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Development of Energy Aware TDMA-Based MAC Protocol for Wireless Sensor Network System

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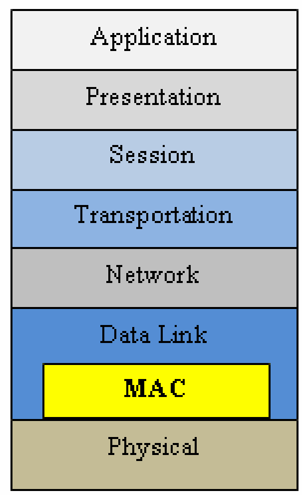
Abstract

The development of wireless sensor networks (WSN) can be motivated by several types of applications such as habitat monitoring, smart healthcare system, building automation, and etc. These applications however, demand an energy-efficient WSN that can prolong the network lifetime and can provide high throughput, low latency and delay, and high packet received rate data communication. The ability of wireless network structure to minimize network lifetime is among the hot topic due to limitation resources such as energy, processing and memory, in sensor network architecture itself. This paper proposes a novel approach that tries to reduce idle energy consumption by implementing active-sleep algorithm named energy aware A-MAC protocol. The result from the computational model shows that the algorithm can prolong network lifetime due to efficiency in energy consumption from time slot management.

1. Introduction

Designing wireless sensor networks with the capability of prolonging network lifetime catch the attention of many researchers in wireless network field. Contrasts with Mobile Ad Hoc Network system (MANET), Wireless Sensor Networks (WSN) designs focused more on survivability of each node in the network instead of maximizing data throughput or minimizing end-to-end delay. In this paper, we will study part of data link layer in Open Systems Interconnection (OSI) model, called medium access control (MAC) layer, which sits on top of physical layer as shown in Fig. 1 below. Since the MAC layer controls the physical (radio), it has a large impact on the overall energy consumption, and hence, the lifetime of a node.

Figure 1: OSI basic reference model

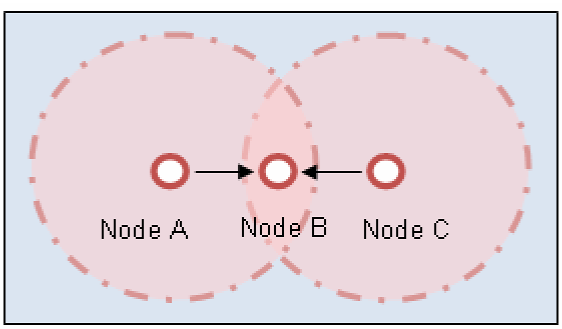


Traditional MAC protocols such as ALOHA [1], CSMA [2], and MACA [3], are designed based on contention-based approach. The classic ALOHA protocol was developed for packet radio communication in the1970s. It uses simple transmission mechanism where node transmits a packet that is generated. The transmission is declared to be a success if the sender receives an acknowledge-ment packet. Else, the transmission failed and the sender retries the transmitting after a random period. Using this mechanism, the probability of a packet collides with other packet is very high, hence increases the energy expenditure due to packet retransmission.

Therefore, in 1975, Kleinrock and Tobagi developed Carrier Sense Multiple Access (CSMA) protocol with the objective of minimizing the collision. They enhanced the ALOHA protocol by implementing a small time for channel listening in order to detect the channel activity. If it does not sense any packet transmission process, it assumes the channel is clear and starts transmitting the intended packet.

However, the protocol cannot solve the hidden terminal problem which normally occurs in ad-hoc networks. The radio range is not large enough to allow communication between arbitrary nodes where two or more nodes may share a common neighbor while being out of each other's reach. Fig. 2 below illustrates this problem. Note that, since node A is hidden from node C and vice versa, any packet that is sent at the same time by both nodes to node B will be disrupted by each other.

