

Building Automation Systems Using Wireless Sensor Networks: Radio Characteristics and Energy Efficient Communication Protocols

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ABSTRACT: Building automation systems (BAS) are typically used to monitor and control heating, ventilation, and air conditioning (HVAC) systems, manage building facilities (e.g., lighting, safety, and security), and automate meter reading. In recent years, the technology of wireless sensor network (WSN) has been attracting extensive research and development efforts to replace the traditional wired solutions for BAS. Key challenges of integrating WSN to a BAS include characterizing the radio features of BAS environments, and fulfilling the requirements of the extremely low energy consumption. In this survey paper, we first describe the radio characteristics of indoor environments, and then introduce the important medium access control (MAC) protocols developed for WSN which can be potentially used in BAS systems.

1 INTRODUCTION

Building automation systems (BAS) can be used in schools, hospitals, factories, offices and homes, to enhance the quality of building services and reduce the operation and maintenance costs [1]. Typical functionalities of BAS include the monitoring and controlling of the heating, ventilation, and air conditioning (HVAC) systems, the management of building facilities (such as lighting, safety and security), and the automation of meter reading.

While traditional BAS systems use wired technologies, most modern buildings do not allow solutions that require complex cabling installation. Wireless technologies, especially wireless sensor networks (WSN) due to its low cost and low power features, become natural candidates for modern advanced BAS systems [2], [3].

A WSN is a collection of nodes with sensing, computing and communication capabilities that continuously observe and collect information on the entities or phenomena of interest in the physical world [4], [5]. Initial research on sensor networks was driven by defense applications and can be dated back to the 1970s [6]. In these early sensor networks (e.g., a radar network used for air traffic control), the sensor nodes are usually large, expensive, and have unconstrained power supply.

Recent advances in MEMS technology, wireless networking and low-power processors have enabled the development of WSNs which typically consist of

diminutive, cheap, and usually battery-powered micro-sensors. Networked microsensor technology has been predicted to be one of the most important technologies for the 21st century, and it could revolutionize spatial information collection and drastically enhance our understanding of the physical environment [7]. Meanwhile, it also poses new technical challenges in energy efficiency, network control and routing, collaborative information processing, sensor management, network security, and other fields [8]. In response to the opportunities and challenges, there has recently been a surge in research interest in sensor networks. Many WSN research groups (e.g., Smart Dust [9], PicoRadio [10], and WiseNet [11]) have been established. Hardware and software products for WSNs manufactured by companies like Chipcon, Crossbow and Ember are now commercially available.

Outdoor environmental monitoring is considered as one of the principle application for WSN networks [13]. One of the earliest known civil applications of sensor networks is in ecological habitat monitoring. A team from University of California Berkeley used a WSN to observe birds on an island, using a base station connected over the web via a satellite communication link [14], [15], [16]. This kind of "unattended" monitoring minimizes disruption to the objects of study by an observer walking around the island to collect data. By contrast, the application of the WSN technology to indoor BAS

systems entails a set of new requirements, and also poses new challenges to wireless communications.

One of the main challenges for applying the technology of WSN to BAS systems, as in most other WSN applications, is the need for an unprecedented system lifetime. A deployed WSN-based BAS is targeted to operate autonomously for several months or even years. A typical sensor node is comprised of a few components such as one or more sensing units for measurement, a microprocessor and a small amount of memory for computing and data storage, and a short range radio for wireless communication. Each of these components consumes energy when a sensor node works. Apart from energy efficiency, other essential requirements of BAS are summarized in Table 1.

Table 1. Essential requirements for building automation network applications

Requirements	Description
Energy efficiency	Network operates at extremely low energy consumption levels
Reliability	Network ensures data delivery with low error rate
Latency	Data delivery with low delay
Scalability	Network is able to grow without excessive overheads
Mobility	Nodes are allowed to move
Safety & Privacy	Network needs to be immune to malicious attacks

Unlike the traditional wireless devices that are typically mains-powered or powered by rechargeable batteries, low-cost and disposable WSN sensor nodes are constrained by limited on-board batteries that usually cannot be replaced or recharged. As a result, it is necessary to minimize energy consumption at all levels of a WSN system. In recent years, tremendous research efforts have been devoted to the area of low-power design for WSNs. It is recognized that medium access control (MAC) protocols play a crucial role in meeting the stringent requirement of energy consumption in sensor networks [11].

