Hindawi Publishing Corporation
International Journal of Distributed Sensor Networks
Volume 2012, Article ID 304329, 12 pages
doi:10.1155/2012/304329

Research Article

An Energy-Efficient MAC Protocol Employing Dynamic Threshold for Wireless Sensor Networks

Kyung Tae Kim and Hee Yong Youn

College of Information and Communication Engineering, Sungkyunkwan University, Suwon 440-746, Republic of Korea

Correspondence should be addressed to Hee Yong Youn, youn@ece.skku.ac.kr

Received 14 June 2012; Accepted 8 September 2012

Academic Editor: Yingshu Li

Energy efficiency is a critical issue for sensor network since the network lifetime depends on efficient management of the energy resource of sensor nodes. Particularly, designing energy efficient MAC protocol has a significant influence on the performance of wireless sensor network with regards to the energy. The existing MAC protocols developed for sensor network try to avoid energy waste during idle listening time by controlling the duty cycle of the transmission period. Since the traffic conditions are diverse, they may not always display improvements in energy consumption. In this paper we propose a new energy efficient MAC protocol called dynamic threshold MAC (DT-MAC), which employs a dynamic threshold for the buffer of each sensor node to maximize the energy efficiency regardless of specific network traffic condition. Here the packets are stored in the buffer, and then transmitted when the number of packets in the buffer exceeds the threshold dynamically decided according to the number of hops of the node from the source in the path of packet forwarding. The simulation results using OMNnet++ show that DT-MAC enables significant improvement in energy consumption compared to the existing MAC protocols. The proposed DT-MAC protocol also reduces the number of transmissions of control packets.

1. Introduction

Recent advances in low power integrated circuit devices, microelectromechanical system (MEMS) technologies, and communications technologies have allowed wide deployment of low-cost,low-power sensors which can be effectively integrated to build wireless sensor networks (WSNs).In general, WSNs consists of tiny sensor nodes forming an ad hoc distributed sensing and data propagation network while collecting the information on the physical environment [1–3]. It has been revolted quickly,and now extensively used in both military and civilian applications, that is, from battlefield surveillance system to modern highway and industry monitoring system, from the emergency rescue system to forest fire detection system, from the very sophisticated earthquake detection system to target tracking and security management. Each sensor node of a WSN has four basic components: sensing unit, processing unit, radio unit, and power unit [4, 5]. It has the capability for sensing, simple computation, data processing, and communication with neighboring sensor nodes. With their capabilities for monitoring the surroundings, the network can provide a fine global picture of the target area through the integration of the data collected from many sensors each providing a coarse local view [6–8].

The WSN applications have noticeably different characteristics and requirements from traditional wireless applications. A node in WSN is expected to be battery equipped, and changing or recharging the power supply is usually very difficult. Therefore, energy efficiency, which is essential for prolonging the lifetime of the sensor node and eventually the network, is a more critical performance metric than others such as throughput and latency adopted for traditional networks. Conserving battery power is a critical issue for WSN in order to maximize its lifetime, and many researchers have been focusing on the development of power saving schemes for WSNs. They include power saving hardware and topology design, power-efficient medium access control (MAC) layer protocol, network layer routing protocol, and so forth [9–20].

Communication in WSNs can be divided into several layers like other communication infrastructure, where one of them is MAC layer. It is described by a MAC protocol, which tries to ensure that no two nodes interfere with each other during communication using a proper coordination mechanism. In general, the main design goal of typical MAC protocols is to provide high throughput, minimized latency, fairness, and QoS (quality of service). Note that most sensor nodes are battery operated and they usually cannot be recharged due to the deployment in harsh and remote environment. Therefore, the MAC protocol for WSN needs to focus on energy efficiency. In other words, the primary design issue for the MAC protocol of WSN is how to support the basic functions of MAC protocol while minimizing energy consumption of the sensor nodes to maximize the lifespan of the network. Moreover, the topology of a WSN often changes dynamically as some nodes die and new nodes are added. The MAC protocol should readily accommodate such network dynamics.

The major sources of energy waste in a MAC protocol are the following [21–23].

(i) *Collision*: takes place when a sensor node receives more than one packet at the same time. A collision results in discarding and retransmission of the packets which boost the energy consumption.

(ii) *Control packet overhead*: size of the control packet used for control signaling should be as small as possible.

(iii) *Overhearing*: occurs when a node picks up the packets destined to other nodes.

(iv) *Idle listening*: listening to the medium for possible data flow, while energy consumption during idle listening dominates all other sources.

(v) *Overemitting*: takes place when a message is sent to the destination even though the receiving node is not ready to accept it.

Note that the major cause of energy waste in MAC protocol is idle listening. In IEEE 802.11, power consumption during idle listening is almost the same as for receiving or transmitting data packets, which is nearly 30% of the total energy consumption in WSN [17–19]. Reducing the idle listening period, thus, has been vigorously pursued, and several approaches have been proposed. Some of them are based on the manipulation of *duty cycle* [24]. Here the sensor nodes periodically turn off their radio and go into sleep mode, which directly shortens the idle listening period. Despite the improved duty cycle with this approach, data transmission with high energy efficiency is hard to achieve since it cannot properly reflect various traffic conditions including *error*, *delay*, and *goodput* [25].

In this paper we propose a new energy efficient MAC protocol, called dynamic threshold MAC (DT-MAC), which consistently performs well regardless of network traffic conditions. The proposed protocol stores the packets in the buffer and transmits them when the number of packets in the buffer exceeds a threshold value so that the energy efficiency can be maximized. The threshold value of the buffer in each node is dynamically decided according to the number of hops from the source in the path of packet forwarding. The effectiveness of DT-MAC is verified through analytical modeling and computer simulation using OMNeT++ [26]. They show that the proposed DT-MAC protocol provides significant improvement in energy consumption compared to the existing MAC protocols applied to the sensor network. In addition, the DT-MAC protocol reduces the number of transmissions of control packets and supports the QoS such as fairness among the nodes and high utilization of channel capacity.

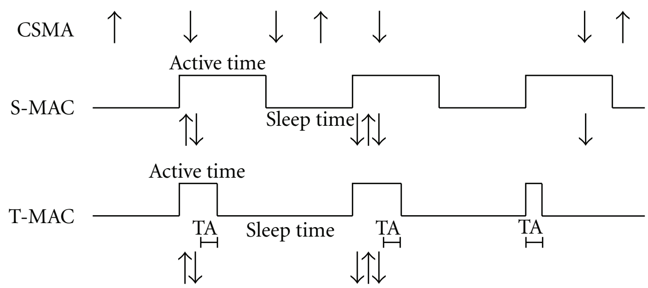

Figure 1: The duty cycles of S-MAC and T-MAC.

The rest of the paper is organized as follows. Section 2 presents the work related to the target research and defines the system model adopted in the DT-MAC protocol. In Section 3 the proposed DT-MAC protocol employing a dynamically adjusted buffer threshold is presented. Section 4 introduces the analytical modeling of the DT-MAC. The simulation results are presented in Section 5, and its performance is compared with two representative existing MAC protocols. We conclude the paper in Section 6.