Figure 2: Hidden terminal problem



The MACA protocol introduces a three way handshake mechanism to make hidden nodes aware of upcoming transmission, so collision at neighboring nodes can be avoided. Consider again the situation in Fig. 2 above, where both node A and node C intend to transmit a packet to node B. Both nodes first need to send a Request-to-Send (RTS) control packet to node B in order to request permission from node B. Before sending the RTS packet, both nodes need to random delay the transmission in order to avoid synchronized transmission. Node B responds with a Clear-to-Send (CTS) packet, which informs all neighboring nodes of the upcoming transfer. The permitted RTS packet sender then starts to transmit the intended data packet to node B. When data is received correctly, an acknowledgement is send back to the sender.

2. Related Works

Note that, all the mentioned protocols above require all nodes to continuously listen to the channel due to unpredictable packet transmission by its neighboring nodes, hence introducing a problem called *idle-listening*. This situation causes a node to expend a lot of wasteful energy and thus, making the implementation of these protocols in WSN inefficient.

Sensor-MAC (SMAC) protocol [4] attempted to solve the problems by introducing an *active-sleep* cycles in the presence of random access channel. Nodes execute a variant of MACA contention-based MAC protocol during active period to minimize the hidden terminal problem, while turning its radio off during sleep period to reduce idle listening problem. Furthermore, SMAC implements neighbors' information variables called *Network Allocation Vector* (NAV) [5] for its collision avoidance technique. Node checks the NAV value before sending the RTS message. Nevertheless implementing contention based mechanism is still vulnerable to collision due to random mechanism in its data packet transmission.

Energy inefficiency caused by the *idle-listening* problem and high collision probability can be avoided in Time Division Multiple Access (TDMA) based protocols. In TDMA-based protocol such as *HiperLan-II* [6], time is divided into several frames, and frame is divided into numbers of time slots. Since all transmissions within the frame are pre-scheduled, it is possible for a node to sleep when it is not expected to transmit or receive packets, thus the TDMA-based MAC protocol can clearly avoid the *over-emitting* problem. Since only the owner of the time slot is allowed to transmit a packet, collision problem can be avoided significantly. However, the dependency on a centralized base station implemented in *HiperLan-II* is not desirable for ad hoc deployed sensor networks, thus the design goal should be to develop a TDMA-based protocol with distributed time slot scheduling algorithm.

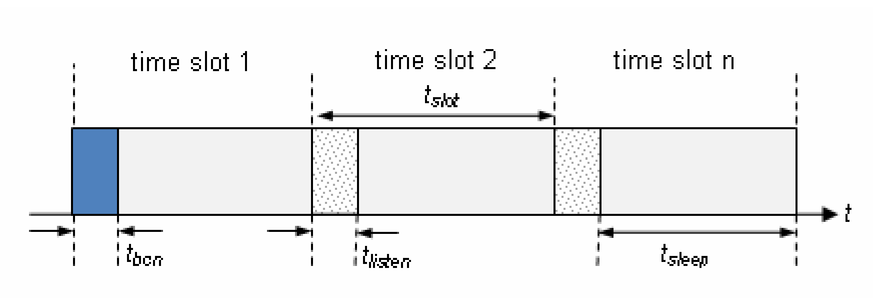
Lightweight Medium Access Control (LMAC) protocol [7] was developed based on EMACS protocol [8]. Frame is divided into several time slots where each time slot consists of a traffic control section and a fixed length data section. When a node wants to transmit a packet, it waits until its time slot arrives and then it broadcasts a message header in the control section which informs its neighboring nodes about the packet destination and length, and then immediately proceeds with transmitting the data. The operation for selecting a time slot is defined into four states where it starts with getting a synchronization node signal in order to know the current time slot number. Node waits for a random frame delay before entering the discovering state. After choosing a time slot, node enters active state where node starts its time slot by sending out a control message. Nodes that receive a control message from its neighboring nodes turn off their radio during the data session if they are not the intended receiver of the scheduled message. LMAC allows either unicast or broadcast message to be transmitted in the data session. LMAC does not implement acknowledgement mechanism for data packet reception confirmation due to the assumption of collision-free channel.

3. The Proposed Design

Advanced Medium Access Control (A-MAC) is a TDMA-based MAC protocol developed for low rate and reliable data transportation with the view of prolonging the network lifetime, adapted from LMAC protocol. Compared to conventional TDMA-based protocols, which depend on central node manager to allocate the time slot for nodes within the cluster, our protocol uses distributed technique where node selects its own time slot by collecting its neighborhood information. The protocol uses the supplied energy efficiently by applying a scheduled power down mode when there is no data transmission activity.

