An Adaptive MAC Protocol considering Real Time in Wireless Sensor Networks

Jeong-Seok On* ***Associate Member,***
Jae-Hyun Kim*, Young-Yul Oh* ***Regular Members***, Jai-Yong Lee* ***Lifelong Member***

ABSTRACT

Leading MAC protocols developed for duty-cycled WSNs such as B-MAC employ a long preamble and channel sampling. The long preamble introduces excess latency at each hop and suffers from excess energy consumption at non-target receivers. In this paper we propose AS-MAC (Asynchronous Sensor MAC), a low power MAC protocol for wireless sensor networks (WSNs). AS-MAC solves these problems by employing a series of preload approach that retains the advantages of low power listening and independent sleep schedule. Moreover AS-MAC offers an additional advantage such as flexible duty cycle as data rate varies. We demonstrate that AS-MAC is better performance than B-MAC through analysis and evaluation.

Key Words : MAC, Low power listening, Preload, Flexible period, WSN

Ⅰ. INTRODUCTION

The energy efficiency of a sensor node is the most important research theme in wireless sensor networks (WSNs). The energy consumption of the sensor node can divide into three sections which are a sensor, processor and radio unit. Among them the energy consumption of the radio unit occupies the dominant proportion. A MAC protocol directly effects on the consumption of the radio part. Therefore several MAC protocols that adapt to WSNs have been developed. One of the primary mechanisms to obtain energy efficiency in several MAC protocols is duty cycling [3, 4, 5, 6, 9]. In this approach, each sensor node periodically cycles between an active state and sleep state. In duty cycling, the expansion of sleep period reduces energy consumption. However per-hop latency is increased.

Leading MAC protocols for duty-cycled WSNs are contention-based MAC protocols, since contention-based MAC protocols are scalable in networks topology and adapt easily to mobility of nodes. In addition the exact synchronization as TDMA-based MAC protocols don't be needed in multi-hop [3].

Contention-based MAC protocols are categorized into synchronous and asynchronous approaches. Synchronous protocols, such as S-MAC [3] and T-MAC [4], share a schedule that specifies when nodes are awake and asleep. Exchanging the schedule information during the beginning of active period in order to communicate each other is control overhead that consume considerable energy. Therefore, asynchronous protocols that have no synchronization overhead are better than synchronous protocols in terms of energy efficiency [5]. Asynchronous protocols such as B-MAC [5], and WiseMAC [9], rely on low power listening (LPL), so called channel sampling, to link a sender to a receiver who is duty cycling. Because an asynchronous MAC protocol doesn't need synchronization, the implementation

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* 연세대학교 전기전자공학과 유비넷 연구실 (onchuck@yonsei.ac.kr)

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can be simplified and its code size can be reduced. While the asynchronous protocols are simple and energy efficient, the long preamble in low power listening exhibits two major disadvantages. One is unnecessary overhearing that causes excessive energy consumption at non-target receivers, and the other is excessive latency at each hop.

We propose a new approach called Asynchronous Sensor MAC (AS-MAC), which employs low power listening scheme. AS-MAC is designed for target monitor application. The target monitor application guarantees the real time service. In this application sensing data is not generated during most of time. But if sensor nodes detect target movement, the burst data is generated. In this environment, it is desirable for each node to operate in ultra low duty cycle in order to increase energy efficiency. Moreover, the burst data should be delivered to one sink node quickly. AS-MAC in ultra low duty cycle can solve the overhearing problem and reduce per-hop latency.

In the following, Section 2 describes related work. Section 3 explains the AS-MAC protocol design in detail. Section 4 will present analysis and performance evaluation. The conclusion will be followed by section 5.

Ⅱ. RELATED WORK

S-MAC [3] is a representative synchronous MAC protocol. S-MAC is a RTS-CTS based MAC protocol that makes use of synchronization between nodes to allow for duty cycling in sensor networks. At the beginning of the active period, the node exchanges synchronization information with its neighbors to assure that the node and its neighbors wake up concurrently. This schedule is only adhered to locally, resulting in a virtual cluster, which mitigates the need for synchronization of all nodes in networks. Nodes that lie on the border of two clusters maintain the schedules of both clusters, which maintain connectivity across the network. After the synchronization information is exchanged, the nodes send data packets using RTS-CTS until the end of the active period and then the nodes enter sleep mode. The active period includes two contention intervals for exchanging synchronization information and RTS-CTS packets. The size of contention interval is proportional to the number of neighbors because of the same listening schedule. Therefore the cost of listening for an entire contention interval is considerable in terms of energy. Moreover, the long active period limits duty cycles to a few percent or more.