In this paper, we first characterize radio communication in a BAS environment, and then give a survey of the energy efficient MAC protocols that could be potentially employed in BAS systems. The remainder of the paper is structured as follows. In Section 2, we describe the requirements of BAS and the features of wireless communication in BAS. In Section 3, we review the important MAC protocols which are recently developed for sensor networks, and categorize the MAC protocol into fixed allocation protocols, random access protocols and hybrid

TDMA/CSMA protocols. Finally, Section 4 concludes the paper.

2 CHARACTERIZING WIRELESS COMMUNICATIONS IN BAS ENVIRONMENT

2.1 Link quality and partition loss

In general, the weather inside buildings is predictable; however, there are many factors, which cause multi-path interference in the indoor environments. Experimental studies of link quality in indoor environments using WSN have been performed [12], [17], [18]. There is no realistic model to show how data reception rate varies with the distance. This combines both radio propagation model and radio reception model. It is clear that data from high power transmitters can be successfully received even with simultaneous traffic [12]. However, energy cost for radio transmissions, receptions and idle listening is quite significant.

It is well-known that, if we consider a contour formed by reception at different locations from same transmitter is not regular. The quality of the transmission link distributions with and without power control strongly depends on environment and individual hardware differences [12]. For example, indoor office environment show poor link quality distribution than free outdoor settings. Swapping transmitter and receiver at same location can change the link quality.

There are three regions of link quality [12]: (i) connected region- high data reception rate (>99 %), (ii) transitional region - data reception rate is vary, referred to as a gray area and (iii) disconnected region - very low data reception rate. In (i), data reception rate is highly reliable over the time and region (ii), there can be very good link quality although transmissions and receptions antennas (sensor node and the hub) are relatively far away as well as poor link quality, regardless of the relative proximity. In the transition region there also can be asymmetric radio links (high link quality in one direction and low link quality in other direction). There is high time variation in the link quality in the transition region. The width of the transitional region can be quite significant as a fraction of the connected area. Nevertheless, in free space this could be very less and office building environment this could be large due to many obstacles, such as, office furniture, room partitions and concrete/brick walls [19].

Halgamuge *et al.* [19], [20] recently performed experimental study to investigate link quality distribution in sensor network deployment for building

environment. This experiment will leverage queries in real sensor network and also will drive development of network architecture. This work investigated the link quality distribution to obtain full coverage of signal strength in a single floor of building environment, as well as multi story building, experimentally. Results confirmed the transitional region is particular concern in wireless sensor network since it accommodates high variance unreliable links. The reason due to this transitional region in inside building environment could be the obstacles including concrete/brick walls, partitions, office furniture and other items affect as additional absorption term to the path loss.

Table 2. Typical partition losses in BAS environment.

Partition type	Partition loss (dB)
Cloth partition	1.4
Double plasterboard wall	3.4
Foil Insulation	3.9
Concrete wall	13.0
Aluminum siding	20.4
All metal	26.0

Dielectric properties of different partition materials fluctuate widely and hence partition losses. Table 2 shows a few examples of partition losses measured at 900-1300 MHz [21]. Values for the partition loss at different frequencies for different partition types can be found in [22].

2.2 Indoor signal attenuation

Indoor settings are different broadly in the materials used for walls and floors, the arrangement of rooms, corridors, windows, and open areas, the location and obstructing objects, and the size of the room and the number of floors [21]. Altogether of these factors have a significant impact on path loss in an indoor environment. Thus, it is difficult to find standard models that can be perfectly applied to verify empirical path loss in a specific indoor setting. Indoor path loss models must accurately summarize the effects of attenuation across floors due to partitions, the same as among floors.

The experimental data for floor and partition loss can be added to an analytical or empirical dB path

$$P_r = P_t - P_L - \sum_{i=1}^{N_f} A_f - \sum_{i=1}^{N_p} A_p,$$

where P_t is the transmit power, P_L is path loss, A_f is floor attenuation factor and A_p is the partition attenuation factor. Number of floors and partition passed through by the signal is given by N_f and N_p , correspondingly.