2. Related Works

2.1. Energy Efficient MAC Protocols for WSN. Due to the energy-constrained environment, one of the most important issues in the design of WSN is energy efficiency. Various researches thus have been conducted regarding this issue. The major component consuming the energy in WSN is the radio communication such as packet transmission, reception, and idle listening. To minimize the energy consumption of the MAC protocol, an algorithm needs to be used which efficiently manages the wireless medium shared by the nodes constructing the network. Recently, a number of MAC protocols have been developed which explicitly target multi-hop sensor networks, including S-MAC [27] and T-MAC [28]. They focus on not only reducing the frequency of idle listening, but also collisions, protocol overhead, and overhearing.

S-MAC employs a contention-based approach with the modification on the IEEE 802.11 standard for sensor networks. It is a true MAC protocol, which also addresses the overheads caused by collision, overhearing, and protocol overhead [27]. As shown in Figure 1, S-MAC divides the time into frames, and each frame is divided into active and sleep periods.

During the sleep period, a node turns off its radio to preserve the energy. The ratio of active period to the frame length is called the duty cycle. During the active period, it can communicate with its neighbors and send the messages queued during the sleep period. Here communication occurs only during the active period. Since all messages are packed into the active period instead of being “spread out” over the whole frame, the time between the messages is reduced. Accordingly, the energy wasted during idle listening is also reduced. The exact energy saving depends on the application: the active period is usually fixed to 300 ms, while the frame length can be set to any value [29]. Consequently, the latency and throughput vary according to the application;

Even though S-MAC needs synchronization between the nodes, it is not as critical as with the TDMA-based protocols; the time scale is much larger for typical frame in the order of 300 ms to 1 second. S-MAC uses a technique called virtual clustering, in which the nodes periodically send special SYNC messages to be synchronized. These messages, transmitted at the start of a frame, also allow new (mobile) nodes to join the ad-hoc network.

The S-MAC protocol uses the RTS/CTS/DATA/ACK signaling scheme of IEEE 802.11 to reduce the number of collisions caused by the hidden node problem. It borrows the overhearing avoidance technique from the PAMAS protocol [30] but uses in-band signaling (i.e., overhearing RTS/CTS packets) since the target platform (i.e., Berkeley motes [31]) has only a single-frequency radio, as is the case for most prototype sensor nodes. Finally, S-MAC includes message passing support to reduce the overhead when streaming a sequence of message fragments.

Although S-MAC reduces the idle listening time, the employment of fixed duty cycle limits its efficiency. S-MAC basically trades the energy efficiency for throughput and latency. While a low duty cycle reduces idle listening time, it results in high latency and low throughput as only one data packet transmission occurs with a frame. On the other hand, if the duty cycle is high, the throughput and latency are improved at the expense of reduced energy efficiency.

T-MAC [28] was proposed to improve the performance of S-MAC under variable loads. T-MAC, as another contention-based protocol, uses an adaptive duty cycle to obtain higher energy efficiency unlike fixed duty cycle as in S-MAC. Similar to S-MAC, the nodes form a virtual cluster to synchronize themselves at the beginning of a frame. Instead of using a fixed-length active period, T-MAC employs the time-out mechanism to dynamically determine the end of the active period. The time-out value, TA, is set to span a small contention period and an RTS/CTS exchange. In T-MAC, the listen period ends if no event (such as sensing communication on the radio) occurs on the channel within a time limit, TA. The nodes keep renewing their time-out values whenever an activation event occurs. If no event occurs during the timeout period, the nodes go to sleep. Thus, TA determines the minimal length of idle listening period per frame. The lower limit of TA is $C + R + T$, where C is the length of contention interval, R is the length of an RTS packet, and T is the turn-around time, that is, the time between the end of reception of an RTS packet and the beginning of reception of the corresponding CTS packet. Receiving the start of the RTS or CTS packet from a neighbor triggers a renewed TA interval. In S-MAC the nodes go to sleep after overhearing an RTS or CTS packet destined to another node, which is called overhearing avoidance. If such overhearing avoidance mechanism is employed in T-MAC, the collision overhead will be higher since a node may miss the RTS and CTS packet while sleeping or disturbing the communication when it wakes up. Therefore, even though overhearing avoidance saves the energy, it is taken only as an option in the T-MAC protocol. Figure 1 compares the duty cycle of S-MAC and T-MAC, where the arrows indicate message transmission and reception.

The time-out approach makes the active period of T-MAC adaptive according to the traffic loads. As a result, T-MAC can balance the energy-throughput-latency trade-off better than S-MAC under a variety of traffic conditions. However, whenever an activation event occurs, all the nodes hearing the event renew their TA timer even though they are not part of the communication. As a result, the nodes still waste some energy.

The adaptive duty-cycle scheme allows T-MAC to effectively cope with the fluctuation in the network traffic, both in time (physical events trigger neighbor-to-neighbor communication) and space (the nodes close to the sink relay more traffic than edge nodes). S-MAC, on the other hand, operates with a single active time for all nodes, which must be chosen conservatively to handle worst-case traffic. The down side of T-MAC’s aggressive power-down policy, however, is that the nodes often go to sleep too early; when node-s wants to send a message to node-r but loses contention to a third node, node-n, which is not a common neighbor, node-s must remain silent and node-r goes to sleep. After node-n finishes the transmission, node-s sends an RTS packet to the sleeping node-r but receives no matching CTS packet. Hence, node-s needs to wait for the next frame and try again. T-MAC includes two measures to alleviate this so-called early-sleeping problem but nevertheless favors energy-saving over latency and throughput is much more stronger than S-MAC.

2.2. System Background. The network model adopted in this paper is a multihop sensor network. Assume that there are N nodes distributed randomly in the target area. The nodes can communicate with each other or send data to the sink using omnidirectional antennas. Each sensor is able to multicast, which means a sensor can send data to several nodes concurrently but not necessarily broadcast. The destined receivers are able to receive the desired packets while others filter them out at the physical layer [24, 32].

Each node has a fixed transmission radius and sensing range. A node receives a message if and only if it is within the transmission radius of the transmitting node. Each node resides in one of the two modes: sleep mode and active mode. During the active mode, the nodes can transmit and receive data or stay idle. All sensor nodes have the same parameter values of power consumption.

The size of each data packet is fixed. A large size packet is divided into smaller ones and transmitted separately. At each sensor node, there is a queue of packets waiting for

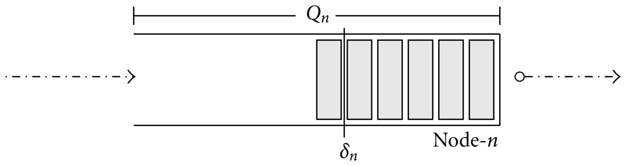

Figure 2: The structure of the buffer of a node.

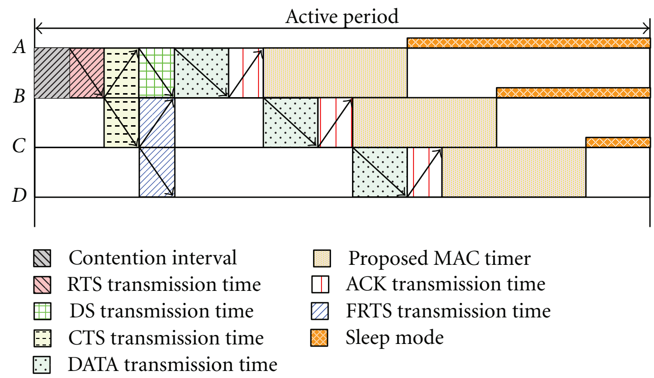

Figure 3: The operation flow of the DT-MAC protocol.

the transmission. The forwarded packets have higher priority than the ones generated by the node itself. When there is a packet to send, the node first sends a control packet to all the neighbors. Only the node whose network address is included in the control frame replies to it. The node then schedules the time for packet transmission and sends the packet in the scheduled time slot. The packet reaches the receiver after one round trip propagation delay. The receiver at the destination should have been tuned to the same channel to receive the packet. An ACK packet is sent once the packet is successfully received. If the sending node does not receive an ACK packet within a certain time limit, it retransmits the packet. It keeps retransmitting the packet until the transmission is acknowledged successfully or the retry time limit is exceeded. We next present the proposed DT-MAC protocol.

