Energy-Aware MAC Protocol to Extend Network Lifetime in Asynchronous MAC-Based WSNs

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SUMMARY In Wireless Sensor Networks (WSNs), sensor nodes consume their limited battery energy to send and receive data packets for data transmission. If some sensor nodes transmit data packets more frequently due to imbalance in the network topology or traffic flows, they experience higher energy consumption. And if the sensor nodes are not recharged, they will be turned off from the lack of battery energy which will degrade network sustainability. In order to resolve this problem, this paper proposes an Energy-aware MAC Protocol (EMP), which adaptively decides on the size of the channel polling cycle consisting of the sleep state (not to communicate with its target node) and the listening state (to awaken to receive data packets) according to the network traffic condition. Moreover, in accordance with the remaining energy state of the sensor node, the minimum size of the channel polling cycle is increased for better energy saving. For performance evaluation and comparison, we develop a Markov chain-based analytical model and an event-driven simulator. Simulation results show that a sensor node with EMP effectively reduces its energy consumption in imbalanced network condition and traffic flows, while latency somewhat increases under insufficient remaining energy. As a consequence, a holistic perspective for enhanced network sustainability can be studied in consideration of network traffic condition as well as the remaining energy states of sensor nodes.

key words: wireless sensor networks, network sustainability, IEEE 802.15, asynchronous MAC, remaining energy

1. Introduction

Recently, widespread instances of Wireless Sensor Networks (WSNs) have appeared such as monitoring systems, tracking systems, mobile robot, mobile intelligent car, etc. [1], and thereby WSNs have gained worldwide attention with the proliferation in Micro-Electro-Mechanical Systems (MEMSs) technology, which has facilitated the development of smart sensors. In particular, sensor nodes inevitably consume their limited battery energy for normal operation to send and receive sensor data packets; that is to say, their remaining energy is going to be reduced. Among the above applications, limited battery-based applications such as enemy-monitoring robots and blood-travelling robots use finite batteries as their only power source for sensor nodes, and thus energy efficiency is one of the crucial design factors to support applications of WSNs. As efforts to enhance energy efficiency, several types of protocols have been proposed as a way of extending the lifetime of WSNs pertaining to deployment protocols of components in WSNs (e.g., the coordinators and sensor nodes) [2], [3], routing [4], [6]–[8], Medium Access Control (MAC) protocols [9]–[18], and data aggregation [19].

In particular, in asynchronous MAC protocols, which are a sort of the representative MAC protocols, a sensor node operates with the channel polling cycle (i.e., duty cycle), which consists of the sleep state (not to communicate with its target node) and the listening state (awaken periodically to receive data packet from its associated sender). Since how to set the size of the sleep state (defined as the sleep interval) and the size of the listening state (defined as the listening interval) can decide energy saving gain and the latency of data transmission according to network traffic, it is of great importance to manipulate those in the channel polling cycle. Additionally, as some sensor nodes transmit data packets more frequently due to their earlier energy depletion, they inevitably suffer from more energy consumption; hence they can be turned off earlier than other sensor nodes. This means that the network sustainability can be degraded due to their different termination time of normal operation; namely, it is difficult to effectively support applications of WSNs. In particular, in a situation that they could not be recharged, it is imperative to control energy consumption even though latency must be sacrificed. For example, once enemy-monitoring robots are arbitrarily distributed in the enemy area, it is almost impossible to recharge the robots. Therefore, when the sensor nodes operate under insufficient remaining energy state, intensive energy conservation is required for maintaining their normal function.

Putting into consideration the remaining energy state, some studies with respect to routing (so called energy-aware routing) were conducted [5]–[8] by exploiting alternative paths including the nodes with sufficient energy. It, however, is impossible to create its positive effect when there is only one path. Thus, it is imperative to efficiently manage the remaining energy state in the viewpoint of a single node. The legacy energy-efficient MAC protocols [9]–[18] have just focused on increase of energy efficiency but not management of the remaining energy [5], [21]. Therefore, in order to complement the inadequacy of the energy-aware routing protocols and provide a new holistic energy management perspective, this paper proposes an Energy-aware
MAC Protocol (EMP) in asynchronous MAC-based WSNs, which considers network traffic condition and controls energy consumption of sensor nodes according to the variation of the remaining energy state of operating sensor nodes. For performance evaluation, we develop a Markov chain-based analytical model and event-driven computer simulator. The results show that a sensor node under the EMP effectively reduces their own energy consumption in tandem with the reduction of their remaining energy states, while enduring the latency increasing under insufficient remaining energy. Thanks to the controlled energy consumption, the EMP can maintain a more similar level of the lifetimes of the sensor nodes in the network than other MAC protocols; this implies that it is possible to extend the lifetime of the network.

