complexity – on/off, finite state machine and continuously variable loads. Examples of on/off loads are light switches and other devices with only two operating states. Finite state machines are appliances with different operating modes e.g. a washing machine with wash, rinse and spin cycles; while continuously variable

loads include power tools and motor loads whose electricity draw varies continuously. Hart’s scheme worked quite well for the first two categories but was unable to disaggregate the last group. His ingenious scheme involved noting step changes in energy use in the P-Q plane, and mapping these step changes to appliance state changes. This enabled the identification of loads along with their energy usage. It however only functioned well in home environments, as it was unable to detect and classify loads smaller than 100W, or continuously varying loads. It was also unable to distinguish between loads of the same type – e.g. two identical light bulbs.

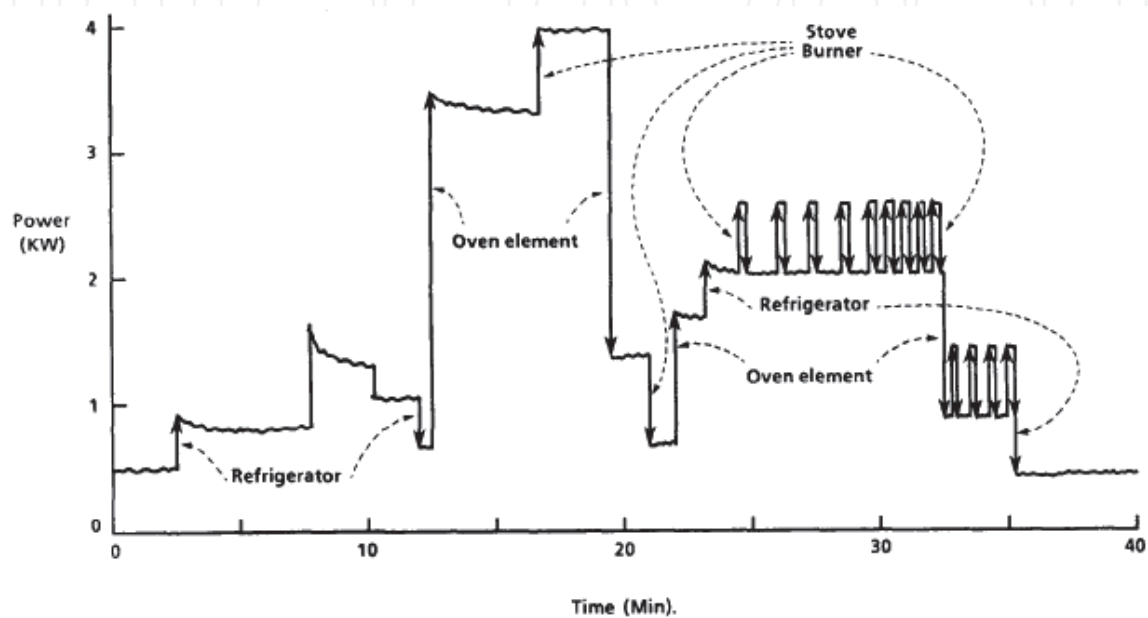


Fig. 4. Energy disaggregation (Hart, 1992)

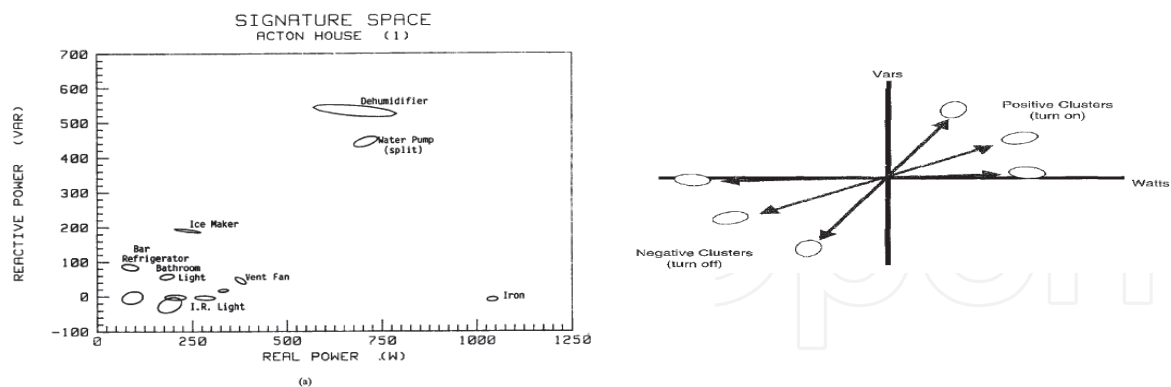


Fig. 5. NALM (Drenker & Kader, 1999)

