Medium Access Control with an Energy-Efficient Algorithm for Wireless Sensor Networks*

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Abstract. This paper proposes an enhanced B-MAC (ENBMAC), a carrier sense Medium Access Control (MAC) protocol with ultra low power operations for wireless sensor networks. Due to battery-operated computing and sensing devices in wireless sensor networks, the development of MAC protocols that efficiently reduce power consumption is an important issue. B-MAC provides bidirectional interfaces such as Clear Channel Assessment (CCA), Low Power Listening (LPL) and uses an adaptive preamble sampling scheme to optimize performance and conserve energy. This reduces the amount of energy by comparing to other MAC protocols in WSNs. However, B-MAC can not achieve the overhearing avoidance. To solve this problem, we propose Node Recognition (NR) algorithm using the next hop address in MAC layer. Because this mechanism tries to handle the overhearing avoidance, ENBMAC makes it possible to extend the lifetime of the wireless sensor networks that contain a large number of nodes. The experiment results show that ENBMAC protocol reduces the energy consumed by receiving up to 90 percent comparing to B-MAC.

1 Introduction

Wireless sensor networks are generally composed of a large number of sensor nodes deployed to measure various physical information and a few data collectors, which are called sink nodes. Wireless sensor networks have recently become of significant interest due to cheap single-chip transceivers and micro controllers. They consist of many tiny devices, powered by small-sized batteries, and operate unattended for prolonged duration. Because sensor nodes may be deployed in remote locations, it is likely that replacing their battery will not be possible. Therefore, power efficient protocols at each layer of the communications are very important for wireless sensor networks [1]. In this paper, we will focus on the medium access control layer.

Conventional MAC protocols have been optimized for maximum throughput and minimum delay. Because of the target, they are not suitable for wireless sensor networks. To reach a major requirement of wireless sensor networks, several energy conserving MAC protocols have been proposed. For example, S-MAC employs the

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RTS/CTS/DATA/ACK signaling scheme, periodic listen and sleep to collision and overhearing avoidance, and message passing [2]. T-MAC is another example that dynamically adapts a listen and sleep duty cycle through fine-grained timeouts [3]. This protocol improves on S-MAC's energy usage by using an active period. The IEEE 802.15.4 uses periodic sleep to reduce energy consumption and requires synchronization to decide on suitable schedules [4]. B-MAC employs not only Clear Channel Assessment (CCA) and packet backoffs to avoid collisions, but also Low Power Listening (LPL) and preamble sampling to reduce duty cycle and minimize idle listening [5].

In this paper, we present ENBMAC protocol, which is an enhanced version of B-MAC. It tries to reduce the waste of energy consumed by overhearing. To achieve overhearing avoidance, ENBMAC employs Node Recognition (NR) algorithm without an additional overhead, while considering wireless sensor communication patterns and hardware limitations. The remainder of the paper is organized as follows. Section 2 summarizes reviews related work on MAC protocols and energy-saving solutions in WSNs. In section 3, we will elaborate on the design of the ENBMAC protocol. Then, in section 4, ENBMAC is evaluated through numerical analysis. Finally, section 5 concludes the paper.

2 Related Work

Because of various limitations and the characteristics of wireless sensor networks, the low power consumption is the main criterion for protocol design at every layer. The medium access control layer is one of the interesting research areas, and provides large opportunities of energy savings by dealing with the situations among nodes. There are several major sources of energy waste in wireless sensor networks: [2]

- ***Collision*** occurs when two nodes transmit at the same time and interfere with each others transmission. Hence, re-transmissions increase energy consumption.
- ***Control packet overhead*** such as RTS/CTS/ACK can be significant for wireless sensor networks that use small data packets.
- ***Overhearing*** means that there is no meaningful activity when nodes receive packets or a part of packets that are destined to other nodes.
- ***Idle listening*** is the cost of actively listening for potential packets. Because nodes must keep their radio in receive mode, this source causes inefficient use of energy.

