Traffic Adaptive IEEE 802.15.4 MAC for Wireless Sensor Networks

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Abstract. IEEE 802.15.4 is a new standard uniquely designed for low rate wireless sensor networks(WSNs). It targets low data rate, low power consumption and low cost wireless networking, and offers device level wireless connectivity. In this paper, the general coordinated sleeping algorithm and the traffic-adaptive algorithm are combined in IEEE 802.15.4 MAC protocol to achieve high energy efficiency and high performance at the same time. By observing that the sporadic traffic characteristic of WSNs, we propose the traffic-adaptive IEEE 802.15.4 MAC with coordinated sleeping algorithm. Through the various performance studies, the proposed algorithm shows significant performance improvements in wireless sensor networks[1].

1 Introduction

Wireless sensor networks will be widely deployed in the future because they can monitor and control the physical environment from remote locations. These sensors are operated with limited battery power, and energy is not always renewable. The traffic inherent to WSNs is highly sporadic and does not necessarily follow any specific traffic pattern. IEEE 802.15.4 [1]-[3] is a new standard uniquely designed for low rate wireless sensor networks. It targets low data rate, low power consumption and low cost wireless networking and offers device level wireless connectivity. In this paper, we introduce an energy efficient MAC protocol that adapts with traffic situations in sensor network applications. We focus on two main attributes. At first, we use the general coordinated sleeping algorithm to achieve the energy efficiency. By considering the sporadic traffic pattern of WSNs, the actual duty cycle of each station is pretty small, which needs energy for operations. Therefore, by using a simple coordinated sleeping algorithm, we can improve the energy efficiency significantly in WSNs. Secondly, traffic information can be determined by checking the queue status of each sensor station which explicitly specify its traffic characteristics. Depending on the application at hand, traffic adaptive mechanism can be relatively simple. According to the traffic information, we dynamically change the length of the active and sleep period to support the traffic adaptive mechanism. IEEE 802.15.4 distinguishes

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itself from other wireless standards such as IEEE 802.11 [4] and Bluetooth [5] by some unique features for wireless personal area networks. IEEE 802.15.4 has been designed as a flexible protocol in which a set of parameters can be configured to meet different requirements. In this paper, we will investigate the operational characteristic of the IEEE 802.15.4 MAC protocol, and induce the energy efficient, traffic adaptive MAC algorithm that provides significantly high performance for WSNs.

In the next section, we explain related research works. Then, we present the newly proposed algorithm in Section 3. The performance evaluations is given in Section 4. In the final section, we present the conclusions.

2 Related Works

2.1 Power Saving Mechanisms for WSN

Many MAC protocols to save power consumption in WSNs have been proposed. Though reservation based MAC protocols have some advantages, in this paper, we focus on MAC protocols based on random access considering sensor networks' applications. One of the main approaches to MAC for WSNs, comes from its counterpart for ad hoc networks, the IEEE 802.11 standard [4]. The IEEE 802.11 standard is a CSMA/CA based protocol which is widely used in wireless LANs. Using plain 802.11 MAC for WSNs has many drawbacks. In particular, the energy consumption due to overhearing and idle-listening, is a major chunk of wasteful energy consumption. The reason for using the energy consumption model with CSMA based MACs is that they perform quite well under most circumstances and the implementation is not complex. Therefore, many researchers have worked to develop efficient CSMA based MAC protocols for WSNs. The PAMAS [12] protocol was one of the first attempts to reduce unnecessary power consumption by turning overhearing stations to sleep. The protocol, however, needs a separate control channel for coordination and avoiding overhearing. It also does not take into account idle listening, which accounts for a large portion of energy consumption. Ye et. al [6][7] proposed the S-MAC protocol that combines scheduling and contention with the aim of improving collision avoidance and scalability. The power saving is based on scheduling sleep/listen cycles between the neighbor stations. After the initial scheduling, synchronization packets are used to maintain the inter-station synchronization. When a station wants to use the channel, it has to contend for the medium. The scheme is very similar to 802.11 with physical and virtual carrier sense and RTS/CTS exchange to handle the hidden station problem. The overhearing control is achieved by putting to sleep all immediate neighbors of the sender and the receiver after receiving an RTS or CTS packet. The S-MAC operation and frame is divided into two periods; the active period and the sleep period. During the sleep period all stations that share the same schedule sleep and save energy. The sleep period is usually several times longer than the active period. Stations listen for a SYNC packet in every frame and the SYNC packet is transmitted by a device infrequently to achieve and maintain virtual clustering.

