An Energy-Efficient MAC Protocol for Delay-Sensitive Wireless Sensor Networks*

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Abstract. In this paper, we propose a new medium access control protocol for wireless sensor networks, named LE-MAC (Latency and Energy aware MAC) that aims to minimize data delivery latency as well as energy consumption. To achieve both goals, we exploit a physical carrier sensing feature in CSMA/CA and combine it with a cross-layer technique. When nodes that are in routing path between source and sink become aware of the traffic based on the carrier signal, they wakeup once more during the sleep period for transmitting data over multiple hops. We evaluated the proposed scheme compared with S-MAC on the ns-2 simulator. The results show that our scheme outperforms S-MAC protocols in balancing the need of low latency and energy consumption.

1 Introduction

The advances in microelectronic mechanical systems have given the way to build miniaturized, low cost sensing and communicating device that can be deployed on the space for collecting perceived physical information. Collection of such intelligent sensors coordinating with each other to transmit sensed data over multiple hops towards the information gathering device called a base station or a sink node forms a wireless sensor networks (WSN).

WSNs are becoming increasingly popular for the applications, where a large number of sensors with processing and communication capabilities are deployed. The sensor devices are normally small in size and powered by battery of limited capacity that are difficult to replace or recharge when exhausted [1]. Due to this reason, network lifetime elongation through better energy management has been a primary research issue in WSN. Recently, several energy-efficient MAC protocols have been proposed that periodically turns off the nodes radio for reducing energy consumption caused by unnecessary communication activities. This approach on the other hand has raised another problem of slow data delivery compared to 'always-on' protocols. A long delay is highly undesirable

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for time-sensitive applications such as critical situation monitoring and security surveillance. In this paper, we propose a medium access control scheme that minimizes both latency and energy consumption in WSNs.

Latency is a common problem in energy-efficient sensor MAC protocols [2]-[6]. Specially, the contention-based MAC protocols that rely on the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism minimize power consumption by allowing sensor nodes to remain in the 'sleep mode' for a long period of time. Nodes periodically wake up for the short duration called 'listen period'. Those wishing to transmit data contend in the listen period for reserving the medium. If successful, the sender and receiver perform data transfer, while the other nodes switch to sleep state and save energy. If failed, both switch to sleep state and wait for the following listen period. This waiting period throughout the listen/sleep cycle (or a *time frame*) is termed as *sleep delay*.

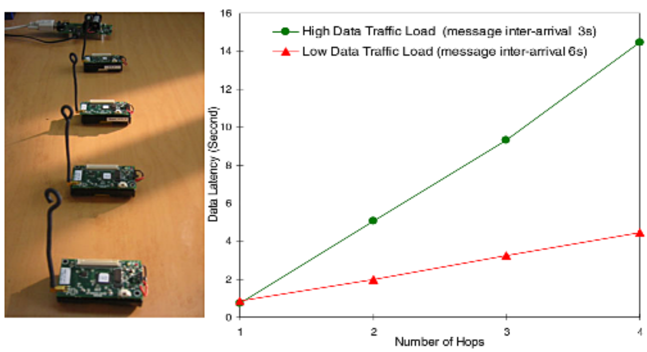


Fig. 1. Data delay of Basic S-MAC [2] in multi-hop environments

To illustrate this problem, we conducted experiment on basic S-MAC [2] with 5 Mica Motes sensor devices[11] arranged in the linear topology as shown in Fig.1. In this experiment, duty-cycle (defined as the fraction of the listen period over a time frame) is set to 10%. We observed that, when the data traffic load is low, a sink node waits for 4s in average for receiving the data from the source i.e. four hops away. This is clearly very long to serve any delay sensitive applications. Increasing the data traffic load almost doubled the latency, which is reflected in Fig.1. These observations motivated us to study the mechanism for reducing latency in the listen-sleep based MAC protocols.

In this paper, we propose a scheme named latency and energy aware MAC (LE-MAC) protocol that minimizes sleep delay in multi-hop topologies. We exploit the physical carrier sensing ability of nodes and dynamically adjust their duty-cycle to reduce latency. We also propose a cross-layer technique that conserves energy. We implemented LE-MAC on the ns-2 simulator. The results show that our protocol consistently reduces the latency and the energy consumption, which makes it suitable for delay sensitive WSN applications.