To reduce energy consumptions by these factors, Polastre et al. develop a versatile low power MAC protocol called B-MAC, which is used as the default MAC for Mica2. By comparing B-MAC to conventional MAC protocol, e.g., IEEE 802.11 Distributed Coordinated Function (DCF), we know that B-MAC is more suitable for sensor networks, for it is optimized to conserve energy. In addition, B-MAC's flexibility results in better packet delivery rates, throughput, latency, and energy consumption than other MAC protocols in WSNs such as S-MAC, T-MAC. However, B-MAC suffers from the waste of energy consumed by overhearing. Since nodes do not know when they will be the receivers of messages from their neighbors, most energy in traditional MAC protocols is wasted by idle listening under low traffic loads. In addition, increasing the sample rate or neighborhood size increases the amount of traffic in the network. As a result, each node consumes much energy by overhearing. There is an example related to overhearing problem in figure 1. Figure 1 shows the general communication architecture of WSNs [1]. When node A sends its physical information to the sink node, some neighboring nodes near node A overhear some packets that they do not need. These activities on the channel reduce energy efficiency of WSNs.

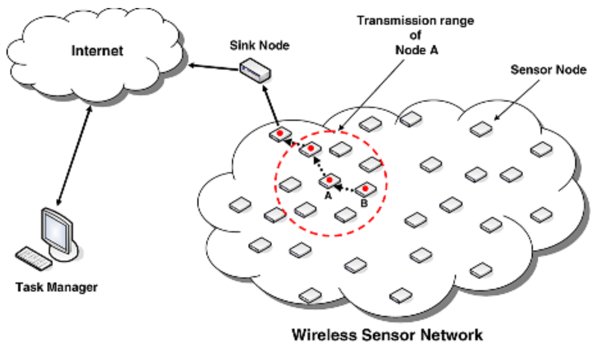


Fig. 1. The general architecture of Wireless Sensor Networks

3 Proposed ENBMAC Protocol Design

Energy dissipation includes three parts: energy dissipation on the sensor transducer, energy dissipation for communication among sensor nodes, and energy consumed by the microprocessor in computation. Since the part of communication consumes more power than other things, the mechanism, which reduces transmission and reception energy, is a necessary factor for MAC protocol design in WSNs. Although B-MAC employs an adaptive preamble sampling to reduce energy consumed by idle listening, it is not optimal. Overhearing from the neighbor nodes decreases energy efficiency.

ENBMAC provides a novel idea, called divided preamble sampling with overhearing avoidance scheme. While reducing the power consumption by the mechanism, ENBMAC preserves the basic properties of the original B-MAC protocol. The details of the implementation steps for ENBMAC protocol are described below sections.

3.1 ENBMAC Protocol

Figure 2 shows the transmission operation of the ENBMAC protocol. When a transmission of each node is requested from its application the node checks for a pending packet. If a pending packet is detected, transmission fails and the information related to the state of transmission is reported to upper layer that deals with retrying the operation. If the node can immediately transmit a packet, it saves the packet to the buffer and sets the random value of the initial backoff periods. After the operation, if the node is in sleep state, the algorithm of transmission puts the node into active mode to send the packet. In order to avoid collisions among neighboring nodes, the node delays for a random number of initial backoff periods and checks the status of the channel using CCA [5]. If there is no activity, the node constructs the MAC frame at once and sends the packet to the destination node or the next hop node. Otherwise, the node performs additional backoffs until Retry Counter (RC) is equal to zero. After transmission, the node turns on the timer related to check interval and goes back to sleep mode. This mechanism is similar to a traditional carrier sense multiple access scheme; however, it returns to sleep mode to reduce energy consumption.