2.2 Traffic-Adaptive Mechanisms for WSN

Although S-MAC [6][7] can reduce the idle listening time, it is not optimal due to a fixed interval of listening mode. Under the network traffic is very light, i.e., no stations have data traffic to send during the active listen period, all stations still have to be awake and waste their energies. If the traffic is very heavy with fixed active period, all stations can not handle properly the traffic because they have to sleep regardless the network traffic situations. This observation leads many researchers to propose new energy efficient sensor MAC protocols that allow the stations to go to active and sleep status considering the traffic information. The Traffic-Adaptive Medium Access (TRAMA) protocol is one of the proposals to implement energy-aware schedule-based medium access with traffic information. TRAMA addresses energy efficiency by having stations going into sleep mode if they are not selected to transmit and are not the intended receivers of traffic during a particular time slot. TRAMA uses traffic information to establish transmission schedules which are propagated to one-hop neighbors. This information is then used to define when stations need to be in receive mode and when they can switch to low-power sleep mode. Besides its energy efficiency benefits, the use of traffic information also makes TRAMA adaptive to the sensor network applications. Though many algorithms are proposed in traffic-adaptive WSNs, most proposed algorithms have the complexity for announcing traffic information. Complex schedule-based protocols exhibit inherently higher delivery delays when compared to contention-based approaches, and they are not desirable considering the implementation aspect of view in wireless channels.

2.3 802.15.4 MAC

The IEEE 802.15.4 standard [1]-[3] defines the specification of physical (PHY) and medium access control (MAC) sublayer for low data rate and low power wireless devices that typically operate in short ranges. IEEE 802.15.4 MAC supports a simple one-hop star networking and, a multi-hop tree or mesh networkings too. Wireless link under 802.15.4 operates in three different frequency bands - 2.4GHz, 915MHz, and 868MHz with the max data rate of 250kbps, 40kbps and 20kbps respectively. The primary devices targeted by the IEEE 802.15.4 MAC include various kinds of wireless sensors and wireless tag or barcode readers. Since they often operate in remote locations with limited battery capacity, their life cycle is more critical aspect than the network performance, such as data throughput or latency. For those power limited devices, we can trade off network performance with power efficiency by utilizing power saving mechanism that comes with IEEE 802.15.4. The IEEE 802.15.4 standard defines beacon enabled mode and superframe structure for power saving purposes. It can operate in either beacon enabled mode or beacon disabled mode. In beacon enabled mode, a network coordinator periodically broadcasts beacons so that other nodes in the network hear the beacons to synchronize to the superframe structure suggested by the coordinator. In beacon disabled mode, however, a network coordinator does not broadcast beacons except when other nodes request beacons for scanning or association purpose. In beacon enabled networks, a coordinator broadcasts beacons with superframe structure information recorded in the beacon. When other nodes in the network receive the beacon, they obtain the superframe information and start to synchronize to the coordinator's superframe structure. A superframe structure is defined by the network beacons. A network beacon marks the start of a superframe, while it also marks the end of previous superframe at the same time. A superframe generally consists of two parts - an active part and an inactive part. The length of a superframe (beacon interval, BI) and its active part (superframe duration, SD) are determined by beacon order (BO) and superframe order (SO), respectively. The length of inactive part can be determined by subtracting superframe duration from beacon interval. The active part is divided into 16 equally sized slots and has two periods - a contention access period (CAP) and an optional contention free period (CFP). During the CAP, IEEE 802.15.4 MAC utilizes slotted carrier sense multiple access with collision avoidance (CSMA-CA) mechanism for channel access. Following the CAP, CFP can be assigned for low latency applications or applications requiring specific data bandwidth. CFP may accommodate up to seven guaranteed time slots (GTSs), each of which may occupy one or more slots.

3 Traffic Adaptive IEEE 802.15.4 MAC Protocol

Energy consumption is the primary focus of our traffic adaptive MAC algorithm. Because it is important to analyze the various sources of energy waste, we have identified the following wasting sources.

- **Control packet overheads** Most protocols need to exchange control packets for management purposes. Because these packets do not contain any application data, they are considered as overheads.
- **Collision** If more than two nodes transmit data at the same time, their radio signals can be jumbled due to packet collisions. Then each node has to retransmit same data which consumes more energy.
- **Overhearing** Because IEEE 802.15.4 MAC shares the medium, any node can hear others in the transmission range. For example, when nodes A, B, and C are in the same transmission range and node A wants to send data to node B, node C picks up the signal because it does not know whether the data is destined for itself or not, until the data is received. Thus, node C wasted energy in receiving an unwanted packet.
- **Idle listening** This is the most evident source of energy waste in most wireless networks. Nodes in wireless networks must always keep their receiver turn on because they have no idea when the data will be received. In applications that send or receive packets infrequently, energy waste in idle listening is significant and must be avoided.

