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Full Length Research Paper

EE-RI-MAC: An energy-efficient receiver-initiated asynchronous duty cycle MAC protocol for dynamic traffic loads in wireless sensor networks

Yueh-Tiam Yong[1]*, Chee-Onn Chow[1], Jeevan Kanesan[1] and Hiroshi Ishii[2]

[1]Department of Electrical Engineering, University of Malaya, Lembah Pantai, 50603 Kuala Lumpur, Malaysia.
[2]Professional Graduate School of Embedded Technology, Tokai University, Minato-ku, Tokyo, 108-8619 Japan.

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Introducing duty cycling in the MAC protocol used in wireless sensor networks has been proven to be an efficient way of prolonging the battery lifetime of the sensor nodes because idle listening is a high energy consumption factor. This concept has been proven efficient in the existing energy-efficient MAC protocols, including receiver-initiated MAC (RI-MAC). In this paper, we further enhance the RI-MAC protocol by introducing an asynchronous duty cycling method, in which the wakeup and sleep periods of a sender are alternating in order to reduce the wakeup period and so the energy efficient can be further improved. This method is called energy-efficient receiver-initiated asynchronous duty cycle MAC protocol (EE-RI-MAC). Specifically, the EE-RI-MAC protocol attempts to reduce the duty-cycle of a sender by adding sleep periods during ideal listening when the wakeup period is longer that certain value. From extensive simulation, it shows that the EE-RI-MAC achieves 17% higher energy efficiency that RI-MAC with the same throughput under a wide range of traffic loads, with a small increase in the delay period.

Key words: Wireless sensor networks, MAC protocol, duty cycling, energy-efficient, idle listening.

INTRODUCTION

Collisions, overhearing, idle listening and control packet overhead are the common factors of energy usage in wireless sensor network (WSN) (Il and Mohapatra, 2007). Collision happens when more than one node is transmitting in the wireless channel. Collisions can be avoided by using medium access protocol such as CSMA/CA (Carrier sense multiple access with collision avoidance) (Kleinrock and Tobagi, 1975) that involves the exchange of control message to reserve the wireless channel before each data message transmission (Kleinrock and Tobagi, 1975). On the other hand, overhearing is an inherent characteristic of wireless communication in which a node always listens to packet transmitted by its neighboring nodes. B-MAC (Polastre et al., 2004) uses the idea of RTS (Ready to Send) preambling to instruct nodes that are not the receiver to go to sleep until the end of this transmission session after hearing a full RTS (Polastre et al., 2004; Bonny and Luo, 2005). Thus, the overhearing period is significantly reduced.

Idle listening is a period in which a receiver waiting for possible traffic. It is important to note that carrier sensing is not part of the idle listening period because it is a protocol requirement to observe the channel before transmission. Generally, the period of idle listening can be reduced by using a timer to end the reception of a transceiver when it is idle for an interval of time to reduce energy consumption. Lastly, reducing control packets to save energy involves in-depth revision on the communication protocols because control packets are generally needed for normal operation of the communication framework. Usually, it involves a tradeoff between efficiency and performance in reducing control overhead for energy conservation.

In this paper, we focus on energy saving through minimizing the period of idle listening of a sender. It has

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*Corresponding author. E-mail: yuehtiam@siswa.um.edu.my, yuehtiam@yahoo.com Tel: +60129406583. Fax: +603-7967-5316.

been proven that the introduction of duty cycling technique (Polastre et al., 2004; Sun et al., 2008b; Ye et al., 2004) can significantly increase energy efficiency in wireless sensor networks. This technique allows a transceiver to turn its radio on and off alternately. For instance, a transceiver with a duty cycle of 50% turns on its radio for 50% of the time during a fixed interval. As a result, 50% energy saving is achieved. One major drawback of this technique is the delay incurred when a sender waits for the receiver to wake up from its sleep (Ye et al., 2004).

The existing contention-based energy-efficient MAC protocols using duty cycle can be divided into two categories. Synchronous MAC protocols, such as S-MAC (Ye et al., 2004), T-MAC (Dam and Langendoen, 2003), RMAC (Du et al., 2007) and DW-MAC (Sun et al., 2008), share the scheduling information that specifies the cycle of active and sleep periods by exchanging control packets with neighbor nodes during the common active period (Kim et al., 2008). One drawback of these protocols is the extra overhead and complexity created to synchronize the duty cycles. Besides, if the neighbor nodes have different schedules, a node may be required to wake up frequently. On the contrary, Asynchronous MAC protocols do not require the exchange of synchronization information but rely on low power listening (LPL) or channel sampling to connect a sender to a receiver in its duty cycle by using a preamble. A receiver will stay awake to receive expected data when a preamble is detected during its duty cycle. Asynchronous approach not only removes the synchronization overhead, but also achieves higher energy efficiency. Unfortunately, this approach is only suitable for light traffic loads because the preamble transmissions becomes longer when the traffic load increases, and leads to higher latency, lower throughput and lower energy efficiency. WiseMAC (Decotignie et al., 2010), RI-MAC (Sun et al., 2008b), B-MAC (Polastre et al., 2004), X-MAC (Buettner et al., 2006) and ADB (Sun et al., 2009) are protocols in this category.

