A Dynamic Duty Cycle MAC Algorithm for Wireless Body Area Networks

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Abstract

A wireless body area network (WBAN) allows the integration of low power, invasive or noninvasive miniaturized sensors around a human body. In this paper, a dynamic duty cycle algorithm is designed to handle energy efficiency, by varying the sleep period according to the amount of traffic that needs to be transmitted. In addition, we propose a priority based carrier sensing method that enhances energy efficiency while still guaranteeing a low latency for the multiple applications used in a body area network. NS-2 simulations have been carried out for the performance evaluation. The simulation results show that the proposed MAC algorithm is archived significant improvement in terms of latency and energy efficiency.

Keywords: *Wireless Body Area Network; Energy-Efficient; Priority MAC*

1. Introduction

Recently, the rapid development of wireless body area networks (WBAN) has made them more and more attractive for use in pervasive healthcare applications [1-3]. WBANs are ideal for the wireless networking of wearable and implantable body sensors which monitor vital body signs, such as heart-rate, temperature, blood pressure, ECGs, EEGs, etc. WBANs are also of particular interest to the healthcare sector for the provision of efficient healthcare services and for ongoing clinical management. WBANs consist of a quantity of low power resource constrained sensor node devices placed around, on, or into a human body. Since a WBAN is based on the body area scale, a star-shaped network topology and a master-slave protocol are generally adopted [5,9].

The most energy consumption in the BAN nodes occurs in the wireless interface; its energy consumption is mainly due to the operation of its Medium Access Control (MAC) [10]. The MAC layer operates between the physical link layer and the upper layers; it handles the access to the communication channel and is vital in providing reliable links for the MAC entities [11]. The MAC layer, being relatively less proprietary and hardware-independent, makes it a good starting point for the development of a customized WBAN communication standard. In this paper, an ultra lightweight MAC protocol is presented. The primary goals for the improved MAC design are to achieve low power consumption, guarantee priority, and to reduce latency.

2. Related work

2.1. WBAN Overview

A WBAN consists of a coordinator and multiple devices placed around and in the human body. As shown in Figure 1, these devices are used to gather vital data. A

WBAN coordinator, otherwise known as a master node, is placed at the center of a star-shaped topology made up of these devices in order to manage and control them.

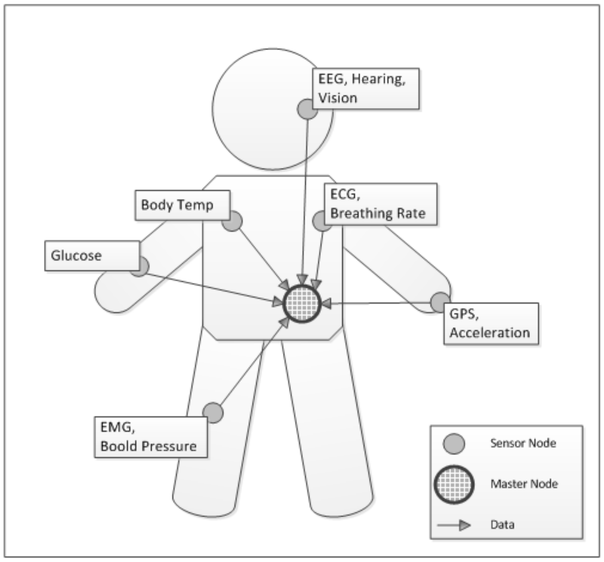

Figure 1. An Example of WBAN Constitution

2.2. WBAN Requirements

As described above, a WBAN is made up of multiple devices with various characteristics around the human body, either inside or outside the body. Therefore, the WBAN MAC protocol has to meet the following requirements in order to provide a certain flexibility among the various devices and applications [6, 7]:

- **Low power consumption**: Since most of the devices are battery based implantable or portable medical sensors, energy efficiency is the most critical issue.
- **Duty cycle**: The duty cycle is a crucial feature in medical devices. A device has to be kept asleep as long as possible, and has to wake up quickly to exchange data when needed.
- **Scalability**: A WBAN has to be scalable for up to 256 devices and has to support various data transfer rates from 1 kbps to 1 Mbps.
- **Latency**: Medical applications that require QoS guarantees, such as applications used for emergency medical situations, need to have a low latency.
- **Periodicity**: Most WBAN devices need to periodically gather vital body signs and exchange data with the WBAN coordinator. A device can have period from 1 ms to 1000 s; the coordinator must be able to provide for this.