The remainder of this paper is organized as follows. Section 2 makes explanations of synchronous and asynchronous MAC protocols for highlighting the need of efficient energy management. Section 3 presents the detailed operation of the proposed EMP. A Markov chain-based analytical model is then presented in Sect. 4. In Sect. 5, the effectiveness of our proposal is shown during the overall operations of sensor nodes with analytical and simulation results. It mainly focuses on the aspect of the variations of performance metrics and network sustainability. Finally, Sect. 6 concludes this study with its remarkable contribution.

2. Related Work

In this section, we present the related works regarding energy-efficient synchronous and asynchronous MAC protocols as the representative MAC protocols. Since energy conservation is a primary concern within WSNs, we concentrate on the energy saving features of these protocols, and then consideration for efficiently managing the remaining energy states of sensor nodes is described for enhancing network sustainability.

2.1 Synchronous MAC

To begin with, let us observe the synchronous MAC protocols, which synchronize the node in WSNs by identifying the sleep and awake state cycle among the sensor nodes in order to limit the idle listening and overhearing caused by the cycle mismatch. On the other hand, the protocols should exchange synchronization packets frequently and make the sensor nodes awake at the moment although there is no packet to receive or transmit, so that they can waste battery energy.

As an initial approach, a cluster-based S-MAC [16] was proposed, which periodically lets sensor nodes transition to the sleep state if they are not involved in any type of communication. It can reduce not only the idle state not to communicate with its target node but the listening state. This concept is similar with the IEEE 802.11 sleep-mode [22] and IEEE 802.16e power-saving mechanism [23], where each sensor node wakes up in the beginning of each beacon interval to check whether it needs to become the awake state or not. In the S-MAC, sensor nodes exchange synchronization and scheduling information with their associated neighboring sensor nodes in the beginning of each listening state. Thus, the S-MAC makes it possible to let two neighboring sensor nodes become the listening and sleep states simultaneously for forming a virtual cluster by keeping a short channel polling cycle; hence each sensor node can conserve energy consumption. On the other hand, the S-MAC still has some flaws on the following aspects: firstly, its short channel polling cycle may result in a long latency for data transmission. Secondly, as the sensor nodes are included in a virtual cluster and scheduled simultaneously, it is fastidious about optimizing all of the associated sensor nodes based on network traffic condition.

As an extension of the S-MAC, an adaptive channel polling cycle-based T-MAC [17] was proposed. Under the T-MAC, sensor nodes in the listening state will not go to the sleep state until there is no activity for a predefined time. Although the T-MAC achieves better energy conservation than the S-MAC, it inevitably suffers from the early sleeping problem, because the potential receivers transit to the sleep state too early. Therefore, even though the T-MAC finds a way of determining the active duration of sensor nodes, it still experiences a long latency for data transmission.

The D-MAC [18] is another protocol that uses an adaptive channel polling cycle. By staggering active times along the data-gathering tree in a Point to MultiPoint (P2MP) communications model, it can achieve better performance in the latency, throughput, and energy conservation compared to the S-MAC. However, like the S-MAC and the T-MAC, the D-MAC still has to wake up all of the sensor nodes at every channel polling cycle; under a low level of network traffic condition, sensor nodes did remain the idle state in most of channel polling cycles.

2.2 Asynchronous MAC

Secondly, let us observe the asynchronous MAC protocols, which are based upon the long preamble transmission mechanisms to ensure the correct reception of data packets. Unlike the synchronous MAC protocols, each sensor node goes to the sleep and listening states independently among the sensor nodes. As a result, the unsynchronized MAC protocols are simpler than the synchronous MAC protocols because the processing and memory resources for data transmission can be smaller and save battery energy by avoiding unnecessary awakening and synchronization packet exchange under less network traffic condition.