One weakness that has been observed in the RI-MAC protocol is that some periods of idle listening still exist. As mentioned previously, idle listening is the factor of energy consumption increase. In this paper, we tackle this problem by combining the idea of receiver-initiated in RI-MAC and the alternative wakeup-sleep in AC-MAC (Ai et al., 2004) in order to create a protocol that is more flexible in to handling contending flows and bursty traffic, and achieve better energy efficiency. It is called energy-efficient receiver-initiated asynchronous duty cycle MAC protocol (EE-RI-MAC).

RELATED WORKS

There have been a lot of research activities and papers studying on the MAC protocol for wireless sensor networks. The conventional MAC protocols can be broadly divided into contention-based and TDMA (Time division multiple access) protocols (Capetanakis,1979). Energy consumption using contention-based protocols is usually very high due to the long period of idle listening. Meanwhile, TDMA approach is naturally more energy efficiency due to lower duty cycle of its radio and no overhead and collision introduced by contention. One of the current active areas focuses on energy-efficiency.

S-MAC, which is based on the IEEE 802.11 standard (Ferrari et al., 2006), was among the first efforts to reduce energy consumption of the wireless sensor nodes by introducing periodic listen and sleep periods (Ye et al., 2004). Each node has a time frame in which it is allows to turn off its radio for a portion of time, to wake up after the sleep period expires, and to stay awake for the remaining portion of time. All nodes are allowed to choose their own listen/sleep schedule but neighboring nodes are preferred to have the same schedule. Basically, this protocol allows the sensor nodes to form their own virtual cluster by synchronizing their schedule by transmitting SYNC messages at the beginning of the frame time. To limit the number of SYNC messages collisions, each sensor node performs a simple contention avoidance algorithm based on a random backoff. This protocol enables a significant reduce in energy consumption, but also causes greater latency and lower throughput. There has been a lot of work that further enhances the S-MAC protocols afterward, such as Dynamic S-MAC (DSMAC) (Lin et al., 2004), T-MAC (Dam and Langendoen, 2003), and AC-MAC (Ai et al., 2004).

DSMAC proposes the use of dynamic duty cycles that adjust automatically based on the measurement of energy consumption level and delay. A sensor node can increase its duty cycle if the per-hop delay has exceeded a threshold and reduce its duty cycle when the traffic has returned to low level. The current traffic condition is estimated by recording the per-hop delay, which is defined as the time taken by a packet to be sent out after it has entered the queue, in header. It is believed that DSMAC introduces very small overhead to the original S-MAC protocol. T-MAC, on the other hand, proposes the use of a timer to end of the active period dynamically. The basic concept behind T-MAC is to send all messages in burst of variable length and allows the node to sleep between burst. The length of each burst is determined dynamically in order to optimize the active time under different loads. The AC-MAC protocol also uses adaptive duty cycle in its design. The frame format of AC-MAC allows a node with queued messages to introduce multiple data exchange periods in its SYNC frame.

The protocols presented so far are source-initiated synchronous protocols. Another category of contention-based MAC protocols for wireless sensor networks is asynchronous approach that allows nodes to operate independently. B-MAC (Polastre et al., 2004) is improved from the CSMA protocol (Kleinrock and Tobagi, 1975) for low power WSN by using a preamble that is slightly longer than the sleep period of a node to notify the receiver that there is incoming information waiting. A sensor node will stay awake to receive data if the preamble is detected. Otherwise, it will return to sleep mode. This mechanism allows each node to have its own schedule. One more problem of B-MAC is the long preamble sending that causes high latency and energy consumption at the sender. A few protocols have then been proposed to overcome these weaknesses. Among them are WiseMAC (Decotignie et al., 2010) and X-MAC (Buettner et al., 2006).

WiseMAC (Decotignie et al., 2010) uses similar techniques as B-MAC in which preamble sampling is used to achieve low power consumption. Every sensor node remembers the sampling offset of its neighbors to reduce energy consumption and may notify them the time until their next channel sampling. A sensor node can delay the preamble transmitting by learning the sampling times of its neighbors until just before the receiver wakes up. Thus, the amount of time a sensor node used to transmit preamble decreases. The energy saving in WiseMAC comes with a price of additional overhead in the ACK messages. On the other hand, X-MAC (Buettner et al., 2006) achieves energy saving and short latency by using short preamble that contains short strobes and receiver's ID to inform neighbor nodes about impending data transfer. This significantly improves the B-MAC protocol because instead of sending a constant stream of preamble packets, small pauses are inserted between packets transmission to allow the sender to listen to the early acknowledgment sent by the receiver. The sender can then stop sending the preamble once the early acknowledgment is detected, and start sending the data packets.