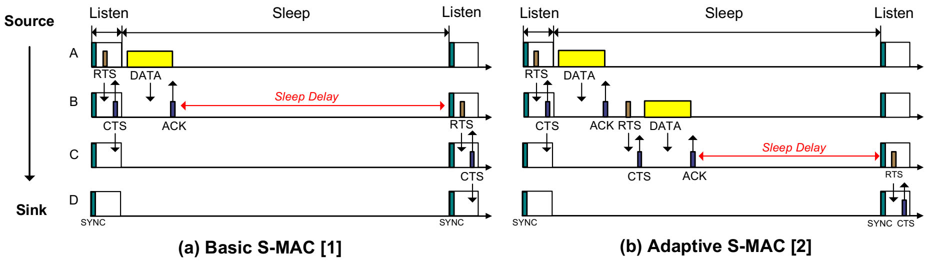


Fig. 2. Example Scenarios for (a) basic S-MAC and (b) adaptive S-MAC

2 Related Works

In this section, we present a brief survey of energy and latency efficient MAC protocols closest to ours. S-MAC [2,3] is one of the most often cited MAC protocol designed for WSN. The basic operation of S-MAC is shown in Fig.2(a). As shown in this figure, the time frame is divided into the listen and sleep periods. The listen period is further subdivided for transmitting SYNC and RTS/CTS control packets[1]. First, SYNC packets are transmitted by CSMA/CA mechanism for achieving synchronization among neighboring nodes. Senders and their corresponding receiver subsequently exchange RTS/CTS packets and continuously remain active to transmit DATA/ACK frames, whereas other neighbors immediately switch to sleep mode for saving energy. For example, in Fig.2(a), after SYNC packets are transmitted, source node A and the intermediate receiver node B exchange RTS/CTS packets, followed by data transmission while next-hop node C switches to sleep state. Since node C is not active, node B is forced to queue the data packets until the next listen/sleep cycle begins, resulting in a sleep delay to incur at node B. In order to solve this problem, the adaptive listening in S-MAC [3] allows nodes overhearing RTS/CTS packets to set up their network allocation vector (NAV) timer and to wake up early even during the sleep period. Hence, in Fig.2(b) node C sets its wake-up timer to receive data from node B in the same cycle, based on the overheard CTS packet. However, node D cannot receive RTS/CTS, thus remains in the sleep mode, which causes sleep delay. This scheme reduces latency in alternate hops, but cannot address multi-hop latency problem. In T-MAC [4], nodes adaptively change duty-cycle and data flows in burst during the variable length active time. After completing transmission, nodes wait for small time period called timeout(TA) and turn to sleep mode if they do not sense any ongoing transmission. [4] proposes future request-to-send (FRTS) scheme for leveraging fast transmission, in which nodes overhearing CTS transmit FRTS packet one more hop further. This scheme reduces sleep delay across 3 hops, however the collision free transmission of FRTS packet is not guaranteed. DSMAC [5] attempts to minimize latency by doubling the duty cycle based on the amount of queued data and the average one-hop

[1] The listen period defined in S-MAC source code of TinyOS [13] is as follows: Listen period (115ms) = SYNC time period (41ms) + RTS/CTS time period (74ms).

latency. SYNC packets are transmitted by the nodes to inform their neighbors about renewed schedule. SYNC packets can be transmitted only up to one hop, thus this scheme also cannot address the multi-hop latency problem. Other pre-defined scheduling schemes [6],[7] establish a wake-up period based on the available routing path or the tree structure. These schemes have a problem of missing wake up schedules due to contention among multiple routing paths or sudden errors (e.g. collision). In our scheme, nodes perform wake up based on the traffic information, which adds more robustness against the environment with probable collisions.

The problem of reducing latency and limiting energy consumption in WSN is an important area of research. In this context, we present a novel approach of using carrier sensing (CS) signals for reducing sleep delay in multiple hops. The intuition comes from the ability of nodes to hear signals within the CS range, even if they are not interpretable. This range is normally twice the actual receiving range [8],[9]. In the researches related to ad hoc networks, CS mechanisms have been mostly studied for maximizing the data throughput. However, its utilization for reducing latency on the design of MAC protocol for WSN has not been suggested by any previous research.