B-MAC [5] is an asynchronous MAC protocol. B-MAC is a CSMA-based technique utilizing a long preamble to achieve low power communication. Each node has an independent schedule. If a node has data, it sends the data packet following with a long preamble that is slightly longer than the sleep period of the receiver. During the active period, a node samples the channel and if a preamble is detected, it remains awake to receive the data. With the long preamble, a sender is assured that at some point during the preamble the receiver will wake up, detect the preamble, and remain awake in order to receive the data. It is low power listening (LPL). The major advantage of LPL is that it minimizes active period when there is no traffic. While B-MAC performs quite well, it suffers the overhearing problem and the long preamble results in considerable energy usage of sender and increases per-hop latency.

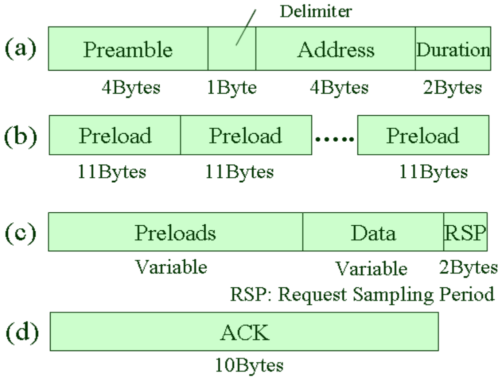

Fig. 1 (a) Preload message format and (b) Preloads frame format and (c) Data frame format, (d) ACK frame format

The overhearing problem is that receivers who are not the target of the sender also wake up during the long preamble and have to stay awake until the end of the preamble to find out if the packet destined for them. This wastes energy at all non-target receivers within transmission range of the sender. The energy consumption of overhearing is proportional to the channel sampling period. Therefore, overhearing problem is serious in ultra low duty cycle. Because the target receiver has to wait for the full before receiving the data packet, the per-hop latency is lower bounded by the preamble length. Over a multi-hop path, this accumulated latency can become quite considerable in ultra low duty cycle.

Ⅲ. AS-MAC PROTOCOL DESIGN

AS-MAC is designed for enhanced performance in burst traffic environment. In this situation, a MAC algorithm operates in long sampling period and has to accommodate burst traffic. AS-MAC can efficiently support these two conflicting design factors; long sampling period for energy efficiency and burst traffic accommodation. AS-MAC works properly in WSN with dense or sparse node density and with low mobility. Data from all nodes is destined to a sink node in the network.

We summarize AS-MAC protocol design as bellows.

- Asynchronous protocol
- CSMA technique (carrier sensing)
- Channel sampling (LPL: Low Power Listening)
- Preload message and ACK packet
- Overhearing avoidance
- Flexible sampling period

3.1 Packet format and parameter design [7, 8]

3.1.1 Preload message

Fig.1 (a) shows the preload message format. The sender transmits the successive preload messages prior to data, which ensures that all nodes in independent schedules can communicate each other. Preamble is used by receiver nodes for chip and symbol synchronization. Delimiter indicates the start of address and duration field. Address field contains the destination address. Duration field informs the remaining time until the start of data.

3.1.2 Preloads frame

the preloads frame is consisted of successive preload messages. The preloads frame size is multiple of 11 byte preload message size (see Fig.1 (b)).

3.1.3 Preloads period

preloads period is the duration of preloads frame. Senders can change it according to data rate (see Fig.1 (c)).

3.1.4 Request Sampling Period (RSP)

If a node has burst sensing data to deliver to sink node, it requests the next forwarding node to change sampling period from the default value to the value indicated in RSP field. The forwarding nodes on multi-hop path also reduce their sampling period when they receive data frame with RSP field. Default sampling period is determined by the network management (see Fig.1.(d)).

3.2 Operation

3.2.1 Sender

Carrier sensing is performed to check channel activity at a sender node which has data to send (see Fig.2). If the channel is clear, the sender transmits the preloads frame during sampling period (initially, default sampling period) and data. The sender transmits the preloads frame as long as default sampling period in order to ensure the forwarding node's wake up. If the sender has burst data packets, it requests the receiver to reduce sampling period using RSP.