Measurements specify that building penetration loss is a function of frequency, height, and the build-

ing materials [21]. Building penetration loss on the ground floor typically ranges from 8-20 dB for 900 MHz to 2 GHz [23], [24]. The penetration loss decreases slightly as frequency increases. It decreases by about 1.4 dB per floor at floors above the ground floor due to reduce of line-of-sight path. The style and number of windows in a building also have a considerable influence on penetration loss [25]. Further, measurements behind exterior walls have about 6 dB high penetration loss than behind interior windows [21].

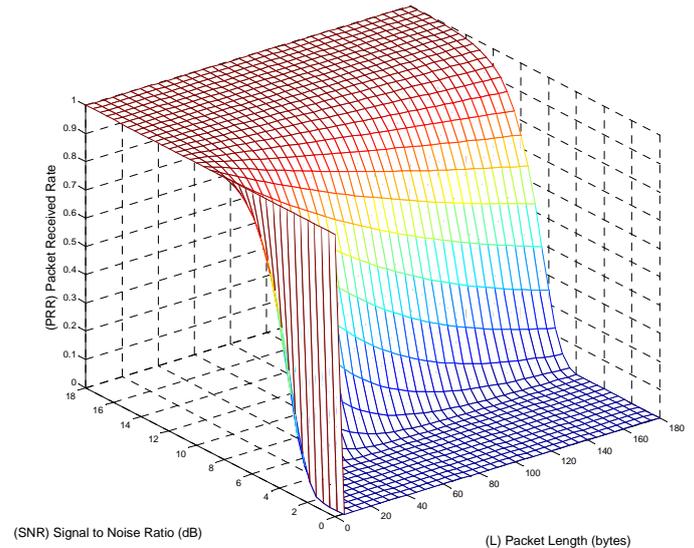


Figure 1 Packet reception rate as function of SNR and packet size.

In wireless communication, bit error rate (BER) is the ratio of number of incorrectly received bits to total number of bits sent during a given time period. Signal to noise ratio (SNR) is ratio of a signal power to noise power or background noise. Thus, higher the ratio is less obstructive the background noise. The bit error rate for specified communication radio is a function of received SNR. Packet reception rate (PRR) depends on frame size and the receiver SNR. As in [26] PRR is given by

$$PRR = \left(1 - \frac{1}{2} \exp\left(\frac{SNR}{1.28}\right) \right)^{8L}$$

where L is length of the packet in bytes. Figure 1 illustrates the PRR as function of SNR and frame size

3 ENERGY EFFICIENT PROTOCOLS FOR BAS SYSTEMS

The primary design goal of WSN MAC protocols is to meet the stringent requirement of energy effi-

ciency. Traditional performance metrics (e.g., throughput, delay and fairness) for data networks become secondary in WSNs and are usually traded for energy cost [27].

The major sources of energy waste in WSNs have been identified as idle listening, collisions, overhearing, protocol overhead and over-emitting [28], [29]. Idle listening refers to the listening performed by nodes for receiving possible traffic that is in fact not sent, and it would occur in many sensor network applications where traffic load is low. Packet collisions also deteriorate the energy efficiency of a WSN. When a transmitted packet is involved in a collision, it would be discarded and possibly retransmitted. Another source of energy waste is overhearing, which means that a node receives packets that are actually not destined for itself. Moreover, protocol overhead consumes energy when control packets are exchanged in the network. The last primary reason for energy waste is over-emitting, which occurs when a node sends a message but its intended receiving node is not ready. In the following, we briefly review the existing WSN protocols that use various strategies to eliminate or mitigate the aforementioned causes of energy waste.

3.1 Fixed allocation protocols

Collisions, idle listening and overhearing can be avoided by using fixed allocation schemes. In [30], Sohrabi *et al.* introduced a distributed protocol called self-organization medium access control for sensor networks (SMACS). This protocol enables nodes to discover their neighbors and build communication schedules without centralized control. Nodes transmit packets using time division multiple access (TDMA) schedules and randomly choose frequencies (or frequency hopping sequences) to allow concurrent transmissions.

