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An Emerging Technology for Improved Building Automation Control

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***Abstract*—Wireless Mesh technology has emerged as a new one for next-generation wireless networking to provide a wide variety of applications that cannot be supported directly by other wireless networks. With the recent emergence of standards, wireless solutions are ready to be deployed in building automation networks. For both new and old structures, wireless networking is expected to improve the existing applications and open up new ones. Wireless Mesh Networks (WMNs) deployed in building automation systems is at an early stage; however, as more and more building functions and applications are controlled electronically and wirelessly, the use of WMNs will offer distinctive advantages in the field of commercial and residential buildings. This paper surveys the developments and applications of WMNs in building automation and control systems and sketches the contours of the directions to achieve our goal towards highly energy-efficient buildings while maintaining a healthy, productive, and safe indoor environment.**

***Keywords*—**Wireless Mesh Networks, Wireless Sensors, Sensor network, Building Automation Control

I. Introduction

A Building Automation System (BAS) is an example of a distributed control system. It describes the functionality provided by the building control system, which is a computerized, intelligent network of electronic devices, designed to monitor and control the mechanical and lighting systems in a building. BAS core functionality keeps the building climate within a specified range, provides lighting control based on an occupancy schedule, monitors system performance and device failures and provides email and/or text notifications to building engineering staffs. The BAS functionality reduces building energy and maintenance costs when compared to a non-controlled building [1]. Based on gathered data about how the building energy is used, intelligent buildings can make decisions on how to control their corresponding subsystems such as lighting, temperature, security, and even window shades system.

Hardwired networking has been used in building automation for many years and proven to be reliable [2]. The advantage of wired network equipment has greatly expanded the small business and residential market. Network components are readily available at commodity prices. Configuration is easier than ever and numerous web sites and consulting services are available to help install and manage them. However, hardwired networks are expensive to install, especially in retrofit situation, and create a rather inflexible design.

Wireless network has been attracting much more attention for the last few years. Dramatic progress in a low-cost high-performance radio frequency (RF) power sensor and Micro-Electro-Mechanical Systems have made many valuable potential applications [3, 4]. Recent advances in both sensor hardware, such as Motes from Crossbow [5] and software, such as TinyOS [6], have enabled the growth of real sensor network applications. With recent advances in technology and decline in cost, as well as the emergence of standards, wireless solutions are ready to be deployed in building automation networks [7, 8]. They bring a number of new flexibility to building automation control. Wireless networks support wireless communications for field devices such as room or zone controllers and associated room temperature sensors, variable frequency drives, electrical meters, and point modules at prominent commercial and industrial facilities, schools, hospitals, universities, government facilities and military bases. The cost of wiring alone is incentive enough for many building owners to look at wireless control systems, since wireless installations can be done anywhere, at any time, and saving from 20% to 80% of the installation cost of controls [9]. Instead of placing controls where wiring permits, building owners are free to place controls where building performance needs to be improved. With careful planning, a wireless control system can be used for lighting and HVAC while monitoring fire and security. This could have a major impact on energy efficiency, reducing wasted lighting and heating expenditure by 50 percent in many cases [10]. For retrofit or new construction, wireless connectivity can save wiring and enhance system performance with several systems connected to the same wireless backbone. Future changes such as moving walls and office floor plan changes are made easier. Therefore, engineering, construction, commissioning and operating cost over the entire life of the building should be dramatically reduced. The benefits for facility managers who are pressed by

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budget constraints are unbeatable. Through remote control, building operators and maintenance personnel can track building operations wherever they are. Ultimately, the decision for building automation control is about which option makes economic sense while meeting all the service requirements. Wireless technologies enable wireless mobility for building occupants, and bridge several networks to communicate over one network.