In a word, energy efficiency and latency are the most important requirements in the WBAN MAC protocol. At the same time, flexibility is required, since there are multiple devices with various characteristics in the WBAN environment. Table 1 shows the typical requirements for various applications.

Table 1. Typical Application Performance Requirements

Application	Target data rate	Latency	BER
Drug Delivery	< 16 kbps	< 250 ms	$< 10^{-10}$
Deep Brain Stimulation	< 320 kbps	< 250 ms	$< 10^{-10}$
Capule type endoscope	< 1 Mbps	-	$< 10^{-10}$
ECG	< 192 kbps (6 kbps, 32 channels)	< 250 ms	$< 10^{-10}$
EEG	< 86.4 kbps (300 Hz sample, 12-bit ADC, 24 channels)	< 250 ms	$< 10^{-10}$
EMG	< 1.536 Mbps (8 kHz sample, 16-bit ADC, 12 channels)	< 250 ms	$< 10^{-10}$
Glucose level monitor	< 1 kbps	< 250 ms	$< 10^{-10}$

2.3. Conventional WBAN MAC Protocol

There are a few studies dedicated to the development of various MAC algorithms. S-MAC [12], T-MAC [13] and DMAC [4] are typical contention-based MAC protocols that try to solve the idle listening problem by applying a synchronized duty cycle schedule amongst the sensor nodes. However, these protocols are computationally complex and contain control package overheads that are redundant in regards to star-shape topology based WBANs.

The design considerations associated with WBANs are typically low energy consumption, limited computational abilities, continuous operation, and robustness. Reference [14] presents an H-MAC Time Division Multiple Access (TDMA) MAC protocol, aiming to improve the BSN energy efficiency by exploiting the heartbeat rhythm information in order to perform its time synchronization. However, this protocol is still premature, since during the in-situ experiments the heartbeat rhythm was inevitably affected by noise.

The main reason for this new study lies in that no wireless standard has yet been adopted which governs medical BANs incorporating implantable and wearable devices. The proposed scheme attempts to provide flexibility, scalability, and adaptability, combined with ultra-low power consumption.

3. The Dynamic Duty Cycle MAC Algorithm

The protocol proposed in this paper has been developed for use in WBANs. The goal of this MAC protocol is to achieve energy efficiency, as described in Section 2; we suggest the following two methods:

First, we propose an algorithm in that a node chooses its sleep period dependent on the amount of its traffic. Conventional WBAN MAC protocols use the TDMA method, wherein a master node assigns the CFP for each sensor node in order to increase the energy efficiency. However, this requires a master node to consume computational power, wastes bandwidth, and increases latency, since the channels are assigned to the sensor nodes without considering the amount of data to be transferred. In response to this we propose the traffic adaptive wakeup method, in which a sensor node determines its sleep period in regards to the amount of traffic it needs to transmit. The proposed algorithm achieves both a higher energy efficiency in the sensor nodes and a lower computational requirement in the master node.

Second, we propose a scheme wherein a node can access the channel based on priority while still avoiding collisions. Each sensor node wakes up and checks to see whether or not the channel is idle with a varying carrier sensing time according to its priority, then transmits its data if the channel is idle.

3.1. Traffic Adaptive Wakeup Method

A sensor node can save diminish its energy consumption at idle by going into sleep mode. In the proposed traffic adaptive wakeup method, nodes can choose their own sleep period dependent on the amount of traffic. After its sleep period, a sensor node has to synchronize with the master node in order to exchange data. Each node follows the following procedure when choosing its sleep period:

First, the sensor node needs to be awake for at least as long as the sync period wherein the master node broadcasts the sync packet used for the time synchronization of each node. Each sensor node synchronizes its time according to the master node's Sync packet. After finishing the time synchronization, each node chooses its sleep period based on its amount of traffic it needs to transmit. For example, nodes with a large amount of data to transmit wake up every $2^k \times T_0 (k = 0)$, whereas nodes with a lesser amount of data to transmit wake up every $2^k \times T_0 (k \geq 1,2,3,....)$ in order to save more energy. Figure 2 displays the pseudo code used to choose each node's sleep period considering its individual traffic requirements.