As an initial type, the B-MAC [12] was proposed. Fundamentally, it adopts Low Power Listening (LPL) as a preamble sampling technique for low power communications in order to determine whether communication is in progress or not. The LPL allows a sensor node to access the medium without turning its transceiver to full power. The B-MAC operates with two parameters, the channel polling cycle (=sleep interval + listening interval) and the preamble length, which are directly related to LPL and are set
prior to network deployment. In the B-MAC, the length of
time between the channel polling interval and the preamble
length are equal and fixed. Therefore, even though it does
not schedule data transmission unnecessarily and synchron-
ize the sensor nodes, it could not outperform synchronous
MAC protocols.

On the other hand, the Wise-MAC [15] also utilizes
similar techniques like the B-MAC on the aspect of opera-
tion. However, in the Wise-MAC, a receiver notifies its as-
associated sender of the time of its next awake period through
an extra field in the ACKnowledgment (ACK) packet. With
this information, the sender can start the preamble just be-
fore the receiver wakes up. Then, the consumed energy can
be reduced when long preambles are sent at the expense of a
field in each ACK packet and memory space can be saved to
record the sender’s schedules. Thus, the Wise-MAC solves
overhearing of preambles.

The X-MAC [9] is an improved protocol over the Wise-
MAC. The long preamble in the B-MAC is replaced by a
series of short preambles in the X-MAC, which are sepa-
rated by small pauses. The pauses make the target receiver
finish the preamble earlier by sending an early ACK. Each
short preamble contains a target address, which alleviates
overhearing of data for unrelated sensor nodes.

Recently, the ContikiMAC [10] is proposed, which
adapts phase-lock optimization from the Wise-MAC and
multiple copies of the data packets as a wake-up strobe from
many algorithms [11] without signalling messages and ad-
ditional packet headers. Although the ContikiMAC reduces
energy consumption by utilizing RSSI signal to judge a data
transmission, deciding RSSI threshold value and recogniz-
ing a sending node among multiple sending nodes are not
mere.

Most of all, a demerit of aforementioned the Wise-
MAC, the X-MAC, and the ContikiMAC is that it is un-
able to adapt to changing network traffic condition. Thus,
considering network traffic condition, the Boost-MAC [13]
was proposed for dynamically setting the channel polling
cycle and preamble length with their exponential increase
and decrease. Also, S. Lee [14] developed the analysis
of low power listening schemes such as the Boost-MAC.
Boost-MAC aims to suit WSNs with constant communica-
tion patterns and bursty networks throughout network life-
time. For example, in a network with constant communica-
tion patterns, the channel polling cycle would reach a
value that fluctuated around the ideal, and network lifetime
would be extended for the traffic scenario. On the other
hand, in a network with bursty communication patterns, the
channel polling cycle would become large during periods
of inactivity, and quickly decrease during times of activity.
Through manipulating channel polling cycles and pream-
bles sizes, the Boost-MAC experiences better power-saving
gains than the Wise-MAC and the X-MAX, especially in the
realm of bursty networks. Also, both parameters are set lo-
cally on each sensor node without any communication and
synchronization overhead with other sensor nodes. As a re-
sult, the Boost-MAC can mitigate the cost of transition be-
tween short and long channel polling cycles, and hence it
can cope with fluctuating levels of network activity. Nev-
evertheless, the Boost-MAC did not consider the remaining
energy state of sensor nodes.