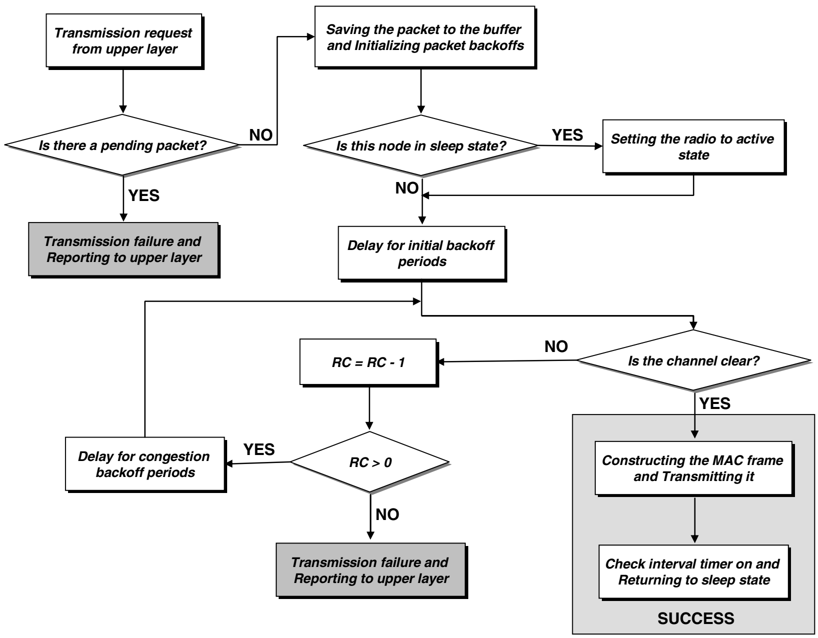


Fig. 2. ENBMAC Subroutine - Transmission

To achieve low power operation of reception, ENBMAC employs a variety of techniques such as divided preamble sampling, NR algorithm, CCA, and LPL (as shown in figure 3). Each node usually keeps up sleep state to minimize power consumption caused by idle listening and wakes up on a timer interrupt, named check interval timer. If the channel is active during check period, the node synchronizes with the preamble field of a preamble segment. A preamble segment consists of a part of preamble and the field of next hop address. After that, the node decodes a preamble segment and compares its address to the next hop address of the preamble segment. This scheme is called NR algorithm. If the incoming packet is destined to this node, the node receives the entire packet, turns on the check interval timer and returns to sleep state for avoiding idle listening. However, the node drops the remainder of the packet when its address is not matched to the next hop address through NR algorithm. From this algorithm, a lot of energy waste consumed by reception is reduced efficiently. To implement NR algorithm, the structure of long fixed preamble must be changed. The novel structure of preamble header and the NR algorithm are discussed more detail in section 3.2 and 3.3 respectively.

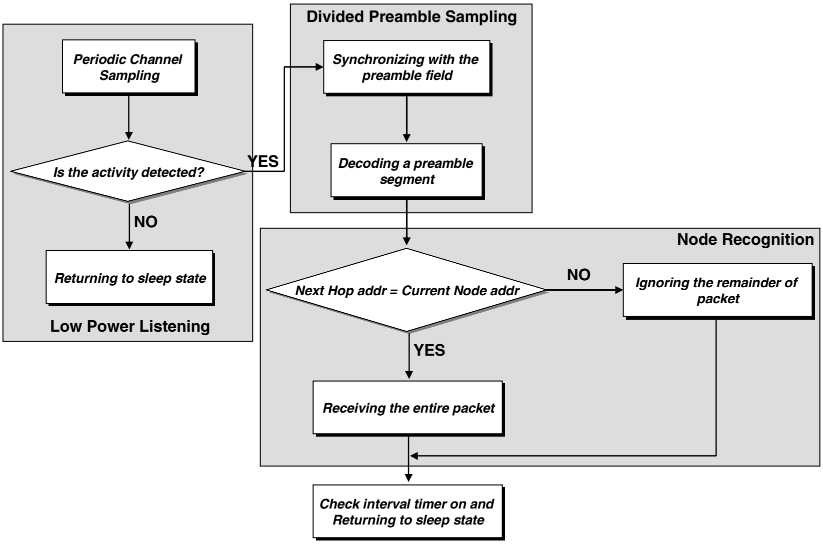


Fig. 3. ENBMAC Subroutine - Reception

3.2 Divided Preamble Sampling

All nodes that use B-MAC usually suffer from long and inefficient preambles. In order to overcome this drawback, a more effective structure and a sampling scheme are proposed. The structure of ENBMAC's entire preamble consists of several preamble segments as shown in figure 4.