3.2.2.2 High-sampling frequency schemes

3.2.2.2.1 NALM combined with harmonics and transients

Hart’s NALM work was extended by his colleagues to utilize a feature vector consisting of harmonics and transients, in addition to complex power (Laughman et al., 2003). This extension enabled the detection of continuously varying loads as well as the resolution of low

power devices, thereby overcoming the primary deficiencies of basic NALM. These deficiencies were present because the original NALM scheme was based on three assumptions which did not always hold, especially in commercial buildings. The assumptions were:

- 1. Each load can be uniquely identified in the P-Q space
- 2. After a brief transient period, load power consumptions settle to a steady state value
- 3. Energy data would be batch processed at the end of the day

It was found that different loads could have almost identical loci on the P-Q plane, leading to inaccurate load classification. Analysis of aggregate power in commercial buildings also showed that in buildings with large numbers of variable speed loads, steady state power draws were never achieved. Finally, the original NALM scheme was designed with batch processing in mind, limiting its utility for real or near real-time energy data analysis.

In this scheme, the aggregate current waveform is sampled at 8 kHz or greater, and the Fourier transform of the sampled waveform is used to obtain spectral envelope of the signal. The spectral envelope is the summary of the harmonic content of the line current and is used to obtain estimates of the real, reactive and higher frequency content of the current. The combination of real and apparent power with harmonic content enables disaggregation of loads which would be indistinguishable using only P-Q information. The spectral envelope is given by equation 1 where  $a_m(t)$  is proportional to real power, and  $b_m(t)$  is proportional to reactive power.

$$a_m(t) = \frac{2}{T} \int_{t-T}^t i(\tau) \sin(m\omega\tau) d\tau$$

(1)

$$b_m(t) = \frac{2}{T} \int_{t-T}^t i(\tau) \cos(m\omega\tau) d\tau.$$

Transient events are learned and used to create signatures which detect appliance events, hence loads are detected via their unique transient profiles, and these profiles can also be used for device diagnosis. They can also detect continuously varying loads such as variable speed drives, and the use of transients to detect device start-up/shutdown is shown in figure 6 below:

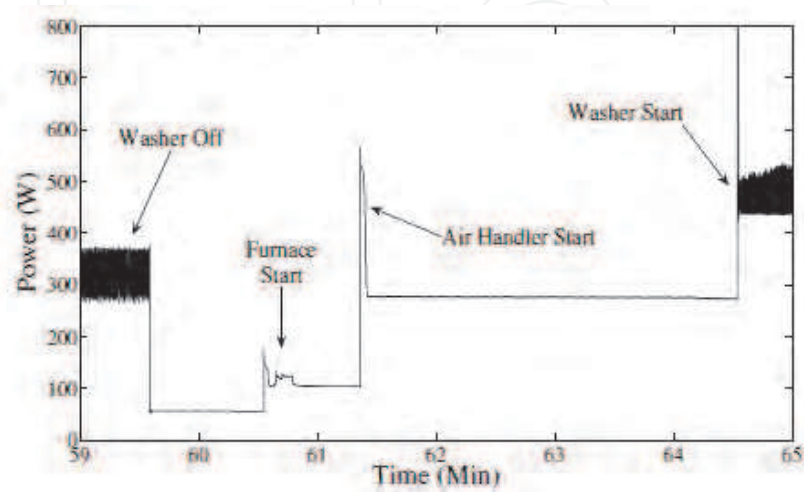


Fig. 6. Transient event detection (Sawyer et al. , 2009)

The use of harmonics enables the disaggregation of loads that appear almost identical in the P-Q plane. This is apparent in figure 7, where the 3rd harmonic is used in conjunction with the real and reactive power respectively to disaggregate an incandescent bulb and a computer.