RSP field informs the forwarding node of the channel sampling period to be changed. How to determine channel sampling period is mentioned

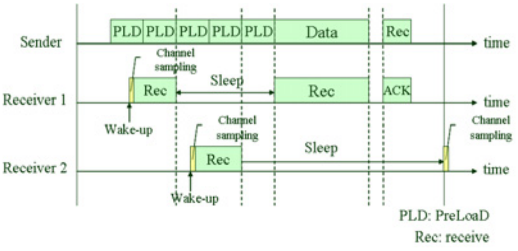

Fig. 2 AS-MAC operation

in section 4 (see Equation (26)). The sender should wait an ACK packet from the forwarding node after sending data frame. It tries to retransmit if the ACK packet is missing for the fixed time. In case that the sender uses RSP and receives ACK frame from receiver, it means the agreement for RSP, the sender should reduce preloads period to the duration specified by RSP value and receiver should reduce channel sampling period according to RSP value.

Each node acts as a forwarding node on one or more routing path and the channel sampling periods on each routing path may be different from each other. Thus, a node has to maintain a preloads table that includes the preloads period and the next forwarding node. When a node sends data to the next forwarding node, it transmits preloads frame as long as the time defined by the preloads period value in the associated table entry. If the sender transmits no data for fixed time to the receiver that changes the sampling period, the sender changes the preloads period to default value. The other table is also used when the node acts as the receiver to determine its channel sampling period.

3.2.2 Receiver

If a node (receivers in Fig. 2) doesn't have any data to send, it wakes up at every sampling time to check channel activity. If another node (sender in Fig. 2) is transmitting the preloads frame to send data packet, the receiver 1 recognizes channel state is active. Entering active mode, the receiver 1 takes the preload message

and identifies destination address. If the packet is targeted to receiver 1, it checks the Duration Value. The receiver 1 can immediately go to sleep mode and keep in this mode during the time indicated in Duration field. The receiver 1 has to wake up after designated duration to receive the preload message from sender. The node sends ACK packet to the sender after successful data packet reception.

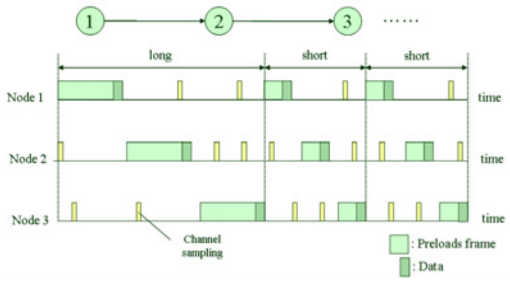

Fig. 3 Low latency in routing path

If data is followed by RSP field, the receiver 1 adds a new entry in the sampling table to save sender address and RSP value. Then it readjusts its sampling period. Only if newly requested sampling period is shorter than the recently used period, the sampling period is reduced to requested value. That is, a receiver always uses the smallest sampling period in the sampling table. If the node receives no data from the sender during fixed time, the entry of the sampling table is deleted. Receivers use default sampling period when no entry is existed in the sampling table.

3.3 Overhearing avoidance

In the existing asynchronous schemes, unnecessary energy consumption by overhearing is increased in proportion to sampling period length. In AS-MAC, this problem is solved by informing of destination address using repetitive preload messages transmission. In Fig. 2 Receiver 2 can identify the destination address of the packet after receiving just a single preload message packet. And those who are not the destination node can immediately enter sleep mode. The node which is designated to the forwarding destination node can also sleep because it can figure out exactly when data transmission is started. Therefore, all nodes in the sender's one hop transmission range save unnecessary energy consumption unlike existing schemes which have to receive long preamble.

3.4 Low latency solution

In ultra low data rate environment, high energy efficiency can be obtained using long sampling period, so called, ultra low duty cycle (below 0.1%). One hop delay for packet forwarding is also increased in proportion to sampling period. In this situation, burst traffic can not be quickly delivered in the multi-hop network. AS-MAC solves this latency problem by way that source node requests all forwarding nodes on the routing path to reduce a channel sampling period only when it has burst data packets to send. In Fig. 3 node 1, 2 and 3, the first data packet from source to sink may suffer rather large delay, but after that nodes on the routing path with reduced sampling period can forward successive packets quickly.