Receiver-initiated MAC (RI-MAC) protocol is also an example of asynchronous MAC protocol that has received a lot of attention (Sun et al., 2008b). In order to efficiently and effectively operate over a wide range of traffic loads, RI-MAC implements receiver-initiated data transmission. A node wake up periodically to check if there are messages intended for this node by broadcasting a beacon message. A node with pending messages to be sent to the receiving node is required to stay awake and starts its transmission immediately upon receiving of the beacon messages. The receiving node then sends an ACK beacon to acknowledge the received packet, and to invite new data transmission. The sender goes into sleep period after transmitted the data and verified that no incoming data. RI-MAC greatly reduces the medium occupancy by a pair of nodes before they reach a common active period for data transmission. The main difference between RI-MAC and the synchronous MAC protocols is that RI-MAC does not require any synchronization, and so it saves the overhead and complexity of clock synchronization.

RI-MAC is designed to support unicast traffic, but it is not efficient for broadcast messages. ADB (Sun et al., 2009) is especially designed to handle broadcast traffic with the objectives of achieving energy-efficient, low latency and reliable multihop broadcast. This protocol is composed of two parts: the encoding of control information and the delegation procedure. The broadcasting progress information allows a node to decide whether to transmit a data packet to its neighbors or not. The information is embedded at the footer of the data and ACK messages. The delegation procedure allows a node to sleep as early as possible and to avoid transmission over links with poor quality. This process required every node to maintain a list of nodes that have received the packet and a list of nodes that will receive the packet from other node, based on the received or overheard data packet. A node can go to sleep if all neighbors are either reached or delegated. Otherwise, it may re-transmit the packet.

EE-RI-MAC DESIGN

Here we describe the design of the EE-RI-MAC protocol. The concept behind the design of EE-RI-MAC is to combine RI-MAC and AC-MAC. As explained earlier, RI-MAC is a receiver-initiated protocol that requires the sender to stay awake whenever it has data to be sent. One possible way to reduce energy consumption is to allow the sender to go to sleep after waiting for a period of time and wake up periodically to listen to beacon, as show in Figure 1, which shows the sender is in active mode during the wake up interval and the receive beacon space (RBS). Considering that the energy consumption at the receiver is extremely low because a receiver only wakes up for a very short interval and goes back to sleep mode if no data is directed to it, the focus for energy saving is still at the sender. In order to further reduce the period of idle period, we adopt the concept of multiple schedules in AC-MAC to allow the sender to alternately turn its radio on and off during this period. Figure 2 gives an overview of the operation of the EE-RI-MAC's sender.

More specifically, a sender goes into sleep mode after waited for a period of W_p, and wakes up after a period of S_p. In other words, the wakeup and sleep periods of a sender are alternating in order to reduce the period of idle listening. Figure 3 illustrates a data transmission scenario between a sender and a receiver in EE-RI-MAC. The receiver wakes up periodically and announces its availability by broadcasting a beacon. Once the beacon is detected by the sender with data waiting to be sent to this receiver, it sends the data packets immediately. During this period, receiver will stay awake to receive the packets. If nothing to be transmitted, sender and receiver will go to sleep.

EE-RI-MAC is an asynchronous duty cycle protocol, in which the sleep and wakeup periods for different nodes are not synchronized, as shown in Figure 4. This

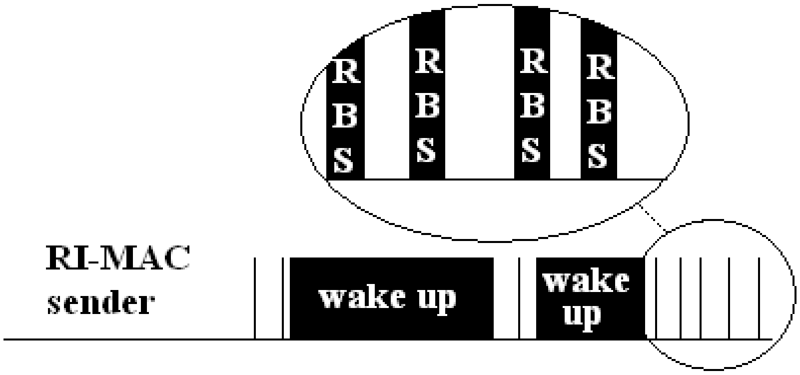

Figure 1. Operation of a RI-MAC's sender.

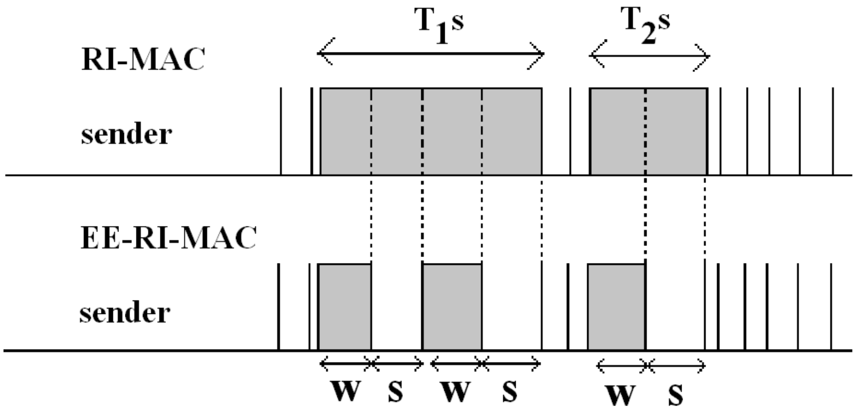

Figure 2. RI-MAC sender vs. EE-RI-MAC sender.