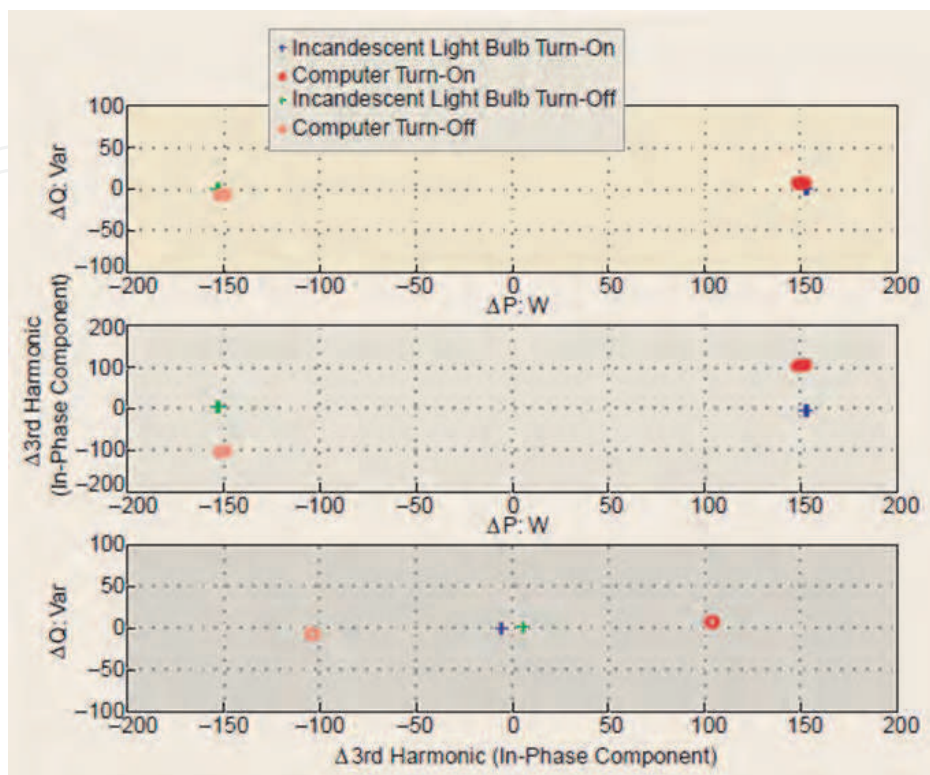


Fig. 7. Complex power and harmonic device signatures (Laughman et al., 2003)

#### 3.2.2.2.2 Noise as an appliance feature

An innovative approach to appliance disaggregation was developed by Patel (Patel et al., 2007). Their scheme utilized transient noise as the feature vector for appliance detection. Real-time event detection and classification were performed via transient noise analysis of device turn on or off events. The novelty of their scheme was the ability to perform single point sensing from any power outlet in the home, obviating the need for professional installation or any work at the meter or junction box. Another advantage is the fact that appliances of the same type have unique features due to their mechanical characteristics and the length of their attached power line. This enables their scheme to not only detect that a light has been switched on, but also which light. Transient noise only lasts for a few milliseconds but is rich in harmonics in the range of 10Hz-100 kHz depending on the device, therefore this scheme requires high sampling rates (1-100MHz).

#### 3.2.2.2.3 Continuous voltage noise signature

Rather than looking at transient noise, Froehlich et al (Froehlich et al., 2011) utilize the steady state noise generated by all electrical appliances as a feature vector. Appliances produce steady state noise during operation, and introduce this noise into the home power wiring. Most appliances (laptop chargers, CFL bulbs, TV's etc.) use switched mode power supplies (SMPS') and it has been found that these units emit unique continuous noise signatures which vary between device types. As with their earlier work, this scheme permits single point sensing from any point in the home. Steady state noise events have longer

periods than transient noise, so the sampling rate required is significantly lower than that for transient noise detection. As a result, sampling rates of only 50-500 kHz are required. A spectrogram of steady state noise signatures is shown in fig 8.

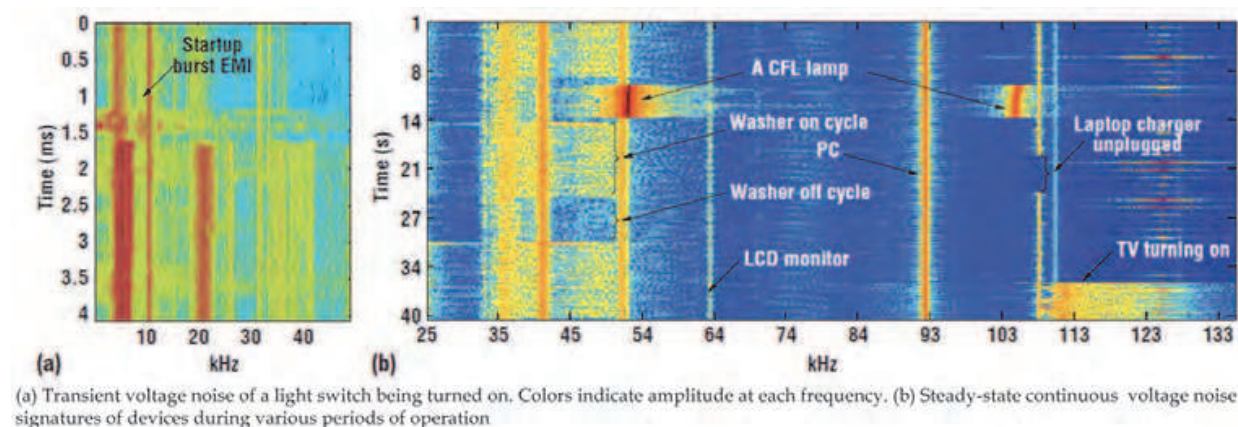


Fig. 8. Spectrogram of steady state noise signatures (Froehlich et al., 2011)

### 3.3 Open issues

The primary question is how can we use existing HAN infrastructure to perform NALM? The high sampling rates required for noise and harmonic signature-based schemes preclude their use in Smart meters which only sample electricity at 1Hz, while conventional NALM schemes have lower sampling rates but are too processor intensive to be incorporated into smart meters. The constraints to widespread NALM adoption are:

- Meter sampling rate
- Meter processing power
- Installation cost
- Consumer privacy concerns

Open issues include finding feature vectors which can be obtained with a sampling rate of 1Hz or less, while providing accurate disaggregation, as this will allow us to harness the smart meter for energy usage measurement without installing additional measurement hardware. The Home Energy Controller can then be leveraged to collect raw power data from the smart meter via wireless links. It can then perform signal processing on the aggregate data and disaggregate energy usage. The HEC can also be used to schedule home appliances in order to reduce residential energy cost.