3 LE-MAC Protocol Overview

As mentioned earlier, the latency in the listen/sleep period based MAC protocols is caused by a sleep delay, due to which continuous packet(s) forwarding is possible across only few hops in one time frame. In our scheme, nodes that are in-route towards the sink and within the CS range of the sender and receiver prepare to wake up in the sleep period and transmit data. This switching of node from sleep state to the active state during the sleep period is named as "traffic aware early wake-up (T-wakeup)". Depending upon the extent of the CS range, our scheme can transmit data across K-hops in a single listen/sleep period. In what follows, we describe how we schedule T-wakeup for faster data transmission and then explain our cross-layer approach for selective T-wakeup for reducing unnecessary energy consumption.

3.1 Traffic Aware Early Wakeup (T-Wakeup)

In our scheme, nodes first attempt to transmit SYNC packets for synchronization in the listen period like the S-MAC protocol. A node having data packets to send then initiates a RTS packet transmission, expecting to get CTS from the corresponding receiver. Like the adaptive listening mechanism [3], any neighboring nodes overhearing CTS may prepare to wake up during the sleep period, such that the data packets can be received in the same cycle. Thus, in this case, data packets are continuously transmitted only up to two hops. However, note that, during the listen period when the RTS/CTS packets are being exchanged, nodes that are multiple-hops away from the sender/receiver can hear the CS signals and become aware of the ongoing transmission. Such nodes prepare to perform T-wakeup during the sleep period.

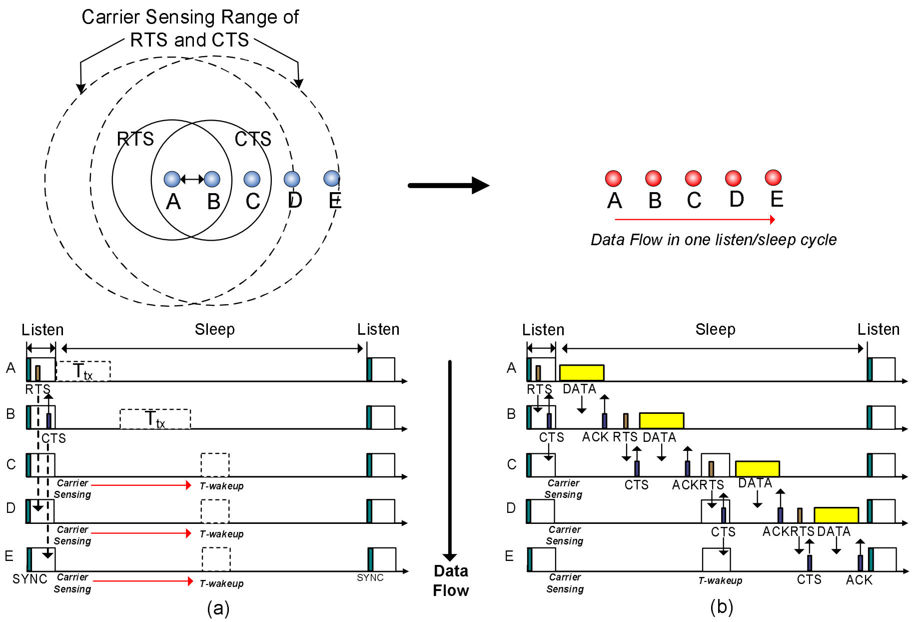


Fig. 3. Traffic aware wake up for multi-hop transmission in one listen/sleep cycle

In Fig.3, the data packet from source node A is sent to destination node E, through B, C and D. Initially, node A and B exchange RTS/CTS packets in the listen period. Node C overhears CTS from node B and sets its timer to wake up according to the NAV in CTS. Nodes C, D and E at the same time also listen to the CS signal as they exist within the interfering range of nodes A and B. Thus they schedule T-wakeup period for continuously transmitting data beyond two hops as illustrated in Fig.3(a). Fig.3(b) shows continuous transmission of the packet from node A to node C by adaptive listening and then from C to E using our scheme in a one time frame. The number of hops between source and destination node is 5 so basic S-MAC [2] waits for 4 cycles to deliver the data packet, which is reduced to 1 in our proposed scheme.