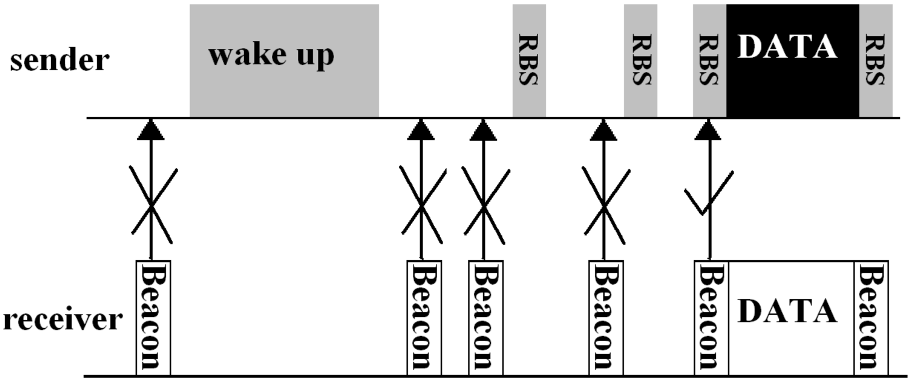

Figure 3. Data transmission in EE-RI-MAC.

characteristic actually matches with the concept of our proposed protocol better than RI-MAC. Imagine a scenario when there are many nodes sending to a single receiver, for example the sink node connecting the infrastructure network, if all senders are awake and trying to send data to the same receiver at the same time, contention may happen. In EE-RI-MAC, the probability of contention is reduced because the senders have different schedules. This contributes to higher energy conservation.

W_p and S_p are the two important parameters that determine the performance of the protocol in terms of average duty-cycle, throughput and end-to-end delay. From Figure 2, we can obtain a general equation that

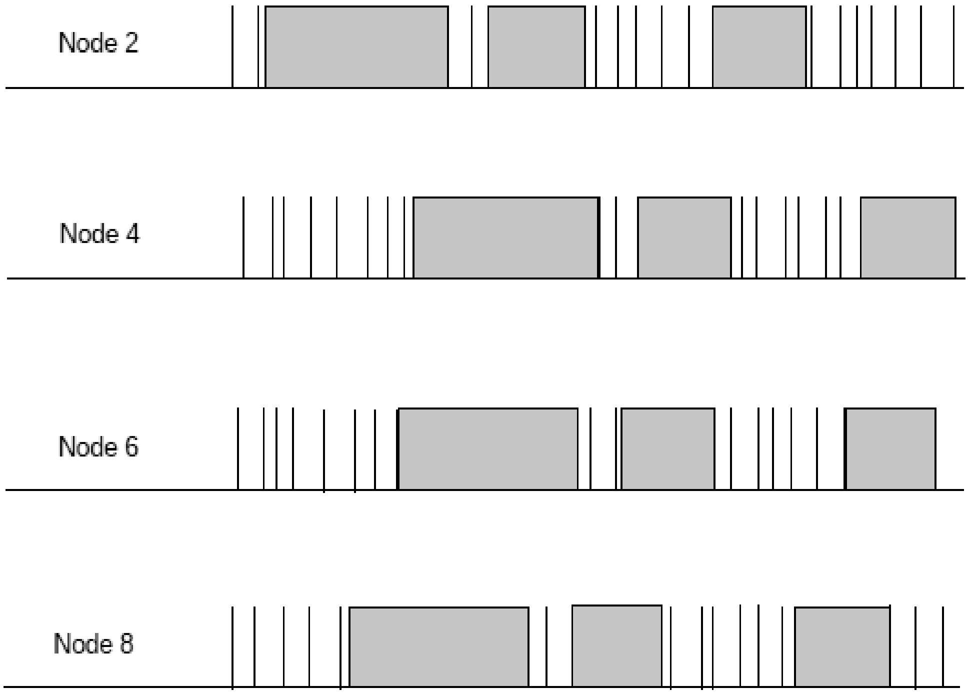

Figure 4. Duty cycle results of RI-MAC's sender.

Table 1. Simulation radio parameters.

Parameter	Value
Bandwidth	250 Kbps
SIFS	192 µs
Slot time	320 µs
Tx range	250 m
Size of hardware preamble	6 B
Size of ACK	5 B
CCA check delay	128 µs
Carrier sensing range	550 m

relates them, as given in Equation (1):

$$W_p + S_p = T_2 \quad \dots \dots \qquad (1)$$

where T_2 is the total time of sleeping period. In order to obtain the best combination of W_p and S_p, we have performed analysis in the next section. Generally, it is desire to have a longer sleep period than wakeup period, so that more energy are saved. The tradeoff between delay and energy is discussed in details in the next section.

PERFORMANCE EVALUATION

We used ns-2 version 2.29 to evaluate the performance of EE-RI-MAC as compared to RI-MAC. The comparison was done against RI-MAC only because it has been proven that RI-MAC outperforms other synchronous and asynchronous protocols (Sun et al., 2008b). We tried to model the same comparison as (Sun et al., 2008b) in order to provide a fair comparison between EE-RI-MAC and RI-MAC. The propagation model used combines the free space and two-ray ground reflection models, and omnidirectional antenna was used at each node. Table 1 shows other parameters used to define the radio in the simulation and the default parameters for RI-MAC and EE-RI-MAC protocols are given in Table 2.

