Real-time Adaptive Medium Access Control Protocol to Improve Transmission Efficiency in Body Sensor Networks

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ABSTRACT

The applications of wireless sensing technology in health monitoring and diagnosis have increased dramatically. These applications have improved the quality of life and allowed medical practitioners to access patients information remotely and timely. However, the wireless communication between the sensing devices can be interfered by body movement. To guarantee data availability and recognition accuracy, each node has to either utilize a high transmission power or involve a packet retransmission mechanism. Increasing the transmission power of a sensor node increases energy overheads and communication range. Larger communication range can produce additional interference with other nodes on the body. Packet retransmission, on the other hand, complicates on-body sensor nodes' MAC layer and increases energy overheads. In this paper, we propose an Adaptive Medium Access Control protocol (AMAC) to improve the delivery rate by duty-cycling the transmission radio according to the predicted activities. We perform extensive experiments to evaluate and compare the protocol against B-MAC, OMAC and OTP using real sensor nodes attached to 50 participants. The results show that the proposed algorithm can achieve a higher packet delivery than B-MAC, OMAC and OTP without additional energy consumption.

Keywords

Body Sensor Networks, Medium Access Control, Gait Analysis, Energy Efficiency, Reliability

1. INTRODUCTION

The advancement of sensor technologies has revolutionized the e-healthcare applications by making the remote and automated monitoring of patients possible for medical practitioners and patients. Small wireless electronic devices with biomedical sensors can be attached on different body parts to provide non-intrusive monitoring and delivery of critical physiological information anytime anywhere. Two or mote sensory devices are usually placed in strategic body location. These devices have the ability to interact with other nodes wirelessly and autonomously to form a network. The data captured are usually transmitted across the network using low power transmission signal in order to prolong the battery lifespan. As a result, the packets may be dropped or loss during transmission.

A major hurdle for the wide adoption of BSN technology is the potential of service disruption due to radio interference [2] and battery depletion [8]. The sensory device is usually powered by an embedded battery source where replacing the battery can be difficult as it may be placed deep underneath the body skin. The communication between the sensing and aggregation nodes can be unreliable due to the movement of the body part such as the hands, arms and legs. Experimental work by Lim et al. shows that radio interference can lead to severe packet drop and packet retransmission affecting the dependability of the networks [2]. The power consumption for a wireless device operating in a noisy environment is usually higher than normal operating environment due to packet retransmission during radio failures. In order to reduce the energy consumption, it necessary to minimize or avoid radio communication when the link quality is not reliable.

To reduce power during transmission, the node is usually switched to the sleep mode when radio transmission is not possible. However, it can be difficult to adjust the sleep and awake cycle in BSN as the user's activities can be difficult to predict. It is not easy to coordinate and control data transmission without predicting the activities of the users so that the radio transmission cycle can be adapted according to the activity patterns. Real-time activity recognition is an important and challenging task.

In this paper, we propose an Adaptive Medium Access Control (A-MAC) protocol that uses the gait analysis to tune the radio's duty-cycle according to the user's activities. The main contributions of the paper are:

- A novel MAC protocol that has the ability to duty cycle the radio according to the user's activity using the collective acceleration measurements.
- A comprehensive analysis of the proposed protocol in term of reliability and energy efficiency.

For the rest of the paper, we present the related works in Section 2. The design of A-MAC is introduced in Section 3 and evaluated in Section 4 using on a real hardware attached to a user. The PDR and current measurements are compared and discussed in detail. Section 5 describes the future work and concludes.

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2. RELATED WORKS

Many WSNs researches have been dedicated to the development of MAC algorithms over the last two decades due to their dominant effect on energy consumption. Contention-based MAC protocols such as S-MAC [10], T-MAC [9], and D-MAC [6] are proposed to solve the idle listening problem using a synchronized duty cycle schedule between the sensor nodes. Ye et al. developed the S-MAC using virtual clusters to enable nodes to communicate within divided time slots according to the exchanged schedule [10]. S-MAC reduces the energy consumption but increases the network latency. In order to improve the energy consumption, Van Dam and Langendoe extended the S-MAC and proposed the T-MAC [9]. By introducing adaptive duty cycle that can adapt to different traffic patterns, T-MAC does not use a conservative slot schedule to accommodate the worst traffic pattern like S-MAC. However, it increases the network throughput and introduces extra delay due to the aggressive sleep schedule.