The wireless mesh networks (WMNs) have been an emerging technology in the recent years in the field of wireless technology. WMNs are based on the IEEE mesh standard of networking. They are self-forming, self-configuring and self-healing [11]. WMNs are an attractive communication paradigm to building because of their low cost and relative ease of deployment. They can be installed with minimal expertise and system administration. These networks typically consist of many base stations (BSs), some of which are directly connected to the Internet [7]. WMNs reduce life-cycle maintenance costs, and can be integrated gradually and seamlessly with the existing standards-based wired networks. Moreover, the gateway/bridge functionalities in mesh routers enable the integration of WMNs with various existing wireless networks such as cellular, wireless sensor, wireless-fidelity (WiFi) [12], worldwide inter-operability for microwave access (WiMAX) [13], WiMedia [14] networks. Consequently, through integrated WMNs, users of the existing networks can be provided with otherwise impossible services of these networks.

The remainder of the paper is organized as follows. In Section 2, we present some existing network problems within building automation control. Technical issues of WMNs in building automation control are summarized in Section 3. In Section 4, some applications of WMNs for building automation control are addressed. Challenges and future research issues influencing building automation design are investigated in Section 5. Finally, a conclusion is drawn in Section 6.

II. EXISTING NETWORK PROBLEMS IN BUILDINGS AUTOMATION CONTROL

Hardwires and cables are commonly used in every commercial, industrial, and residential property. Although this kind of controllable networks is very expensive due to the complexity in its deployment and maintenance, hardwired networks have not achieved satisfactory performance for BAS network design. In contrast, wireless networking systems are generating good opportunities in an array of applications [15]. They would be more convenient and efficient, less dangerous and less costly as opposed to a wired networked sensing solution. However, the widespread implementation of wireless technologies, to date, has been constrained by building occupant concerns.

A. Network Coverage

Wireless coverage is complex and often uncontrollable within buildings. In comparison to outdoor line-of-sight transmission where the received signal power drops off in proportional to the square of the path distance, indoor RF signal propagation condition is much harsher and more dynamic [7]. In many commercial and residential buildings, networks cannot conveniently reach all of the areas where service needed. Many dead zones within buildings are found without service coverage [16]. Stringing network cables to some rooms is impractical. Even with wireless networks, some places, such as corner bedrooms, a study, or a porch cannot be reached by WiFi radio signals. Solutions like installation of multiple access points are expensive and inconvenient because Ethernet wiring from access points to wireless backbone is sometimes difficult to implement [17]. Communications between end nodes through two different access points have to go all the way back to the access hub. This is not an efficient solution, especially for broadband networking.

B. Bandwidth issue

Building automation controllers typically operate in the range of tens to hundreds of Kilobits per second (Kbps) [7]. However, more bandwidth is needed due to various service requirements, such as data transmission, voice/video communications and entertainment. Wireless network that can provide sufficient bandwidth and Quality of Service (QoS) are required for all building applications.

C. Energy-efficient network

Energy efficiency has been a major topic of discussion in the history of Wireless Sensor Networks (WSNs) for quite a long time [18]. Sensors and actuators have to be as energy-efficient as possible because they are battery-driven. Other benefits of controlling the energy usage include the increase in capacity due to the spatial reuse [19] and reduction of node-to-node interferences during communication. Although several contributions have been tailored towards studying power control problems in energy-constrained conventional IEEE 802.11 wireless network standards [20], little attention has been drawn to the power control problems in WMNs. This is mainly because the backbone wireless mesh routers are static and have usually been assumed [11] to have electrical main power supply, and hence, are purported not to have power constraints. However, networks are sometimes deployed in campuses across multiple buildings. Some between-building nodes may not have access to AC power and must operate for years on batteries. The mesh nodes have thus to rely on exhaustible energy supply, e.g., battery, or renewable means of energy supply, e.g., solar or wind. Furthermore, the mesh client, such as RFID (radio frequency identification) reader, BACnet (building automation and control networks) controller etc., is power-constrained [11].