The initial value of backoff window (BW) is 32 and the receiver may adjust its according to binary exponential backoff (BEB) method that takes values of 0, 31, 63, 127 and 255. Retransmission was allowed and the maximum allowable tries was set to five. We used the same method used in (Buettner et al., 2006; Texas Instrument, 2007) to evaluate the power efficiency. It is important to note that energy consumption changes significantly in different or the same radios state (Klues et al., 2007). The initial wakeup time of each node was randomized and the sleep interval was 1 second for both protocols. Sleep intervals of RI-MAC and EE-RI-MAC was also set randomly.

In the first part of the performance evaluation, we studied on the optimization of the parameters of EE-RI-MAC. Subsequently, we evaluated the protocols using different networks topologies: clique network that contains 8 nodes nearby each other, a 7x7 grid network and random networks. Beacon-on-request was not applied in clique network because it is not a multi-hop network, but it was implemented in the grid and the

Table 2. Simulation MAC protocol parameters.

Parameter	RI-MAC	EE-RI-MAC
Backoff window (BW)	0–255	0–255
Retry limit	5	5
Frame	Beacon	Beacon
Frame size	6 –9 B	6 –9 B
Dwell time	Variable	Variable
W_p	-	1.5
S_p	-	2.5

Table 3. Five cases with different W_p and S_p.

Case	W_p(s)	S_p(s)
I	1	3
II	1.25	2.75
III	1.5	2.5
IV	1.75	2.25
V	2	2

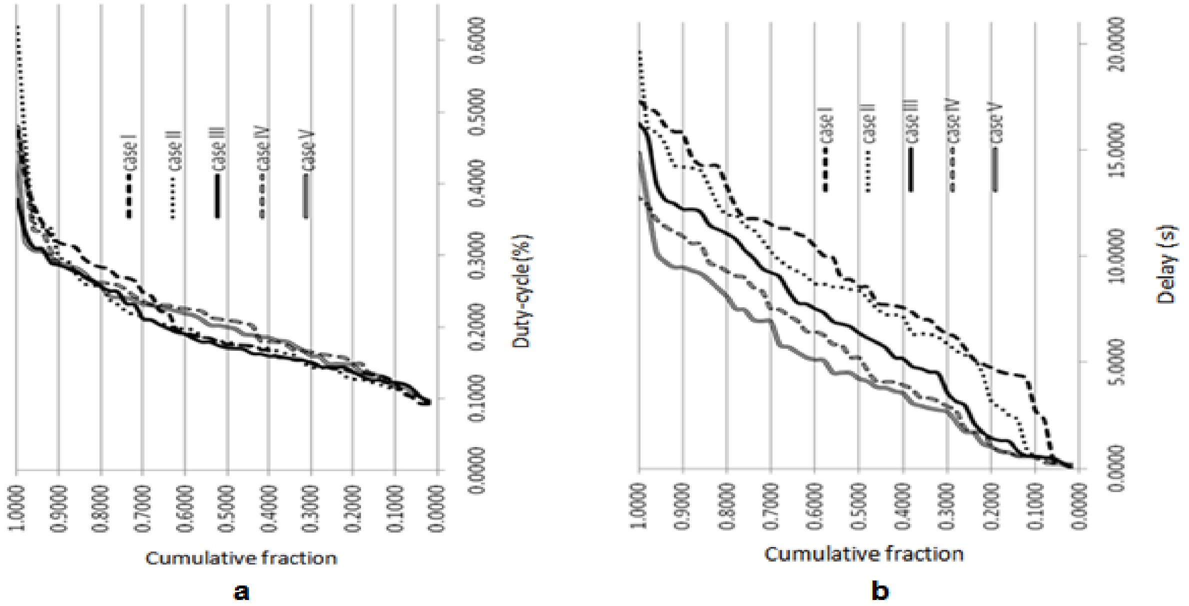

Figure 5. (a) CDF of average duty cycle (b) CDF of end-to-end delay.

random networks.

Optimization of W_p and S_p

In this part, we studied the effects of W_p and S_p taking different values. By taking T_2 equals to 4 s, five sets of values for W_p and S_p were chosen, as given in Table 3. The general concept is to have at least one-to-one ratio for sleep and wakeup period, which is given by case V. Subsequently, we reduce the wakeup period in a step of 0.25 until the sleep period is 1 second in case I, which represents 25% duty cycle.

Figures 5(a) and (b) demonstrate the duty cycle and the end-to-end delay, respectively. In terms of duty cycle, case II and case III are more suitable than the other cases because their curves are nearest to zero at the beginning. Case II has the maximum duty cycle of about 0.6%, which is higher than the original protocol.

