Integration of Wireless Sensor Networks with Building Energy Management Systems

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***Abstract*— Reducing energy consumption within buildings has been an active area of research. Energy usage both in commercial and residential buildings represents a significant portion of overall energy consumption. The viability of Wireless Sensor Network (WSN) technologies can be integrated with Building Energy Management Systems (BEMS) in order to reduce energy consumption within buildings. This paper targets the description of a generic architecture and classification of WSN-based BEMS.**

Keywords - Wireless Sensor Networks; Smart buildings; Building Energy Management Systems.

I. INTRODUCTION

The use of electricity in commercial and residential buildings represents a significant portion of overall energy consumption. Effective energy conservation within buildings will result in a significant decrease in energy demand. This demands that customers be provided with accurate and detailed information concerning their energy usage in real time. Such information is a prerequisite for effective feedback provision as well as for enabling the deployment of remote intelligent autonomous energy control systems. Recent advances in wireless communications, low-power integrated circuits, sensor design, and energy storage technologies have enabled the effective deployment of Wireless Sensor networks (WSNs) in a range of real-world application domains [1]-[3]. WSNs can be used by environmental and event monitoring systems, such as Building Energy Management Systems (BEMS). BEMS harness WSNs to harvest detailed information concerning energy consumption within buildings, as well as the prevailing context under which such consumption occurs. BEMS are an integral part of so-called intelligent or smart buildings. In this article, a classification of the WSNs based BEMS for smart buildings is presented. In this context, the rest of this article is organized as follows: An overall presentation of WSN technology is provided in Section II, while Section III describes BEMS and a generic BEMS architecture is provided in Section IV. Then, in Sections V-VII, energy monitoring, energy feedback and control systems are presented. Finally, Section VIII list some of BEMS challenges and Section IX states the conclusions.

II. WSN TECHNOLOGY

A. *Characteristic Features of WSNs*

A WSN can be seen as a node network that gathers information from the surrounding environment, thus enabling interactions in predefined cases. WSNs usually include sensor nodes, actuator nodes, gateways and clients. A large number of sensor nodes are deployed randomly inside of or near the monitoring area (sensor field), form networks through self-organization. During the transmission process, the monitored data are processed and forwarded by multiple nodes to finally reach the gateway node. The cost of WSN equipment has dropped dramatically and WSN applications are gradually expanding to industrial and commercial fields.

B. *Sensor Nodes*

The sensor node is one of the main parts of a WSN. Hardware implementation of sensor nodes typically includes four parts: the power and power management module, a sensor, a microcontroller, and a wireless transceiver. The power module is responsible for the provision of the appropriate power (i.e., in terms of frequency and nominal voltage value) for secure and reliable operation. The sensor module is responsible for data acquisition from the surrounding environment. A sensor is in charge of collecting and transforming the signals, such as light, vibration and chemical signals, into electrical signals and then transferring them to the microcontroller. The latter receives data from the sensor and processes them according to predefined operations. The Wireless Transceiver module transmits data to other wireless nodes, mobile devices, or control centers. At this point, it should be noted that all parts of a WSN node consider the WSN node features should be of tiny size and limited power [4].

C. *Topology*

In general, a WSN consists of a number of sensor nodes and a gateway for the connection to the Internet. The general deployment process of a WSN can be described as follows: first, the sensor network nodes broadcast their status to the surroundings and receive the corresponding status from other nodes to detect each other. Afterwards, the sensor network nodes are organized into a connected network, according to a predefined topology. After the

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establishment of the network topology, optimal paths are computed for transmitting the sensing data. The power of sensor network nodes is usually provided by batteries, in order to keep transmission distance of WSN nodes in a short range. The transmission distance can be up to 800-1000 meters in the open outdoor environment under line of sight. However, in the case of indoor environments, this distance can be significantly reduced. In such situations, the coverage of a network can be extended by the use of multi-hop transmission mode. In these cases, the sensor network nodes act both as transmitters and receivers. The source node sends data to its preferred node within its range (called parent node) based on predefined metrics. The next node, again, forwards the data to one of its nearby nodes along the path towards the gateway. The forwarding is repeated until the data arrives at the gateway, the destination. All protocols and some implementation techniques of WSNs can be adapted to the mature architecture and technologies of wireless and wired computer networks.