Pei and Chien [31] proposed a power aware clustered TDMA (PACT) MAC protocol which uses passive clustering to rotate the duties of being the communication backbone nodes based on battery energy levels. In PACT, each frame consists of control mini-slots and data slots. In the beginning of a frame, every node turns on its radio to confirm the allocation of the TDMA data slots by exchanging control packets in the control mini-slots. It then shuts down the radio during the slots where it does not transmit or receive packets.

Some other TDMA-based MAC protocols for WSNs can be found in [32], [33], [34]. These protocols are inherently free of collision and idle-listening, but they suffer from increased protocol overhead, packet delay and system complexity. In

addition, it is inefficient to use static slot assignments in dynamic network environments where the number of active nodes is constantly varying.

3.2 Random access protocols

In a random access MAC protocol, backlogged nodes contend for the medium to transmit packets, and thus it is more flexible and requires less central control compared to a fixed allocation scheme.

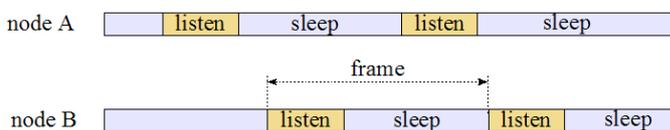


Figure 2 S-MAC duty cycle.

Ye *et al.* [28] proposed Sensor MAC (S-MAC), which uses carrier sense multiple access with collision avoidance (CSMA-CA) for channel access. As depicted in Figure 2, S-MAC operates using low duty cycles, and each node chooses a sleep schedule and shares it with its neighbors before a listen-sleep cycle starts. Nodes that have common sleep schedules form virtual clusters to reduce control overhead. In S-MAC, nodes only stay awake if involved in communication tasks. To reduce delay, S-MAC uses a technique called adaptive listening, in which a node who overhears its neighbor's transmission will wake up for a short period at the end of the transmission in case it is the next hop for the packet. S-MAC also introduces a message-passing technique, in which long messages are fragmented into many small fragments and transmitted in a burst, and only RTS/CTS exchange is used. The length of time period to transmit all the fragments and their ACK packets is included in the duration field of RTS/CTS packets. Nodes that hear these RTS/CTS packets will go to sleep until the transmission is finished.

One of the challenges of using S-MAC in a real sensor network is to appropriately determine a sleep schedule, especially under varying traffic loads. The timeout MAC (T-MAC) was introduced by van Dam and Langendoen [35] to adaptively choose a duty cycle. In T-MAC, if a node does not detect any activation event for an empirically determined time threshold T_A , it assumes that no neighboring nodes want to communicate with it, and goes to sleep.

When a node overhears an RTS/CTS message indicating that other nodes will commence transmitting, it temporarily turns off its radio. The node wakes up again at the end of the transmission and starts a new time-out.

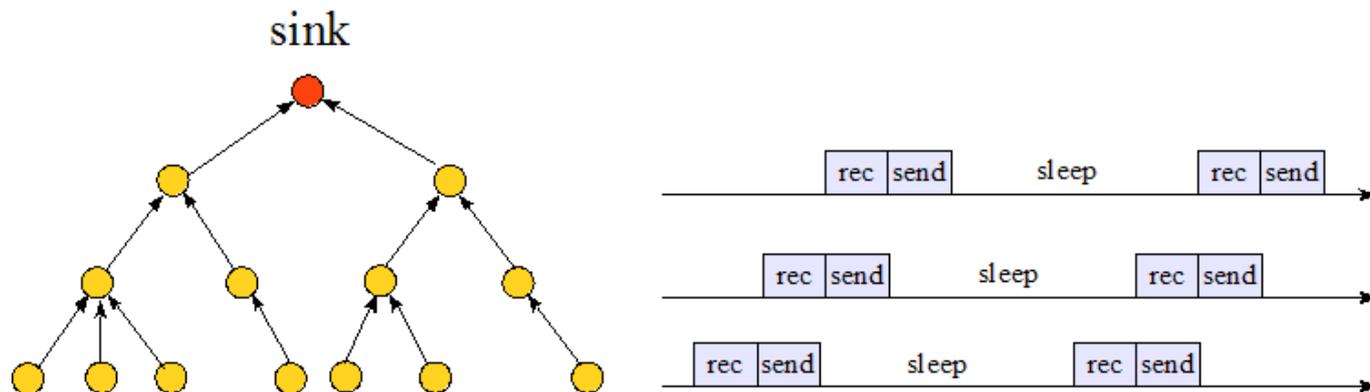


Figure 4 DMAC in data gathering tree.