In most cases, the energy waste caused by overheads, collision, and overhearing is relatively small compared to that of idle listening. Control packet overheads of

IEEE 802.15.4 MAC are MAC commands, beacons, and acknowledgements. Because we measured power consumption after the network had fully established, MAC commands for scanning and association were ignored. Only network beacons and acknowledgements were taken into account for measuring energy consumption. Regarding the collision, the efficient CSMA-CA is used. Additional collisions from hidden terminal problem are ignored due to lack of support for Request-to-send (RTS) and Clear-to-send (CTS) mechanism [4]. Thus, we designed our traffic adaptive IEEE 802.15.4 MAC with focusing on the energy waste in idle listening to be minimized. As stated above, beacon enabled IEEE 802.15.4 network uses the superframe structure to save energy consumption. Determining the superframe order is important because it has a direct relationship to the amount of energy consumed.

3.1 Traffic Adaptive Scheme

The IEEE 802.15.4 network supports broad range of applications. This means that traffics generated from these applications also vary greatly in amount. Even in the same application, traffic loads can change at the need of the application. Consider a wireless temperature sensor network that measures temperature upon the demand of an application. If the application is up to scientific purposes which need a great degree of accuracy, the temperature sampling cycle is short, like several times in a second, generating large number of packets to be transmitted. In some applications, on the other hand, such as room temperature sensors for air conditioner or heater, temperature sampling happens occasionally, several minutes or even hours, generating fewer packets than applications with short cycles. We designed traffic adaptive MAC protocol based on IEEE 802.15.4 MAC with these various circumstances under considerations. In high traffic situations, the duty cycle of the medium increases by extending the active part in the superframe to deliver packets efficiently. Likewise, the duty cycle decreases in low traffic situations by reducing the active part, thereby increasing the inactive part for power saving.

3.2 Protocol Design Overview

We should know the amount of traffic generated by the application in order to adjust the duration of the active part. One way to do this is to monitor the transmission (TX) queue of the nodes. When the traffic is high enough, a transmitter of the node will be unable to process all the packets generated. In this case, the node has to buffer the incoming packets in its own TX queue until they get processed and sent. Therefore, we can assume the traffic loads at a given moment by monitoring the TX queue status. Queue monitoring happens every time when a node wants to send packets to one of its neighboring nodes. When IEEE 802.15.4 MAC receives a packet from an application, it first buffers the packet in its TX queue. Following the packet buffering, it checks the queue status to see how many queue slots were used for packet buffering. If 80% or more of the queue slots are occupied, the node reports its current queue status by sending a special packet called Queue Status Indicator (QSI) to the coordinator for requesting modification to current superframe configuration. QSI packet is a control packet with unique identifier set into the reserved bits of IEEE 802.15.4 MAC frame control field. It must be sent right away upon request, so that a network coordinator receives it and makes changes to its superframe configuration to better deal with the high traffic situations. The problem is that the general queue puts the QSI packet at the end of the TX queue because it considers the QSI packet just as other data packets. Then the QSI packet has to wait until all of the previous 80% of packets are processed and sent. Therefore, we moved the QSI packet to the very first slot of the TX queue. This makes QSI packets be sent as soon as it enters the queue. When a network coordinator receives the QSI packet, it immediately maximizes the active period (100% duty cycle) at the next superframe by setting the superframe order equal to beacon order. This allows the node which sent the QSI packet to flush its TX queue by taking advantage of the maximized active period. If the coordinator receives more QSI packets even if it maximized the active period, it waits until when there is no more QSI packets arriving. If the coordinator receives no further QSI packets for at least n consecutive superframes (application dependant) after receiving the last QSI packet, it resets superframe order to *previous superframe order* + 1. If the superframe order was 2 before receiving the QSI packet, *previous superframe order* has the value of 2. We added 1 to this value because *previous superframe order* might not suffice the current traffic load of the network. Setting superframe order to *previous superframe order* is meaningless because nodes possibly generate another QSI packet if the traffic load at hand is still high. On the other hand, if the coordinator receives no QSI packets during m consecutive superframes (application dependant), it decreases the superframe order by 1. This enables network coordinators and nodes to deal with low traffic situations where there is no need for a long active period. The smallest number possible for the superframe order is 2 in our traffic adaptive IEEE 802.15.4 MAC.