D. Low-cost IP interconnection technology

The choice during the design of the first sensor networks was to use private addresses to manage the sensor network nodes. Due to its relatively short length, the address was suitable for implementing in low-power embedded sensor nodes. However, the management of private addresses increased the difficulty of interaction between the sensor network nodes and the traditional IP network nodes. Therefore, there is a need to resolve the connectivity problem of WSN and IP network. As it is known, IPv4 addresses have been gradually depleted, and the new IPv6 addressing scheme is suitable for a wide range of sensor network deployment, providing each sensor node with its unique, public IPv6 address. As a result, 6LoWPAN low-power wireless technology based on IPv6 has emerged. The 6LoWPAN has generally implemented a simplified IPv6 protocol above the link layer of the IEEE 802.15.4 protocol [5]. Header compression and packet fragmentation reloading is implemented by adding an adaptation layer between the IP layer and the link layer, which is a reliable method to achieve protocol adaptation between the IPv6 network and the sensor network.

III. Building Energy Management Systems

The advent of Building Management Systems (BMS) is sometimes also referred to as Building Automation Systems (BAS). Though energy control systems were becoming progressively more sophisticated, an increased awareness of the importance of consumption feedback to consumers as an instrument of affecting positive behavior change was emerging. Initial studies, mainly conducted by psychologists, demonstrated the potential of feedback to reduce wasteful energy usage and save on energy cost. Energy consumption feedback has been studied as a mechanism for affecting behavior change in energy conservation within residential buildings. In the 1990's thermostats, many with dead zones, were harnessed extensively to control temperature within buildings; this technology was subsequently improved by using Proportional-Integral-Derivative (PID) controllers. The potential of Artificial Intelligence (AI) techniques was also considered. Environmental parameters served as input in the control of Heating Ventilation and Air-Conditioning (HVAC) systems. Due to the invisible nature of energy consumption in residential and commercial buildings, a major challenge faced by early researchers concerned the collection of real-time and detailed information on energy consumed by individual electrical devices within a building. To enable energy disaggregation at the appliance level, researchers formulated Nonintrusive Load Monitoring (NILM) or Nonintrusive Appliance Load Monitoring (NIALM). NILM enables per-appliance energy consumption by identifying changes in energy usage data, as recorded by a meter. A new generation of BEMS emerged with the introduction of WSN technologies [6]. Acquiring information on energy usage at different levels, such as appliance, building, or circuit, was made possible through the aid of WSNs. In recent years, wireless smart meters and smart plugs have been developed that can be installed inside the circuit-breaker box and on outlets close to individual appliances. Such devices integrate traditional metering systems with communication interfaces to deliver detailed information on resource consumption in real time, as well as to offer additional features, such as remote actuation. Thus, smart meters are a fundamental component of the current generation of BEMS. In addition, the concept of Internet of Things (IoT) integration in BMS is a challenging research field, as it allows the interconnection of various diverse functions in the concept of smart cities (i.e., energy demand and consumption of various components) to be integrated in order to maximize energy efficiency [7].