The advantage of T-MAC is that it dynamically adjusts itself to network traffic fluctuations. However, the aggressive turn-to-sleep policy may cause an early sleep phenomenon where a node goes to sleep when a neighbor node still has messages for it.

Lin *et al.* [36] proposed a dynamic sensor-MAC (DSMAC) by adjusting duty cycles with varying traffic conditions to achieve a good trade-off between energy consumption and packet delay. In DSMAC, all nodes use a common basic service duty cycle at the beginning. When a node sends a packet, the one-hop delay of the packet (the time difference between the arrival of a packet and its departure) is piggybacked. If the receiver node notices that the packet delay is intolerable, it makes a decision to double the duty cycle by reducing the length of sleep period. In the synchronization period of the next cycle, the new duty cycle is announced, and a node will adopt it only if its queue is non-empty and the battery level is above a certain threshold.

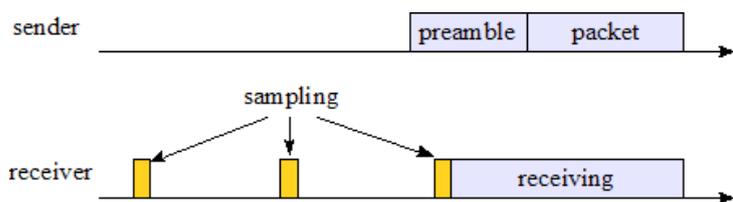


Figure 3 Preamble sampling technique.

In [37], Polastre *et al.* introduced a CSMA-based protocol called Berkeley MAC (B-MAC) which provides configurable interfaces of system services for performance optimization. In B-MAC, clear channel assessment is performed by using a weighted moving average of samples for effective collision avoidance. Instead of using exponential backoffs, B-MAC includes a configurable linear backoff mechanism to minimize packet delay. Furthermore, an adaptive low power listening technique is employed to reduce duty cycles and minimize idle listening.

El-Hoiydi *et al.* [38] developed the wireless sensor MAC (WiseMAC) protocol that uses a preamble sampling technique. Preamble sampling is based on a carrier sense technique that effectively shifts the energy cost from the receiver to the senders. As illustrated in Figure 3, a sender node transmits a wake-up preamble followed by the backlogged message. In WiseMAC, all nodes in the network perform channel sampling periodically with independent sampling offsets. If the channel is detected busy, it continues to listen and receives data. To reduce the energy caused by unnecessarily long preambles, the authors introduced a scheme where sampling schedules are shared among direct neighbors by piggybacking schedules into acknowledgement frames. Consequently, a sender node can transmit a minimized wake-up preamble just before the sampling moment of the intended receiver to minimize energy consumption.

Lu *et al.* [39] designed the data gathering MAC (DMAC) protocol to achieve very low packet delay without compromising energy efficiency. As shown in Figure 4, a hierarchical node-to-sink data gathering tree is formed in DMAC. The protocol operates using a low duty cycle, and each cycle is divided into receiving, sending and sleep periods. The main design feature of DMAC is that it uses a staggered wake-up schedule such that packets can be transmitted continuously from nodes to sink along a multihop path (see Figure 4). In a receiving state, a node receives packets from its leaf nodes which contend for the medium based on a CSMA protocol.

Despite the flexibility and low protocol overhead, random access MAC protocols may suffer from collisions, idle listening, and long packet delay under high contention levels.

3.3 Hybrid TDMA/CSMA protocols

A few hybrid MAC protocols that combine the strengths of TDMA and random access have been proposed. Rajendran [40] developed the traffic-

adaptive MAC (TRAMA) protocol for energy-efficient and collision-free channel access in WSNs. In TRAMA, time is divided into random access and scheduled access periods, as depicted in Figure 5. In the random access period, nodes transmit signaling packets, establish two-hop topology information among neighboring nodes, and exchange transmission schedules. As a result, backlogged nodes are allocated dedicated slots in the scheduled access periods for data transmission.

