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LETTER

A Retransmission-Enhanced Duty-Cycle MAC Protocol Based on the Channel Quality for Wireless Sensor Networks

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SUMMARY Duty-cycle MAC protocols have been proposed for wireless sensor networks (WSNs) to reduce the energy consumed by idle listening, but they introduce significant end-to-end delivery latency. Several works have attempted to mitigate this latency, but they still have a problem on handling the packet loss. The quality of the wireless channel in WSNs is quite bad, so packets are frequently lost. In this letter, we present a novel duty-cycle MAC protocol, called REMAC (Retransmission-Enhanced duty-cycle MAC), which exploits both the network layer and the physical layer information. REMAC estimates the quality of the wireless channel and properly reserves the wireless channel to handle the packet loss. It can reduce the end-to-end packet delivery latency caused by the packet loss without sacrificing the energy efficiency. Simulation results show that REMAC outperforms RMAC in terms of the end-to-end packet delivery latency.

key words: *WSN, duty-cycle MAC, low latency, energy efficiency, wireless channel quality*

1. Introduction

Wireless sensor networks (WSNs) consist of a huge number of distributed autonomous sensor nodes which are densely deployed in the sensing field to cooperatively perform the sensing task. Sensor nodes, which detect an interesting event such as a bushfire, generate data and report it to a sink (user) through multihop communication. Because sensor nodes are powered by a limited battery and it is often difficult to change the exhausted battery, the scarcest resource is energy. The battery power in the sensor node is mostly consumed by a radio module. Usually a typical sensor network application generates very light traffic because nothing is transmitted if nothing is sensed. Therefore, it wastes significant energy for sensor nodes to always listen to the wireless channel. This idle listening (listening to the wireless channel while nothing is transmitted) is one of the largest sources of energy consumption.

To mitigate the idle listening problem, duty-cycle MAC protocols have been proposed for WSNs. For example, in S-MAC [1], each node periodically turns on and off the radio module while following a synchronized listen/sleep schedule. In the listen mode, each node listens to the wireless channel to see if any other nodes want to send data to it or attempts to send data if having data. Sensor nodes also exchange their schedules by broadcasting a SYNC frame to all their neighbors. In the sleep mode, sensor nodes turn off their radio modules to save the battery power. With the duty-cycle mechanism, S-MAC can efficiently reduce the energy consumption of idle listening, but it has limitation. In each operation cycle, a packet can be forwarded over a single hop only since an intermediate relaying node has to wait for its next downstream node to wake up to receive the packet. Consequently, in S-MAC, as the path length increases, the end-to-end packet delivery latency increases linearly.

RMAC [2] was presented to deal with the delivery latency problem. It exploits cross-layer routing information to forward a packet over multiple hops in a single operation cycle. RMAC uses a control frame, called a PION (Pioneer Control Frame), which includes all fields as in an RTS and especially routing information: the final destination address of the current flow. When a node receives a PION, it gets the next-hop address for this destination from its own network layer and transmits its own PION to the downstream node, so the PION can be forwarded over multiple hops along the path to the sink. While relaying the PION, intermediate relaying nodes are scheduled when to be awake to receive data from the upstream node and forward it to the downstream node. By forwarding data over multiple hops in a single operation cycle with routing information, RMAC can efficiently reduce end-to-end packet delivery latency. However, if data or an ACK get dropped, no retries are made in the current operation cycle, since intermediate relaying nodes are not scheduled to be awake to receive the retransmitted packet. The current operation cycle is cancelled and data transmission is postponed until the next operation cycle. Consequently, the end-to-end packet delivery latency is increased by the frequent packet loss.

Wireless channel in WSNs is known to be notoriously unpredictable. The quality of the wireless channel depends on the modulation and coding schemes, the individual communication device characteristics, and especially the environment [3]. Usually, sensor nodes use the low-power radio module and are deployed in the harsh environment which exhibits significant multi-path communication, such as forest, urban area, and indoor area. Consequently, the packet loss rate in WSNs is high. Without handling the lost packet, the packet delivery latency will be dramatically increased.

To mitigate the above problem, in this letter, we present a novel duty-cycle MAC protocol, called REMAC (Retransmission-Enhanced duty-cycle MAC), that exploits both the network layer and the physical layer information. Like RMAC, REMAC exploits routing information to forward data over multiple hops along the path to the sink. Sim-

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ilar to the PION in RMAC, a control frame, called an RES (Reservation Control Frame), is used to schedule the wake up time of intermediate relaying nodes. More importantly, the RES reserves the proper amount of wireless channel depending on the quality of the link between a transmitter and a receiver. The reserved wireless channel is used to retransmit data in the current operation cycle when a packet gets dropped. Efficiently handling the packet loss, REMAC can reduce the end-to-end packet delivery latency without sacrificing the energy efficiency.