Ⅳ. ANALYSIS AND PERFORMANCE EVALUATION

We will analyze the expected power consumption of B-MAC (LPL) and AS-MAC. Our analysis is based on a single-hop network model. Consider a network of n + 1 nodes, where all nodes can hear each other directly, so each node has n neighbors. Each node generates one data packet every data packet period $1/r_{data}$. Here we consider unicast traffic. Each node is a sender and a receiver once data generation period. Our analysis focuses on the energy consumption by the radio, and we do not consider other components, such as the processor or sensors. There are five radio states: transmitting, receiving, listening, and sleeping. Each state consumes the power of P_{tx}, P_{rx}, P_{listen} and P_{sleep} respectively. Channel sampling is different from normal listening. We denote average sampling duration as t_{spl}, and its average power consumption as P_{sample}. It includes the time that the radio transitions from sleep to listen and the brief sampling time to detect channel activity. We ignore radio transition costs for other states. Based on the model, we derive the lower bounds of power consumption for both B-MAC (LPL) and AS-MAC.

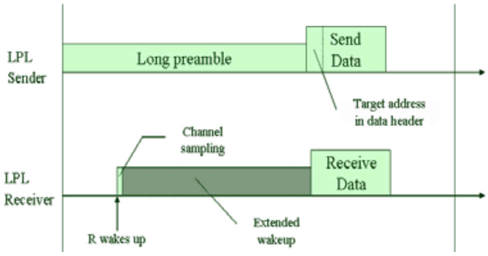

Fig. 4 Operation of B-MAC (LPL)

Both B-MAC (LPL) and AS-MAC are contention-based MACs, so transmission happens after carrier sensing. We denote the average time in carrier sense as t_{csl}. After the date is transmitted, the average time that the sender waits for the ACK packet is denoted as t_{scl}. The energy consumption of the radio is determined by how much time it spends in carrier sensing, transmitting the data frame, waiting for the ACK packet, transmitting/receiving the ACK packet, receiving the data frame, overhearing, sampling channel and sleeping. These are denoted as t_{cs}, t_{tx}, t_{sc}, t_{Ack}, t_{rx}, t_{over}, t_{sample} and t_{sleep} respectively. All these time values are normalized to one second.

In Table 1, all of our terms are summarized typical values by the Chipcon CC1000 [1] and

Table 1. Symbols used in radio energy analysis, and typical values for the Chipcon CC1000 and CC2500

Symbol	Meaning	CC1000	CC2500
P_{tx}	Power in transmitting	31.2mW	63.6mW
P_{rx}	Power in receiving	22.2mW	38.4mW
P_{listen}	Power in listening	22.2mW	38.4mW
P_{sleep}	Power in sleeping	3uW	1.2uW
P_{sample}	Power in channel sampling	7.4mW	9.6mW
t_{spl}	Avg. time to sample channel	3ms	3ms
t_{csl}	Avg. carrier sense time	7ms	7ms
t_{scl}	Avg. space time	0.2ms	0.2ms
t_B	Time to Tx/Rx 1byte	416us	416us
T_P	Channel sampling period	Varying	Varying
r_{data}	Data packet rate	Varying	Varying
L_{data}	Data packet length	50bytes	50bytes
$L_{preload}$	Preload message length	11bytes	11bytes
$L_{preloads}$	Preloads frame length	Varying	Varying
L_{SP}	RSP field length	2bytes	2bytes
L_{Ack}	ACK packet lengthl	10bytes	10bytes
n	Number of neighbors	Varying	Varying

CC2500 [2]. For both B-MAC (LPL) and AS-MAC, the expected power consumption per node is the sum of the expected power in each state:

$$E = E_{cs} + E_{tx} + E_{rx} + E_{over} + E_{sample} + E_{sleep} \tag{1}$$

We next derive the expected power consumption for both B-MAC (LPL) and AS-MAC.

4.1 B-MAC (LPL) analysis [5, 11]

B-MAC (LPL) sends a long preamble before each packet. The duration of the preamble is at least the same as the sampling period T_P. The preamble length is (see Fig. 4.)

$$L_{preamble} = T_P / t_B \tag{2}$$

where t_B is the time needed to transmit or receive a byte.