Therefore, case III is a better option to avoid high

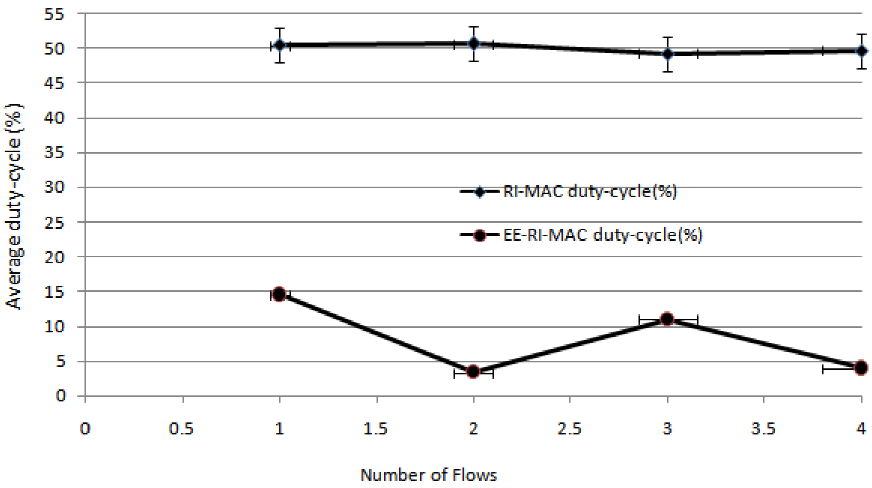

Figure 6. Simulation results for clique networks: average duty cycle.

energy consumption. As for end-to-end delay, case V has the lowest end-to-end delay followed by IV, III, II and I. Considering both factors, we have chosen case III because the primary objective of EE-RI-MAC is energy saving.

Clique networks

A clique network is a network in which all nodes in the network are within transmission range of each other, with the traffic load being varied by changing the number of independent flows originated from and directed to different nodes. The clique network used in this simulation is the same as reported in (Sun et al., 2008b). There were eight nodes in this topology, which means the number of flows increased from one to four. Packets were generated with an inter-packet interval distributed uniformly between 0.5 and 1.5 s. The wakeup and sleep periods were randomized within the first 10 s of the simulation. The simulation time was 50 s and 10 random scenarios were used for each number of flows to obtain the average results.

In all simulations, both RI-MAC and EE-RI-MAC give the identical throughput. In terms of energy consumption, EE-RI-MAC outperforms RI-MAC, as given in Figure 6. The average duty cycles of all senders in EE-RI-MAC remains between 3.3 and 14.5%, but RI-MAC gives about 50%. Obviously, allowing the senders to wakeup and sleep during idle listening contributes to significant energy saving. There is no change to the duty cycle of the receivers for both protocols because the duty cycle has been minimized to very low. The end-to-end delay of both protocols also is almost the same because the network topology used is rather simple. With this in mind, simulation was also carried out using grid and random topologies.

Grid network

A 7 x 7 grid network with a distance of 200 m between two nodes was used in this part of simulation. The sink node is located at the center of the network and all other nodes are sender. The random correlated-event (RCE) model based on the correlated-event workload (Hull et al., 2004) was used to assign the traffic to senders (Sun et al., 2008). For each event, RCE picks a random (x, y) location and if this location is within the sensing range of a node, the node will generate packets to report this event to the sink node. With this setting, adjusting the sensing range (R) of a node introduces different level of work load. In other words, larger R represents higher traffic. A new event was generated every 60 s and the event of sending packet to the receiver was sensed by each node.

Table 4 shows the average number of packets generated for each event with different sensing range, from 200 to 500 m. Each packet that transmitted from a sender to receiver takes between 1 and 6 hops, with an average of 3.50 hops. This configuration aims to evaluate the efficiency of a protocol in handling different degree of traffic load. Unicast packets triggered by a series of 100 events were sent toward the sink node in each of the simulations. Results of 30 random runs were averaged to obtain the final results.

Both the EE-RI-MAC and the RI-MAC protocols maintain 100% packet delivery ratio across all sensing ranges. Figure 7 shows the comparison of average duty cycle. For RI-MAC, the duty cycle increases when the sensing range increases. It can also be observed that EE-RI-MAC achieves a lower duty cycle than RI-MAC. The decrease in duty cycle is as high as 17%. Undoubtedly, the alternating wakeup and sleep period while waiting for the receiver to wake up contributes to this significant improvement.

Table 4. Average number of packets generated for events under different sensing ranges.