IV. Generic BEMS Architecture

A. Key components

A generic architecture for such a BEMS is presented in Figure 1. Conceptually, it can be considered as comprising of three key components, namely Sensor Layer, Computation Layer, and Application Layer.

a) Sensor Layer

Buildings, and the electrical devices and appliances within them, are monitored by a sensor configuration that collects data on energy usage and temporal contextual environmental parameters. This information is made available to the computation layer for further data processing and analysis. The sensor layer is a physical-level configuration composed of a suite of sensor nodes deployed inside a building that periodically measure relevant phenomena and forward measurements to the computation layer for further analysis and storage [8]. This component can be seen as comprising three subcomponents:

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- *energy sensing*: consists of a smart meter (sensor) deployment that monitors energy usage within and throughout a building.
- *environmental sensing*: consists of an array of sensors that collect information on prevailing environmental factors, such as luminance level, temperature, relative humidity, carbon dioxide level, and so on.
- *human sensing*: addresses the monitoring of occupant presence and behavior and the development of behavior models for a given environment.

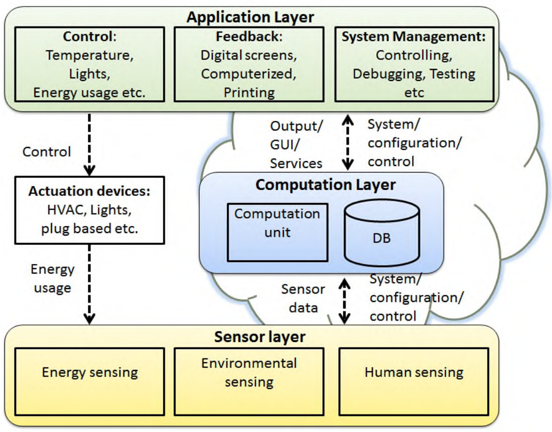

Figure 1. Architecture of BEMS.

b) Computation Layer

The function of the computation layer is to analyse all information collected by the sensor layer using algorithmic calculations and statistical analysis. It compromises two components:

- The *computation software* and
- The *database* that records all data, including real time and event driven, such as energy usage comparisons, and historical calculations.

c) Application Layer

What analysis occurs, and what tools to adopt, for example, logical reasoning, data mining, and so on, will be driven by the needs of the application layer. This layer can be further categorized into two application subcategories: appliance control and the provision of user feedback across a range of modalities. Implicit within this layer is a management component allowing for system testing. BEMS functionality is realized in the application layer. Two categories of functionality may be identified:

- *Energy feedback* systems provide building services, in inhabitants, and any other interested party with information concerning energy consumption. Such systems can present both real-time and historical energy usage information. Ambient displays, mobile devices, or Web portals may be harnessed for visualisation purposes.
- *Energy control* systems control devices and appliances within the building in accordance with policies and preferences defined by consumers. Preferences may be defined using intuitive user interfaces; likewise, control can be exercised via a range of digital displays. Computational intelligence techniques may be harnessed for enabling autonomous behavior.

In each of the two categories, an interface and control component for system management activities is necessary.

B. Cloud-enabled BEMS

Local computational capabilities may prove insufficient to represent and manage data of BEMS using WSN. One possible solution may involve the harnessing and integration of cloud computing with BEMS [9]. They will initially be realised as cloud services in the commercial context. A service-oriented paradigm may evolve where a wide range of services is hosted on the cloud, but consumers access them on a subscription basis, as their needs dictate. For example, domestic consumers may be driven by a simple need to save money.

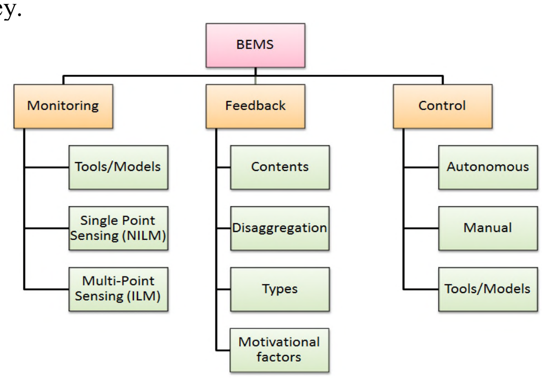

Figure 2. Classification of BEMS

In contrast, industrial and business users may perceive cloud services as an appropriate solution for legislative adherence, insurance provision, as well as enabling contractual fulfilment. BEMS can be classified in three categories, namely monitoring, feedback, and control (see Figure 2) [6].