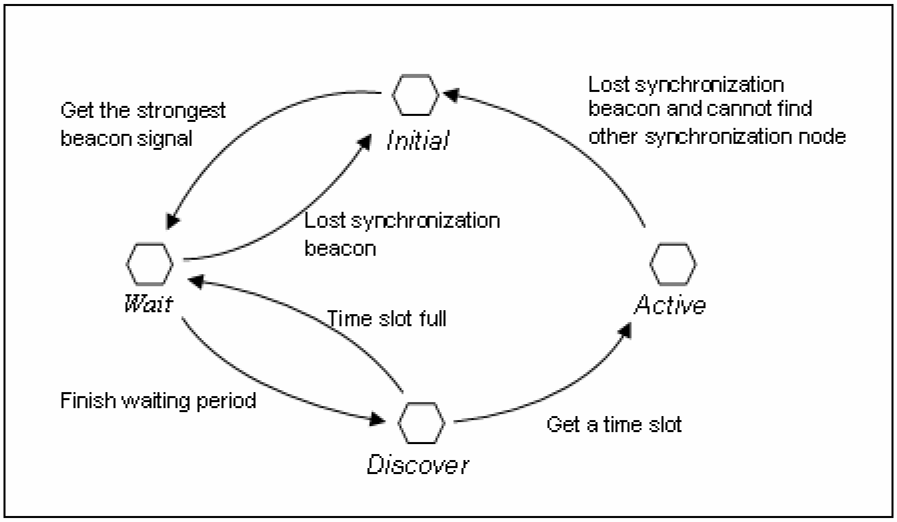
The protocol is structured into several frames, where each frame consists of several time slots. As shown in Fig. 3 below, each node transmits a beacon message at the beginning of its time slot, which is used for two purposes; as synchronization signal and neighbor information exchanges. By using this message, the controlled node informs which of its neighboring nodes will be participating in the next data session. The intended nodes need to stay in listening mode in order to be able to receive the intended packet, while other nodes turn to power down mode until the end of current time slot.

Figure 3: Structure of A-MAC frame



The operation of time slot assignment in A-MAC is divided into four states; *initial*, *wait*, *discover*, and *active*. As illustrated in the Fig. 4 below, a new node that enters a network starts its operation in initial *state* where node listens to the channel for its neighbor's beacon message in order to synchronize with the network. Node starts synchronization when it receives a beacon message from one of its neighbors and adjusts its timer by subtracting the beacon received time with beacon transmission time. Node remains in this state for *aListenFrame* frames in order to find the strongest beacon signal. This is important as to continuously receive the signal from the synchronized node. Else, a potential synchronization problem with the rest of neighboring nodes might arise due to the resulted drift problem caused by imprecision of microcontroller's timer.

Figure 4: State diagram of A-MAC operation



Before entering the *wait* state, node randomly chooses a number of waiting frame. This is done in order to decrease the probability of nodes enter the *discover* state at the same time, which then increase the probability of several nodes selecting the same time slot. If a node lost its synchronization beacon for *aMaxBeaconLost* while in the *wait* state, node returns back to *initial* state to find a synchronization beacon again.

Node enters the *discover* state when the waiting counter expired and start collecting its neighborhood information by listening for its neighboring node's beacon messages for a period of *aListen-Frame* frames. By using bitmap vector in the beacon message, node randomly selects an unoccupied time slot from the result of combining all bitmap vectors from its neighboring nodes using Equation 1

$$z_{OR}(x_1, x_2, \ldots, x_N) = x_1 \vee x_2 \vee \ldots \vee x_N \quad (1)$$

where x_i is the i^{th} time slot and $\vee$ is an OR operation. The resultant bitmap pattern from this operation will be in terms of 1's and 0's where 1's indicate occupied time slot, while 0's indicate the vacant ones. Hence, a node randomly chooses its time slot identification from the list of vacant ones (indicated by 0's).