The greatest cost savings are achieved when energy usage is correlated with real-time pricing, hence the synergy between appliance energy management and the smart grid. Unfortunately, the usage of the smart grid introduces security and privacy concerns which need to be addressed. These issues are related to the visibility into appliance energy usage and the availability of information which enables the profiling of occupant habits and behaviour, we therefore address this issue in detail in section 5 of this paper.

## 4. Intelligent lighting

Lighting accounts for 28% of all commercial building electricity expenditure (US Department of Energy,) and represents a potential source of energy savings. These systems also directly influence workplace comfort and occupant productivity. Improvements to

lighting systems promise significant energy and cost savings (Rubinstein et al., 1993), as well as improved occupant comfort (Fisk, 2000).

A substantial amount of research has been done on energy efficient lighting e.g. CFL's etc., now the next challenge is the addition of intelligence and communication capabilities. The objective is to drive down energy usage even further, while enhancing occupant comfort and productivity. The integration of WSN's into lighting systems permits granular control of lighting systems, permitting personalized control of workspace lighting.

The functions of a lighting control system are workspace illumination, ambience and security. They directly affect workspace safety and occupant productivity, but are also one of the largest consumers of electricity. A system diagram of an intelligent lighting control system is provided in Figure 9.

Lighting systems consist of ballasts and luminaires or lighting fixtures. Ballasts provide the start-up voltages required for lamp ignition, and regulate current flow through the bulb. Newer ballasts enable fluorescent dimming using analogue or digital methods, enabling granular control of lighting output. It has been discovered that the human eye is insensitive to dimming of lights by as much as 20%, as long as the dimming is performed at a slow enough rate (Akashi & Neches, 2004), thereby permitting significant savings in energy use.

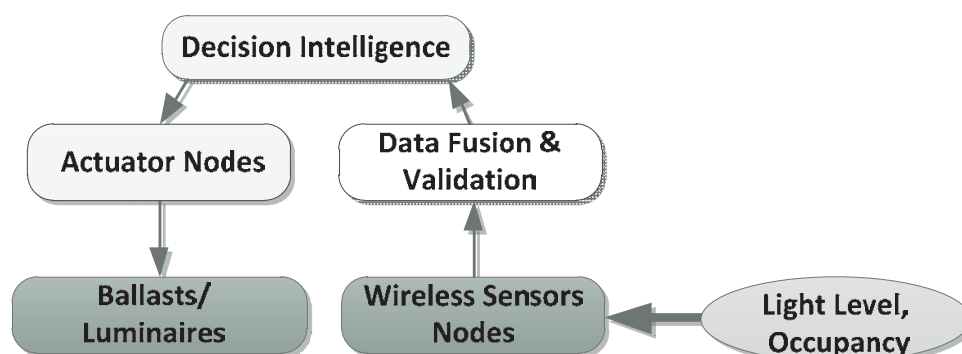


Fig. 9. Intelligent lighting system

#### 4.1 Sensors

Sensors serving as the eyes and ears of the intelligent environmental control system allow the system to detect and respond to events in its environment. The most commonly utilized sensors are occupancy and photo sensors, although some systems incorporate the use of smart tags to detect and track occupants. However, these smart tag based schemes are yet to gain widespread acceptance due to privacy concerns.

Occupancy sensors are used in detecting room occupancy and are utilized in locations with irregular or unpredictable usage patterns such as conference rooms, toilets, hallways or storage areas (DiLouie, 2005). The primary technologies used in occupancy sensors are ultrasonic and Passive Infra-red (PIR) sensors.

Photo sensors detect the amount of ambient light, and use this information to determine the amount of artificial lighting required to maintain total ambient lighting at a defined value. Therefore, photo sensors are an integral component of daylight harvesting systems.

#### 4.2 Lightning control modes

Basic lighting control modes include on/off control, scheduling, occupancy detection, and dimming. More advanced schemes include daylight harvesting, task tuning and demand response. Daylight harvesting involves measurement of how much ambient light is present,

and harnessing ambient light to reduce the amount of artificial lighting required to keep the amount of light at a pre-set level. Task tuning involves adjusting the light output in accordance with the function or tasks which will be performed in the lighted area. Demand response is the dimming of lighting output in response to signals from the utility. As discussed earlier this dimming is often un-noticeable to building occupants. Intelligent lighting control systems combine digital control with computation and communications capabilities. The result is a low cost, yet highly flexible lighting system. These systems were surveyed in (Iwayemi et al., 2010) and a taxonomy of the schemes is provided in figure 10.