2.3 Need for Efficient Management of the Remaining En-
ergy States of Sensor Nodes

The aforementioned MAC protocols have considered how to
increase energy efficiency of WSNs by efficiently manipu-
lating the size of channel polling cycle but not put into con-
sideration the remaining energy state. To the best of our
knowledge, there have been only such a consideration in
routing protocols [6]–[8]. In order to enhance network in-
tegration among sensor nodes, a robust connectivity-aware
routing protocol [6] was proposed; it deliberates the remain-
ing energy states of sensor nodes by making upper bound
of energy consumption of sensor nodes. In addition, an
energy-aware routing protocol [7] was proposed for wire-
less industrial sensor networks in order to guarantee real-
time and reliable communications. It also considers a trade-
off relationship among energy cost, delay and reliability of
a path to the sink node. As one of the representative rout-
ing protocols mostly focusing on controlling the remaining
energy states of sensor nodes, an energy aware multi-tree
routing protocol [8] was proposed in order to prevent early
energy depletion of certain sensor nodes that are normally
the crucial routers of the network. However, in spite of
the efforts to avert the early energy exhaustion of the par-
ticular sensor nodes, the routing protocols will confront a
limitation to look for a substitute if there is no other path;
thus, there is only one cluster node for data trans-
mission from the end nodes to the sink node in clustered
sensor network architecture [19]. As one of the alternative
solutions for the aforementioned problems, there have been
a remaining energy-aware management mechanism pertaining
to data aggregation [21]. Consequently, the studies to
get over the energy depletion problem in viewpoint of the
MAC layer protocol are also required to enhance network
sustainability.

3. Proposed Energy-Aware MAC Protocol (EMP)

3.1 Problem Statement

Fundamentally, sensor nodes operate with their limited bat-
tery energy and recharging is not available in some network
environments. Thus, efficient management of their remain-
ing energy state needs to be checked for keeping normal op-
eration to send and receive sensor data packets. As opera-
tion time passes, their remaining energy will be decreased,
and hence the importance of energy conservation increases
[20]. In particular, if some sensor nodes transmit data pack-
ets more frequently, they could suffer from earlier remaining
energy depletion. Thus, it is impossible to support WSN ap-
lications due to the earlier turning off of the sensor nodes,
and thereby the network sustainability degrades. Therefore,
a policy of controlling remaining energy state is compulsory for enhanced network sustainability.

3.2 System Design

Before starting to explain the operation of the EMP, we will present our available system design for the EMP, shown in Fig. 1. Fundamentally, like the Boost-MAC, the EMP needs the synchronization of the channel polling cycles among sensor nodes [14]; we thus adopt a clustered sensor network architecture [19]. The system consists of a monitoring computer, which connects with a coordinator and multiple clustering sensor nodes (i.e., the number of N nodes). The clustering sensor nodes are connected to multiple sensor nodes (i.e., the number of M end nodes). The clustering sensor node is functionally the same as the end node, but it turns on and off frequently to deliver data messages of coordinator node and end nodes. The data transmission is requested by the monitoring computer and the request message is transmitted from the monitoring computer to the target sensor nodes (end nodes). After the target sensor nodes receive the request, their sensor data packet is transmitted to the monitoring computer as a response via coordinator node and clustering sensor node.

3.3 Operation Description of the EMP

Now, we will explain how the EMP operates with Fig. 2 in details. It is assumed that \( T_{\text{cur}} \) is the current channel polling interval, \( T_{\text{MIN}} \) is the minimum value of the channel polling interval, \( T_{\text{MAX}} \) is the maximum value of the channel polling interval, \( T_{\text{min}} \) is the newly manipulated low bound value of the channel polling interval in consideration of the remaining energy state of the sensor node, \( M \) is a constant standing for the stage of the channel polling interval, \( R_{\text{cur}} \) is the ratio of the current remaining energy state of the sensor node, and \( V_{\text{st}} \) is the state value of controlling the \( T_{\text{min}} \). The aforementioned parameters are initialized before starting normal operation. After that, the sensor node operates under the asynchronous MAC protocol by repeatedly transition between the channel polling interval and listening interval; the channel polling interval is exponentially increased from \( T_{\text{min}} \) to \( T_{\text{MAX}} \). The EMP is applicable when the sensor node reaches the beginning time of the next channel polling interval. The following three steps are the main operation of the EMP. Firstly, Step 1 is to reflect network traffic condition in updating the value of \( T_{\text{cur}} \) under receiver perspective. Thus, the EMP is built on the top of the Boost-MAC in order to take the merits of the Boost-MAC that is adaptive manipulation of \( T_{\text{cur}} \). Next, Step 2 is to consider the remaining energy state of an operating sensor node by updating the value of \( T_{\text{min}} \) under power management perspective. After that, it is possible to achieve a target performance by controlling energy consumption and the latency. Lastly, Step 3 is a simple data transmission under transceiver perspective. In addition, The channel polling interval contains the channel polling interval and the listening interval. Moreover, the request period is an inter-arrival time of a data packet.