3. The Proposed DT-MAC Protocol

In this section we introduce the proposed DT-MAC protocol which transmits data with properly adjusted buffer threshold. DT-MAC redefines the timer used in T-MAC and employs a novel contention window dynamically adjusted based on the buffer status. DT-MAC substantially improves the energy efficiency compared with the existing MAC protocols and thus extends the network lifetime of WSNs.

3.1. Overview. To improve the energy efficiency of sensor network operating in various traffic conditions, the DT-MAC protocol transmits data if the buffer size exceeds the specified threshold value and reduces the number of control packets which cause extra energy consumption. The major features of the DT-MAC are as follows:

(i) dynamically adjusting the threshold of the buffer of each sensor node,

(ii) optimal setting of the threshold with respect to energy efficiency,

(iii) deciding the contention window based on the buffer status in each node,

(iv) redefining the timer for active mode,

(v) modifying the structure of control packet.

Figure 2 shows the structure of the buffer of a node in DT-MAC. Q_n and δ_n denote buffer size and buffer threshold of Node-n, respectively. As shown in Figure 2, data are transmitted when the accumulated data exceeds the threshold of the buffer.

The timer in DT-MAC is set to a smaller value than in T-MAC. In DT-MAC, the node switches to sleep mode when it does not detect any activity until the timer expires to maximize the energy efficiency. Whereas the efficiency of existing protocols degrades in some traffic conditions, DT-MAC consistently performs well using the dynamically adjusted buffer threshold.

3.2. Operation. To solve the hidden node problem and exposed node problem of wireless networks, the nodes send and receive the RTS/CTS packet before data transmission. However, the transmission overhead of RTS/CTS packet can increase if data are transferred via several hops. DT-MAC uses the FRTS (Future RTS) packet to reduce the transmission overhead of RTS/CTS packet.

The basic operation of the DT-MAC is explained using an example of four nodes (Node-A, -B, -C, -D) connected in the linear topology (Node-A first and Node-D last) as shown in Figure 3. The basic procedure of DT-MAC is as follows.

(i) If the size of accumulated data in the buffer of Node-A (Q_A) is smaller than its threshold ($Q_A < \delta_A$), Node-A triggers the timer. If it does not receive RTS, CTS, or FRTS packet from the neighboring nodes until the timer expires, it enters sleep mode.

(ii) If $Q_A \geq \delta_A$, Node-A transmits an RTS packet to Node-B.

(iii) After Node-B receives an RTS packet, it transmits a CTS packet to Node-A and Node-C by broadcasting.

(iv) After Node-C receives a CTS packet from Node-B, it reserves a channel by sending an FRTS packet to Node-D. Here, Node-D receiving the FRTS packet is able to send or receive data with only Node-C.

(v) The transmission of Node-C may affect Node-B. When Node-C transmits an FRTS packet to Node-D, collision occurs if Node-A sends data to Node-B. To avoid this, Node-A sends a DS (data-send) packet to Node-B while Node-C transmits an FRTS packet to Node-D. Here, the DS packet contains no data but it is used for only avoiding any collision between the nodes.

(vi) After Node-A transmits a DS packet, it sends data packet to Node-B.

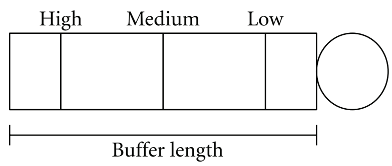

Figure 4: The three threshold levels.

(vii) During the transmission of data packet from Node-*A* to Node-*B*, Node-*D* can reserve a channel by sending an FRTS packet to the next node. However, DT-MAC limits the reservation of channel up to Node-*D* for not significantly degrading the channel utilization.

(viii) Node-*B* receiving the data packet from Node-*A* sends an ACK packet to Node-*A*. After that, Node-*B* immediately transmits the data packet to Node-*C* without an exchange of RTS/CTS packet.

(ix) Node-*C* forwards the data packet to Node-*D* like Node-*B*.

DT-MAC significantly improves data transmission delay and energy efficiency by reserving the channel using the FRTS packet. However, the nodes receiving an FRTS packet are not able to use the channel because it cannot send or receive data with other nodes not participating in the current session. Therefore, the number of hops the FRTS packet is allowed to take should be limited. In this paper it is set to one. Consequently, the number of hops an RTS packet can take is limited to three.

3.3. Contention Window. In DT-MAC protocol developed for contention-based communication, each node transmits the data if the accumulated data exceeds the specified threshold of the buffer. However, due to the contention-based communication, the node failing to earn the medium cannot transmit data although the buffered data exceeds the threshold. Therefore, in DT-MAC the threshold of a buffer is classified into three levels—HIGH, MEDIUM, and LOW—as shown in Figure 4.The threshold level of a buffer and contention window are changed depending on the length of the buffer. The priority of a buffer, α, is decided according to the threshold level such that it is 0.9, 0.7, and 0.5, for the threshold level of HIGH, MEDIUM, and LOW, respectively. Note that the more data in the buffer, the higher the priority is. The contention window (CW) is adjusted according to the priority to enhance the fairness between the nodes.

Let r denotes the number of retransmissions. Then $\mathrm{CW} = (\mathrm{CW}_{\min} \times 2_r)$ is defined as the contention window increasing exponentially according to the number of retransmissions.Here, $\mathrm{CW}_{\min}$ is the minimum value of contention window. The length of CW, t_{cw}, is defined as

$$t_{\mathrm{cw}} = \lfloor (1-\alpha) \times \mathrm{CW} \times \mathrm{RAN}() \rfloor \times \text{slot time}. \tag{1}$$

Here RAN() is a random value between 0 and 1.

3.4. Timer. In DT-MAC the sensor nodes check the amount of accumulated data in the buffer and transfer data only when it is larger than the threshold. The FRTS packet is used to reserve a channel required for multi-hop packet transfer. It can reduce data transmission delay and power consumption.

To reduce unnecessary idle listening time after data transmission, T-MAC uses a timer defined in (2) to switch to sleep mode and conserve the energy if there is no data received during t_T

$$t_T = \mathrm{CW} + T_{\mathrm{RTS}} + T_{\mathrm{SIFS}}. \tag{2}$$

Here, T_{RTS} is the transmission time of an RTS packet and T_{SIFS} is the short time interval between the end of the RTS and the beginning of the CTS packet. T_{SIFS} is identical to SIFS (short interframe space) of 802.11 MAC. Similarly, the timer for DT-MAC, t_P, is

$$t_P = T_{\mathrm{RTS}} + T_{\mathrm{CTS}} + T_{\mathrm{FRTS}}, \tag{3}$$

where T_{RTS}, T_{CTS}, and T_{FRTS} are the transmission time of RTS packet, CTS packet, and FRTS packet, respectively. With the DT-MAC the data are transferred for three hops as a unit, and the timer counts after the contention period. Since the timer length is shorter than that of T-MAC protocol, DT-MAC can reduce the waste of energy due to idle listening.