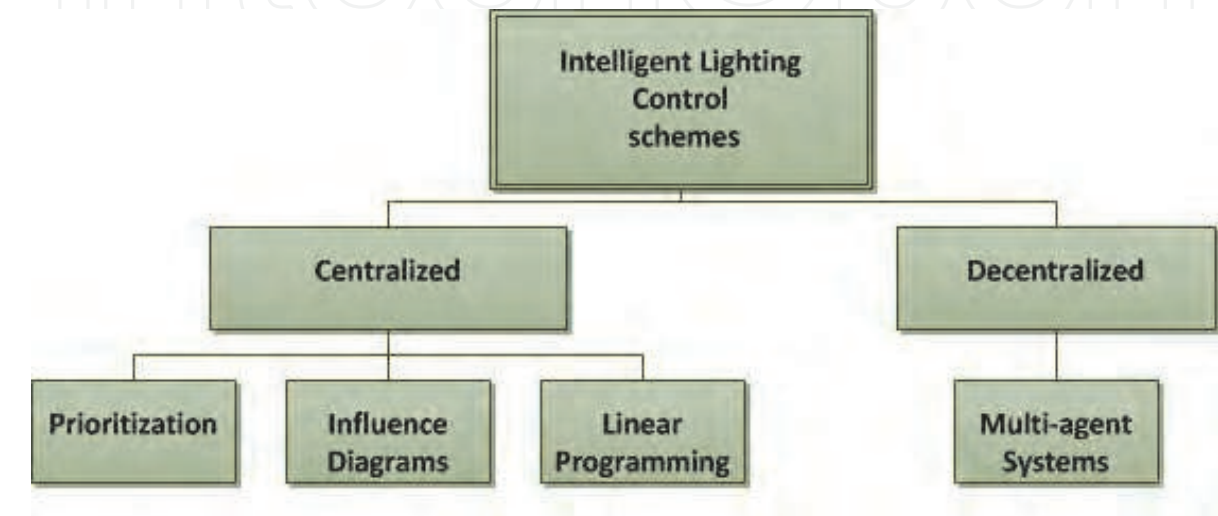


Fig. 10. Taxonomy of intelligent wireless lighting control (Iwayemi et al., 2010)

Centralized intelligent lighting schemes deliver faster performance and lower convergence times than de-centralized schemes, but this comes at the cost of scalability and single-point of failure issues. An overview of the various schemes is provided in Table 1.

4.3.1 Prioritization

This is the most basic intelligent lighting scheme, where conflicting occupant lighting requirements are resolved by the assignment of user rankings or priorities. In this system, area lighting settings are determined by the occupant with the highest ranking. Such a scheme was deployed by Li (S.-F. Li, 2006) and used a WSN-based lighting monitoring and control test bed with pre-assigned user priorities.

4.3.2 Influence diagrams

An influence diagram is a graphical representation of a decision problem and the relationship between decision variables. The relationship between decision variables is determined by means of marginal and conditional probabilities, enabling the use of Bayes rule for non-deterministic decision-making and inference (Granderson et al., 2004). Influence diagrams are directed acyclic graphs made up of three node types, namely state, decision and value nodes. Decision nodes are denoted by rectangles and represent the control actions available to controllers/actuators within the system. State nodes are denoted by ellipses, and represent uncertain events over which we have no control, while value nodes represent the cost functions we seek to minimize or maximize. They are represented

	Prioritization	Influence Diagrams	Linear Programming	Multi-agent Systems
Overview	Conflicts resolved by deferring to the highest priority user present	Complex interrelationships formulated using simple graphs. Non-deterministic decision-making	Effective optimization scheme for modeling and satisfying competing objectives	Ideal for environments where learning and prediction are essential while interrelationships between system parameters are either unknown or not well-defined
Approach	Node prioritization	Bayesian probabilities	Linear optimization, scalarization,	Artificial Intelligence - Neural networks, expert systems
Response time	Fastest	Rapid response	Rapid response	Medium
Scalability	Centralized architecture which limits scalability and produces single-point failures			Highly scalable due to distributed architecture
Weaknesses	Can only guarantee comfort for a single occupant	Probabilities must be determined via experimentation	Optimization problem formulation is a non-trivial task	No wireless scheme currently deployed due to complexity of the problem

Table 1. Comparison of intelligent lighting control schemes

by hexagons. These nodes rank the different options available to the system controller based on the current system state, with the optimal decision being the choice that maximizes (or minimizes) the selected cost function. Arcs represent the interrelationships between system nodes. Input arcs (arcs from state nodes to decision nodes) represent the information available to decision nodes or controllers at decision time, while arcs from decision nodes to state nodes indicate causal relationships. An influence diagram for intelligent lighting control is shown in fig 11 and displays the various states, decision nodes and inputs. Granderson (Jessica Granderson, 2007; Jessica Granderson et al., 2004), and Wen (Wen, J. Granderson, & A.M. Agogino, 2006) utilize influence diagrams to provide intelligent decision-making capabilities for WSAN-based lighting schemes. Their systems utilized dimmable ballasts and were able to satisfy conflicting occupant preferences in shared workspaces.