In our earlier work, we proposed an Optimistic Medium Access Control (OMAC) to transmit the packet when the leg is at the most forward position [5]. Using the accelerometer to predict the leg movement of the users, the aggregation node has received more packets than using CSMA/CA. However, it assumes that the walking paces and strides are similar and is only tested on limited activities. Different users may exhibit different walking patterns that can affect the accelerometer reading [1]. The same performance cannot be achieved when the user is walking in uneven and dynamic stride or running [3]. The distance and relative antenna orientation between the BSN transmitter and receiver changes for different activities [7]. This affects threshold parameter applied by OMAC to predict the forward leg position and required retraining.

3. ADAPTIVE MEDIUM ACCESS CONTROL PROTOCOL

A-MAC is based on a TDMA-based energy efficient MAC protocol designed for BSNs. It uses the accelerometer reading to transmit the packet. Accelerometer is usually built into a BSN mote. As a TDMA protocol, A-MAC assigns dedicated time slots to each mote to guarantee collision-free transmission. On the other hand, by taking advantage of body movement, A-MAC can achieve TDMA time synchronization without distributing periodic timing information, which reduces the energy cost. In A-MAC, each mote extracts the necessary synchronization information from its own accelerometer, which is correlated with to the body movement, in a distributed way.

We exploit the acceleration information provided by the sensor to adjust the radio cycle. The idea is motivated by the following observations. The movement of the body part such as the leg and hand usually exhibits periodic characteristics. The hand and leg usually swing left and right when someone is moving in the forward or backward direction. As the leg moves toward the front, the acceleration increases and eventually reaches the maximum and back to the minimum when the other leg swing forward. Although the maximum values are not perfectly aligned due to different stride, it exhibits a periodic cycle that varies between activities. Experimental results from [3] have shown that the reliability of the packet transmission increases when the leg crosses the midpoint position of the body. Hence, in this paper, we developed a MAC protocol that will turn on its radio when the leg is above the midpoint position and before it reaches the maximum acceleration. As the maximum accelerations between the left and right leg are not usually the same, A-MAC will assign dedicated time slots to each bio-sensor for collision-free network transmission.

3.1 The Design of A-MAC

A-MAC protocol operates in several stages: Pre-processing, Computing and Response. During pre-processing stage, the acceleration measurements are captured and analyzed. Following the analysis, an acceleration waveform is generated. The waveform is divided into cycles by determining the maximum acceleration and the time different between two maximum acceleration is one cycle. Once the acceleration cycle has been determined, A-MAC will compute the time slot for transmission. From the waveform, A-MAC captures the acceleration peak-to-peak (A_{pk-pk}) to determine the intensity of the activities and the acceleration period (P_a) to determine the duration variation. The statechart of the A-MAC is shown in Figure 1.

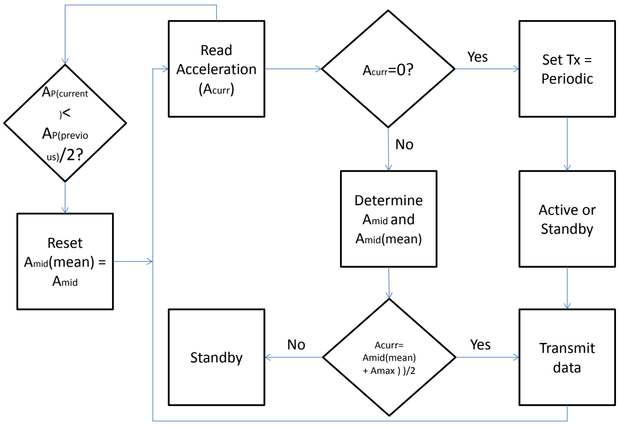

Figure 1: The A-MAC Flowchart to duty cycle the node's radio

Using these two information, we determine the mid-point between the peak using equation 1 and compute the mean of the acceleration midpoint A_{mid}(t) with equation 2:

$$A_{mid}(t) = \frac{A_{pk-pk}(t) - A_{pk-pk}(t-1)}{2} \tag{1}$$

$$A_{mid}(mean) = \frac{\sum_{t=1}^{n} A_{mid}(t)}{n} \tag{2}$$

where n=number of cycle

As the means of A_{mid} will vary depending on the (A_p), we configure A-MAC to turn the radio on when the foot is current acceleration reading between the A_{mid} and A_{max}. Hence, the radio is on at $\frac{A_{max}-A_{mid}(mean)}{2}$. To allow the A-MAC to adapt to different foot activities, the $A_{mid}(mean)$ will be reset to A_{mid} when P_a(t)$\leq\frac{P_a(t-1)}{2}$.