4 Protocol Implementation

We have implemented our traffic adaptive IEEE 802.15.4 MAC to show the effectiveness of our design compared to that of general IEEE 802.15.4 MAC. We used Chipcon CC2420 Demonstration Board [9] as our development platform. The board contains Atmel 128L microcontroller [11] with built in 128 KB flash memory for programming and debugging, 32 KB external SRAM for data storage, and CC2420 RF transceiver [10]. There are two different modes that we can choose from when compiling software layer - Full Function Device (FFD) mode and Reduced Function Device (RFD) mode. We only used FFD mode for implementation.

We have carried out experiments for three different IEEE 802.15.4 MAC schemes - 10% duty cycle, 100% duty cycle, and traffic adaptive MAC. Results are given and compared to each other in the following subsections.

4.1 Experiment Environment and Parameters

The total of eight Chipcon CC2420 DBs was used for our experiments. One of them took a role as a network coordinator and remaining seven operated as network nodes. We used IEEE 802.15.4 association MAC commands to make each node join the network. Node 0 through node 6 are children of the coordinator and each node has address information on its neighboring nodes. Therefore, node 0 can send packets directly to node 1, node 1 can send packets directly to node 0 or node 2, and so on, without routing the packets to the coordinator. Node 0 is a sink for packets generated by node 6 (the source node). Packets generated by the source travels through the intermediate nodes (node 1 through node 5) to reach the destination. Parameters related to our experiments can be found on Table 1. The meaning of the variables m and n is defined in section 3. Regarding the traffic for the network, we generated 200 data packets (113 bytes each including MAC packet header) to be passed from their sources to their sinks for energy measurements. We changed the traffic load by varying the inter-arrival period of packets for checking the network throughput. In our experiments, the packet inter-arrival period varied from 0.1 to 3s. For the low rate wireless network, we also experimented with other inter-arrival periods longer than 3s.

Beacon order	6
Superframe order	2 to 6
Duty cycle	6% to 100%
Address mode	16 bit short
m	4
n	2

Table 1. Parameters for experiments

4.2 Performance Results

We provide two experiment results in this paper - energy consumption and, aggregated throughput. We carried out the same experiment several times and average the results from each experiment to get the final results. To measure the energy consumption, we have identified three sources - transmitting and receiving of the packets, idle listening, and sleeping. To calculate the energy consumed from packet transmission and reception, we count the total number of packets transmitted and received by all nodes in each experiment. Packets include beacons, data frames, acknowledgements, and QSIs. From the length of each packet, we can calculate how many bytes were transmitted and received. Once the total bytes are known, we can also calculate the total symbol time spent in transmitting and receiving by multiplying total byte count with 2 because IEEE 802.15.4