3.5. Buffer Threshold. In DT-MAC the threshold of the buffer in each node is determined for maximizing the lifetime of the network. Assume that there are N nodes in the target region, which are connected in the linear topology as shown in Figure 5.

Here λ_i and γ_i are the arrival rate of sensed data and relayed data, respectively, and δ_i is the threshold of node$_i$ ($\delta_i \geq 1$). The maximum cumulative buffer size, B, is expressed by the following equation:

$$\sum_{i=1}^{n} \delta_i \leq B. \tag{4}$$

The packet arrival rate of node$_i$ per round, $f(i)$, is as follows:

$$\begin{aligned} f(i) &= \lambda_i + \gamma_i, \\ f(1) = \lambda_1, \qquad f(2) &= \lambda_2 + f(1), \ldots, f(n) \\ &= \lambda_n + f(n-1) \\ (\gamma_1 = 0, \gamma_2 &= \lambda_1 + \gamma_1, \ldots, \gamma_n = \lambda_{n-1} + \gamma_{n-1}). \end{aligned} \tag{5}$$

The energy consumption of node$_i$ per round is defined by (6)

$$E(i) = \frac{C}{\delta_{i-1}} \cdot f(i-1) + \frac{R}{\delta_i} \cdot f(i) + D f(i), \tag{6}$$

where C and R are the length of the CTS and RTS packets, respectively, and D is the size of the data.

Here, in order to maximize the network lifetime, the buffer threshold of the nodes needs to be decided to minimize the energy consumption of the node, which consumes the largest energy among the nodes. It is represented as follows:

$$\min_{\delta_1 \delta_2 \cdots \delta_n} \left\{ \max_{1 \leq i \leq n} \{E(i)\} \right\}. \tag{7}$$

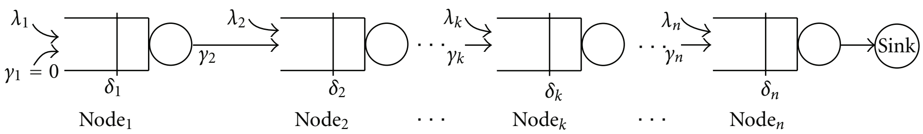

Figure 5: The nodes in linear topology.

Theorem 1. *In* (7), $\max_{1\le i\le n}\{E(i)\}$ *is equal to* $E(n)$, *the energy consumption of the last node.*

Proof. Assume that $E(k)$ is the largest. Using (6), $E(k) > E(k+1)$ can be represented as

$$\begin{aligned}\frac{C}{\delta_{k-1}}\cdot f(k-1)+\frac{R}{\delta_k}\cdot f(k)+Df(k) &> \frac{C}{\delta_k}\cdot f(k)\\ &\quad+\frac{R}{\delta_k}\cdot f(k+1)+Df(k+1),\\ \frac{C}{\delta_{k-1}}\cdot f(k-1)+D\cdot\left(f(k)-f(k+1)\right) &> \frac{R}{\delta_\kappa}\cdot f(k-1).\end{aligned} \tag{8}$$

Because $f(x) = f(x-1)+\lambda_x$ $(\lambda_x \ge 1)$,

$$\frac{C}{\delta_{k-1}}\cdot f(k-1) - D\cdot\lambda_{k+1} > \frac{R}{\delta_{k+1}}\cdot f(k+1). \tag{9}$$

Note that the size of CTS packet is similar to that of RTS packet, while data packet is usually larger than control packet. Therefore, we assume that $C = R$ and $D = iC$ (i is a positive integer). Equation (9) then becomes

$$\frac{f(k-1)C}{\delta_{k-1}} - \lambda_{k+1}iC > \frac{f(k+1)C}{\delta_{k+1}}. \tag{10}$$

The topology is linear and the sensed data are generated constantly in each node. Thus, $f(i) = i$. With $\lambda_{k+1} = 1$,

$$\frac{k-1-i\delta_{k-1}}{\delta_{k-1}} > \frac{k+1}{\delta_{k+1}}. \tag{11}$$

Since $\delta_{k-1} \ge 1$, $\delta_{k+1} \ge 1$, and $k-1-i\delta_{k-1} > 0$, $k > i\delta_{k-1}+1$, $k > i\delta_k$. Finally,

$$k < \delta_k \Longrightarrow E(k) < E(k+1). \tag{12}$$

Thus, when k is smaller than $i\delta_k$, energy consumption of the last node is the highest.

$$\max_{1\le k\le n}\{E(k)\} = E(n). \tag{13}$$

For example, if the ratio of control packet and data packet is 1 : 10, energy consumption of the last node of a 10-node topology is the highest. Therefore,

$$\min_{\delta_1\delta_2\cdots\delta_n}\left\{\max_{1\le i\le n}\{E(i)\}\right\} = \min_{\delta_1\delta_2\cdots\delta_n}\{E(n)\}. \tag{14}$$

Combining (13) and (14),

$$\min_{\delta_1\delta_2\cdots\delta_n}\left\{\frac{C}{\delta_{n-1}}f(n-1)+\frac{R}{\delta_n}f(n)+Df(n)\right\}. \tag{15}$$

In (15), $Df(n)$ is for data packet, and it is not affected by the buffer threshold. Therefore, the object function to be minimized without $Df(n)$ is

$$\overline{E} = \frac{C}{\delta_{n-1}}f(n-1)+\frac{R}{\delta_n}f(n). \tag{16}$$

$\overline{E}$ becomes minimal when δ_{n-1} and δ_n are maximum. Therefore, the maximum δ_{n-1} and δ_n need to be found considering the size of the buffer.

Recall that $\sum_{i=1}^{n}\delta_i \le B$ by (4). If δ_i $(1 \le i \le n-2) = 1$, $\delta_{n-1} = B-\delta_n-(n-2)$. The δ_n value minimizing $\overline{E}$ is represented as

$$\begin{aligned}\min_{\delta_1\delta_2\cdots\delta_n}\left\{\overline{E}\right\} = \min_{\delta_1\delta_2\cdots\delta_n}\Bigg\{&\frac{C}{B-\delta_n-(n-2)}\cdot f(n-1)\\ &+\frac{R}{\delta_n}\cdot f(n)\Bigg\}.\end{aligned} \tag{17}$$

The optimal threshold, δ_n^*, is as follows:

$$\delta_n^* = \frac{B-N+2}{1+\sqrt{(R/C)\cdot\left(f(n-1)/f(n)\right)}}. \tag{18}$$

□

4. Numerical Analysis

In this section we analyze the performance of the DT-MAC protocol in terms of active time, data transmission delay, energy efficiency, and channel efficiency, which are the key factors in designing sensor network. Table 1 lists the parameters used in the analysis.