3.2 Hardware Architecture

The A-MAC can be used in any IEEE-802.15.4 compliance devices. It does not need any additional hardware except an accelerometer sensor that is commonly found in a typical BSN device. As shown in Figure 2, A-MAC can be installed between the access and physical layers of the protocol stack to allow the A-MAC to adapt the radio duty cycle according to the user's activities.

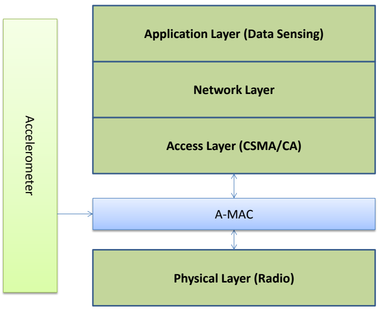

Figure 2: The A-MAC in IEEE 802.15.5 Protocol Stack

3.3 Hardware Setup

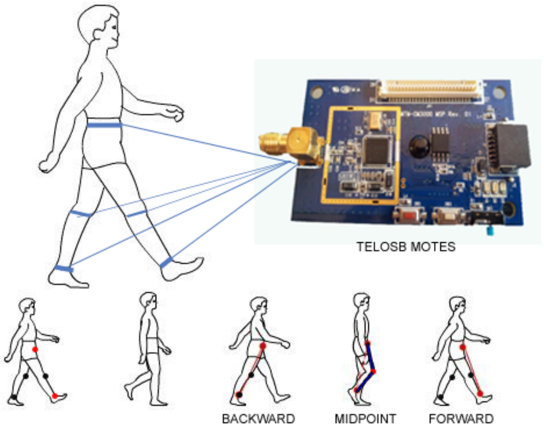

Figure 3: The placement of the sensing nodes and the aggregation node

In this section, we present the hardware deployment for A-MAC. Although the proposed protocol can support any number of nodes, we only focus on 5 nodes attached to the lower part of the body shown in Figure 3. These five nodes are configured to perform different tasks namely sensing, packet forwarding and packet collector. The collector, attached on the waist, is used to receive information from the sensing nodes. The sensing node is used to capture the sensor measurements and store the data temporary in the memory buffer, These information are only transmitted when a sufficient number of readings is collected. The nodes placed on the knee can function as a sensing node, forwarding node, or both. In addition to five nodes, a base node in the form of mobile phone is used to collect the data from the collector.

4. PERFORMANCE EVALUATION

In this section, we perform an experiment evaluate the A-MAC against T-MAC, OMAC and CSMA/CA. We hypothesis each activity exhibits different waveforms. 50 participants are selected to conduct the experiments. Each participant wears five TelosB motes on his or her body with a node attached to the waist to receive and aggregate the data transmitted by the sensing nodes, and four sensing nodes on the knees and ankles to collect and transmit the sensor data as shown in Figure 3. To ensure that proposed protocol can support different activities, each participant is requested to perform the following tasks: *Walking*, *Running*, *Walking up the stairs* and *Walking down the stairs*. For each task, the accelerations are captured at the sampling frequency of 50Hz. The configurations of each node are shown in table 1.

Table 1: The configuration of the node

Parameters	Values
Medium Access Protocol	CSMA/CA
TelosB Node Tx Power	1
Radio Channel	26
Max sensing reading can be stored in memory	1000 packets
Default sensing intervals	10ms
Acceleration Sampling Rate	50Hz

4.1 Evaluation Metrics

In this section, we presentation the reliability and the energy efficiency metrics that are used to evaluate the protocols.