D. Network cross-function issue

Another practical barrier is that the systems are not cross-functional. A controller designed for HVAC is not typically designed to do anything with data from a lighting control system. If there were a third system that could take data from both, it could use it to gain efficiencies, improve comfort, and increase security. Ideally, there are thousands of nodes in high-performance automated buildings. That means in every corner of a building, valuable data is being gathered. Unfortunately, those systems and their data remain substantially isolated. Sharing data and intelligence among systems creates a larger intelligent control system. Meanwhile, these systems can solve larger, more complex problems. Consider the dilemma of HVAC energy waste with operable windows. If the HVAC control system network can connect to the security system, cooling an open room can be avoided.

III. WMNS IN BUILDING AUTOMATION CONTROL

The never ending quest for better service in a wireless environment has led to the emergence of WMNs [21]. They use distributed intelligence to communicate with all other devices within their range. Not only can all nodes send and receive messages, but they also function as routers and can relay messages for their neighbors. Through this relaying process, a packet of wireless data finds its way to its ultimate destination, passing through whatever intermediate nodes are available.

A. WMNs

The general architecture of WMNs is composed of three distinct wireless network elements [22-24]: a Network Gateway (a mesh router with gateway/bridge functionalities), Access Points (mesh routers) and mobile or stationary nodes (mesh clients). In those networks, each node acts not only as a client but also as a router. The WMNs architecture can be classified into three main groups [11]: Infrastructure/BackBone WMNs, Client WMNs and Hybrid WMNs. In Infrastructure/BackBone WMNs, mesh routers form an infrastructure for clients. In Client WMNs, all client nodes constitute the actual network to perform routing and configuration functionalities. Hybrid one is the combination of the former two. Mesh clients can perform mesh functions with other ones as well as access the network.

In WMNs, each node operates both as a host and router. The nodes in them automatically establish an Ad Hoc network and maintain mesh connectivity. Nodes are dynamically self-organized and self-configured. Unlike WiFi hotspots, which need a direct connection to the Internet, mesh networks pass a data request until a network connection is found. Each node can communicate directly with one or more peer nodes and automatically establish and maintain mesh connectivity among other nodes. Mesh node operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. This differs from traditional wireless networks (e.g. 802.11 WLANs) requiring centralized access points to mediate the wireless connection. In those wireless networks, more access points (APs) are required to provide a service over a larger area. This is not a cost-effective solution. Therefore, WMNs are honored as an effective solution to the above question [25].

B. Major wireless protocol standards

1) ZigBee

ZigBee is based on IEEE 802.15.4 standard, which is a Wireless Personal Area Network (WPAN). The ZigBee 1.0 specification was ratified on December 2004. And the first ZigBee Application Profile, Home Automation, was announced in November 2007. ZigBee targets on three major markets: residential properties, commercial buildings, and industrial facilities. Four of the five top vendors of building automation systems, Johnson Controls, Siemens, TAC, and Trane, introduced wireless products based on ZigBee in the past years, and Honeywell as the fifth is moving toward doing so. Over the next five years, up to 20% of commercial building automation system field equipment may "go wireless," seeking the lower cost, better control, and greater flexibility that such systems deliver. ZigBee is intended for those purposes. It is a low-cost, low-power, wireless mesh networking standard. The low cost allows the technology to be widely deployed in wireless control and monitoring applications; the low power-usage allows longer life with smaller batteries; and the mesh networking provides high reliability and larger range. ZigBee will likely emerge as the dominant wireless mesh networking technology. It operates in the industrial, scientific and medical radio bands; 868 MHz in Europe, 915 MHz in countries such as USA and Australia, and 2.4 GHz in most jurisdictions worldwide. ZigBee is simpler and less expensive than other WPANs such as Bluetooth. It is evolving to become a global sensor network standard. The following features are provided by ZigBee [26]:

- Low power consumption, with battery life ranging from months to years. ZigBee devices allow batteries to last up to years using primary cells. Redundancy of network devices leads to low maintenance cost.
- Maximum data rates allowed for each of the frequency bands are fixed as 250 kbps at 2.4 GHz, 40 kbps at 915MHz, and 20 kbps at 868 MHz.
- High throughput and low latency for low duty-cycle applications (<0.1%).
- Channel access using Carrier Sense Multiple Access with Collision Avoidance (CSMA - CA).
- Addressing space of up to 64 bit IEEE address devices, 65,535 networks.
- 70-100m range.
- Low cost to the uses in terms of device, installation and maintenance.
- High density of nodes per network: ZigBee's use of the IEEE 802.15.4 PHY and MAC allows networks to handle any number of devices. This attribute is critical for massive sensor arrays and control networks.
- Fully reliable "hand-shaked" data transfer protocol.