4.1. Active Time. We first compare the lengths of active time of the protocols since most energy is consumed during active period of each sensor node. For this, we analyze the active time of S-MAC, T-MAC, and DT-MAC under relatively low traffic condition which is expected in real situation. Recall that S-MAC uses fixed duty cycle. Therefore,the length of active time increases in proportion to the total time.The total active time of S-MAC protocol, $TA_{\text{S-MAC}}$, is

$$TA_{\text{S-MAC}} = \sum_i\left(S_{F_i}\times S_{C_i}\right) = \sum_i\left(T_{\text{off}_i}-T_{\text{on}_i}\right). \tag{19}$$

T-MAC protocol is classified into two cases. One case with no data to be transmitted with the probability of ρ

$$TA^{\rho}_{\text{T-MAC}} = \rho\times TO_T \tag{20}$$

and the other case that data exist with the probability of r

$$TA^{r}_{\text{T-MAC}} = r\times(T_l - T_{\text{on}}) + TO_T. \tag{21}$$

Table 1: The list of the parameters.

Parameter	Meaning
S_F	Frame length of S-MAC
S_C	Duty cycle of S-MAC
TA	Total active time
T_{on}	Time the radio is ON per frame
T_{off}	Time the radio is OFF per frame
TO_T	Timeout interval of T-MAC
TO_{DT}	Timeout interval of DT-MAC
T_l	Transmission time of packet during active time
$r = (1-\rho)$	Probability that data exist in active time with T-MAC
P	Probability that $\delta_n < n_p$ (n_p is the number of packets in the buffer)
Q	Probability of $0 \le n_p < \delta_n$ and no RTS packet received with DT-MAC
$t_{\text{cont},n}$	Average of the contention window in nth hop
$t_{\text{DT-cont},n}$	CW of nth hop with DT-MAC
T_{CTS}	Transmission time of CTS packet
T_{data}	Transmission time of DATA packet
T_{ack}	Transmission time of ACK packet
E_{tx}	Energy consumption for packet transmission per time unit
E_{rx}	Energy consumption for packet reception per time unit
E_{idle}	Energy consumption during idle listening per time unit
N_{ideal}	The number of hops that can be reserved with an RTS/CTS packet with S-MAC and T-MAC
N_{DT}	The number of hops that can be reserved with an RTS/CTS packet with DT-MAC
C	Channel capacity of the DT-MAC

After the SYNC section of an active period, if no event occurs until the timer expires, the node returns to sleep mode. Thus, the total active time of the T-MAC protocol, $TA_{\text{T-MAC}}$, is (where, $r+\rho=1$)

$$\begin{aligned} TA_{\text{T-MAC}} &= \sum_i \left(TA^r_{\text{T-MAC}_i} + TA^\rho_{\text{T-MAC}_i}\right) \\ &= r\sum_i \{(T_{l_i} - T_{\text{on}_i}) + TO_{T_i}\} \; + \rho\sum_i TO_{T_i}. \end{aligned} \tag{22}$$

DT-MAC protocol has three cases. If the probability that $\delta_n \le n_p$ is p, then

$$TA^p_{\text{DT-MAC}} = p\{(T_l - T_{\text{on}}) + TO_{\text{DT}}\}. \tag{23}$$

Assume that $0 \le n_p < \delta_n$. If an RTS packet is not received with the probability of q, then

$$TA^q_{\text{DT-MAC}} = q \times TO_{\text{DT}}, \tag{24}$$

when an RTS packet is received and packets are transmitted to a neighbor node with the probability of $1-p-q$, then

$$TA^{1-p-q}_{\text{DT-MAC}} = (1-p-q) \times \{(T_l - T_{\text{on}}) + TO_{\text{DT}}\}. \tag{25}$$

The total active time of the DT-MAC, $TA_{\text{DT-MAC}}$, is given by

$$\begin{aligned} TA_{\text{DT-MAC}} &= \sum_i \left(TA^p_{\text{DT-MAC}_i} + TA^q_{\text{DT-MAC}_i} + TA^{1-p-q}_{\text{DT-MAC}_i}\right) \\ &= p\sum_i \{(T_{l_i} - T_{\text{on}_i}) + TO_{\text{DT}_i}\} + q\sum_i (TO_{\text{DT}}) \\ &\quad + (1-p-q)\sum_i (T_{l_i} - T_{\text{on}_i}) + TO_{\text{DT}_i}. \end{aligned} \tag{26}$$

DT-MAC protocol has shorter transmission time and timer than T-MAC protocol. Also, it has different active time because r is smaller than p. In T-MAC, the case that the node does not participate in the transmission ($n_p = 0$) is the case of not receiving any packet from other node. This case with DT-MAC protocol is $0 \le n_p \le \delta_n$. Therefore, r is smaller than p. Active time with S-MAC protocol increases according to the number of frames because its active time is fixed. However, active time with T-MAC and DT-MAC protocol depends on the packet transmission rate because it varies with the timer.

4.2. Data Transmission Delay. In this subsection data transmission delay of each protocol is analyzed. The elements of delay are contention window for priority contention, back-off delay for retransmission, transmission delay for transmission, propagation delay, processing delay, and queuing delay in the buffer [33]. In this paper, we assume that one

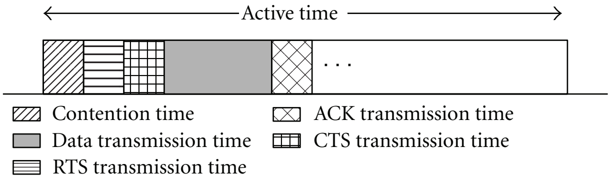

Figure 6: Packet transmission during active period.

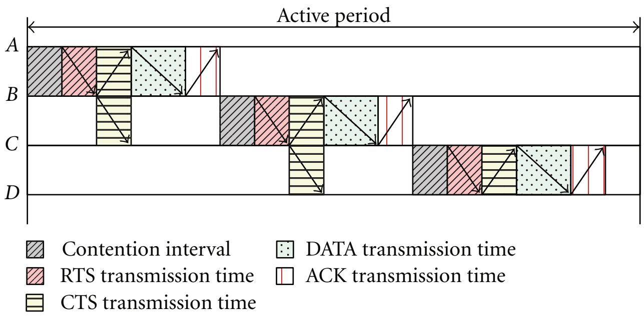

Figure 7: Packet switching with S-MAC protocol.

hop packet transfer delay is one unit time and traffic volume is small. The propagation delay, processing delay, queuing delay, and back-off delay are not considered since they are all common in the three protocols compared, and the start of a frame is assumed to be in the active section.

In S-MAC and T-MAC, the maximum number of hops that a data packet can be transmitted in one frame depends on the active time, TA. It is obtained as follows:

$$N = \left\lfloor \frac{TA}{t_{\text{cont},n} + 2(T_{\text{RTS}} + T_{\text{CTS}}) + T_{\text{data}} + T_{\text{ack}}} \right\rfloor. \tag{27}$$

Figure 6 shows the timing of packet transmission in active period based on the expression of (27). When data are transferred between two nodes of one hop distance, delay occurs due to contention window and transmission time of the control packet (RTS/CTS packet). Also, transmission time of data and ACK packet are needed. Indeed, the number of hops allowed during the active period is determined by the time taken for the transmission of data and control packet.

Figure 7 shows packet transmission covering three hops with S-MAC protocol. A diagram similar to Figure 6 also works for T-MAC protocol. One aspect different from S-MAC protocol is, however, that switching to sleep mode occurs quicker than S-MAC when there is no event in active period with the timer is on.