Figure 5: Time slot assignment with reuse

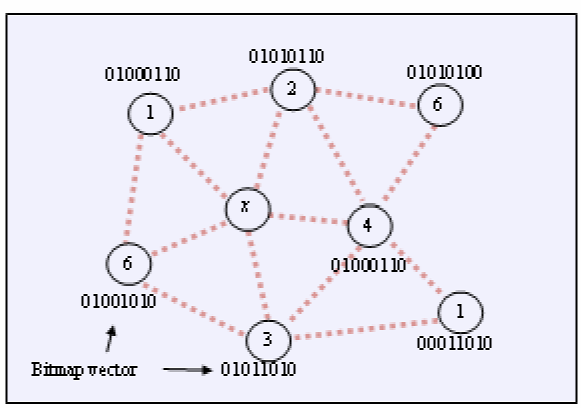


Fig. 5 above shows an example of a network which consists of seven nodes operating in active condition and one new node (*node x*). The bitmap vector consists of 8 bits with most significant bit correspond to time slot 7, while time slot 0 represented by least significant bit. Using Equation 1 above, the vacant time slots is 0, 5, and 7. Therefore, *node x* will randomly select its time slot from the list of vacant time slots.

Node enters *active* state when it successfully selects a time slot. In this state, node continuously transmits a beacon message at the beginning of its time slot as shown in Fig. 3 above. It also needs to listen to the channel at the beginning of other time slot in order to be able to listen for a beacon message from its neighboring nodes. Node enters sleep mode in two scenarios. First, after transmitting a beacon message and no more data packet scheduled to be transmitted. Second, if received beacon message from it neighboring node indicates no incoming data packet.

Compared to LMAC, our designed protocol allows node to transmit to multiple destinations. Furthermore, A-MAC implements an additional flag field in the data packet header called *MORE_PACKET* flag that is used to indicate if the sender has more packets to be transmitted to the intended receiver. By using the *MORE_PACKET* flag, the intended receivers can immediately enter the sleep mode after receiving all packets destined to it.

4. Analysis of Energy Efficiency

We analyze the efficiency of energy consumption in A-MAC protocol for a network without data transmission. We formulate the energy expenditure of A-MAC protocol in a frame as shown in Fig. 3 above, which consists of N_{ts} number of time slot, as

$$E_{A-MAC} = (N_{ts} - 1)P_{rx}t_{listen} + P_{tx}t_{bcn} + P_{pd}t_{sleep} \tag{2}$$

where parameters P_{rx} , P_{tx}, and P_{pd} are the powers used in receive mode, transmit mode, and power down mode respectively, and can be calculated as

$$P = V \times I \tag{3}$$

where I is the current consumed for the given mode and V is the operating voltage for the radio transceiver. The value of I for each mode and V are shown in Table 1 below.

Table 1: Electical specification for radio transceiver CC2420 from Chipcon [9]

Parameter	**Value**
Current consumption, receive mode, I_{rx}	18.8 mA
transmit mode (at 0dBm), I_{tx}	17.4 mA
power down mode, I_{pd}	20 µA
Operating voltage, V	3.0 V

The variable t_{listen}, t_{bcn}, and t_{sleep} represent time for beacon listening period, beacon transmitting period and node sleeping period respectively, as illustrated in Fig. 3 above. Therefore, the total energy consumption for n number of nodes in a network can be formulated as

$$E_{total} = n \times E_{A-MAC} \tag{4}$$

We analyze the correlation between the number of time slot and the network lifetime. Fig. 6 plots the number of days that a network can stay alive for a given number of time slots from Equation 2, where we assume t_{listen} is equals to t_{bcn}. The size of beacon message is 19 bytes and the transmission bandwidth of the CC2420 radio transceiver is 250kbps. The network lifetime is defined as

$$t_{lifetime} = \frac{E_i}{E_{A-MAC}} \times t_{slot} N_{ts} \tag{5}$$

where E_i is the given initial energy and t_{slot} is the time slot length. From Fig. 3, the time slot length is calculated as

$$t_{slot} = t_{sleep} + t_{bcn} \tag{6}$$

To see the correlation between energy consumed per frame with the length of time slot, we put the Equation 6 into the Equation 2.