(a) Step 1 for decision of the value of \( T_{\text{cur}} \) in consideration of network traffic condition: when a sensor node reaches the beginning time of the next channel polling cycle, the sensor node checks whether a request arrives for data transmission or not. If a request arrives, the \( T_{\text{cur}} \) is set to half of the previous \( T_{\text{cur}} \) (for reducing the value of \( T_{\text{cur}} \); if the newly updated \( T_{\text{cur}} \) is smaller than \( T_{\text{min}} \), it is set to \( T_{\text{min}} \). Otherwise, go to next step (Step 2). On the other hand, if there is no request, the \( T_{\text{cur}} \) is set to double of the previous \( T_{\text{cur}} \) (for increasing the value of \( T_{\text{cur}} \)); if the newly updated \( T_{\text{cur}} \) is larger than \( T_{\text{MAX}} \), it is set to \( T_{\text{MAX}} \). Otherwise, go to next step (Step 2). Based upon this step, it is possible to adaptively set the \( T_{\text{cur}} \) in consideration of traffic condition of an operating sensor node under receiver perspective.

(b) Step 2 for decision of the value of \( T_{\text{min}} \) with regards to the remaining energy state: after the Step 1, Step 2 is to check the level of the current remaining energy state \( (R_{\text{cur}}) \) of a sensor node and adjust the \( T_{\text{min}} \) based on the calculated \( V_{\text{st}} \). As a decision criterion regarding the ratio of the current remaining energy state of an operating sensor node, \( R_{\text{cur}} \) is given by:

\[
R_{\text{cur}} = \frac{E_{\text{cur}}}{E_{F}},
\]

and then the state value of deciding the size of the channel polling interval is achieved by:

\[
V_{\text{st}} = \left\lfloor \frac{1}{R_{\text{cur}}} \right\rfloor,
\]

where \( E_{\text{cur}} \) is the current remaining energy state and \( E_{F} \) is the amount of fully-charged energy. As the value of \( R_{\text{cur}} \) decreases, we need to pay more attention to energy conservation than the reduction of the latency time. Therefore, the channel polling interval is adaptively manipulated in reciprocal proportion to the current remaining energy with the following equation:
\[ T_{\text{min}} = \min(2^{V_s} \cdot T_{\text{MIN}}, T_{\text{MAX}}), \] (3)

For example, when the \( R_{\text{cur}} \) is bigger than 0.5 (50\% of fully-charged energy), \( V_s \) is set to 1 (i.e., \( T_{\text{min}} \) is set to double of \( T_{\text{MIN}} \)). Additionally, when the \( R_{\text{cur}} \) is bigger than 0.33 (33\% of fully-charged energy), \( V_s \) is set to 2 (i.e., \( T_{\text{min}} \) is four times of \( T_{\text{MIN}} \)). As the remaining energy decreases, the given bigger value of \( V_s \) achieves intensive reduction of energy consumption without concerning about the increased latency.

(c) Step 3 for data transmission: after considering network traffic condition in Step 1 and power management in Step 2, the sensor node transmits a data packet. At the beginning of each channel polling cycle, the aforementioned three steps are repeatedly conducted.

By applying the operation of the EMP, it is possible to put into consideration network traffic condition as well as the remaining energy state of a sensor node. Therefore, when a sensor node is under insufficient remaining energy state, it mostly focuses on extending its lifetime and thus it is available to support enhanced network sustainability by maintaining termination time of sensor nodes as similar as possible.

4. Analytical Model

This section presents an analytical model of the EMP for performance evaluation. Each data packet is assumed to arrive at the coordinator with a Poisson process with rate \( \lambda \). The request period (i.e., inter-arrival time) of data transmission is exponentially distributed with mean \( 1/\lambda \), equal to the average request period of data transmission (\( T_I \)).