The expected power consumption of B-MAC (LPL) is

$$\begin{aligned} E_{LPL} &= E_{cs} + E_{tx} + E_{rx} + E_{over} + E_{sample} + E_{sleep} \\ &= P_{listen} t_{cs} + P_{tx} t_{tx} + P_{rx} t_{rx} + P_{rx} t_{over} \\ &\quad + P_{sample} t_{sample} + P_{sleep} t_{sleep} \end{aligned} \tag{3}$$

The normalized time of each state is demanded in due to (3).

The normalized time of carrier sense is

$$t_{cs} = t_{csl} r_{data} \tag{4}$$

where r_{data} is the data rate on each node. The normalized time of transmitting state is

$$\begin{aligned} t_{tx} &= \left(L_{preamble} + L_{data}\right) t_B r_{data} \\ &= \left(T_P + L_{data} t_B\right) r_{data} \end{aligned} \tag{5}$$

A node will periodically receive n packets from n neighbors. Among them, only one packet is destined for the node. The rest are the overhearing packets. The average time of the received preamble for each packet is $T_P/2$. The normalized time of receiving state is

$$t_{rx} = \left(T_P / 2 + L_{data} t_B\right) r_{data} \tag{6}$$

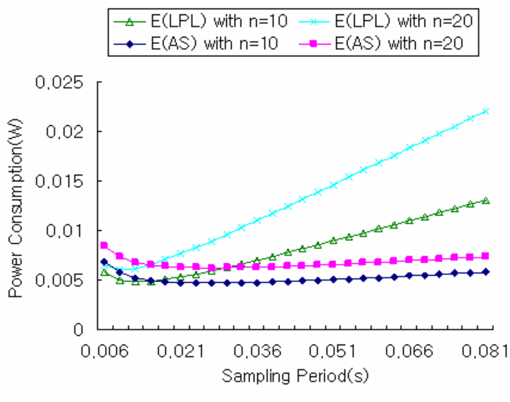

Fig. 5 Mean power consumption of AS-MAC and B-MAC (LPL) with rdata=1 and n=10, 20 as the sampling period varies

The normalized time of overhearing state is

$$t_{over} = (n-1)\left(T_P / 2\right) r_{data} \tag{7}$$

The normalized time of channel sampling state is

$$t_{sample} = t_{spl} / T_P \tag{8}$$

The normalized time of sleeping state is

$$t_{sleep} = 1 - t_{cs} - t_{tx} - t_{rx} - t_{over} - t_{sample} \tag{9}$$

Substituting Equations (4)~(9) into (3) and using Equation (2), we obtain the expected power consumption of B-MAC (LPL) as

$$\begin{aligned} E_{LPL} =& \left(P_{tx}\left(T_P + L_{data} t_B\right) + P_{rx}\left(n T_P / 2 + L_{data} t_B + t_{csl}\right)\right) r_{data} \\ & + P_{sleep}\left(1 - \left(t_{csl} + \frac{n+2}{2} T_P + 2 L_{data} t_B\right) r_{data} - t_{spl} / T_P\right) \\ & + P_{sample} t_{spl} / T_P \end{aligned} \tag{10}$$

Where $P_{rx}=P_{listen}$ is used in Equation (10).

Next we turn to the expected power consumption for AS-MAC.

4.2 AS-MAC analysis

First we derive the expected power consumption in each state from Equation (1). The expected power consumption in carrier sensing is

$$E_{cs} = P_{listen} t_{cs} \tag{11}$$

The energy consumption in transmitting state includes the energy spent for waiting and receiving ACK packet. The expected power consumption in transmitting state is

$$E_{tx} = P_{tx} t_{tx} + P_{listen} t_{sc} + P_{rx} t_{Ack} \tag{12}$$

Where tsc is the waiting time of the ACK packet. The t_{Ack} is the transmitting/receiving time of the ACK packet.