2. Retransmission-Enhanced Duty-Cycle MAC

In previous work, RMAC, if data or an ACK get dropped, the current operation cycle is cancelled and data transmission is postponed until the next operation cycle. It makes the packet delivery latency longer. To reduce the packet delivery latency caused by the packet loss, REMAC estimates the quality of the link between two nodes and properly reserves wireless channel to immediately retransmit data in the current operation cycle. To estimate the quality of the link, REMAC defines the data retransmission function which needs the distance between two nodes as input. In this letter, we assume that all nodes know their position through localization schemes. Self-localization capability is an essential characteristic of most WSN applications [4]. In environmental monitoring applications such as bush fire surveillance and water quality monitoring, the measurement data are meaningless without knowing the location from where the data are obtained. Thus, in most WSN applications, this assumption is not required additional overhead. After deployment of sensor nodes, they exchange their location information with neighbors by broadcasting a SYNC frame.

Figure 1 shows an overview of the operation of REMAC. REMAC bases on a combined scheduling and contention scheme. A single operation cycle of a sensor node in REMAC is divided into three periods: SYNC, DATA, and SLEEP. In the SYNC period and the DATA period, sensor nodes turn on their radio module to communicate each other (listen mode), but turn off their radio module to save energy in the SLEEP period (sleep mode). Each sensor node follows a periodic synchronized listen/sleep schedule. In the SYNC period, each node broadcasts a SYNC frame to synchronize the clocks on nodes and exchange

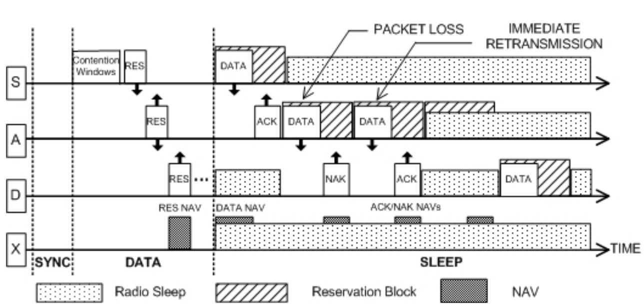

Fig. 1 Overview of the REMAC's operation; Node S sends data to node D via node A. Node X is one-hop neighbor of node A.

the listen/sleep schedule and their location information with neighbors. When a node has data to send, it initiates its request at the start of the DATA period. In Fig. 1, if node S has data to send to some destination, node S first detects the status of the medium during the random time in its contention windows. If the medium is idle and continues to be idle for a period of time set in DIFS (Distributed Inter Frame Space), then node S gains access to the medium (as in IEEE 802.11 CSMA/CA).

Before sending an RES to the next-hop node A to request the data transmission, node S decides how many reservation blocks are to be reserved for node A based on the link quality between node S and node A. REMAC does not measure the link quality by receiving the packet but estimates it using the data retransmission function (describe next section). After getting the number of the reservation blocks for node A using the data retransmission function with the distance to node A, node S puts it in its RES and transmits to node A. The reservation block $B_{reservation}$ is

$$B_{reservation} = D_{DATA} + D_{ACK/NAK} + 2 \times SIFS \tag{1}$$

where D_{DATA} and $D_{ACK/NAK}$ are the duration to transmit a DATA frame and an ACK/NAK frame respectively and SIFS is Short Inter-Frame Spacing.

The RES includes all fields as in an RTS, such as current node's address, the next-hop address, and the duration of the transmission (the number of reservation blocks $N_{reservation}$), and the final destination address of the current flow like a PION. The RES also includes some additional information: the accumulated number of reservation blocks along the path $N_{accumulated}$ for scheduling the wake up time and the number of reservation blocks of the previous-hop node $N_{previous}$ for setting the NAV (Network Allocation Vector).

When node A receives node S' RES, it gets the next-hop address for the destination address in the RES from its own network layer and estimates the quality of the link to next-hop node D. Node A transmits its own RES after a SIFS period. The RES from node A serves as a CTS to node S and simultaneously an RTS to node D. This process of receiving an RES and transmitting another RES continues until either the final destination has received the RES or the end of the current DATA period is reached. The DATA period of the operation cycle is used only to send and receive the RES, setting up the schedule for the actual data transmission.