According to the operation of the EMP, the channel polling cycle (\( C_k \)) is given by:

\[ C_k = \min[2^{k-1}T_{\text{min}}, T_{\text{MAX}}] + T_L, \text{ for } 1 \leq k \]

(4)

where \( T_L \) is the size of the listening state. Thus, the probability (\( P_k \)) that there is no data transmission during \( C_k \) is then obtained from:

\[ P_k = e^{-\lambda C_k}, \text{ for } 1 \leq k \leq M, \]

(5)

And, the probability that there is at least one data transmission during \( C_k \) is given by: \( 1-e^{-\lambda C_k} \). Therefore, the probability (\( P_k^C \)) that there is at least one data transmission in the \( k^{th} \) channel polling cycle is given by:

\[ P_k^C = \sum_{a=0}^{k-1} P_a \cdot (1 - P_k). \] (6)
Let $\pi_i$ be the steady state probability when the size of operating channel polling interval ($T_{\text{cur}}$) is $2^i \cdot T_{\text{MIN}}$ (0 ≤ $i$ ≤ $M - 1$). We have the following steady state equations (presented in Fig. 3).

For $i = 0$, we have

$$0 = \pi_i P_i + \pi_{i+1} (P_{i+1} - 1). \quad (7)$$

For $1 \leq i \leq M - 2$,

$$0 = \pi_{i-1} P_{i-1} + \pi_i (-1) + \pi_{i+1} (1 - P_{i+1}). \quad (8)$$

For $i = M - 1$

$$0 = \pi_{i-1} P_{i-1} + \pi_i (P_i - 1). \quad (9)$$

For brevity, $\pi_i$ values out of the range (0 ≤ $i$ ≤ $M - 1$) take the value zero. Then, we have the normalization equation:

$$\sum_{i=0}^{M-1} \pi_i = 1. \quad (10)$$

The arrivals of requests for data transmission are random to the channel polling interval because those follow a Poisson process; thus, the average latency per data transmission between the coordinator and sensor nodes ($LTA$) is achieved by:

$$LTA = \sum_{i=0}^{M-1} \pi_i \sum_{k=1}^{\infty} P_k^C \left( \frac{C_k}{2} + L_R + L_D + T_{\text{sen}} \right), \quad (11)$$

where $C_k/2$ is the average channel polling cycle, $L_R$ is the length of request packet, $L_D$ is the length of data packet, and $T_{\text{sen}}$ is the total carrier sense time for data transmission.

The average number of channel polling cycles before next data transmission ($CHA$) is obtained by:

$$CHA = \sum_{i=0}^{M-1} \pi_i \sum_{k=i+1}^{\infty} k \cdot P_k^C. \quad (12)$$

The average power consumed by a sensor node in receiving a data packet ($ECA$) is given by:

$$ECA = \sum_{i=0}^{M-1} \pi_i \sum_{k=i+1}^{\infty} P_k^C \sum_{a=1}^{L} (S_p + L_R) \cdot P_{Rx} + L_D \cdot P_{Tx}, \quad (13)$$

where $S_p$ is the size of short preamble, $P_{Rx}$ is power consumed in receiving or listening, and $P_{Tx}$ is power consumed in transmitting.

### Table 1 Simulation properties.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_F$</td>
<td>Full remaining energy states of sensor nodes</td>
<td>$10^6$</td>
<td>joule</td>
</tr>
<tr>
<td>$DRA$</td>
<td>Average data rate of sensors</td>
<td>250</td>
<td>kbps</td>
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<tr>
<td>$PTx$</td>
<td>Power consumed in transmitting</td>
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<td>mW</td>
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<tr>
<td>$PS$</td>
<td>Power consumed in receiving or listening</td>
<td>56.4</td>
<td>mW</td>
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<td>$T_{Se}$</td>
<td>Average carrier sense time</td>
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<td>Size of short preamble</td>
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<td>Bytes</td>
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<tr>
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<tr>
<td>$LR$</td>
<td>Length of request packet</td>
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</tr>
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</table>

## 5. Performance Evaluation

This section evaluates the performance of the proposed EMP compared to the Boost-MAC but not others because performance comparison with other MAC protocols has been already done [9],[12]–[18].