Since a packet is transmitted up to 2 hops by adaptive listening mechanism, t-wakeup period (T_{tw}) is scheduled after $2(t_{backoff}+t_{tx})$ time period. $t_{backoff}$ denote the average delay due to contention and t_{tx} represents the single-hop transmission time for a fixed length packet. If the nodes sense no activity during T_{tw}, they switch to sleep state. The length of T_{tw} is long enough to exchange RTS/CTS packet and expressed as $t_{backoff}+t_{rts}+t_{sifs}+t_{cts}+t_{guard}$ where, t_{sifs} is the short inter-frame space time, t_{rts} and t_{cts} are the transmission time for RTS and CTS packets respectively and t_{guard} is the guard time for preventing small synchronization errors.

As done in [3], we perform the latency analysis of the basic and adaptive S-MAC and compare with our scheme. For simplicity, we assume that there are no queuing (except in the first hop) and processing delays. Thus, a time frame

(T_{cycle}) of basic S-MAC is equal to $t_{backoff} + t_{tx} + t_{s1}$. The $t_{backoff}$ is average delay due to contention, t_{tx} transmitting time of fixed sized data packet across 1-hop and t_{s1} is the remaining sleep period after data transmission. A possibility that a sensor radio is off during the event causes a new generated data packet to be queued in the source node for some time. We denote this delay as t_{q1}. In [3], N-hop delay of basic S-MAC is expressed as:

$$\begin{aligned} D(N) &= t_{q1} + \sum_{i=2}^{N} T_{cycle} + (t_{backoff} + t_{tx}) \\ &= t_{q1} + (N-1)T_{cycle} + t_{backoff} + t_{tx} \end{aligned} \tag{1}$$

Since, $t_{backoff}$ + t_{tx} = T_{cycle} - t_{s1}, eq.(1) can be expressed as:

$$D(N) = t_{q1} + (N)T_{cycle} - t_{s1} \tag{2}$$

The T_{cycle} in adaptive S-MAC is equal to $2(t_{backoff} + t_{tx}) + t_{s2}$ because a packet can traverse up to 2 hops in one time frame. t_{s2} is the remaining sleep period after the the 2 hops transmission of a data packet. Thus, N-hop delay in adaptive S-MAC is expressed as:

$$D(N) = t_{q1} + (N/2 - 1)T_{cycle} + 2(t_{backoff} + t_{tx}) \tag{3}$$

Replacing $2(t_{backoff} + t_{tx})$ by $T_{cycle} - t_{s2}$ we get:

$$D(N) = t_{q1} + (N/2)T_{cycle} - t_{s2} \tag{4}$$

Our scheme transmits data continuously till K^{th} hop in one listen/sleep cycle depending upon the extent covered by the carrier signals. So, we express T_{cycle} in our scheme as the delay over K-hop as follows:

$$T_{cycle} = Kt_{backoff} + Kt_{tx} + t_{rest\_delay} \tag{5}$$

t_{rest_delay} is the left-over time after data transmissions, which is small compared to t_{s1} or t_{s2}. Using equation(5), we express N-hop delay of LE-MAC as follows:

$$\begin{aligned} D(N) &= t_{q1} + (N/K - 1)T_{cycle} + Kt_{backoff} + Kt_{tx} \\ &= t_{q1} + (N/K)T_{cycle} - t_{rest\_delay} \end{aligned} \tag{6}$$

Comparing equation (2), (4) and (6), we observe that the delay in LE-MAC is reduced K^{th} times.

3.2 Selective T-Wakeup Using a Cross-Layer Technique

Since wireless sensor nodes are normally equipped with an omni-directional antenna, the CS signal spreads in all direction and any node receiving the CS signal performs T-wakeup. If the node within the range is not in the path towards the sink, extra energy will be consumed that increase proportionally with the node density. In our scheme, routing information plays an important role in deciding whether to perform T-wakeup or not. The MAC layer acquires information from the routing agent to know if it is in the routing path towards the sink. For example, Directed Diffusion [10] sets up a unit routing path by reinforcement and each node can learn whether it belongs to the path or not by observing the routing table. Clearly, if the node is included in the path, it performs T-wakeup while other nodes continuously sleep until the next scheduled listen/sleep period.