4.3.3 Linear optimization

This is the most common scheme for minimizing lighting energy consumption subject to the constraint of satisfying conflicting user requirements. It seeks to maximize or minimize an objective function subject to constraints, and there is a rich collection of work in this area (Akita et al.,2010; Kaku et al., 2010; M. Miki et al., 2004; Pan, et al., 2008; Park et al., 2007; Singhvi et al.,2005; S. Tanaka, M. Miki et al., 2009; Tomishima et al., 2010; Yeh et al., 2010). For example, Wen (Wen & Alice M. Agogino, 2008) created an illuminance model of the

room to be lighted, and this model captured the effect of each individual luminaire on work surface lighting. Their objective was the minimization of work surface illuminance levels subject to the satisfaction of lighting preferences of current room occupants. Their system calculates the optimal linear combination of individual illuminance models and lighting levels which minimizes energy usage.

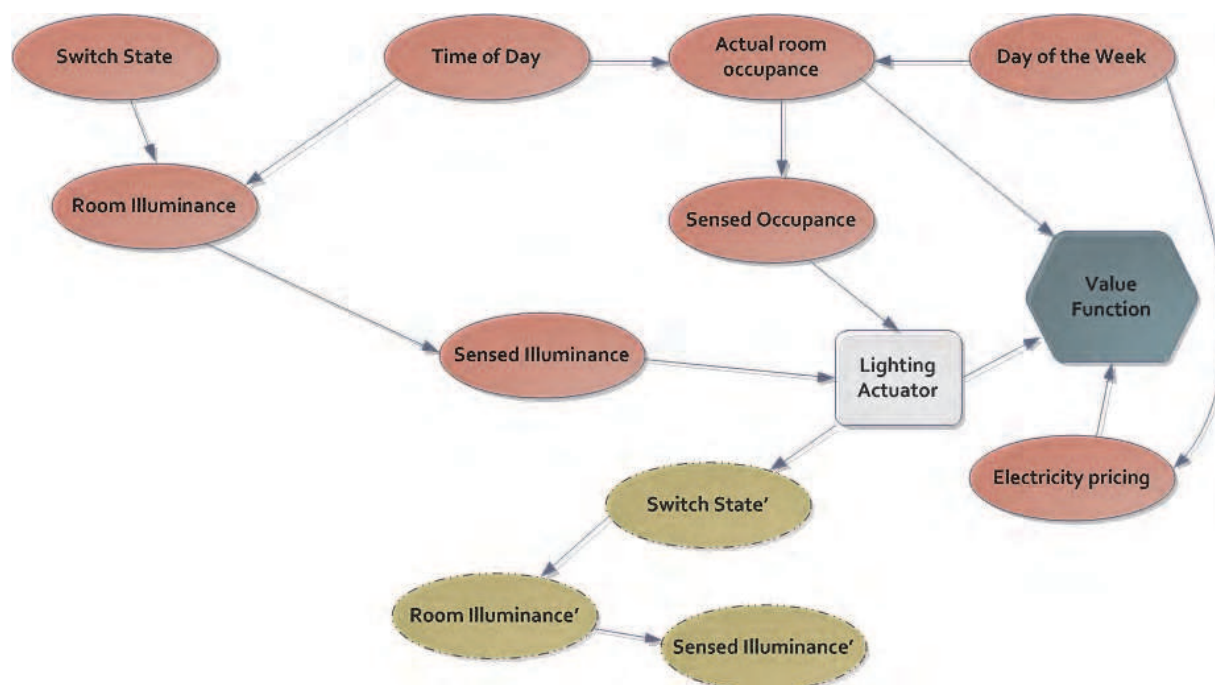


Fig. 11. Inference Diagram for Intelligent lighting control

#### 4.3.4 Multi-agent systems

Multi-agent systems utilize large numbers of autonomous intelligent agents which cooperate to provide decentralized control of complex tasks. These schemes incorporate the advantages of inference diagram based lighting control schemes, without requiring centralized control. Their advantages include scalability, self-configuration and adaptation by means of machine learning techniques. A theoretical framework for such a system was proposed by Sandhu (Sandhu, 2004).

