Heartbeat Driven Medium Access Control for Body Sensor Networks
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Abstract—A novel Time Division Multiple Access (TDMA) based MAC protocol designed for Body Sensor Networks (BSNs) is presented, H-MAC aims to improve Body Sensor Networks energy efficiency by exploiting heartbeat rhythm information, instead of using periodic synchronization beacons, to perform time synchronization. Heartbeat rhythm is inherent in every human body and observable in various biosignals. Biosensors in a BSN can extract the heartbeat rhythm from their own sensory data by detecting waveform peaks. All rhythms represented by peak sequences are naturally synchronized since they are driven by the same source, i.e., the heartbeat. Following the rhythm, biosensors can achieve time synchronization without having to turn on their radio to receive periodic timing information from a central controller, so that energy cost for time synchronization can be completely eliminated and the lifetime of the network can be prolonged. An active synchronization recovery scheme is also developed, including two resynchronization approaches. The algorithms are simulated using the discrete event simulator OMNet++ with real world data from the MIT-BIH multi-parameter database MIMIC. The results show that H-MAC can prolong the network life dramatically.

Index Terms—Sensor networks, biosensors, wearable computers, medium access control.

I. INTRODUCTION

Using wireless communication instead of traditional wired connections in healthcare systems not only reduces the maintenance cost and gives the patients more freedom and comfort, but also makes pervasive and mobile healthcare possible. Enabled by wearable/implantable biosensors and wireless communication technologies, pervasive and mobile healthcare can help physicians to perform early diagnosis and treatment, develop and verify new therapies through continuously monitoring and analyzing human vital signs.

Body Sensor Network (BSN), a.k.a. Body Area Sensor Network (BASN), is a sensor network whose nodes are biosensors either implanted in, worn on, or close to human bodies. BSNs are capable of sensing, communicating and processing various physiological parameters. Designed to specially address the needs of ultra-low-power wireless communication between wearable or implantable biosensors, BSN is considered as a promising networking solution for pervasive and mobile healthcare. As shown in Fig. 1, a body sensor network usually consists of implantable or wearable biosensors, such as electrocardiogram (ECG), phonocardiography (PCG), ambulatory blood pressure (ABP) and oxygen saturation (SpO2) sensors, piezoplethysmography or photoplethysmography (PPG) ring sensor, temperature sensors and even ingestible camera pills. These sensors continuously monitor vital signs and report data to a powerful external device, such as a PDA, a cell phone or a wrist-worn smart watch. Benefiting from their miniature size and biocompatible sensor nodes, the interference of BSN to the daily life of their users can be reduced to the minimum. Therefore BSN is ideal for context-aware, noninvasive and ubiquitous health monitoring, which helps to detect, evaluate and diagnose various diseases as soon as possible.

Medium access control (MAC) for wireless sensor networks has been attracting lots of researchers in the past couple of years, since it is crucial for the energy efficiency and hence the lifetime and usability of a wireless sensor network. In body sensor networks, replacing sensors or charging batteries is difficult and sometimes involves serious surgery operations. Traditional MAC protocols focus on improving fairness, latency, bandwidth utilization and throughput (which are secondary for BSNs), and lack energy conserving mechanisms. Studies reveal that energy wastage in existing MAC protocols occurs from four major sources: collisions, overhearing, control packet overhead and idle listening [1].

Contestion-based and schedule-based medium accesses are two major categories of current MAC protocols designed for wireless sensor networks. Contention-based methods usually use CSMA/CA, while scheduled-based methods use TDMA a lot. The advantages of contention-based approaches are the simplicity, infrastructure-free ad hoc feature and good
adaptability to traffic fluctuation. However contention-based approaches are subject to energy cost by idle listening, overhearing and packet collisions due to their out-of-order medium competition.

Traffic correlation is one of the most important features of BSNs [2]. In BSNs, the main task of the sensors is to collect all kinds of physiological parameters from patients. Many of these parameters, if not all, are dependent and coupled. For example, when a patient gets a fever, his/her body temperature rises, the heartbeat rate and the blood pressure rise too, and so does the breath rate. Subsequently, all these changes may be reflected in the oxygen saturation level (\(\text{SpO}_2\)) in the blood. This kind of coupling of physical parameters unavoidably brings traffic correlation. In other words, the data transmission requests from different sensors are often simultaneous. A single physiological fluctuation may wake up several sensors radio and incur a series of medium access requests.

Due to traffic correlation, contention-based MAC protocols, such as CSMA/CA, may encounter severe medium access competition and end up with a major collision, resulting in extra energy waste and network latency. TDMA is a good solution to the traffic correlation problem because of its collision-free and deterministic transmission features. However, common TDMA schemes need to pay an extra energy cost for time synchronization. Periodic timing information has to be sent and received by all the sensors in a network in order to get their clocks synchronized.

In this paper, we propose a novel TDMA based MAC protocol designed for body sensor networks, H-MAC, which aims to improve energy efficiency by exploiting heartbeat rhythm information to perform time synchronization. Heartbeat rhythm is inherent in every human body and reflected in various biosignals. Biosensors in a BSN can extract the heartbeat rhythm from their own sensory data by detecting waveform peaks. All the rhythms represented by peak sequences are naturally synchronized since they are driven by the same source, i.e., the heartbeat. Following the rhythm, biosensors can achieve time synchronization without having to turn on their radio to receive periodic timing information from a central controller, so that energy cost for time synchronization can be completely avoided and the lifetime of the network can be prolonged. In a star-topology BSN, the typical traffic pattern is data logging, i.e., reporting from distributed sensors to a central BSN coordinator. The coordinator also needs to send control packets to sensors when necessary. Since the power and size limitation often makes the communication exist only between sensors and the coordinator, we do not consider multi-hop communication in this paper.