At the start of the SLEEP period, node S transmits data to node A immediately (Fig. 1). After node A receives data, it sends an ACK to node S. After receiving the ACK, node S goes to sleep mode to save energy. Node A immediately forwards the data to node D. This data relaying process continues at each hop until the final destination is reached. Like RMAC, REMAC can send data over multiple hops in a single operation cycle. Except the source node (node S) and its next-hop node (node A), other nodes in the multi-hop path that took part in the RES transmission in the current DATA period go to sleep to save energy. Each node later wakes up at the right time to receive the data from the upstream node and send it to the downstream node. For example, node D can go to sleep when the SLEEP period begins, but it wakes up at the scheduled time when node A is ready to forward data to node D. The scheduled wake up time of the intermediate relaying nodes can be calculated from the accumulated number of reservation blocks in the RES. Scheduled wake up time T_{wakeup} of the ith-hop node should be

$$T_{wakeup}(i) = T_{SLEEP} + N_{accumulated}(i-1) \times B_{reservation} \quad (2)$$

where T_{SLEEP} is the start time of the SLEEP period.

Setting the Network Allocation Vector (NAV): The Network Allocation Vector (NAV) at each node is used in IEEE 802.11-sytle MAC protocols for virtual carrier sense, to avoid packet collisions. A non-zero NAV implies a busy medium and hence prevents a node from transmitting. For example, in Fig. 1, if node X is a neighbor of node A, to avoid collision at node A, node X should not transmit if node A is potentially receiving anything. Node A will receive an RES form node D, data from node S, and NAK/ACK from node D, Therefore, node X should set its own three NAVs (RES NAV, DATA NAVs, and ACK/NAK NAVs) at those periods. These NAVs can be calculated using information in the RES which node X overhears from node A to node D during the DATA period. Each NAV of the node is calculated like below

- RES NAV: $[T_{RES-START}, T_{RES-END}]$
  - $T_{RES-START} = NOW + SIFS$
  - $T_{RES-END} = T_{RES-START} + D_{RES}$

  where NOW is the time when a node overhears the RES during the DATA period and D_{RES} is the transmission duration of an RES frame.

- DATA NAVs: $[T_{DATA-START}, T_{DATA-END}]$
  - $T_{DATA-START}(i) = T_{SLEEP} + (N_{accumulated} - N_{previous}) \times B_{reservation} + B_{reservation} \times (i-1)$
  - $T_{DATA-END}(i) = T_{DATA-START}(i) + D_{DATA}$

  where i is $1, 2, \ldots, N_{previous}$. $N_{accumulated}$ and $N_{previous}$ are from the RES frame.

- ACK/NAK NAVs: $[T_{ACK/NAK-START}, T_{ACK/NAK-END}]$
  - $T_{ACK/NAK-START}(k) = T_{SLEEP} + N_{accumulated} \times B_{reservation} + D_{DATA} + SIFS + B_{reservation} \times (k-1)$
  - $T_{ACK/NAK-END}(k) = T_{ACK/NAK-START}(k) + D_{ACK/NAK}$

  where k is $1, 2, \ldots, N_{reservation}$. $N_{accumulated}$ and $N_{reservation}$ are from the RES frame.

After setting NAVs for node A, if node X receives another RES in the current DATA period that requests node X to relay data, then node X confirms the RES only if the relaying frames (immediate RES and future ACK/NAK and data transmission) do not conflict with its current NAV settings. If any of these relaying frames conflict with the current NAVs, then node X does not transmit a confirmation RES.

Handling the packet loss: Sensor nodes are deployed in harsh and inaccessible environments, which exhibit significant multi-path communication. Moreover, many of the current sensor platforms use low-power radios which do not have enough frequency diversity to reject multi-path propagation [3]. Consequently, there is high packet loss rate in WSNs.

The quality of each link between two nodes is affected by the distance and any obstructions between nodes. REMAC does not measure the quality of link by receiving the packet but estimates it using the data retransmission function. Based on shadowing radio propagation model [4], we estimate wireless channel's quality and reserve the proper amount of wireless channel in the SLEEP period depending on link's quality. Sensor nodes are stationary and there are large obstructions such as hills or buildings that obscure the main signal path between the transmitter and the receiver in the sensing field, so the shadowing radio propagation model is suitable to estimate the quality of the wireless channel in WSNs. The reserved wireless channel is used to retransmit a packet when a packet gets dropped. For example, in Fig. 1, because the quality of the link between the node S and node A is better than the quality of the link between node A and node D, the node S reserves 1 reservation block whereas node A reserves 3 reservation blocks. To decide how many reservation blocks are to be reserved to successfully transmit data in a single operation cycle, we define the data retransmission function.