2) Bluetooth

The smallest-scale network is a personal area network (PAN), which allows devices to communicate with each other over short distances. Bluetooth is the best example of a PAN. Bluetooth is an open standard specification for an RF-based, short-range connectivity technology that has changed the face of computing and wireless communication. It is designed to be an inexpensive, wireless networking system for all classes of portable devices, such as laptops, PDAs, and mobile phones. It also enables wireless connections for desktop computers, making connections between monitors, printers, keyboards, and the CPU cable-free.

In comparison with Bluetooth and ZigBee, they have much in common. Both are types of IEEE 802.15 WPANs. Both run in the 2.4-GHz unlicensed frequency band, and both use small form factors and low power. However, they have their own characteristics. In intelligent building control systems, ZigBee is focused on control and automation, while Bluetooth is focused on connectivity between laptops and PDA's. ZigBee uses low data rate, low power consumption, and works with small packet devices; Bluetooth uses a higher data rate, higher power consumption, and works with large packet devices. ZigBee networks can support a larger number of devices and a longer range between devices than Bluetooth does. Because of these differences, the technologies are not only geared toward different applications, they do not have the capability to extend out to other applications. As an example, for its applications, Bluetooth must rely on fairly frequent battery recharging, while the whole goal of ZigBee is for a user to be able to put a couple of batteries in the devices and forget about them for months to years. In timing critical applications, ZigBee is designed to respond quickly, while Bluetooth takes much longer and could be detrimental to the application.

Therefore, WMNs can be well supported by ZigBee [27]. The reverse is ZigBee technology is adopted as the mainly wireless communication approach and uses the self-organizing WMNs for data transmission medium. Mesh networking has profound implications for building owners. If existing BACnet access points are replaced by mesh routers, the deployment cost can be significantly reduced [11]. WMNs can make building automation easier and more efficient by combining lighting, HVAC, security, safety systems, and other monitoring networks into a single platform.

IV. Advantages and Applications of Wireless Mesh Sensor Networking in building automation

A. *Advantages of WMNs for Building Applications*

The innovative WMN platform allows building automation manufacturers to offer new solutions that provide excellent reliability, power-efficiency, adaptability, and scalability. Low-profile mesh modules can be easily embedded and integrated with the existing sensing devices throughout a building to form seamless networks [5].

1) Faster Retrofitting

One of the major causes of cost overruns and time-delays in retrofitting office space arises from the labor-intensive movement of utility wiring to conform to new wall configurations. Using WMNs, property owners can relocate thermostats and other sensors quickly and conveniently without intrusive, disruptive, and costly rewiring efforts.

2) Simplified maintenance

WMNs are easy to maintain. Low maintenance costs are a key concern. The self configuring and self healing capabilities of mesh networking combined with its low power usage provide a very affordable solution. Maintenance personnel can use a laptop or handheld diagnostic device to communicate and perform diagnostics without running wires [28]. This is a significant advantage in cases where controllers are inside storage tanks, on top of towers, or in other hard-to-reach locations.

3) Reduced life-cycle costs

Installation cost saving is enough to justify the use of wireless controllers [9]. Additionally, wireless networks continue to generate savings throughout their life-cycle because they are easy to maintain, move, or replace. Low installation cost, ease of reconfiguration, and low maintenance requirements result in a system with life cycle costs that are significantly less than traditional wired installations.

4) Seamless upgrades, transitions

With the ZigBee Alliance [29] and the ASHRAE BACnet Committee [30] now coordinating their efforts and industry leaders delivering open products, the transition to a wireless solution is not an all-or-nothing proposition. WMNs can be phased in easily - one room, area, floor, or building at a time. A building undergoing floor plan or other changes is an ideal opportunity to install wireless controllers.