Reliability: To evaluate the reliability of the packet transmission, the Packet Delivery Ratio (PDR) is calculated using the formula:

$$PDR = \frac{Number\ of\ Packets\ Received}{Number\ of\ Packets\ Sent} \times 100 \tag{3}$$

Energy Efficiency: To compare the energy efficiency of the protocols, we measure the initial current reading $A_{initial}$ by connecting the node to the ammeter before the experiment. After each experiment, we repeat the procedure to determine the remaining power in the battery.

To calculate the average current consumption, the following formula is applied

$$A_{Average} = \frac{\sum^{N}(A_{initial}(t-1) - A_{final}(t))}{N} \tag{4}$$

where N = Total Number of Nodes.

From the average current utilization for one participants, the final average is calculated using the equation

$$Final\ Average\ Current = \frac{\sum^{P}(A_{Average})}{P} \tag{5}$$

where P = Total Number of Participants.

4.2 Results and Discussions

To analyze the results, a box-and-whiskers plot showing the median and upper and lower quartiles of the PDR is presented. We performed a statistical test to measure the statistical and scientifically significance using the Conceptual Statistical Test Framework (CSTF) proposed by [4].

Table 2: Statistically (P-Test) and Scientifically (A-Test) Significant tests on the differences between the transmission protocols using the results collected the hardware experiments

	Walk			Run			Stair(Up)			Stair(Down)		
	BMAC	OMAC	OTP	BMAC	OMAC	OTP	BMAC	OMAC	OTP	BMAC	OMAC	OTP
p-test	1.11E-18	4.06E-11	0.001	2.76E-18	5.48E-08	0.001	1.13E-18	9.11E-17	0.398	1.66E-18	1.66E-17	4.72E-14
a-test	1	0.874	0.716	1	0.812	0.709	1	0.971	0.452	1	0.985	0.928

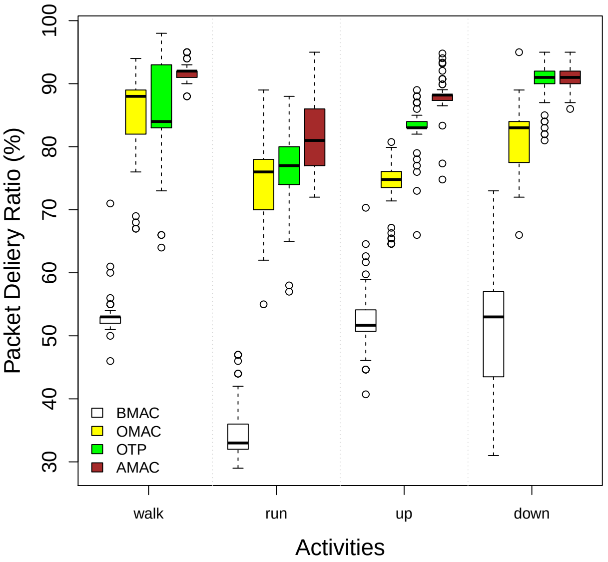

Figure 4: shows the PDR distributions when the participants are asked do different activities

The tests applied are the Rank-Sum and A-Tests. For energy efficient, we computed the average current utilization in Ampere in Table 3.

Table 3: Average Current Consumption

Activities	A-MAC	OTP	OMAC	B-MAC
Walking	0.38mA	0.41mA	0.42mA	0.70mA
Running	0.51mA	0.54mA	0.59mA	0.81mA
Stairs (Up)	0.41mA	0.52mA	0.56mA	0.81mA
Stair (Down)	0.40mA	0.51mA	0.58mA	0.79mA

From Box-and-Whiskers in Figure 4, A-MAC has achieved higher PDR than B-MAC. The performance of A-MAC is similar to OMAC and OTP when walking but improved when the users are running and going up the stair. The differences between A-MAC and OMAC and OTP are both statistical and scientifically significances as shown in Table 2. The average current consumed by A-MAC is lower. Hence, A-MAC is more energy efficient and can adapt to user activities.

5. CONCLUSION

In this paper, we have shown that by adapting the transmission protocol according to the user's activities, the current utilization in the node is more efficient. More packets can be delivered successfully. However, further tests are still required to evaluate A-MAC under normal clinical conditions.

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