If data can be transmitted for n-hops in one frame period, data transmission delay of S-MAC and T-MAC protocol, $D_{\text{ST-MAC}}$, is represented as

$$\begin{aligned} D_{\text{ST-MAC}} &= \sum_{n-1}^{N} D_n \\ &= \sum_{n-1}^{N} t_{\text{cont},n} + N(2(T_{\text{RTS}} + T_{\text{CTS}}) + T_{\text{data}} + T_{\text{ack}}). \end{aligned} \tag{28}$$

On the other hand, in DT-MAC protocol, the number of hops that can be reserved with an FRTS packet is one. Therefore, data transmission delay in DT-MAC, $D_{\text{DT-MAC}}$, is given by

$$\begin{aligned} D_{\text{DT-MAC}} = \sum_{n-1}^{N} (& k_n t_{\text{DT-cont},n} + 3k_n(T_{\text{RTS}} + T_{\text{CTS}}) \\ & + T_{\text{data}} + T_{\text{ack}}), \end{aligned} \tag{29}$$

$$k_n = \begin{cases} 1, & n = 1, 4, 7, 10 \cdots \\ 0, & \text{otherwise.} \end{cases}$$

In DT-MAC, the number of hops covered by an RTS packet is limited to three. Therefore, the delay caused by the control packet occurs only once per three hops. All the hops except the first one are allowed without an exchange of RTS/CTP packet.

4.3. Control Packet Overhead. In terms of energy efficiency, the control packet overhead is one of main factors in wireless sensor networks. DT-MAC employs a modified structure of control packet to minimize the amount of unnecessary traffic. As a result, it can reduce energy consumption and data transmission delay compared to the existing protocols.

In S-MAC and T-MAC, CPO (control packet overhead) for n-hop data transmission is $2n$. DT-MAC can transmit data for three hops with an RTS packet using the FRTS packet. The control packet overhead thus can be reduced.

CPO for n-hop transmission with DT-MAC is represented as

$$\text{CPO} = \sum_{n-1}^{N} k_n,$$

$$k_n = \begin{cases} 3, & n = 1, 4, 7, 10, \dots \\ 1, & n = 2, 5, 8, 11, \dots \\ 0, & \text{otherwise.} \end{cases} \tag{30}$$

Equation (30) can be simplified into

$$\text{CPO} = 3\left\lfloor \frac{N+2}{3} \right\rfloor + \left\lfloor \frac{N+1}{3} \right\rfloor. \tag{31}$$

4.4. Energy Consumption. In analyzing the energy consumption of the protocols compared, the nodes are assumed that they cannot be switched to sleep mode before receiving the data.

In S-MAC protocol, when data are transmitted n-hops during one frame duration, the energy consumption, $E_{\text{S-MAC}}$, is

$$\begin{aligned} E_{\text{S-MAC}} = {} & N(2(T_{\text{RTS}} + T_{\text{CTS}}) + T_{\text{data}} + T_{\text{ack}})(E_{\text{tx}} + E_{\text{rx}}) \\ & + (N-1)(T_{\text{RTS}} + T_{\text{CTS}})E_{\text{rx}} \\ & + \left[\sum_{n-1}^{N} t_{\text{cont},n} + 2(t_A - T_{\text{set1}}) + (N-1) \right. \\ & \left. (t_A - T_{\text{set1}} - (T_{\text{RTS}} + T_{\text{CTS}})) \right] E_{\text{idle}}. \end{aligned} \tag{32}$$

Here, T_{set1} is $2(T_{\text{RTS}} + T_{\text{CTS}}) + T_{\text{data}} + T_{\text{ack}}$.

In T-MAC protocol, data can be transmitted up to 3 hops in one frame period. Therefore, energy consumption for N-hop transmission with T-MAC is

$$\begin{aligned} E_{\text{T-MAC}}(N) &= N(2(T_{\text{RTS}}+T_{\text{CTS}})+T_{\text{data}}+T_{\text{ack}})(E_{\text{tx}}+E_{\text{rx}}) \\ &\quad + (N-1)(T_{\text{RTS}}+T_{\text{CTS}})E_{\text{rx}} \\ &\quad + \Bigg[\sum_{k=1}^{N+1}\sum_{n-1}^{k} t_{\text{cont},n} - t_{\text{cont},N+1} + (N+1)TO_T \\ &\qquad + (N-1)(T_{\text{set1}} - (T_{\text{RTS}}+T_{\text{CTS}})) \\ &\qquad + \frac{(N-1)(N-2)}{2}T_{\text{set1}}\Bigg]E_{\text{idle}}. \end{aligned} \tag{33}$$

In the DT-MAC protocol data can be transmitted up to three hops for fixed active period. Therefore, when data are transmitted n-hops in m-frame period, the consumed energy, $E_{\text{DT-MAC}}$, becomes

$$\begin{aligned} E_{\text{DT-MAC}}(N) &= \left(3\left\lfloor\frac{N+2}{3}\right\rfloor + \left\lfloor\frac{N+1}{3}\right\rfloor\right)(T_{\text{RTS}}+T_{\text{CTS}})E_{\text{tx}} \\ &\quad + \left(2\left\lfloor\frac{N+2}{3}\right\rfloor + N\right)(T_{\text{RTS}}+T_{\text{CTS}})E_{\text{rx}} \\ &\quad + N(T_{\text{data}}+T_{\text{ack}})(E_{\text{tx}}+E_{\text{rx}}) \\ &\quad + \Bigg[\text{NTO}_{\text{DT}} + (N+1)t_{\text{cont},1} \\ &\qquad + \sum_{l=1}^{\lfloor(N-1)/3\rfloor}\sum_{n=3l+1}^{N}(n=3l+1)t_{\text{cont},3l+1} \\ &\qquad + \sum_{n=1}^{N-1}\left\lfloor\frac{n}{3}\right\rfloor T_{\text{set2}} + \left(2\left\lfloor\frac{N+1}{3}\right\rfloor + \left\lfloor\frac{N}{3}\right\rfloor\right) \\ &\qquad \times (T_{\text{RTS}}+T_{\text{CTS}}) \\ &\qquad + \sum_{n=1}^{N}\left(\left\lfloor\frac{n}{3}\right\rfloor + \left\lfloor\frac{n-1}{3}\right\rfloor\right)(T_{\text{data}}+T_{\text{ack}})\Bigg]E_{\text{idle}}. \end{aligned} \tag{34}$$

In (34), T_{set2} is $3(T_{\text{RTS}}+T_{\text{CTS}})+T_{\text{data}}+T_{\text{ack}}$.

4.5. Channel Efficiency. With the existing protocols, the nodes do not immediately transmit the received data to the next node until the exchange of RTS/CTS packet is over. However, the proposed FRTS packet enables continuous transmission with a single RTS/CTS packet. The node receiving the FRTS packet, however, needs to reserve the resource and cannot transmit its own data. As a result, the channel utilization may be reduced. In this paper, thus, we assume that a node can reserve the channel up to maximum three hops by the rate of use of channel defined in

$$C = \frac{N_{\text{ideal}}}{N_{\text{DT}}} \times 100. \tag{35}$$

Table 2: The parameters used in the simulation.