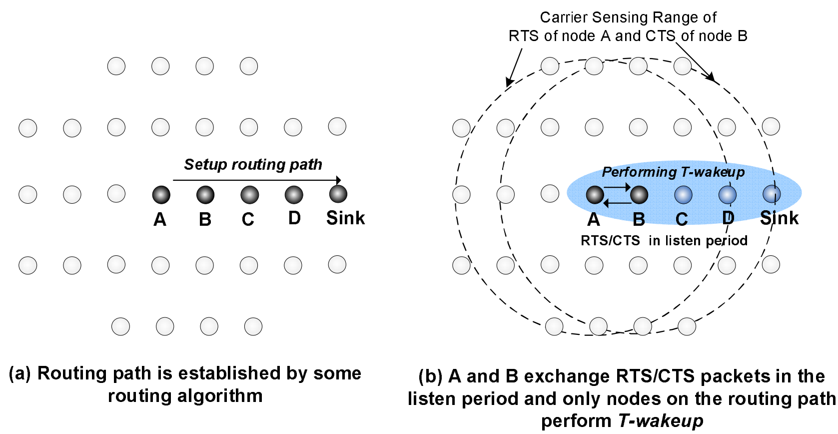


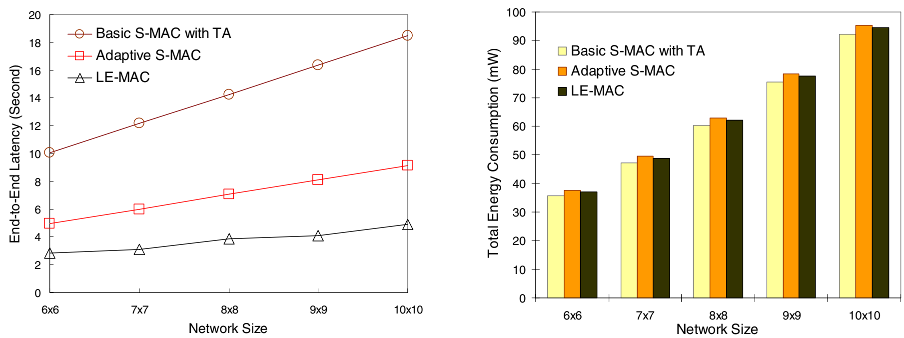
Fig. 4. Cross layer operations of MAC and Routing

Fig.4 illustrates that only those nodes on the path towards the sink, (node C and D) perform T-wakeup and others remain in the sleep mode and save energy. Note that, in adaptive S-MAC, all neighboring nodes that receive CTS packet wakes up, regardless of whether or not they are in the route causing extra energy consumption. In our scheme, since only those nodes belonging to the routing path wakes up, lesser energy is consumed than the adaptive S-MAC.

If multiple routing paths for different flows are established, our scheme consumes more energy because those nodes that have route information of other traffic also perform T-wakeup upon receiving carrier signals. These cases are possible because carrier signals outside the transmission range cannot be decoded. However, the duration for T-wakeup (T_{tw}) is very short compared to the total listen/sleep interval, thus trade-off over energy is very small compared with the performance increase in latency and throughput.

4 Performance Evaluation

We implemented our scheme on the ns-2 network simulator [12]. In our simulation model, we use a grid topology that has a fixed 40m distance between two nodes. The transmission range and the CS range are set to 55m and 110m respectively. We use the same power consumption model in the adaptive S-MAC[3] and set the switching time for the on-off interface to 2ms, as referred in [14]. The routing protocol uses greedy approach, where sink node first sends the interest packets to the target nodes by greedy flooding [15]. The target nodes then periodically transmit data back to the sink node. The size of the data packet is set to 100 bytes and the duty cycle is 10%. Total simulation time is 400s. We compare our scheme with the modified basic S-MAC with timeout mechanism[2] like T-MAC. This reduces an idle listening problem when communication nodes continuously maintain their active states after finishing data transmission.



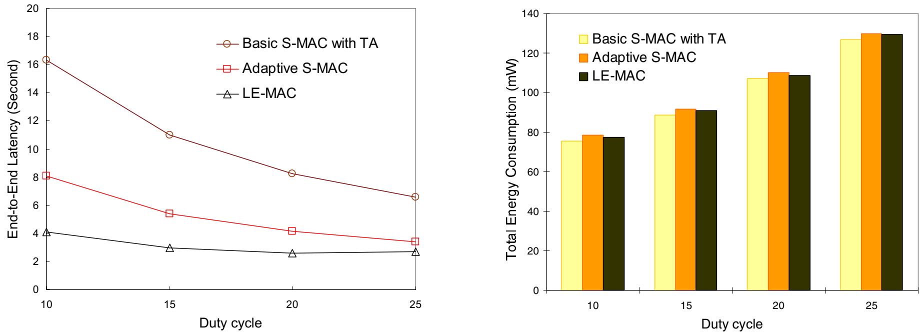
(a) (b)