### 5.1 Assumptions

The results were obtained with the following assumptions:

(i) the system to be evaluated is set to a two hop topology (clustered sensor network architecture: the available system designs described in Sect. 3.2), (ii) there are one coordinator which requests sensor data, one clustering sensor node, and ten sensor nodes (end nodes) which send sensor data according to the request from the coordinator node (similar hierarchy like Fig. 1); (iii) there are seven types of channel polling interval (M=7): 12.8, 25.6, 51.2, 102.4, 204.8, 409.6, and 819.2 (ms); (iv) the requests arrival to the coordinator follows the Poisson process with rate $\lambda$; (v) the simulation is run until the remaining energy of one of the sensor nodes is fully exhausted. The parameters used in analytical and simulation results are summarized in Table 1.

### 5.2 Performance Metrics

To get the values of the performance metrics, it is assumed that the average request period of data transmission ($T_i$), which means the frequency of sensor data requests, is set to 640 ms.

Figures 4 and 5 present the effect of the EMP on the aspect of energy saving gain: the remaining energy state of the clustering and end sensor nodes and the average energy consumed by the clustering sensor nodes ($ECA$), respectively. Initially, under the sufficient remaining energy state,
Fig. 4 The remaining energy state of the clustering and end sensor nodes.

Fig. 5 The average energy consumed by the clustering sensor nodes over operation time ($ECA$).

Fig. 6 The average number of channel polling cycles of the clustering sensor nodes ($CHA$).

Fig. 7 The average latency of the clustering sensor nodes ($LTA$).

the trend of decreasing remaining energy under the EMP is same with that under the Boost-MAC; this effect comes from the same $ECA$ due to normal operation. However, as operation time passes, the remaining energy of the evaluated sensor node decreases, and thus transitions from normal operation to intensive energy-saving mode occur step by step. As a positive effect, these transitions decrease the $ECA$. The effect of controlling the $ECA$ is achieved by controlling the average number of channel polling cycles of the evaluated sensor nodes ($CHA$), as presented in Fig. 6. However, as a trade-off relationship of the increased energy saving, the EMP inevitably incur the increased average latency of the sensor nodes ($LTA$) as shown in Fig. 7, which presents the average latency for data transmission over operation time. Especially, when the sensor node is under the insufficient remaining energy state, the degradation of the $LTA$ significantly occurs. As a result, during all of the operation time, the energy saving is adaptively controlled in order to achieve a target performance considering the remaining energy state.

5.3 Network Lifetime

A definition of network lifetime widely used in WSNs is the period in rounds from the time when the network sup-
ports their applications to the time when there is the first sensor node not working due to the depletion of its remaining energy. Some sensor nodes close to the sink need to consume more energy for relaying traffic of other sensor nodes in a multi-hop network environment, and thereby those will drain off their energy much faster than others. Thus, the lifetime of these sensor nodes decides how long the WSN can survive.

Figure 8 shows network lifetime of the WSN under the Boost-MAC and EMP. Also, the ratio of the extended lifetime under the EMP to that under the Boost-MAC ($RE$) is presented, which is given by:

$$RE = \frac{T^E_L - T^B_L}{T^B_L},$$

where $T^E_L$ is the network lifetime under the EMP and $T^B_L$ is the network life time under the Boost-MAC. In order to show the effectiveness of the EMP, we vary the average request period of data transmission ($T_I$) from 160, 320, 640, to 1280 ms. As the $T_I$ increases, the network lifetime is also increased due to the diminished number of data transmission in both Boost-MAC and EMP. Owing to intensive energy saving modes, the network lifetime under the EMP is better
than that under Boost-MAC regardless of the $T_I$.

6. Conclusion

Improving the energy efficiency of sensor nodes powered by batteries with limited capacities is one of the most important issues in order to support WSN applications. In order to resolve this issue, this paper proposed an Energy-aware MAC Protocol (EMP) and studied its performance by developing a Markov chain model and an event-driven simulator. Basically, the EMP puts into consideration network traffic condition as well as the remaining energy state of sensor nodes by controlling the size of channel polling interval. Especially, under the insufficient remaining energy state, the enhanced efficiency for energy saving compensates for the deterioration of the latency. Additionally, the EMP concept of adaptively controlling energy consumption can be applied to other kinds of Medium Access Control (MAC) protocols (described in the related work, Sect. 2) if the detailed operational mechanism is enabled to be manipulated. As a consequence, this approach can be one of the promising solutions for designing enhanced network sustainability-based WSNs due to our proposed holistic power management perspective.

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References

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