## 5. Smart grid security

Smart environments promise great convenience through the use of autonomous intelligent agents which learn and predict occupant desires, and smart appliances which monitor and automatically regulate energy use. As noted by Cavoukian et al (Cavoukian et al., 2010), these environments generate and observe tremendous amounts of detailed data about their occupants, providing them with information to control their energy consumption and electricity bills; reduce greenhouse gas emissions; and improve occupant comfort and quality of life. The benefits to the utility (via smart metering and other smart grid technologies) are the provision of real-time billing, customer energy management, and highly accurate system load prediction data.

Unfortunately the use of these technologies poses tremendous security and privacy risks due to the type and quality of the data they capture (Callaghan et al., 2009). The home is

man's most private place, and analysis of fine-grained smart metering data by NALM enables the utility to learn occupant habits, behaviours and lifestyles (Bleicher, 2010; Quinn, 2009). The smart grid increases the amount and quality of personally identifiable information available, and there is significant concern that this information will be used for applications beyond the purposes for which it was originally collected. This information is extremely valuable to third parties such as advertisers, government agencies or criminal elements, and has led to the fear that users can be spied upon by their meters, negatively impacting smart meter deployment (Bleicher, 2010). In addition, the networking of smart meters with the electricity grid also raises the spectre of smart meter fraud, and increases the vulnerability of these devices to malicious attacks such as Denial of service (DoS) attacks. We discuss these issues in more detail below, along with some proposed solutions.

### 5.1 Privacy issues

The use of earlier discussed non-intrusive appliance load monitoring technology (NALM) has enabled the identification of appliances by means of their unique fingerprint or "appliance load profiles." Data mining and machine learning tools enable utilities to determine which appliances are in use and at what frequency. This provides access to information including the types of appliances a resident possesses, when he/she has their shower each day (by monitoring extended usage of the heater), how many hours they spend using their PC, or whether they cook often or eat microwave meals. This has led to the very valid fear that customers can be profiled, and monitored by means of their smart meter (Hansen, 2011). In addition, improper access to such data can lead to violations of privacy or even make one open to burglary by determining the times the house is empty. As with internet advertising companies that track users and build profiles based on browsing histories, utilities will be in a position to create detailed profiles of their customers which they can mine or sell to third parties.

In order to address this privacy concerns, we need to determine the type, amount and quality of information required by utilities to provide real-time billing and other smart grid services. Utilities require insight into electricity usage patterns in order to optimize their operations and scale them appropriately, while residents desire the benefits of the smart grid but do not want to exchange them for their privacy. Therefore a balance between these two extremes is required.

Smart grid security issues can only be solved by a combination of regulatory and technological solutions. A regulatory framework is required to specify who has access to smart meter data and under which conditions, as well as enforcement of penalties for data misuse (McDaniel & McLaughlin, 2009). Technological solutions focus on anonymization or privacy-preserving methods.

Quinn (Quinn, 2009) suggests aggregating residential data at the neighbourhood transformer and then anonymizing it by stripping it of its source address before transmitting it to the utility. Kalogridis et al (Kalogridis et al., 2010) provide privacy by obscuring load signatures by means of a rechargeable battery as an alternate power source, a process they term "load signature moderation". In this scheme, a power router and a rechargeable battery are added to the HAN network. The power router determines the amount of electricity required by an appliance and 'routes' the power to the appliance via various sources. For example, a fridge could be supplied by a combination of utility power, a solar cell and rechargeable battery. This power mixing is performed in conjunction with

battery recharge events which obscure load signatures and prevent their disaggregation by means of NALM (figure 12).