Fig. 5. The variation of *network size* (a) Latency and (b) Total Energy Consumption

In the grid of 9x9sqm, we allocate one source and a sink node on the two opposite corners. For the first simulation, we increased the network size and fixed the packet generation interval as 12s (low traffic load) to analyze the performance when the delivery ratio is same for all protocols. Note that the number of packets arrived at the sink within the simulation time is different for the three protocols when the traffic load is high. Increasing the network size increases the number of hops for the packet to traverse. In Fig.5(a) our scheme shows the lowest latency for all the variations of the network size. The reason is the minimization of the amount of sleep delay in our scheme. Energy consumption of the basic S-MAC as shown in Fig.5(b) is less since there are no extra wakeup period at all. Energy consumed by our scheme is comparative to the basic-SMAC as it activates only those nodes participating in the communication based on the selective T-wakeup. Adaptive S-MAC however causes all CTS receiving nodes to wake up consuming extra energy.

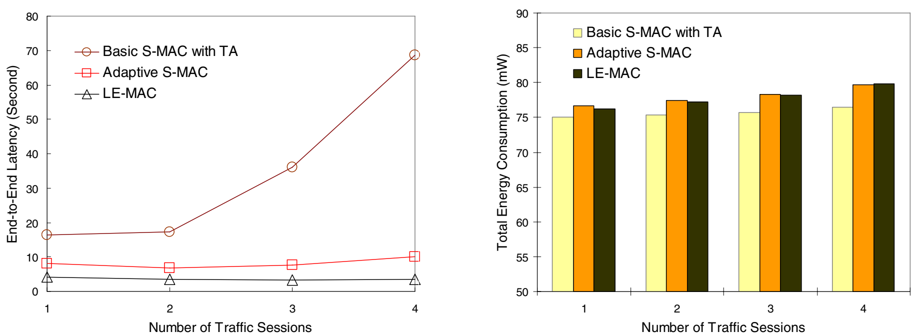
Another important factor that affects the latency and energy consumption is the duty-cycle. Duty cycle is defined as the ratio of the listen period (115ms) and the time frame (one cycle) [3]. With a high duty-cycle, the listen/sleep interval is frequent, so the energy consumption increases whereas sleep delay decreases due to short sleep period. In this experiment we increase the duty cycle from 10%

[2] The length of interval TA is defined as $T_{cs} + T_{rts} + T_{sifs}$ in [4].



(a) (b)

Fig. 6. The variation of *duty cycle*: (a) Latency and (b) Total Energy Consumption



(a) (b)

Fig. 7. The variation of *source-sink pairs*: (a) Latency, (b) Total Energy Consumption

to 25% in low data traffic. From Fig.6(a), we see that the latency of our scheme in 10% duty-cycle is 50% and 75% lesser than that of the adaptive S-MAC and basic S-MAC. Moreover, the total energy consumption is close to basic S-MAC (Refer to Fig.6(b)). From this result, we verify that LE-MAC is affected less by the duty cycle than others.

Cross-layer technique favors the assumption of single source and a sink because no matter how many nodes in the region are influenced by carrier signal only one routing path is available. To compare the performance with multiple routes, we injected 4 traffic sessions using 4 source nodes and one sink node. Each source transmits 15 packets with 12s message inter-arrival time. Fig.7(a) shows that our protocol consistently performs better in terms of latency. In the other hand, energy consumption increases with more traffic sessions because many nodes perform T-wakeup upon sensing a carrier and consume more energy. However, the trade-off over energy is very small as shown in Fig.7(b) (Note that the scale is from 55mW to 90mW) and is likely the marginal overhead compared with the performance increase in latency and throughput.

5 Conclusion

In this paper, we propose a novel scheme LE-MAC that considers end-to-end latency as well as energy consumption. By using physical CS and the cross layer technique, LE-MAC performs T-wakeup to continuously transmit data in one listen/sleep cycle. We prove such an improvement in terms of the end-to-end latency and energy consumption through the numeric analysis and simulation study. Our proposed scheme can be useful in various delay-sensitive sensor network applications. A performance comparison with some more recent works, such as WiseMAC or B-MAC, will be one of our future works.

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