FUNCTION SelectSleepPeriod(node i)

Calculate traffic indicator I_i of node i
IF $I_0 > I_i$ THEN
set priority k_i to maximum value k_{th}
ELSE IF $I_0 < I_i < I_{th}$ THEN
subtract one to priority k_i
ELSE IF $I_i \geq I_{th}$ THEN
set priority k_i to zero
ENDIF
Set sleep period T_i to $2^{k_i} \times T_0$

Figure 2. The Pseudo Code for Traffic Adaptive Wakeup

Each node has a priority k_i, according to the amount of its traffic. I_i is the traffic indicator of node i, and is determined by measuring the amount of traffic it needs to transmit. I_0 is the minimum value of the traffic indicator. If the traffic indicator of a sensor node is smaller than I_0, it means that the sensor node has a small amount of data of which there is no need to immediately transmit, and therefore has time on its side. As a result, the node has the lowest priority and maintains its sleep period. If the traffic indicator is located between I_0 and the threshold value I_{th}, it means that the sensor node has data to transmit. In this case, the sensor node reduces its sleep period by half by subtracting 1 from its priority value in order to reduce its latency. If the traffic indicator is equal to or larger than I_{th}, the node sets its sleep period to T_0, which is the default value, in order to minimize its latency. I_0 and I_{th} are set according to the target data rate of each sensor. Figure 3 shows the time relationship amongst sensor nodes. Sensor node 1 has a sleep period of $2^2 \times T_0 = 4 \times T_0$, sensor node 2 is $2^3 \times T_0 = 8 \times T_0$, and sensor node 3 is $2^0 \times T_0 = T_0$, i.e. the default value.

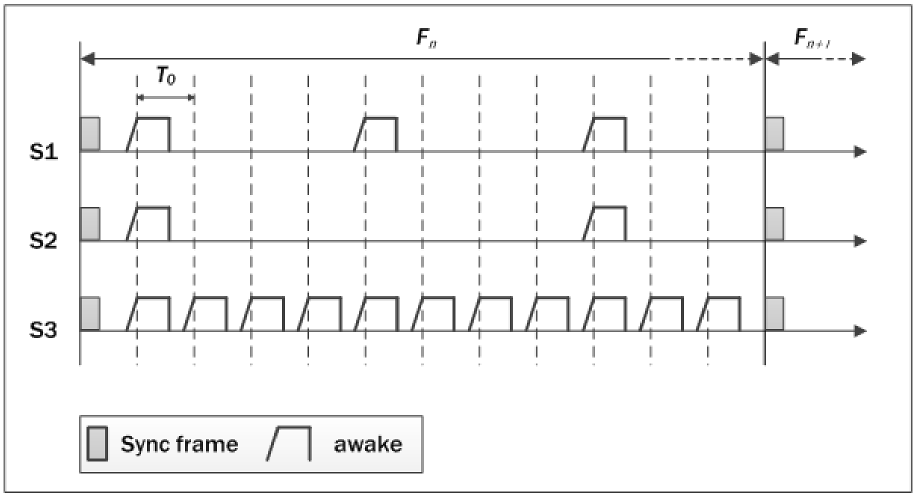

Figure 3. An Example of Traffic Adaptive Wakeup

3.2. Priority based Carrier Sensing Scheme

Since they are arranged in a star topology, the multiple sensor nodes might send data to the master node simultaneously or within a very short time interval. Therefore collision avoidance is of vital importance. However, the conventional Carrier Sense Multiple Access / Collision Avoidance (CSMA / CA) mechanism using RTS / CTS / DATA / ACK between the sender and the receiver [8] is relatively 'overweighed' when deployed in a single-master-centralized WBAN. For example, the complex control overhead inevitably deteriorates the network latency. For this reason we developed a Priority based carrier sensing mechanism in order to simplify this situation.

The major change as compared to the conventional protocol is that our protocol does not use the collision avoidance method, but uses a carrier sensing method to avoid collisions. Each sensor node acquires its priority k_i in the traffic adaptive wakeup stage. When each sensor wakes up from its sleep period, it performs carrier sensing for $k_i \times t_0$, a product of its priority and the default carrier sensing time. If the channel is idle, a node transmits its data and waits for the ACK. The default carrier sensing time t_0 is 16 µs, which is equal to the default backoff timer slot duration laid out in the IEEE 802.15.4 standard. Although the proposed scheme is not much more precise than the conventional collision avoidance methods using RTS/CTS, a sensor node can individually detect a collision in the wireless channel by not receiving an ACK. Along with the traffic adaptive wakeup algorithm, the proposed scheme can reduce the overhead compared to the conventional RTS/CTS method while still minimizing the latency, and can enable a sensor node to exchange data without violating its priority. Figure 4 shows an example of the priority based carrier sensing method.