$$E_{A-MAC} = (N_{ts} - 1)P_{rx}t_{listen} + P_{tx}t_{listen} + P_{pd}(t_{slot} - t_{bcn}) \quad (7)$$

Intial energy E_i in Equation 5 is taken to be 4000 mAh, which is equal to energy from two AA alkaline batteries [10]. As illustrated in Fig. 6 below, the increment of network lifetime is shortened when the number of time slot is bigger than 10. Simultaneously, the network lifetime curve displays a marked slow increment starting from 32 months and above. This is because the energy consumed for sleeping mode is very large compared to the energy consumed for transmitting or receiving. Figure 7 shows the relationship between the network lifetime and the time slot length. The graph shows that the increment of the network lifetime is linear to the increment of time slot length. This is due to longer period of P_{pd} where most energy dissipates at a very low rate and thus resulted in minimal power consumption.

Figure 6: Plot of network lifetime vs number of time slot

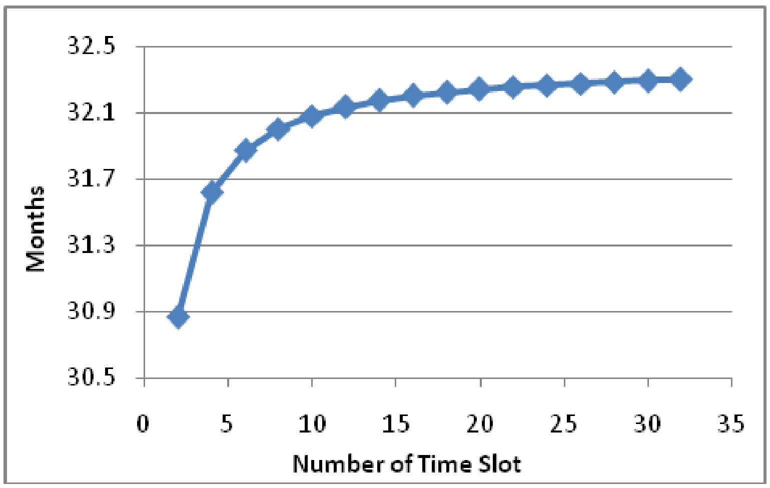
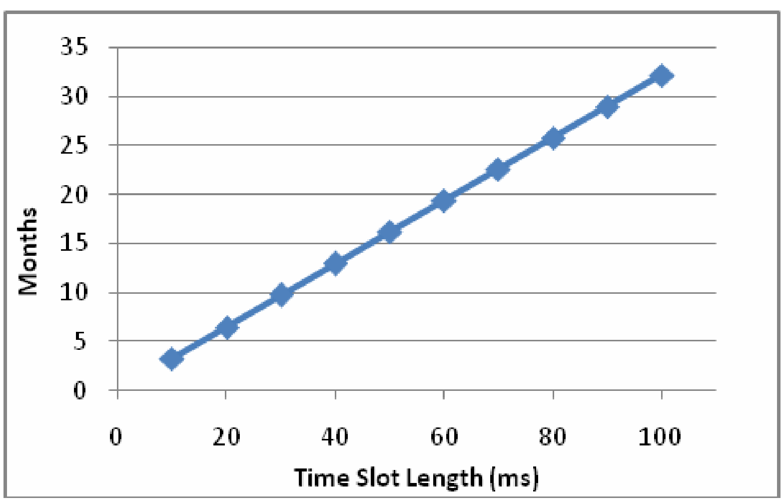


Figure 7: Plot of network lifetime vs time slot length



5. Conclusion

This paper presents a novel approach that tries to reduce idle energy consumption by implementing scheduled active-sleep algorithm named energy aware A-MAC protocol. From the computational model, we show that the algorithm can prolong the network lifetime by switching to sleep mode when there is no packet scheduled to be transmitted or received. Simulation study also has been done to prove the A-MAC algorithm can prolong the network lifetime compared to the classical CSMA approach.

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