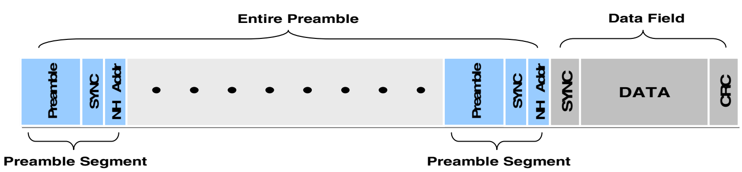


Fig. 4. The Structure of ENBMAC Frame

A preamble segment has three kinds of fields. The first is a preamble field that consists of the minimum length of bit pattern. The preamble length must be matched to the check interval when a node uses B-MAC protocol because of checking for activity on the channel reliably. If the channel is sampled every 100 ms, the entire preamble for detecting the activity must be at least 100 ms long. Although preamble is necessary for the bit synchronizer to synchronize correctly, a long and fixed preamble is not an essential factor to transmit packets. The minimum length of the preamble depends on the acquisition mode selected and the settling time. Typically, the preamble length is recommended by the manufacturer [6]. We employ the length in this field. The second is the SYNC field that notifies the end of short preamble for correct synchronization. The third field is the next hop address, which becomes a resource to eliminate overhearing. When the node constructs a preamble segment, it obtains the information of next hop node from upper layer and adds the information to a segment. When a node has a packet requested from upper layer, it constructs the MAC frame with several preamble segments made up of the equal value to reliably receive packet. ENBMAC can provide the opportunity to ignore a large part of the entire packet through this structure.

3.3 Node Recognition Algorithm

B-MAC provides ultra low power operation, effective collision avoidance, and high channel utilization through a flexible interface. ENBMAC can operate a NR algorithm without destroying these advantages. It also has a flexible interface proposed in B-MAC and provides an additional interface related to the divided preamble sampling. As described in section 3.1, a node wakes up every check interval and detects activity on the channel, and receives the packet. At that time, the node that receives incoming packet does not need to listen to all parts of the packet if it is not a destination node or a next hop node. Figure 5 represents the basic example of transmission, reception, and overhearing avoidance of ENBMAC. If the packet transmitted by node A is destined to node C, node B can achieve low power reception with overhearing avoidance. There are no additional burdens in constructing MAC frame.

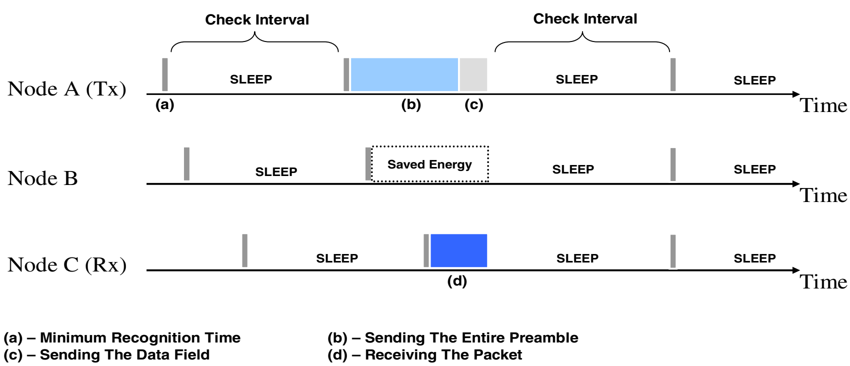


Fig. 5. The basic operations of ENBMAC protocol

At a starting point of a reception mode, a node must keep up the minimum recognition time in order to sense activity on the channel, fetch node address from a preamble segment, and compare node addresses. If a node cannot guarantee the recognition time, it is able to fail receiving the packet. To avoid this type of energy waste, ENBMAC must guarantee a period of turning on the radio and running NR algorithm. Therefore, the length of the entire preamble is defined as

$$L_{preamble} \times T_{txbyte} \geq T_{interval} + \alpha \tag{1}$$

where $L_{preamble}$ is the length of the entire preamble, T_{txbyte} and $T_{interval}$ are the time of sending one byte and the check interval time respectively, and α is the minimum recognition time. After Manchester encoding in the CC1000 used in Mica2, the data rate is 19.2kbps [6]. Because we can get the value of T_{txbyte} from the data rate, $T_{interval}$ and α from the bidirectional interface, we are able to calculate the suitable length of the entire preamble.