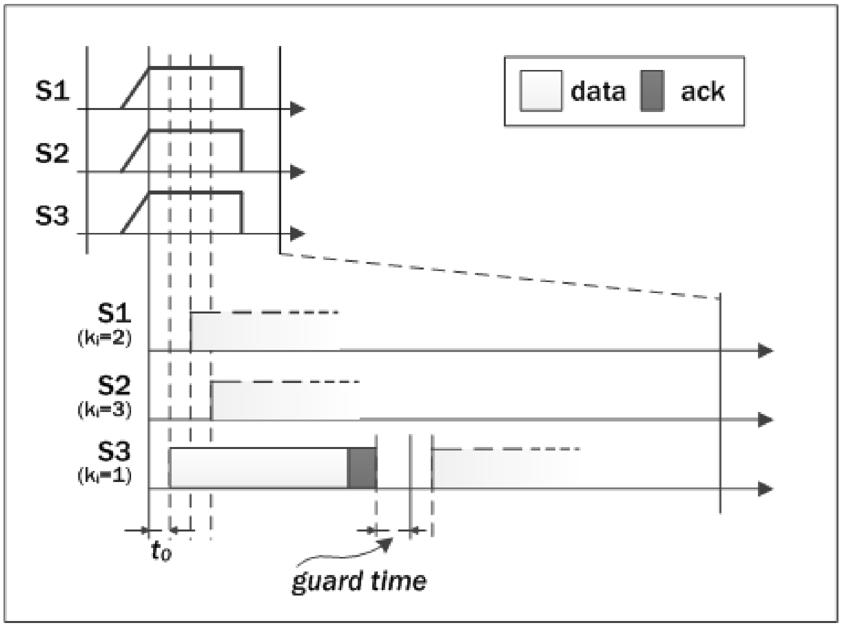

Figure 4. An Example of Priority based Carrier Sensing

4. Performance Analysis

4.1 Simulation Environment

In order to evaluate the performance of the dynamic duty cycle MAC algorithm, we set up simulations using an NS-2 simulator. The simulations were carried out assuming a star-shaped topology with a master node as the central controller. Because the WBAN physical layer is still open to design, in our simulations the physical layer parameters are defined according to the IEEE 802.15.4 standard. For the simulation, 10 nodes were used, 1 master node and 9 sensor nodes in a star topology deployed over the same 1m distance. In addition, the sensor nodes transmitted packets using the 2.4 GHz RF band for 10000 seconds of simulation time. The performance of the channel allocation algorithm was tested using three different beacon intervals in the NS-2 simulator. In the proposed algorithm, the default sleep period T_0 was set to 15.35 ms, the base superframe duration from the IEEE 802.15.4 standard.

4.2 Simulation Analysis

First, we measured the average duty cycle of the sensor nodes with respect to the total required utilization of the channel by adjusting the sensor node traffic in order to analyze the proposed scheme’s energy efficiency. Figure 5 shows the relationship between the total required utilization and the duty cycle when varying the interval between the Sync frames. The interval between Sync frames is a product of the default sleep period T_0 and the number of slots. Figure 5 shows that there is a low average duty cycle if the interval between the sync frames is small when the total required utilization is 10 %. As the total required utilization increases, a low average duty cycle results when the interval between the Sync frames is large. Therefore, choosing the appropriate sync frame interval according to the load in the WBAN channel is essential for an effective adaptation of the proposed algorithm to WBANs.