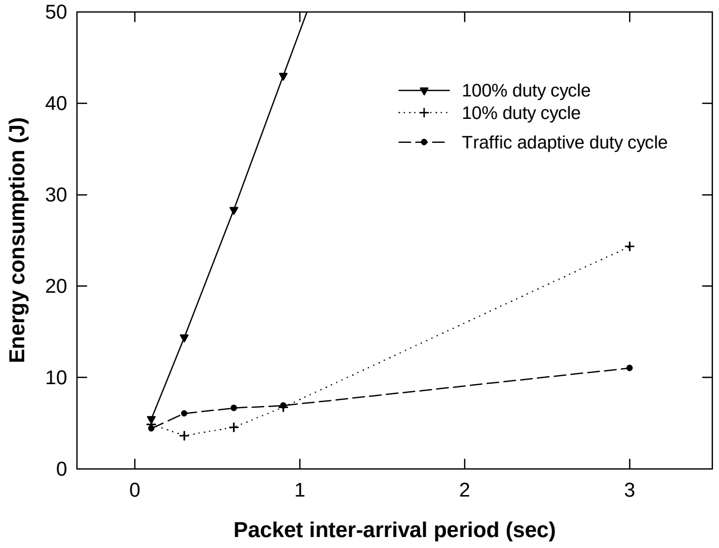

Fig. 1. Total energy consumption of the nodes

takes two symbols to transmit single byte. From the fact that one symbol time corresponds to 16 us, we can calculate the total time spent in seconds. Idle listening time can be calculated by subtracting time spent in transmitting and receiving packets from the duration of the active period. Finally, sleeping time is equal to the duration of the inactive period. Then, we can calculate the energy consumption by multiplying the time with the required power. Figure 1 shows the measured total energy consumption over the seven nodes in the network. As expected, IEEE 802.15.4 MAC with 100% duty cycle consumed far more energy than 10% duty cycle and traffic adaptive MACs. It is interesting to note that IEEE 802.15.4 MAC with 10% duty cycle generally consumed less energy than traffic adaptive 802.15.4 MAC in packet inter-arrival periods from 0.1s to 1s. This is because the duty cycle of traffic adaptive IEEE 802.15.4 MAC can go as low as 6% meaning that each node has less time to send packets from source to destination than IEEE 802.15.4 MAC with 10% duty cycle. Packets may have to be buffered waiting for the active period of the next superframe. This requires higher number of superframes (more energy) and more time (more delay and fewer throughputs) for packets to be delivered, thereby causing more energy consumption. However, traffic adaptive IEEE 802.15.4 MAC performed better as the inter-arrival period gets longer. As in Figure 1, when the inter-arrival period was longer than 1s, traffic adaptive IEEE 802.15.4 MAC consumed less energy than 802.15.4 MAC with 10% duty cycle. The power consumption at 3 inter-arrival period of IEEE 802.15.4 MAC with 100% duty cycle is over 140J, so, it is not shown in Figure 1. For much longer inter-arrival periods like 10s or more, the traffic adaptive IEEE 802.15.4 MAC outperformed the other two MACs by saving huge energy consumptions.

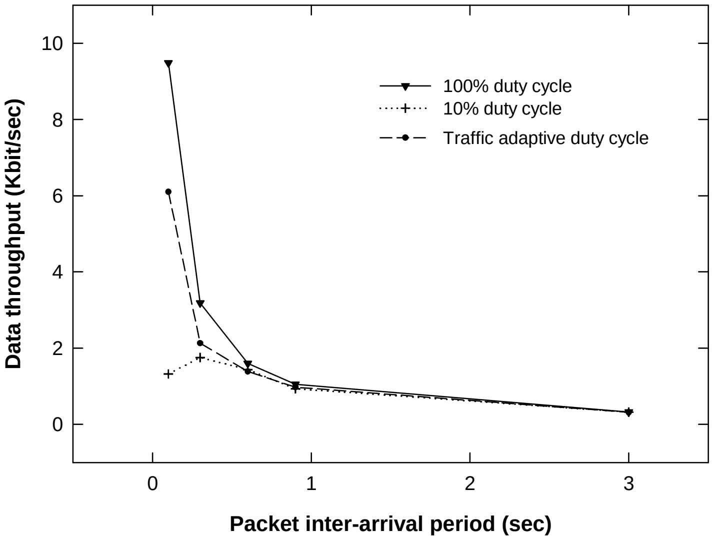

Fig. 2. Aggregated throughput

Figure 2 shows data throughput of the network. As expected, IEEE 802.15.4 with 100% duty cycle performed better than the other two MACs by fully utilizing the available resource. When the inter-arrival period was less than 0.6s, traffic adaptive IEEE 802.15.4 MAC showed better performance than IEEE 802.15.4 MAC with 10% duty cycle because traffic adaptive MAC adjusted superframe order accordingly depending on the traffic situation. On the other hand, when the inter-arrival period was longer than 0.9s, all of the three MACs performed almost equally. This means that the traffic was light enough to be handled by 10% duty cycle MAC without increasing superframe order. From Figure 1, it is clear that, for inter-arrival periods longer than 0.9s, each MAC showed a different level of energy consumption, while the data throughput of the three MACs was almost the same. It shows that the traffic adaptive IEEE 802.15.4 MAC was energy efficient while achieving the same throughput performance. The IEEE 802.15.4 MAC with 100% duty cycle was the worst energy efficient MAC. When the inter-arrival period was 3s, IEEE 802.15.4 MAC with 10% duty cycle consumed energy more than twice than that of traffic adaptive IEEE 802.15.4 MAC. From Figure 1 and 2, we can see that the energy consumption difference between 10% duty cycle and traffic adaptive MAC will be larger as the inter-arrival period increases, while the data throughput of the three MACs will remain the same.

5 Conclusions

This paper proposed the traffic adaptive IEEE 802.15.4 MAC protocol specially designed for low data rate wireless sensor network applications. Energy efficiency is our primary concern in designing the whole MAC protocol. In this paper, we suggested traffic adaptive MAC protocol with high power efficient scheme in low traffic conditions as well as high traffic conditions. To achieve this, our traffic adaptive MAC algorithm increases the active duty cycle in high traffic conditions for higher throughput and reliable packet delivery, while it decreases the active duty cycle in low traffic conditions to save more energy. Traffic adaptive MAC has been implemented using CC2420 demonstration board from Chipcon and based on the IEEE 802.15.4 standard. We compared our traffic adaptive MAC to other fixed duty cycle MACs and showed that the proposed MAC achieved high energy efficiency especially in low traffic conditions, while preserving high throughput performance and easy implementation structures.

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