V. Energy Monitoring Tools and Techniques

A. Approaches

Traditionally, meters installed in buildings between the baseline and the external power line fail to provide sufficiently detailed data on energy usage, nor do they offer a communication interface by which one could obtain such data in real time. Research has proposed WSN-based solutions that include energy usage monitoring using smart meters/outlets and distributed approaches for appliance activity monitoring. These are advanced energy monitoring systems that measure energy consumption and provide communication interfaces by which to transmit data in real time. There are two major approaches being harnessed to monitor energy usage and in the literature are referred to as single-point monitoring and distributed monitoring:

- single-point monitoring (NILM): they use a single metering device installed at the fuse box to monitor the entire building energy usage. To identify energy consumption at the appliance level, the data is then analyzed using estimation algorithms to identify the different load usage patterns generated by various appliances when in use.

- distributed monitoring (ILM): this approach is used for monitoring appliance-level energy consumption. It harnesses either smart plugs/outlets or various types of sensors for each individual appliance.

B. Single-Point Monitoring (NILM)

A smart clip-on meter is installed at the main electrical panel outside the building and it meters the entire building energy usage in real time and reports this to a PC via a gateway. This data is sometimes referred to as the aggregated energy usage measurement of a building. The next step is to disaggregate appliance-specific information from this measurement. Appliance signatures are created by turning appliances on/off during the training phase and appropriately annotating the dataset. These signatures are then used by machine learning algorithms to disaggregate energy data. Appliances that have different energy usage patterns (or signatures) are easily identifiable but those with similar patterns are harder to distinguish. Some examples of smart metering and WSN-based systems are the following:

a) Direct Energy Monitoring

Direct energy monitoring systems require an in-line installation of the metering component to measure energy usage. Most of the systems surveyed provide broadly similar functionality, however, each of them uses varying sensor types and is designed using different hardware/software techniques, such as circuit-panel meter and energy consumption display.

b) Indirect Energy Monitoring.

Instead of an in-line installation of a clip-on meter, this method uses a plugin sensor to capture electrical noise generated on power lines by the running of appliances. This approach is used to capture appliance activity information. Electrical Noise Sensing is an approach to identifying appliance status is pre-sented. The system uses a single plugin sensor to detect electrical noise on power lines created by electrical appliances when they are switched on. Different appliances generate different electrical noise signals. This technique computationally expensive and also requires a complex and time-consuming training process compared to other NILM techniques.

C. Distributed Monitoring (ILM)

In the case of distributed sensing, each appliance in a monitored environment typically has one or more sensors allocated to it. These sensors measure a range of activities from energy usage to appliance state activity. Distributed sensing can be considered as the most accurate approach for appliance-level monitoring but it is very expensive. This type of sensing consists of using either smart meters/outlets to measure appliance level energy usage or various types of sensors to infer appliance-specific activities [10].

a) Direct Energy Monitoring

The installation of smart metering systems usually occurs inside the circuit breaker box and, due to safety concerns, may require an electrician for installation. To ease installation, a range of smart outlets have been developed and used. Smart outlets are installed between AC plugs of appliances and the standard wall power sockets. Using a gateway, the data is acquired by a PC and is then visualized on a variety of media. Such systems are straightforward, provide accurate appliance-level metering, but provide limited functionality regarding data aggregation, analysis, and visualization.

b) Indirect Energy Monitoring

While smart power outlets and meters are appropriate for appliances that provide standard AC plugs, they cannot be easily installed to operate with major energy consuming devices, such as HVAC systems, ceiling lights, and electric boilers because these devices are typically connected directly to the main power line. To address such issues, various types of sensors for indirect energy usage monitoring have been used. Most of these techniques are used to obtain fine-grained appliance activity information within buildings and differ from each other on the basis of the hardware (sensor nodes) they have adopted and software implementation. The main approaches follow:

- *Electromagnetic Sensing.*

It is an indirect and detailed power monitoring system in which wireless sensors are used to report appliance state information. The system provides detailed feedback on appliance-level electricity consumption using a collaboration between sensor nodes placed in close proximity to appliances and the main power meter that reports overall electricity usage. It uses three types of sensors: magnetic, sound, and light sensors. Magnetic sensors, placed near an appliance or a power line, can sense magnetic field variations when the current flows in the power line.