Packets	Range (m)
3.1	200
6.4	300
10.6	400
15.2	500

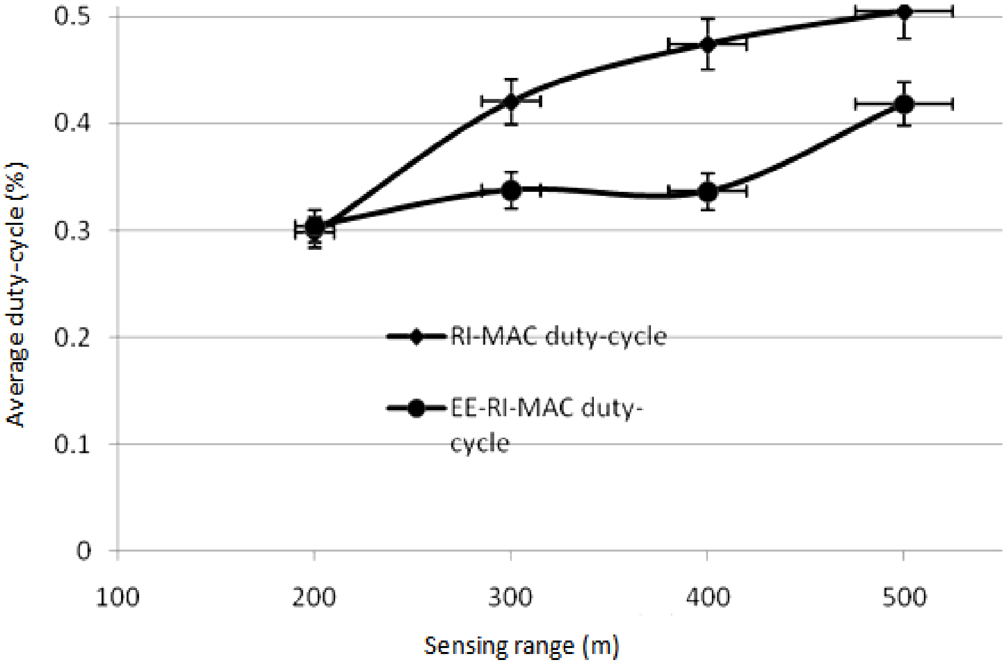

Figure 7. Simulation results for grid networks: average duty cycle.

Figure 8 shows the end-to-end delay of packets in the RCE model as the sensing range increases. The EE-RI-MAC protocol introduces a higher latency in packet delivery, mainly due to the periodical sleep and wakeup intervals that causes lower probability in having both sender and receiver wakeup at the same interval. This delay is somehow expected and one way to reduce the latency is to reduce S_p and to increase W_p.

Random networks

In this set of simulations, 100 topologies containing 50 nodes located randomly within a 1000 x 1000 m area was used to compare the performance of EE-RI-MAC and RI-MAC in more realistic implementation. The node movement was created using node-movement generator (Greis, 1999) and the RCE model with sensing range of 250 m was used to generate one event every 60 s for a total of 100 events. The average number of packets generated is 763 in each run.

In all simulation, the throughput is 100% because retransmission is allowed so that the delay can be calculated accurately. The simulation results are presented in Figures 9 and 10. Figure 9 shows cumulative distribution function (CDF) of average duty cycle. The average values for the duty cycles of all sensors for EE-RI-MAC and RI-MAC, are 0.096 and 0.36%, respectively. Clearly, EE-RI-MAC gives significant improvement on the duty cycle. This saving is very important considering that the duty cycle for the receiver is also below 0.1%. It means that EE-RI-MAC achieves almost the highest possible energy saving.

Figure 10 gives the CDF of the average end-to-end delay. The packet latency for EE-RI-MAC and RI-MAC are 3.32 and 2.36 s, respectively. The difference in delay is about 1 s. As mentioned earlier, this delay can be reduced by introducing higher duty cycle, which will cause lower energy saving. The tradeoff of energy saving and latency is experienced in the proposed protocol as in

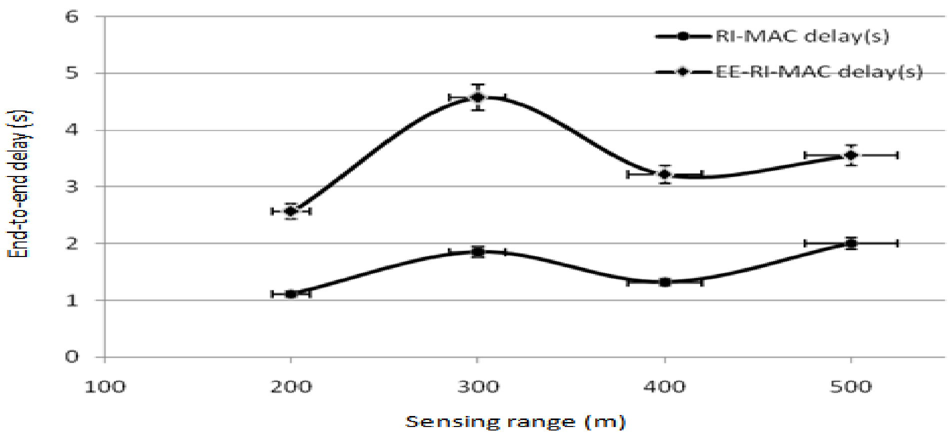

Figure 8. Simulation results for grid networks: end-to-end delay.