5) Flexibility

Free from wiring and all the associated problems and cost, building owners can place wireless controllers virtually anywhere. Instead of hiring wiring architects and teams of technicians, then phasing installation over a period of weeks or months, one person can walk around the building, placing controllers wherever needed. Instead of placing controllers where they are easy to wire, controllers can be placed where they are actually needed to optimize building performance, and keep up with floor plan changes. WMNs provide easily reconfigurable systems to create adaptable workspaces or less intrusively retrofit the existing infrastructures while saving time and money.

B. *WMNs in Building Applications*

1) Siemens APOGEE

Siemens Building Technologies was among the first to answer the question of building owners about the application of WMNs in building [31]. The solution, APOGEE Wireless, employs ZigBee network, and enables Siemens to deliver cost-saving energy efficiency while optimizes the comfort level. Siemens has incorporated reliable, redundant mesh networking technology to ensure its new wireless room temperature sensors to be immune to signal interruption. It uses new routing algorithms that are more reliable and versatile than older wireless technologies. Since mesh networks are self-forming, devices can automatically figure themselves into the network and establish communications with as many other devices as possible. This way messages can travel multiple redundant paths, insuring that messages and control commands arrive reliably at their destination. With the mesh network structure, a single device failure does not necessarily cause other devices to go offline. For many applications, wireless devices are easily installed, reconfigured and expanded than traditional hard wire networks.

2) HomeMesh

Due to the limitation of current WiFi coverage (most of the time within several tens of meters), He *et al.* [32] study and prototype a simple and low-cost mesh network for the home environment. In HomeMesh, the algorithm is adaptive to network dynamics and changes due to continuous message exchanges within a mesh router. HomeMesh consists of APs, mesh routers, and clients. The mesh routers can self-configure to form a backbone connecting to the Internet. They provide wireless access to their clients.

In HomeMesh, however, only the WiFi coverage in building is extended. Building occupants still need a network that can seamlessly connect other networks used in building such as wireless LANs (WLANs). Furthermore, because of contention and interference, the channel assignment algorithm is embedded in HomeMesh. While, in fact, a single–channel assignment change can lead to a series of channel changes cascading through the entire network. Under current circumstance, the channel switching cost is actually significant in WMNs [33]. To resolve the above networking issues, a communication network with mesh nodes is expected to be built to make the network more flexible, robust simple and cost-effective.

V. CHALLENGES AND FUTURE RESEARCH ISSUES OF WMNS IN BUILDING APPLICATION

Building owners have a list of issues to deal with today. They want to provide potential tenants the latest technologies. Especially for building owners of historically significant structures, they want to offer the same capabilities as new buildings but without destroying historical architecture. And lately, more and more building owners want to "go green" and use energy more efficiently [29]. Building control systems must meet a higher standard, and there is no room for controllers that are constantly going offline as network connections fade or break down. The ideal building automation network should be able to serve IEEE 802.11 devices and be scalable to support a number of devices deployed in buildings. Under such circumstance, heterogeneous technologies have to be combined into an appropriate networking solution. WMNs should be seamlessly connected with other existing building networks. For buildings equipped with wired backbone, future wireless network should connect them smoothly. To date, several companies have already realized the potential of WMNs in building automation design and many research issues are waiting to be solved.

A. Network Topology

There is no networking technology that can fulfill all building requirements simultaneously. Different networks are being aggregated on a building automation bus system, such as EIB (European Installation Bus) or KNX (Konnex), Local LON (Local Operating Networking) [35] and BACnet [36]. Heterogeneous technologies are expected to be combined into appropriate networking solutions. Wireless building automation solutions promise to revolutionize home and commercial building management. Fast deployment, increased building efficiency and optimal occupant comfort and convenience have top priorities. Wireless building automation should have the ability to support people and/or device mobility, easy building reconfiguration, data, voice and video applications and emerging indoor location-based services.