- *Environmental Sensing*

It is an environmental sensing approach that harnesses various types of sensors to infer appliance state activities based on measured environmental parameters. A sound sensor records the sounds produced by appliances and a light sensor obtains information regarding light status when switched on/off. All sensors transmit their data to a PC that processes the data and visualizes power usage per appliance. In order to automate the NILM training process, a temporary deployment of wireless sensors to each appliance is done and then appliance activity information is inferred based on the data reported by these sensors. Systems have been developed to reduce the energy consumption of meeting rooms by identifying waste. Placing various types of sensors close to appliances increases overall accuracy level but also increases system complexity. Such approaches demand more time for deployment while increasing installation and maintenance cost as compared to other indirect sensing techniques [4].

- *Thermal Sensing*

Systems that disaggregate total power usage into appliance-level consumption by observing the heat patterns generated by appliances have been developed and used. A power meter to obtain overall energy usage and one thermal

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camera to observe heat patterns on the appliance surface have been also used.

D. *Monitoring Subsystem*

The monitoring subsystem, is composed of a number of electricity sensors, measuring the power consumption of each single electrical appliance in the building. In addition to electricity sensors, the monitoring subsystem also includes environmental sensors for monitoring parameters, such as temperature, light intensity, human presence, and so on. Such information will be used by the energy manager application to minimize energy wastes, according to energy conservation strategies defined by the user(s). Data collected by both electricity and environmental sensors are communicated wirelessly to a base station located on the same floor (there is at least one base station per floor) and, then, conveyed to a central server. The communication between base stations and the central server typically occurs through a wired LAN (e.g., Ethernet) [4]. The central server has the responsibility to collect and process data. It provides users with real-time and/or periodic reports on energy consumption and costs. The server also sends alert messages to notify of specific events (e.g., a device being in active mode when it is supposed to be in inactive mode) suggesting possible actions to save energy.

VI. ENERGY FEEDBACK SYSTEMS

The content of feedback given to users may contain different reporting units, such as energy consumption and cost, appliance-state information, or environmental impacts (for example, carbon emissions). These units, when displayed, have different impacts on motivating users to reduce energy consumption. A classification of these systems follows:

- *Energy Consumption and Cost*

Usually, feedback systems provide information on energy consumptions and the cost of energy used to help users make financial savings.

- *Appliance-State Information*

Some feedback systems provide information on appliance state, whether active or otherwise. With this information, consumers can understand where energy is being wasted inside a building and, as a result, they can turn appliances off if they are not needed. Systems with high accuracy use either smart outlets or various types of wireless sensors to obtain appliance-state information.

- *Environmental Impacts*

One of the motivational factors of energy conservation is to lower carbon emissions to further the goal of a greener environment.

- *Feedback Disaggregation*

Providing disaggregated feedback results in more energy conservation. There are five major types of disaggregation to help users understand their energy usage in detail: space-specific, user-specific, appliance-specific, time-specific, and service-specific. Space-specific disaggregation is achieved by dividing a building into smaller areas. Division can be based on rooms, circuit breakers, or appliance types. Appliance-Specific disaggregated information is considered as highly enriched feedback targeting energy estimation at appliance level. Time-Specific Disaggregation, feedback on different time-scales, past, present, and future is given to help users know when and over what timescale energy was consumed and wasted. User-Specific Disaggregation or personalized feedback can help individuals in a building to keep track of their own energy usage. Service-Specific Disaggregation supports energy conservation based upon a broader perspective through the possible reconfigurations of services.