The expected power consumption in receiving state is

$$E_{rx} = P_{rx} t_{rx} + P_{listen} t_{sc} + P_{tx} t_{Ack} \tag{13}$$

The expected power consumption in overhearing state is

$$E_{over} = P_{rx} t_{over} \tag{14}$$

The expected power consumption in channel sampling is

$$E_{sample} = P_{sample} t_{sample} \tag{15}$$

The expected power consumption in sleeping state is

$$E_{sleep} = P_{sleep} t_{sleep} \tag{16}$$

Substituting Equations (11)~(16) into Equation (1) and using equation $P_{rx} = P_{listen}$. The expected power consumption of AS-MAC is

$$\begin{aligned} E_{AS} &= P_{rx}\left(t_{cs} + 2t_{sc} + t_{Ack} + t_{rx} + t_{over}\right) + P_{tx}\left(t_{tx} + t_{Ack}\right) \\ &\quad + P_{sample} t_{sample} + P_{sleep} t_{sleep} \end{aligned} \tag{17}$$

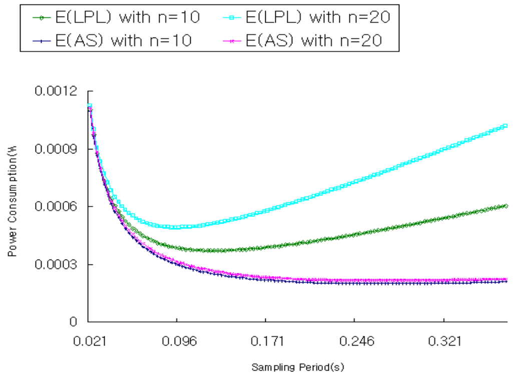

Fig. 6 Mean power consumption of AS-MAC and B-MAC (LPL) with rdata=0.01 and n=10, 20 as the sampling period varies

Next we will derive the normalized time in each state.

The preloads period is at least the same as the channel sampling period TP. The length of the preloads frame is $L_{pls} = T_P / t_B$.

The normalized time of carrier sense is equal to Equation (4).

The normalized time of transmitting state is

$$t_{tx} = (L_{pls} + L_{data} + L_{sp}) t_B r_{data} \tag{18}$$

The normalized time in waiting for ACK packet is

$$t_{sc} = t_{scl} r_{data} \tag{19}$$

The normalized time in transmitting/receiving the ACK packet is

$$t_{Ack} = L_{Ack} t_B r_{data} \tag{20}$$

The average length of the received preload for each data packet is $3L_{pl}/2$. The normalized time of receiving state is

$$t_{rx} = \left(\frac{3}{2} L_{pl} + L_{data} + L_{sp}\right) t_B r_{data} \tag{21}$$

The normalized time of overhearing state is

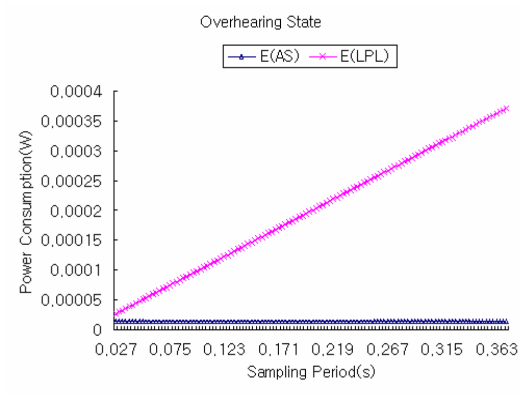

Fig. 7 Energy consumption of overhearing state with rdata=0.01 and n=10 as the sampling period varies

$$t_{over} = (n-1)\left(\frac{3}{2}L_{pl}\right)t_B r_{data} \tag{22}$$

The normalized time of channel sampling state is equal to Equation (8).

The normalized time of sleeping state is

$$t_{sleep} = 1 - t_{cs} - t_{tx} - t_{rx} - 2t_{sc} - 2t_{Ack} - t_{over} - t_{sample} \tag{23}$$

Substituting Equations (4), (8), (18)~(23) into Equation (17), the expected power consumption of AS-MAC is

$$\begin{aligned} E_{AS} = {} & P_{rx}\left[t_{csl} + 2t_{scl} + \left(\frac{3n}{2}L_{pl} + L_{data} + L_{sp} + L_{Ack}\right)t_B\right]r_{data} \\ & + P_{sample}t_{spl}/T_P + P_{tx}\left[\left(L_{data} + L_{sp} + L_{Ack}\right)t_B + T_P\right]r_{data} \\ & + P_{sleep}\left\{1 - \left(\frac{3n}{2}L_{pl} + 2L_{data} + 2L_{sp} + 2L_{Ack}\right)t_B r_{data}\right. \\ & \left. - \left(t_{csl} + 2t_{scl} + T_P\right)r_{data} - t_{spl}/T_P\right\} \end{aligned} \tag{24}$$