Parameter	Values
Energy consumed for transmission	10 mA
Energy consumed for reception	4 mA
Energy consumed during sleep mode	20 μA
Control packet	8 Bytes
DATA packet	100 Bytes
SYNC packet	10 Bytes
Frame time	610 ms
Time out	15 ms
Contention time	9 ms

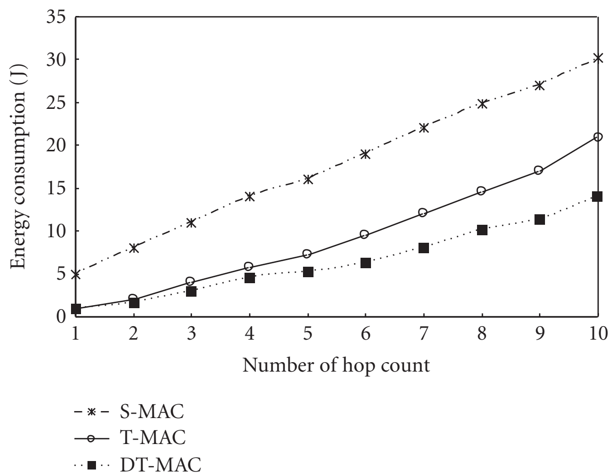

Figure 8: The comparison of energy consumptions of the three protocols.

5. Performance Evaluation

In the previous section the DT-MAC protocol was compared with S-MAC and T-MAC protocol by analyzing the data transfer delay, control packet overhead, and energy required for transmission. In this section we present the results of computer simulation to evaluate and compare the performance of the DT-MAC operating in realistic environment. For the simulation, OMNeT++ discrete event simulation package [26] is used. The data for S-MAC and T-MAC are quoted from the corresponding paper published. The parameter values chosen for the simulations are summarized in Table 2.

One of the merits of the DT-MAC is the reduction of energy consumption in each node. Figure 8 shows the energy consumed to transmit one data packet with S-MAC, T-MAC, and DT-MAC. Observe from the figure that, when the data are transmitted for 10-hops, energy consumption of the DT-MAC is approximately 48% and 68% of S-MAC and T-MAC protocol, respectively. DT-MAC efficiently uses the active time like T-MAC. It, however, further saves the energy by reducing the number of control packets.

Figure 9 shows the transmission delays as the number of hops of transmission varies. As shown in the figure, data transmission delay of the DT-MAC is decreased

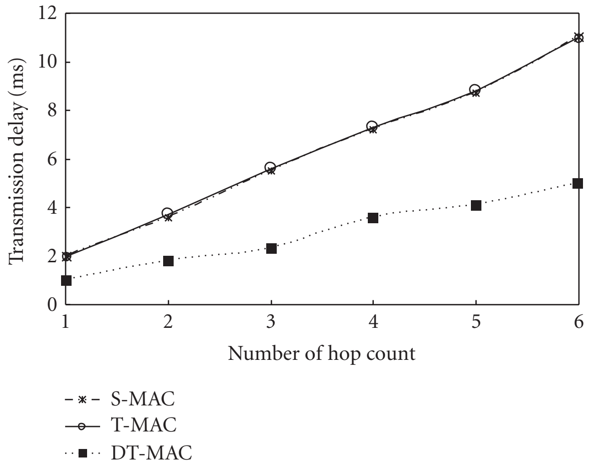

FIGURE 9: The comparison of transmission delays of the three protocols.

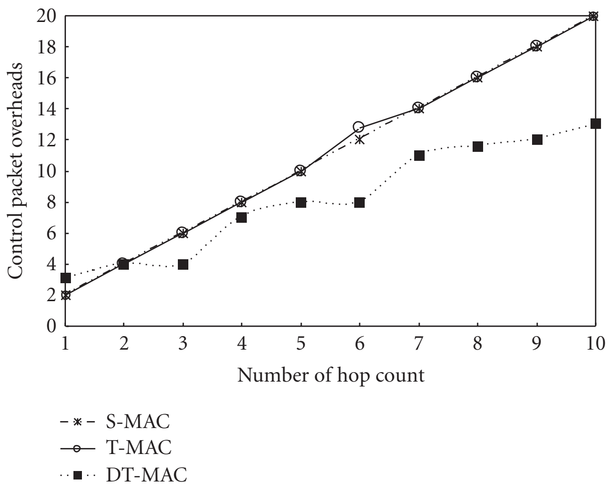

FIGURE 10: The comparison of control packet overheads.

approximately 55% compared to S-MAC and T-MAC when a data packet is transmitted for 6 hops. This is achieved by decreasing the transmission time of RTS/CTS packet.

Figure 10 shows the number of control packets transmitted with each of the MAC protocols. As shown in Figure 10, DT-MAC requires smaller number of transmissions of control packets than the other two protocols, and the difference gets larger as the number of hops increases. The transmission of control packets is one of the primary energy consumption factors in MAC protocol for wireless sensor networks. Therefore, the energy consumption with DT-MAC will be smaller than that of the existing protocols.

Figure 11 shows the relationship between the channel utilization and the number of reserved hops with the FRTS packet. The channel utilization is checked based on two-hop reservation with one RTS/CTS packet such as S-MAC and T-MAC. As shown in Figure 11, when the number of hops increases, channel utilization is decreased even though the energy efficiency is enhanced.

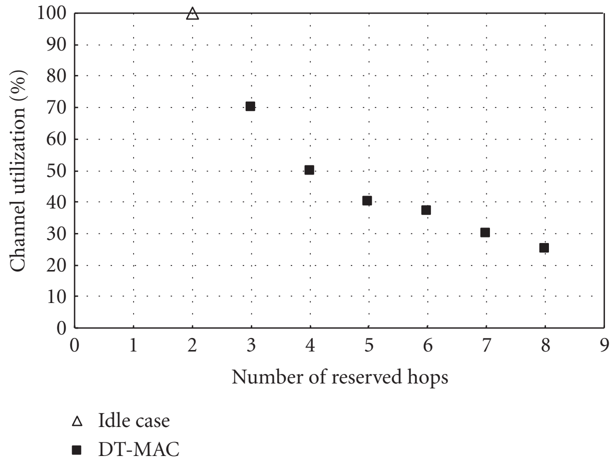

FIGURE 11: The channel efficiency versus the number of reserved hops.

As shown above, DT-MAC protocol provides higher energy efficiency than S-MAC and T-MAC protocol because it reserves the channel with the FRTS packet. Moreover, fairness among the nodes is provided using a threshold value of the buffer by letting the nodes hold the packets until the data exceeds the threshold. However, the number of hops reserved by the FRTS packet is set to a relatively small number since reserving resources for multiple hops can decrease channel utilization.

6. Conclusion and Future Work

Wireless sensor networks are used in a variety of applications which require continuous monitoring and detection of events. They are used in industrial, medical, consumer, and military applications. Sensor nodes are constrained by battery lifetime which cannot be recharged or replaced. Therefore, energy efficiency is the most important design factor in wireless sensor networks.

Energy consumption can be minimized by designing energy efficient MAC protocols since they have a large impact on the efficiency of wireless sensor networks. Designing MAC protocols for wireless sensor networks raises a distinctive set of challenges. Even though the research field of wireless sensor networks and in particular the MAC protocols is relatively new, there exist numerous MAC protocols proposed in the literature designed specifically for wireless sensor networks.

In this paper we have proposed a new energy efficient MAC protocol, called dynamic threshold MAC (DT-MAC), which employs a dynamically adjusted threshold for the buffer of sensor node. It was designed to display consistent performance for various network traffic conditions. In addition, DT-MAC reduces the number of control packets by transmitting data up to three hops with only one RTS/CTS packet. As a result, DT-MAC can improve the energy efficiency which is one of critical issues of MAC protocol for sensor networks in addition to the QoS including fairness among the nodes, channel utilization, delay, and so forth.