4 Performance Evaluation

Basically, wireless sensor networks are able to support scalability of a network since the number of sensor nodes deployed in the field widely may be in the order of hundreds or thousands. In the case of B-MAC, the expansion of a network leads to the increase of total overhearing overhead. In order to offer the fault tolerance feature of WSNs, engineers have to provide high density networks. For this reason, more nodes that employ B-MAC suffer from serious overhearing problems, which result in a reduction of a network's lifetime. Therefore, if the traffic load or the number of nodes increases owing to various circumstances, B-MAC-applied-WSNs become exhausted from receiving no meaningful parts of packets. ENBMAC has accepted the properties of the existing B-MAC. Nevertheless, it is able to shorten energy exhaustion in many different ways.

In this section, the efficient factors of ENBMAC are shown through various equations and results. The focus is on comparing ENBMAC with B-MAC because B-MAC is shown to have higher throughput and better energy efficiency than S-MAC and T-MAC.

Table 1. Parameters for comparing ENBMAC and B-MAC

Parameter	Description	Values used in simulation
X_i	The waking up point of node i	Uniform Distribution
L_{packet}	Packet length of the application	40 Bytes
T_{txbyte}, T_{rxbyte}	Transmission and reception time of 1 byte	416us (19.2Kbps)
C_{rx}	Current used in reception mode	15 mA
C_{sleep}	Current used in sleep mode	0.03 mA
V	Voltage	3 V
$T_{arrival}$	Inter-arrival time of traffic	300 second (In a case of simple network)
$L_{preamble}$	In a case of simple network	151 Bytes (50ms), 271 Bytes (100ms), 391 Bytes (150 ms), 511 Bytes (200ms)
	In a case of multi-hop network	271 Bytes (fixed 100ms)
$N_c(i)$	The number of children nodes at node i	0~3 nodes

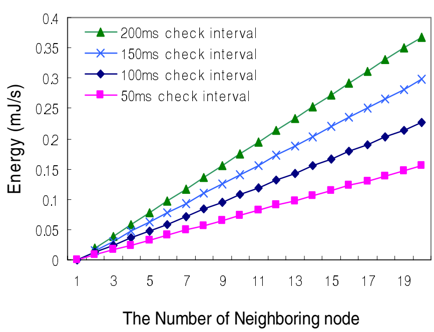
First, the simple one-hop network is considered. It is assumed that the network in figure 1 uses B-MAC and node B only transmits the sensing information to node A. The other nodes, except node B, regularly sense the surroundings and send information to the other nodes excluding node A. At that time, node A consumes much energy by overhearing caused by the six neighboring nodes except node B. Each of these six neighboring nodes has a different point of waking up time. Thus, in a case of a simple network, each node has an overhearing overhead as high as E_{over} per second.

$$E_{over} = \sum_{i=1}^{N-1}\left(\frac{(L_{preamble} + L_{packet} - X_i)\times T_{rxbyte} \times C_{rx} \times V}{T_{arrival}}\right) \tag{2}$$

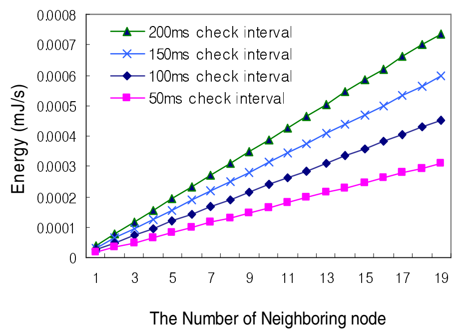
In the case of ENBMAC, every node maintains a sleep state for overhearing duration after performing a NR algorithm. If the energy consumption of the additional sleep duration is E_{asleep}, we can calculate the quantity of E_{asleep} by replacing C_{rx} with C_{sleep} in equation (3). The saved energy by using ENBMAC is presented as:

$$E_{save} = E_{over} - E_{asleep} \tag{3}$$

Figure 6 represents the simulation result of the above equation using Table 1. We can understand how much overhearing is caused by check interval and the number of neighboring nodes through figure 6(a). If the node density or check interval increases, the number of bytes, which do overhear also rises. However, ENBMAC consumes in quantity of E_{asleep} instead of such overhearing energy as shown in figure 6(b).