What is the optimal value T_P to minimize the energy consumption, given a fixed n and r_{data}? We can obtain the optimal value by solving the following equation.

$$\frac{dE_{AS}}{dT_P} = 0 \tag{25}$$

Substituting Equation (24) into (25), we find the optimal T_P for AS-MAC is

$$T_P^* = \sqrt{\frac{\left(P_{sample} - P_{sleep}\right)\cdot t_{spl}}{\left(P_{tx} - P_{sleep}\right)\cdot r_{data}}} \tag{26}$$

4.3 Performance evaluation

We compare the energy performance of AS-MAC and B-MAC (LPL) as the sampling period varies. With static traffic loads we can optimize each for maximum energy conservation. Fig.5 shows the power consumption per node in high traffic environment. This result reveals that B-MAC outperforms AS-MAC in low value of the sampling period, since AS-MAC uses the ACK packet for reliable communication. However as the sampling period increasing, the power consumption of B-MAC increases more rapidly than that of AS-MAC.

Fig.6 represents power consumption of AS-MAC and B-MAC (LPL) in low traffic environment. AS-MAC has better performance than B-MAC in all sampling period. The reason is that the overhearing problem of non-target nodes and the unnecessary energy consumption of the target node are mitigated in AS-MAC. The unnecessary energy consumption of the target node is reduced by duration field of preload message.

The energy consumption of the overhearing state is proportional to the sampling period in B-MAC (LPL). However AS-MAC has regular energy consumption of the overhearing state. The overhearing problem is related to the number of neighbors. The energy consumption by overhearing is increased according to the number of neighbors. Therefore, the destination address in preload message prevents the nodes within one hop to overhearing the long preamble.

That is, AS-MAC operates more energy efficient than LPL in ultra low duty-cycled situation (see Fig.7).

V. CONCLUSION

This paper describes AS-MAC, a new approach for low power communication in WSNs. AS-MAC employs successive preloads approach by transmitting a series of preload messages, each containing the address of the target node and remaining time until data transmission. The series of preload messages prevents non-target nodes from consuming energy in overhearing state.

Both flexible preloads period and sampling period can allow for lower latency. The preloads and sampling period of only nodes on the routing path is changed. In addition AS-MAC finds out the optimal value for preloads and sampling period that minimizes the power consumption per node.

We verified that AS-MAC outperforms traditional B-MAC (LPL) through analyzing the protocol. That is, AS-MAC operates more suitable for target monitor application than other existing schemes.

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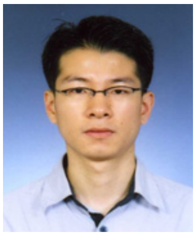
온 정 석 (Jeong-Seok On) 준회원



2005년 8월 연세대학교 전기전자공학과 졸업(학사)

2005년 9월~현재 연세대학교 전기전자공학과 통합과정

<관심분야> Wireless Senor Network Routing/MAC Protocol Design

김 재 현 (Jae-Hyun Kim) 정회원

1999년 광운대학교 전자공학과 (학사)

2003년 연세대학교 전자공학과 (석사)

2003년~2004년 4월 SK텔레텍 연구원

2004년~현재 연세대학교 전자공학 (박사과정)

<관심분야> 센서 네트워크

오 영 열 (Young-Yul Oh) 정회원

1993년 연세대학교 전자공학과(학사)
1995년 연세대학교 전자공학과(석사)
1999년 연세대학교 전자공학과(박사)
2007년 1월~현재 연세대학교 전기전자공학부 연구교수
<관심분야> 센서 네트워크

이 재 용 (Jai-Yong Lee) 종신회원

1977년 2월 연세대학교 전자 공학과 졸업
1984년 5월 IOWA State Univ. (공학석사)
1987년 5월 IOWA State Univ. (공학박사)
1987년 7월~1994년 8월 포항 공과대학 교수
1994년 9월~현재 연세대학교 전기전자공학과 교수
<관심분야> Protocol Design for Wired/Wireless QoS Management, Ubiquitous Sensor Network, Wireless Multimedia Support Protocol