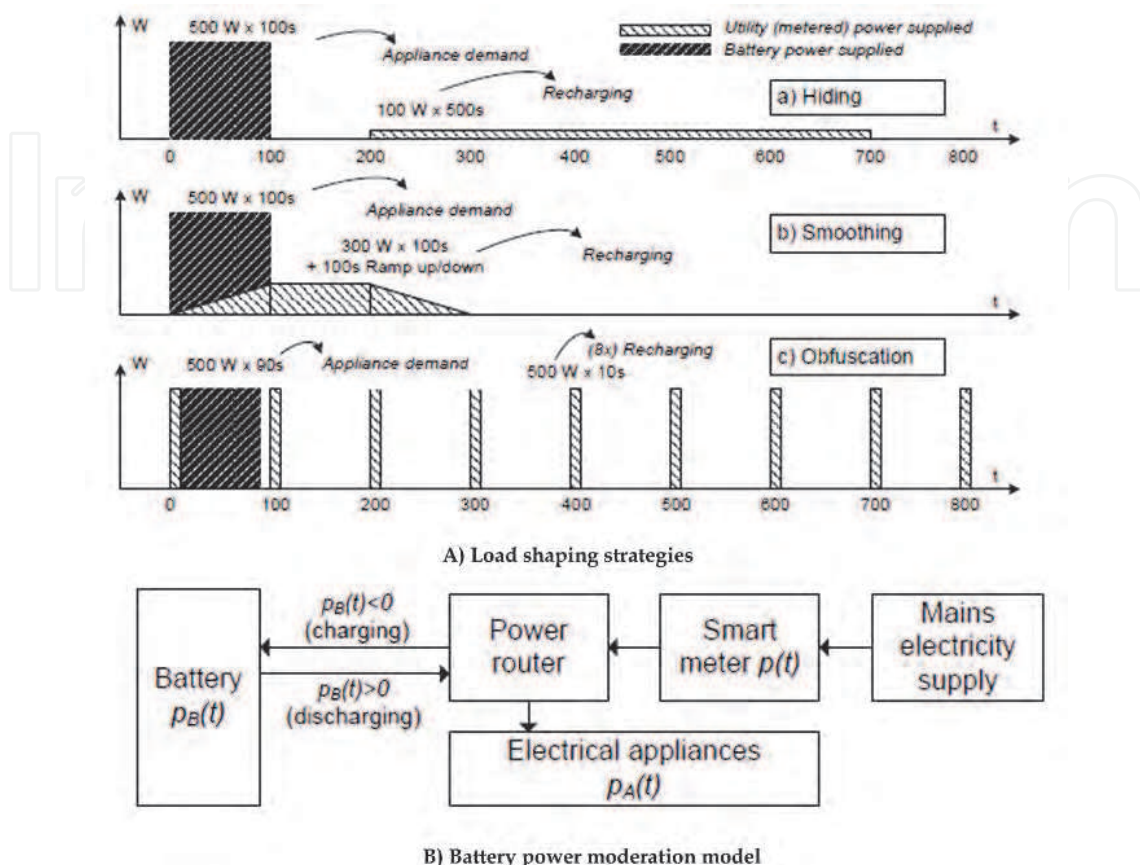


Fig. 12. a) Load shaping and b) battery power mixing (Kalogridis et al., 2010)

Other schemes include Rial and Danezis' (Rial & Danezis, 2010) privacy preserving smart metering scheme. In this scheme, the smart meter provides certified readings to the user who then combines with a certified tariff policy to generate a final bill. The bill is then transmitted to the utility along with a zero-knowledge proof which confirms that the billing calculation is correct. The advantage of this scheme is that no additional information is sent to the utility apart from what is required for billing purposes. However, their scheme also permits the disclosure of individual or aggregate readings to facilitate load prediction.

We propose a digital rights management system (DRMS) based scheme which extends that proposed in (Fan et al., 2010). Users license permission to the utility to access their data at varying levels of granularity. By default the utility would have access to monthly usage and billing data, but customers have to grant the utility permission to access their data at higher levels of granularity in exchange for rebates or other incentives. Such a system eliminates the need for an intermediary between the utility and the consumer, but requires a means of guaranteeing that the utility cannot access restricted customer data.

## 5.2 Smart meter fraud

Users can manipulate their smart meter readings in order to reduce their electricity bills, as the desire for lower electricity bills provides a compelling incentive for smart meter fraud. The ability to report inaccurate data to the utility means that customers can reduce their bills

by falsely claiming to supply power the grid, or consume less power than they actually do. The commercial availability of smart meter hacking kits means that those with sufficient skill and interest can engage in meter fraud (McDaniel & McLaughlin, 2009).

### 5.3 Malicious attacks

The internetworking of smart meters makes them especially vulnerable to denial of service attacks in which several meters are hijacked in order to flood the network with data in order to shut down portions of the power grid, or report false information which can result in grid failures.

## 6. Conclusion

Commercial and residential buildings are the largest consumers of electricity in the United States and contribute significantly to greenhouse gas emissions. As a result, building energy management schemes are being deployed to reduce/manage building energy use; reduce electricity bills while increasing occupant comfort and productivity; and improve environmental stewardship without adversely affecting standards of living. The attainment of these energy management goals requires insight into appliance usage patterns and individual appliance energy use, combined with intelligent appliance operation and control. This is achieved by application of distributed and single-point sensing schemes to provide appliance energy sensing and measurement, and the use of intelligent WSN-based lighting control schemes. We have therefore surveyed the two schemes which promise the greatest reductions in residential and commercial building energy use – non-intrusive appliance load monitoring, and intelligent lighting.

Our survey of NALM techniques indicates that there is currently no one size fits all solution, and that the schemes with the highest resolution also tend to have the highest processor and sampling rate requirements. An open issue is how to leverage smart meter and HAN infrastructure for NALM as this will provide the cheapest and most convenient approach to widespread NALM deployment.

We have also demonstrated the utility of WSN-based intelligent lighting for providing substantial energy savings, especially in commercial buildings, and provided a taxonomy of intelligent lighting schemes. In addition, the security and privacy problems inherent to smart grids and pervasive computing environments were discussed and solutions proffered. Building energy management is poised to experience tremendous growth over the next decade as the issues outlined in this work are addressed and resolved, leading to cleaner, more efficient buildings.

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