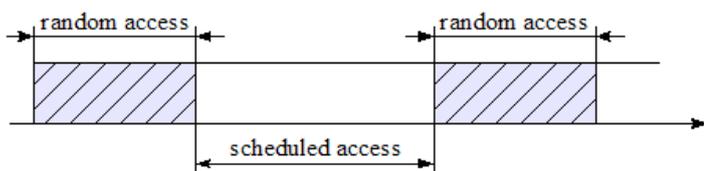


Figure 5 Slot organization in TRAMA.

In [41], Rhee *et al.* introduced a hybrid MAC protocol, called zebra MAC (Z-MAC), which operates adaptively to the contention level of the network. In Z-MAC, a time slot is assigned to an owner node of the slot, and the other nodes that can also use the slot are called non-owners of the slot. Unlike fixed slot assignment in TDMA, CSMA-based random access is used for data transmission in Z-MAC. The owner node of a slot has the priority to access the slot by using a smaller initial contention window than those of the non-owner nodes. When the contention level is high, the owner nodes have prioritized channel access to their slots to avoid collisions so that Z-MAC behaves like TDMA. Under low contention, however, the protocol operates like CSMA because the owner node of a slot may not have data to transmit and the non-owner nodes can contend for the use of the slot. In this way, the Z-MAC protocol is able to dynamically switch between TDMA and CSMA depending on the traffic load.

The MAC of the IEEE 802.15.4 standard [42] also uses hybrid TDMA/CSMA protocols. In an IEEE 802.15.4 network, one node is appointed as the central controller (CC). In the beacon-enabled mode of the standard, a beacon frame is broadcast by the CC for maintaining network synchronization. Such a network operates with a super frame structure, which may consist of active and inactive portions, as depicted in 6. Time is divided into consecutive time intervals called beacon intervals (BI). At the beginning of a BI, the nodes simultaneously wake up and the coordinator broadcasts a message called the beacon frame (BF) to the nodes. The BF includes, among other things, the next wake-up time, which is used to establish network synchronization.

The BF is immediately followed by the contention access period (CAP), in which backlogged nodes

can contend for the medium using a CSMA-CA mechanism. The super frame duration (SD), which denotes the active portion of the super frame, may consist of a BF, a CAP and a contention free period (CFP). If a node is allowed to transmit in the CFP, it will be allocated guaranteed transmission slots and can transmit without contention in a TDMA fashion.

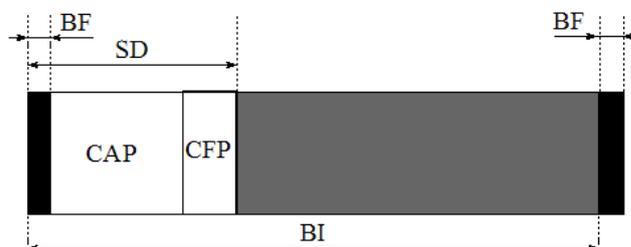


Figure 6 IEEE 802.15.4 Superframe structure. The gray area represents inactive duration of time.

3.4 Other protocols

Some other WSN MAC protocols that use distinct energy saving techniques from the aforementioned protocols were also proposed. In [43], Schurgers *et al.* developed the sparse topology and energy management (STEM) protocol, in which a low-power secondary paging channel is used for transmitting wake-up signals. Upon receiving a wake-up signal, a node turns on its primary radio for data transmission. The authors show that the protocol is especially suitable for networks having sporadic traffic.

Tay *et al.* [44] proposed a CSMA/p* protocol that uses optimal channel access probabilities for CSMA to minimize the probability of collision. The same authors empirically chose a non-uniform probability distribution for channel access and developed the Sift protocol that is a suboptimal version of CSMA/p* in the case of unknown network size [45].

4 CONCLUSIONS

Integrating the technology of WSN into BAS systems can bring many advantages such as reducing installation and maintenance costs. However, to fulfill the design requirements, the unique wireless environment to which a BAS is applied needs to be carefully taken into account. Furthermore, the energy efficiency of BAS systems needs to be achieved by choosing an appropriate technology. In this paper, we have investigated the key characteristics of wireless communication in BAS, including link quality and partition losses, and indoor signal attenuation. We then presented a review on the existing energy efficient MAC layer protocols, which can be potentially used for BAS systems.

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