- *Feedback Presentation*

The information on energy consumption should be displayed using a medium that can capture attention, such as digital screens, smart TVs, mobile phones, and in written form; it should also be delivered in a way that is inter-active using graphs, figures, and easily understandable numerical data is preferred.

- *Motivational Factors*

Apart from motivational factors described in the previous sections, there are several other approaches to motivation, such as using comparisons, goal settings, media campaigns, and rewards has led to reduced energy usage.

VII. ENERGY CONTROL SYSTEMS

A. *Architecture*

A variety of building automation and control systems use WSNs to conserve energy. These systems usually adopt a three-tier architecture:

- a network of sensor nodes, that report energy usage, occupant behaviour, and environmental conditions;
- a central control server; and
- a set of intelligent plugs and relays that control electric appliances within a building.

The first layer provides information to the control server. The control server performs computation on information received from the sensors as well as information obtained from other sources, such as weather conditions/forecast using the Internet. The data is then harnessed by intelligent algorithms to control energy by switching off electric appliances, turning off lights, reducing HVAC parameters, and so forth. Based on the techniques and implementation details, the energy control systems consist of three major categories: autonomous energy control systems, manual energy control systems, and energy forecast/modelling systems [10].

B. *Autonomous Energy Control*

Autonomous energy control systems, once configured, can reduce energy consumption within a building by con-trolling electrical appliances, such as HVAC and lights

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without requiring continuous user interaction. Such systems primarily target HVAC and lighting systems that consume a significant portion of overall energy consumption within commercial buildings. A combination of different sensor nodes, such as temperature, PIR (Passive Infrared for occupancy detection), ambient light, and sound sensors inform the control server about the monitored environment. The control server can then make decisions and send signals to actuators. The overall goal is to switch off (or lower) HVAC, lights, and other loads in the building when not needed.

C. *Manual Energy Control*

Manual energy control systems provide user functionalities to monitor and control electric appliances remotely. BEMS provide GUIs that visualize energy consumption per appliance (mostly HVAC and lights) and provides control options for these devices. Manual energy control systems use smart outlets for plug-based appliances and standard actuation devices for HVAC and ceiling-light control.

D. *Energy Modeling Systems*

The use of software tools for energy management within buildings has become quite popular. These tools enable users to estimate the energy consumption of buildings as well as provide energy control features. Energy modelling tools offer a number of functionalities regarding energy consumption auditing, prediction, and design and evaluation of energy control systems. Such tools are helpful in motivating users to improve building energy consumption by enabling them to understand the spectrum of energy usage within buildings, especially when there are limited resources and many technical challenges to face.

VIII. Challenges of Managing Building Energy Infrastructure

In building energy management, a number of challenges can be identified:

- Installing resource monitoring can prove demanding in terms of the required technical knowledge and associated deployment time, both for single-sensor and distributed approaches.
- Monitoring energy consumption demands sensing the environment as to patterns of movement, potential activities within, and occupancy levels.
- Engineering and sustaining behavior change is fundamental and core to the success of building energy management systems. User feedback is the instrument through which behaviour change may be achieved.
- Building energy management systems is extremely heterogeneous and there is a need for the development tools to support the rapid prototyping of standards-compliant BEMS.

IX. Conclusions and Future Work

With increasing demand and costs in energy production and limited supply of energy resources, energy conservation has emerged as a critical environmental issue. Much of this attention has been directed to the use of energy in the buildings, as energy consumption in commercial and residential buildings, and there is a need to examine ways in which energy consumption may be reduced.

This article presents energy monitoring, feedback, and control strategies aimed at energy conservation within the built environment. Also, a generic architecture for BEMS incorporating WSNs has been given to achieve such a solution. Finally, a classification of BEMS has also been presented.

Future work includes the implementation of the proposed architecture and its extended testing and comparison with existing architectures and approaches.

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