B. Multipath Interference

Radio frequencies, used by WMNs, are subject to interference from each other. A challenge of wireless deployment that has remained pervasive over the past fifteen years is interference. WiFi and mesh networks operate in the unlicensed bands and have no particular claim to the spectrum they use. They must share frequencies not just with other wireless LANs but with a broad range of products, from cordless phones to microwave ovens to wireless video surveillance cameras. In addition, physical objects, like buildings, pose major problems for wireless transmissions. Interference introduces complex interdependencies. For instance, how much a node can safely send packets depends on how much other nodes are sending and vice verse. The development of measurement science that can be used to measure the WMN interference in building is challenging due to the variability in both building types and application requirements.

C. Robustness

As more and more building functions are controlled electronically, it is imperative that they work in ways users expect, address both random and deliberate interference issues, and withstand the rigors of daily use. Failure of an automation system is almost as severe as power loss, perhaps even rendering the building unusable until the problem is resolved. When WMNs are used, multiple backhaul access modems can be shared by all nodes in the entire network, and thus improve its robustness and resource utilization. WMNs can grow easily as the enterprise expands.

D. Openness

All of the system upgrades is impossible if the right tools and personnel are not in place to monitor and manage the systems and keep the building's performance in an optimal state. This is where open systems are especially important so that building system data, facility management systems and the business or property management software platforms can be fully integrated to provide actionable information on the building's performance. Installing a BAS is a long-term investment. No one wants to be locked into a single vendor over decades. Open standards assure healthy competition and compatibility among multiple players, thereby reducing the risk of obsolete or orphaned equipment.

E. Network Security

Building privacy and security in the initial building automation networks design should ensure that all necessary or required controls exist to protect access to and dissemination of personal information over the entire WMNs. WMNs must be able to protect them from attack. If attackers gain unauthorized access to a building automation sensor network, they are able to compromise building integrity perhaps even jeopardize life and property. The WMNs must be able to determine the trustworthiness of control requests, and reject unauthorized commands [37].

F. Battery

The devices of a building automation system are dispersed over a large area. Due to the high node count in the WMNs, changing or charging the batteries of each wireless sensor every few days makes WMN solutions infeasible. Battery lifetimes have to achieve at least several months. It would certainly be better if it achieves several years. Communication protocol design is of leading importance. It has to maximize the sleep time of each sensor as well as minimize the time it has to be in a "listening" status.

G. Scalability issue

WMNs deployed in commercial buildings must be able to scale up to hundreds of nodes. The network should be able to connect with IEEE 802.11 devices and it should be scalable to support a number of other devices that can be found in a large building.

H. Responsiveness to unique building layout characteristics

Each building has a unique set of characteristics and requirements to determine the placement of the sensor network modules. For example, a building might require that mesh nodes be installed only in public/shared space, or elevator shafts must be used for between-floor routing, or special equipment may create RF interference in an area of a building. A highly responsive topology discovery method is not available to enable these unique requirements to be addressed.

I. Development of Testbed for WMNs in Buildings

Advanced sensor technologies promise to enable the deployment of a large number of sensors in and around buildings to better measure the in-situ performance of building systems, to diagnose any construction or operational defects that waster energy, and to provide feedback to occupants on net energy consumption. The development of measurement science that can be used to assess the performance and reliability of WMNs in buildings is extremely challenging due to the variability in both building types and application requirements. No testbed is ready to use to evaluate the performance of wireless sensor systems in building.

As WMNs continues to advance, new applications will emerge. They will help expand the ability of building owners to manage and control their buildings for both performance and savings.

VI. CONCLUSION

WMNs are recognized as a cost-effective and flexible solution for building automation and control. They can dramatically reduce installation costs, and produce savings through simplified maintenance as well as improve building performance. Wireless Mesh technology promises to make building automation as common as wired networks. Sensors and actuators should be as energy-efficient as possible since they are battery-driven. WMNs should provide enough data to maintain building performance. Further research and development is needed to fulfill this vision.

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