We model the received signal strength at distance d, $RSS(d)$, as a log-normally distributed random value with a distance-dependent mean value. That is,

$$RSS(d)\,[\text{dBm}] = P_0(d_0)\,[\text{dBm}] - 10n_p \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (3)$$

where $P_0(d_0)$ is a known reference power at a reference distance d_0, n_p is the path loss exponent, and X_σ is a zero mean Gaussian distributed random variable with standard deviation σ. We derive the reception probability $P_r(d)$ at distance d from (3). It is,

$$P_r(d) = P[RSS(d) \geq \theta] = \int_\theta^\infty \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad (4)^\dagger$$

where θ is a receive power threshold that is determined by the communication hardware and the modulation and coding scheme and μ is $P_0(d_0)\,[\text{dBm}] - 10n_p \log_{10}(\frac{d}{d_0})$. Finally, we derive the data retransmission function to get the number

†Using a standard normal distribution table, time complexity of this equation is O(1).

of reservation blocks N to successfully transmit data over the system threshold $\Phi^{\dagger}$. That is,

$$\sum_{k=1}^{N}(1 - P_r(d))^{k-1}P_r(d) \geq \Phi$$

$$N = \left\lceil \frac{\log(1 - \Phi)}{\log(1 - P_r(d))} \right\rceil \quad (5)$$

Except the distance between two nodes, all other values for the function are determined before sensor nodes are deployed. Therefore, to get the number of reservation blocks, nodes only need to know the distance to next-hop node.

If the node wakes up to receive data and receives nothing until after a predefined timeout, it sends a NAK to the upstream node. The upstream node then immediately retransmits data in the current operation cycle using the reserved reservation block unlike RMAC where data retransmission is postponed until the next operation cycle. In Fig. 1, node A transmits data in the first reservation block, but it is dropped, so node D sends a NAK and then node A immediately retransmits data in the second reservation block. After receiving the ACK from node D, node A goes to sleep though it has the additional reservation block. In this case, node D does not transmit data immediately but goes to sleep until it is scheduled to transmit data to the downstream node.

3. Performance Evaluation

In this section, we evaluated the performance of REMAC using version 2.29 of the NS-2 simulator. To evaluate our work, we compared it with RMAC [2].

We use the shadowing radio propagation model and simulate in three types of sensing areas: free space, shadowed urban area, and in building. Table 1 gives the parameters of this propagation model which are the default settings in the NS-2 simulator. Other key parameters of the simulation are shown in the Table 2; except the power consumption model, which is typical value for Mica2 radios (CC1000), we use the settings used for evaluation of RMAC [2]. The receive power threshold is modelled after the 914 MHz Lucent WaveLAN DSSS radio interface. The duty cycle R is defined as the proportion of the listen time of an operation cycle time. We set up the duty cycle R as 5% in both REMAC and RMAC. During the DATA period, a PION or an RES is forwarded over multiple hops, maximum 4 hops.

The 200 sensor nodes are uniformly randomly distributed in a $2000 \times 2000\,\text{m}^2$ sensing field. There are one sink and 100 source nodes among the sensor nodes. All the nodes have a path to the sink. Most of the nodes are about 8 to 11 hops from the sink which is located at the top right corner of the sensing area. All traffic in the network is from a sensor node to the sink. At a periodic interval, a sensor node is selected to send one data packet. During the simulation, 100 data packets are sent to the sink. There is no data aggregation and compression. We also assume all the nodes in the network have already been synchronized to use a single listen/sleep schedule.

Figure 2 shows the results of the end-to-end packet delivery latency. Basically, the delivery latency in all the sensing areas of both RMAC and REMAC increases as the hop count of the path increases. However, the shape of curves in free space increases at a much slower rate compared to the others. It is because there is low possibility of the packet loss due to the good channel quality. In the shadowed urban area and building, REMAC reduces the delivery latency over RMAC by about 17%. The average time required to send data over one hop in the shadowed urban area is 2.9 ms and 3.5 ms in REMAC and RMAC, respectively. Because of the high packet loss rate in those sensing areas, data retransmission is frequently postponed until the next operation cycle in RMAC in case of the packet loss. As the length of the operation cycle increases, the difference of the delivery latency between REMAC and RMAC increases.