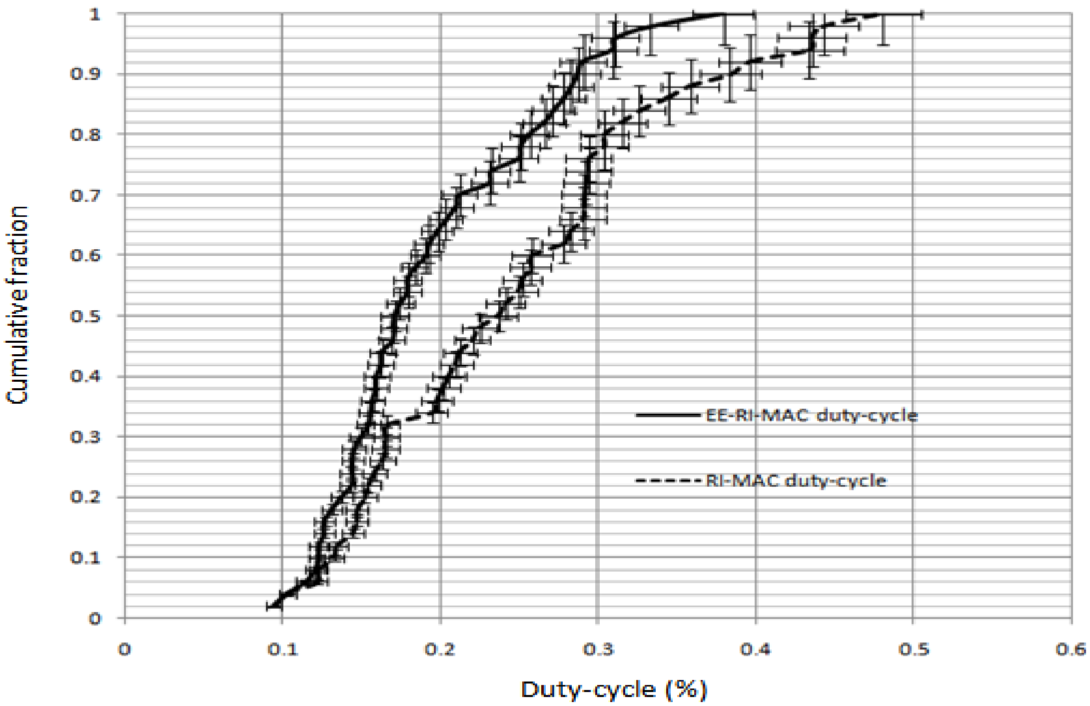

Figure 9. Simulation results for random networks: CDF of average duty cycle.

other protocols.

CONCLUSIONS

In this paper we proposed energy-efficient receiver-initiated MAC (EE-RI-MAC) protocol for handling dynamic traffic loads in wireless sensor networks. It is an enhanced version of the well-known RI-MAC protocol. Generally, the EE-RI-MAC protocol achieves higher energy efficiency by using an alternating wakeup and sleep periods during the waiting period. For this purpose, it is important to firstly optimize the W_p and S_p that represent the wakeup period and sleep period, respectively, of the sender during idle listening. We found that a duty cycle of about 37.5% during idle listening gives us the optimum solution considering both energy-efficiency and end-to-end delay factors. Simulation shows that the EE-RI-MAC protocol achieves better power efficiency that the original RI-MAC protocol with the same throughput under a wide range of traffic loads. Besides, EE-RI-MAC also achieves the same throughput as RI- MAC

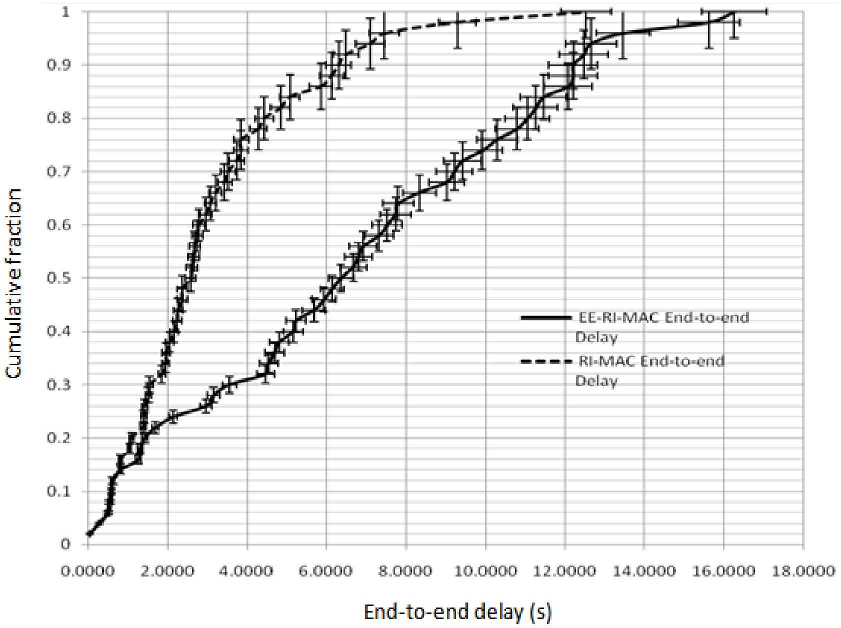

Figure 10. Simulation results for random networks: CDF of end-to-end delay.

when there are contending flows, such as bursty traffic or transmissions from hidden nodes. Even the delay in EE-RI-MAC protocol is higher than RI-MAC, but it is still a feasible approach especially in non-critical monitoring systems, such as weather monitoring and water level monitoring. These applications required sensor nodes that work for a long period of time, but the delay is of less importance.

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