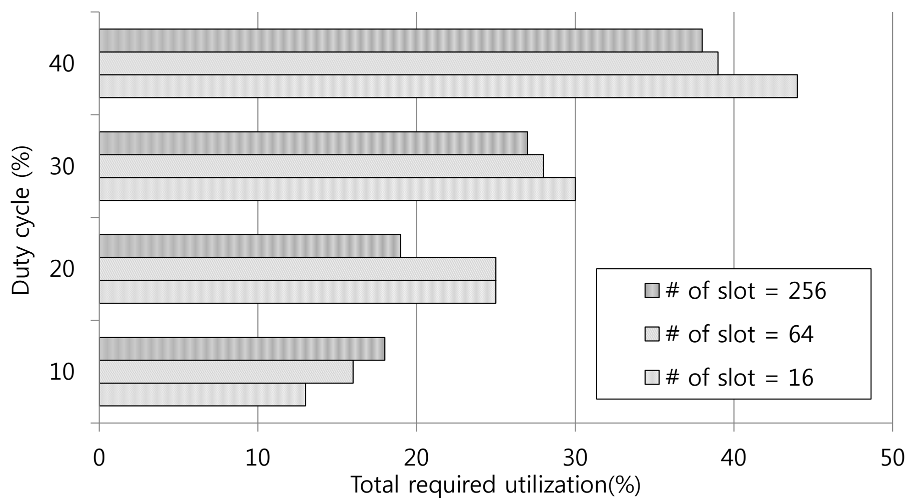

Figure 5. The Duty Cycle Comparison

Figure 6 shows the delivery ratio for the proposed scheme and the IEEE 802.15.4 protocol using various duty cycles, with respect to the total required utilization. For the proposed scheme, 64 slots were used for the sync frame interval. For the IEEE 802.15.4 protocol, the duty cycle was set from 1.6 % to 100 % by fixing the BO to 6 and changing the SO to 0, 2, 4, and 6. In Figure 6, the IEEE 802.15.4 protocol with the SO=6 shows a better performance than the proposed algorithm. Although it shows a better performance, the sensor nodes consume energy continuously as they have a 100 % duty cycle and so do not go into sleep mode. Considering that the duty cycle in the proposed scheme is lower, it can be said that the proposed scheme boasts both a better energy efficiency and delivery rate compared to the IEEE 802.15.4 protocol.

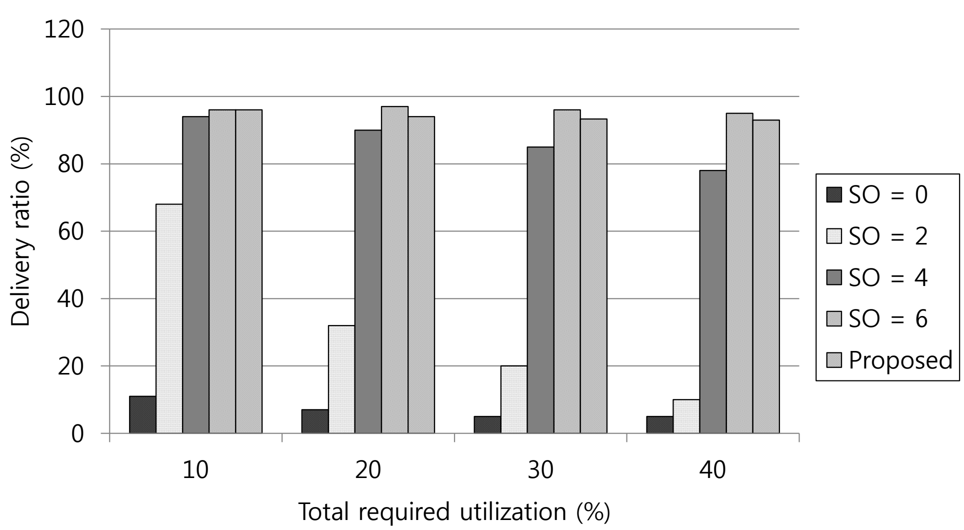

Figure 6. The Delivery Ratio Comparison

5. Conclusion

Wireless body area networks have different requirements in terms of communication energy, throughput and resilience to packet-losses compared to other wireless network strategies. In this paper, we presented a dynamic duty cycle algorithm for use in WBANs. Our scheme dynamically adjusts the sleep period for each sensor node based on its priority calculated from the amount of traffic that the sensor node has to transmit. It has been demonstrated through simulation that our scheme attained a higher delivery rate and better energy efficiency. We intend to extensively investigate this scheme's performance in the future, including its energy efficiency and compare its performance to other mechanisms.

Acknowledgements

This work was supported by the Key Research Institute Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0018394) and by Inha University Research Grant.

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