(a) Overhearing Energy



(b) Additional Sleep Energy

Fig. 6. The result of simple network

Finally, the effect of a multi-hop network is evaluated. In real wireless sensor networks, every node cannot be placed by one-hop distance from sink node. In this case, routing protocol is essential and the energy waste should come with a routing algorithm. The traffic through a node must include all the packets routed by the node and its neighbors. When there are N numbers of neighboring nodes in the viewpoint of one node, then transmit frequency per second is:

$$\frac{1}{T_{arrival}}\sum_{i=1}^{N}(N_c(i)+1) \tag{4}$$

Therefore, while considering the real condition of WSNs, the quantity of saved energy of each node in ENBMAC is:

$$E_{save} = \sum_{i=1}^{N-N_c(0)}\left(\frac{(N_c(i)+1)((L_{preamble} + L_{packet} - X_i)\times T_{rxbyte} \times C_{rx} \times V)}{T_{arrival}}\right) \tag{5}$$

where $N_c(0)$ is the number of children nodes itself.

Figure 7 shows the simulation result of a multi-hop network. According to figure 7(a), the shorter the inter-arrival time of traffic becomes, the more the traffic load increases and the greater amount of energy is saved by ENBMAC. In other words, ENBMAC is more suitable for the facts closely related to the transmit frequency such as inter-arrival time and node density. In figure 7(b), the comparison between ENBMAC and B-MAC shows that the former is able to save 90 percent of the reception energy per second in each inter-arrival time of the latter. By using the NR algorithm, ENBMAC eliminates the overhearing factor, the biggest weak point of B-MAC, and makes it possible to extend the lifetime of the wireless sensor networks.

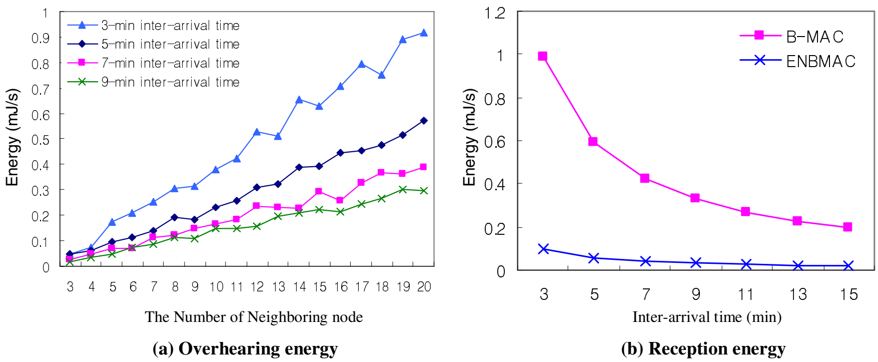


Fig. 7. The result of multi-hop network

The energy efficiency of ENBMAC is even better when nodes increase in number due to network expansion and node density in a specific area gets higher for fault tolerance. Furthermore, in the case of applying a routing condition, ENBMAC can work more on its own merits when transmission and reception get complicated and the number of communications becomes larger. Consequently, it is obvious that ENBMAC is far more efficient than B-MAC in supporting the properties of general WSNs efficiently. Overhearing can be reduced in the existing B-MAC when using the RTS-CTS mechanism. Nevertheless, it is not efficient to reserve channels using RTS-CTS mechanism in B-MAC. Because the reception node has to listen the channel status during a certain period to let the receiver hear RTS, the energy efficient operations of the node tend to be inefficient.

5 Conclusion

An energy-efficiency MAC protocol in Wireless Sensor Networks is an open research area in which we are conducting further studies. To solve the problem of overhearing and reach our goal in WSNs, we have proposed the ENBMAC protocol that employs NR algorithm. This protocol uses a novel idea, called divided preamble sampling to implement the mechanism. The structure of preamble segment provides various opportunities to improve energy efficiency. The performance results have shown the

ENBMAC protocol is more suitable for general WSNs and can achieve conserving energy in reception mode up to 90 percent comparing to B-MAC protocol.

This novel protocol is the subject of an ongoing study, and we plan to implement the ENBMAC protocol on the node that we made. Therefore, we expect more results related to energy efficiency, latency, and throughput in the future.

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