In Fig. 3, the results of the total energy consumption of the sensor nodes are depicted. The total energy consumption is the amount of energy consumed by all the nodes during the total simulation time. The total energy consumption in free space is half compared to the others. The battery power

Table 1 Shadowing propagation model parameters.

Environment	Free space	Shadowed urban area	In building
Shadowing deviation σ	4 dB	10 dB	9.6 dB
Path loss exponent n_p	2	5	6

Table 2 Simulation parameters.

Parameter	Value	Parameter	Value
Tx Power	31.2 mW	Size of ACK/NAK/DATA	10/10/100 B
Rx Power	22.2 mW	Size of PION/RES	14/16 B
Idle Power	22.2 mW	Receive Power Threshold θ	$3.652e^{-10}$ W
Sleep Power	3 μW	System Threshold Φ	90%
DIFS/SIFS	10/5 ms	Retry Limit	5

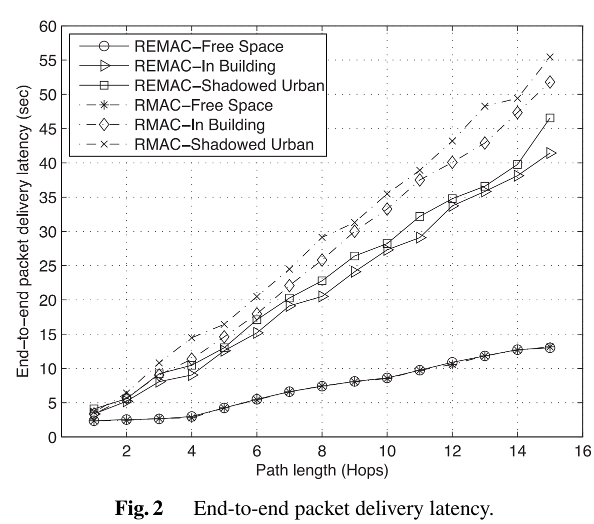

Fig. 2 End-to-end packet delivery latency.

†This value depends on both an application requirement and the environment of the sensing field.

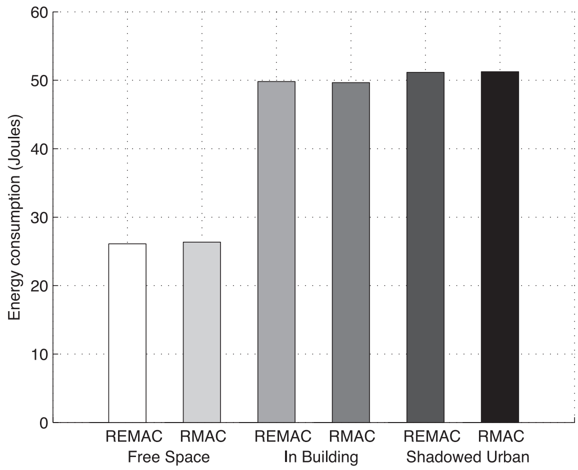

Fig. 3 Total energy consumption of the sensor nodes.

for retransmission is far less wasted due to the good channel quality in free space. The results show that REMAC's energy consumption is almost the same as that of RMAC although the RES is 2 bytes bigger than PION and moreover, the NAK is sent in case of the packet loss in REMAC while nothing is sent in RMAC. This is because RMAC sends the new PION to set up the new data transmission in the next operation cycle when data or an ACK gets lost whereas REMAC retransmits the data without sending any RES.

We have simulated the packet delivery success ratio of two protocols and the results show that most packets can be sent successfully because all the nodes have paths to the sink and each node tries to send a packet five times per link when it gets dropped.

4. Conclusion

In this letter, we have presented REMAC, a new energy efficient duty-cycle MAC protocol designed to reduce the end-to-end packet delivery latency in high packet loss rate environments. By exploiting the physical layer information, REMAC estimates the quality of the wireless channel based on the shadowing radio propagation model and adaptively reserves the reservation blocks to retransmit the packet in a single operation cycle in case of the packet loss.

To evaluate the performance of REMAC, we compared REMAC with RMAC. The results show that REMAC outperforms RMAC with low end-to-end packet delivery latency. REMAC reduces delivery latency by 17% compared to RMAC without increasing the energy consumption. Moreover, as the length of the operation cycle increases, the difference of the delivery latency between REMAC and RMAC increases.

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