We have compared the performance of S-MAC, T-MAC, and DT-MAC by numerical analysis and computer simulation with OPNET. The results have shown that the DT-MAC protocol significantly outperforms the S-MAC and T-MAC protocols in terms of energy efficiency and control packet overhead. Also, it decreases the average end-to-end delay using enhanced control packet structure and timer.

In the future we are planning to extend the proposed DT-MAC protocol for supporting more sophisticated operational environment. Also, we will develop a scheme which can achieve the target performance without degrading the channel utilization.

Acknowledgments

This research was supported by DAPA and ADD (UD10070MD), the second Brain Korea 21 project, and Korea Association of Industry, Academy and Research Institute (C0017380), and Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (Grant no. 2012R1A1A2040257).

References

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[2] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, "Wireless sensor networks for habitat monitoring," in *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, pp. 88–97, Atlanta, Ga, USA, September 2002.

[3] C. Pandana, Ph.D. thesis, University of Maryland, College Park, 2005.

[4] D. Kumar, T. C. A. Patel, and R. B. Patel, "Prolonging network lifetime and data accumulation in heterogeneous sensor networks," *International Arab Journal of Information Technology*, vol. 7, no. 3, pp. 302–309, 2010.

[5] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Transactions on Wireless Communications*, vol. 1, no. 4, pp. 660–670, 2002.

[6] M. H. Jo, H. Y. Youn, S. H. Cha, and H. S. Choo, "Mobile RFID tag detection influence factors and prediction of tag detectability," *IEEE Sensors Journal*, vol. 9, no. 2, pp. 112–119, 2009.

[7] D. Li, K. D. Wong, Y. H. Hu, and A. M. Sayeed, "Detection, classification, and tracking of targets," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 17–29, 2002.

[8] K. T. Kim, H. K. Yoo, B. H. Son, and H. Y. Youn, "An energy efficient clustering scheme for self-organizing distributed wireless sensor networks," in *Proceedings of the 10th IEEE International Conference on Computer and Information Technology (CIT)*, pp. 1468–1473, Bradford, UK, July 2010.

[9] R. Min, M. Bhardwaj, S. H. Cho et al., "Energy-centric enabling technologies for wireless sensor networks," *IEEE Wireless Communications*, vol. 9, no. 4, pp. 28–39, 2002.

[10] M. Jo, H. Y. Youn, and H. H. Chen, "Intelligent RFID tag detection using support vector machine," *IEEE Transactions on Wireless Communications*, vol. 8, no. 10, pp. 5050–5059, 2009.

[11] M. I. Brownfield, T. Nelson, S. Midkiff, and N. J. Davis IV, "Wireless sensor network radio power management and simulation models," *The Open Electrical and Electronic Engineering Journal*, vol. 4, pp. 21–31, 2010.

[12] A. C. Santos, F. Bendali, J. Mailfert, C. Duhamel, and K. M. Hou, "Heuristics for designing energy-efficient wireless sensor network topologies," *Journal of Networks*, vol. 4, no. 6, pp. 436–444, 2009.

[13] C. Li, M. Ye, G. Chen, and J. Wu, "An energy-efficient unequal clustering mechanism for wireless sensor networks," in *Proceedings of the IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS)*, pp. 604–613, Washington, DC, USA, November 2005.

[14] O. Younis and S. Fahmy, "HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Transactions on Mobile Computing*, vol. 3, no. 4, pp. 366–379, 2004.

[15] E. H. Jung, S. H. Lee, J. W. Choi, and Y. J. Park, "A cluster head selection algorithm adopting sensing-awareness and sensor density for wireless sensor networks," *IEICE Transactions on Communications*, vol. 90, no. 9, pp. 2472–2480, 2007.

[16] K. T. Kim and H. Y. Youn, "PEACH: proxy-enable adaptive clustering hierarchy for wireless sensor networks," in *Proceedings of the International Conference on Wireless Networks (ICWN'05)*, pp. 52–56, June 2005.

[17] M. K. Jha, A. K. Pandey, D. Pal, and A. Mohan, "An energy-efficient multi-layer MAC (ML-MAC) protocol for wireless sensor networks," *AEU—International Journal of Electronics and Communications*, vol. 65, no. 3, pp. 209–216, 2011.

[18] S. Ray, I. Demirkol, and W. Heinzelman, "ADV-MAC: advertisement-based MAC protocol for wireless sensor networks," in *Proceedings of the 5th International Conference on Mobile Ad-hoc and Sensor Networks (MSN'09)*, pp. 265–272, Fujian, China, December 2009.

[19] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Transactions on Networking*, vol. 12, no. 3, pp. 493–506, 2004.

[20] S. N. Parmar, S. Nandi, and A. R. Chowdhury, "Power efficient and low latency MAC for wireless sensor networks," in *Proceedings of the 3rd Annual IEEE Communications Society on Sensor and Ad hoc Communications and Networks (Secon'06)*, pp. 940–944, Reston, Va, USA, September 2006.

[21] A. Roy and N. Sarma, "Energy saving in MAC layer of wireless sensor networks: a survey," in *Proceedings of the National Workshop in Design and Analysis of Algorithm (NWDAA)*, Tezpur University, Assam, India, 2010.

[22] I. Demirkol, C. Ersoy, and F. Alagöz, "MAC protocols for wireless sensor networks: a survey," *IEEE Communications Magazine*, vol. 44, no. 4, pp. 115–121, 2006.

[23] C. Ceken, "An energy efficient and delay sensitive centralized MAC protocol for wireless sensor networks," *Computer Standards and Interfaces*, vol. 30, no. 1-2, pp. 20–31, 2008.

[24] Y. Z. Zhao, M. Ma, C. Y. Miao, and T. N. Nguyen, "An energy-efficient and low-latency MAC protocol with adaptive scheduling for multi-hop wireless sensor networks," *Computer Communications*, vol. 33, no. 12, pp. 1452–1461, 2010.

[25] S. Tilak, N. B. Abu-Ghazaleh, and W. Heinzelman, "Infrastructure tradeoffs for sensor networks," in *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications(WSNA'02)*, pp. 49–58, Atlanta, Ga, USA, 2002.

[26] A. Varga, "The OMNeT++ discrete event simulation system," in *Proceedings of the European Simulation Multiconference (ESM'01)*, pp. 319–324, Prague, Czech Republic, 2001.

[27] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM)*, vol. 3, pp. 1567–1576, 2002.

[28] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems (SenSys'03)*, pp. 171–180, November 2003.

[29] G. P. Halkes, T. van Dam, and K. G. Langendoen, "Comparing energy-saving MAC protocols for wireless sensor networks," *Mobile Networks and Applications*, vol. 10, no. 5, pp. 783–791, 2005.

[30] S. Singh and C. S. Raghavendra, "PAMAS—power aware multi-access protocol with signalling for ad hoc networks," *ACM SIGCOMM Computer Communication Review*, vol. 28, no. 3, pp. 5–26, 1998.

[31] http://webs.cs.berkeley.edu/tos/.

[32] M. Stojmenovic and A. Nayak, "Localized routing with guaranteed delivery and a realistic physical layer in wireless sensor networks," *Computer Communications*, vol. 29, no. 13-14, pp. 2550–2555, 2006.

[33] W. Ye, J. Heidemann, and D. Estrin, "Medium acess control with coordinated adaptive sleeping for wireless sensor networks," USC/ISI Technical Report ISI-TR-567, 2003.