II. RELATED WORK

There has been a lot of research effort dedicated to the development of medium access control algorithms due to their dominant effect on energy consumption. S-MAC [1], T-MAC [3] and D-MAC [4] are typical contention-based MAC protocols. They are proposed to solve the idle listening problem by applying a synchronized duty cycle schedule between sensor nodes. S-MAC introduces virtual clusters to enable nodes to communicate within divided time slots according to the exchanged schedule. S-MAC trades off energy for latency. T-MAC improves on S-MACs energy consumption through introducing adaptive duty cycle which can adapt to different traffic patterns. Because of the adaptability, T-MAC neednt use a conservative slot schedule to accommodate the worst traffic pattern like S-MAC. However it sacrifices the throughput and introduces extra delay due to the aggressive sleep schedule. D-MAC also has an adaptive duty cycle and aims to support only one kind of communication: converge-cast (sensor to sink reporting). S-MAC, T-MAC and D-MAC all suffer from synchronization overhead and periodic exchange of sleeping schedules. And they are typically designed for multi-hop ad hoc wireless sensor network, while in this paper our main concern is star-topology body sensor networks.

Compared with contention-based MAC, schedule-based approaches (TDMA) have their natural advantage, such as collision-free, low overhearing and low-duty-cycle operations. Since nodes can only transmit data during their assigned time slots in every predetermined period, collision can be completely avoided. Nodes only need to turn on the radio during their assigned time slots, so that low overhearing and low-duty-cycle operations can be achieved. Moreover, TDMA protocols can effectively reduce the transmission latency and increase transmission determinism by guaranteeing dedicated time slots for each node periodically. Those natural advantages of TDMA make it more energy efficient compared with contention-based schemes and attractive for wireless sensor networks, especially body sensor networks.

L-MAC [5] is a simple schedule-based MAC protocol. In L-MAC, time slots have a traffic control section and a fixed-length data section. Nodes send data in a round-robin pattern. The major problem of L-MAC is the overhearing because nodes have to continuously listen to the control sections of all slots of a frame even if it is not the destination at all. ER-MAC [6] introduces the concept of energy-criticality of sensor nodes. It is a function of energy levels and traffic rates. Depending on the energy-criticality, this protocol makes more critical nodes sleep longer to balance the energy consumption of the whole network. However, ER-MAC suffers from overhearing because of the leader-election with regular TDMA communication.

All TDMA protocols need time synchronization to guarantee collision-free transmission. There are many kinds of time synchronization for wireless networks [7]–[9], ranging from very complex and difficult to implement to lightweight and easy to implement. Although quite different in the design, all the existing synchronization approaches unavoidably need to consume extra power to exchange timing information periodically in order to perform clock synchronization.

In the work of [5], non-invasive biosensors at multiple points on the body are used to monitor the cardiac output and cardiovascular system. Using the multi-channel blind system identification method, the authors can estimate the cardiac output (blood volume coming out of the heart), peripheral resistance (the most critical factor determining the blood pressure), and other important measures of perfusion and health conditions in general. A biometrics approach that uses the human biometric trait to secure wireless BSNs for
telemedicine and m-health is proposed in [10]. Interpulse interval (IP) is used to generate 128-bit binary code for identifying different BSNs. The authors assume the time synchronization has been done by existing algorithms. To the best of the authors knowledge, there is no study exploiting the biosignal features in body sensor networks to perform TDMA time synchronization.

III. ALGORITHM DESCRIPTION AND DISCUSSIONS

A. H-MAC Overview

H-MAC is a TDMA based energy efficient MAC protocol designed for star-topology body sensor networks, in which a powerful external network coordinator exists. The coordinator could be a wrist-worn pulse monitoring watch, a PDA or a smart cell phone. Since the external device can be recharged easily, it could possess more computing resources and serve as a gateway to other networks. As a TDMA protocol, H-MAC assigns dedicated time slots to each biosensor to guarantee collision-free transmission. On the other hand, by taking advantage of heartbeat rhythm that is inherent in every human body, H-MAC achieves TDMA time synchronization without distributing periodic timing information, which reduces the energy cost. In H-MAC, biosensors extract the necessary synchronization information from their own sensory biosignals, which are correlated with or directly driven by the heartbeat pulsation, in a distributed way.

B. Biosignal Rhythm Information

To avoid the radio energy consumption for transmitting timing synchronization beacons, we exploit the rhythm information embedded in different biosignals to achieve body sensor network synchronization. The idea is motivated by the following observations. Many biosignals in body sensor network have a similar rhythm, the rhythm generated and regulated by the inherent rhythmicity of cardiac muscle. Carried by the blood, the heartbeat rhythm can propagate to the human body through the circulatory system. A series of changes in the physiological parameters of a person will then be triggered by the heartbeat pulsation. All these changes and biosignal rhythm can be detected by corresponding biosensors. This physiologic parameter correlation can also explain the network traffic correlation phenomena in a body sensor network. The unique rhythm of a person is accessible for various biosensors in a body sensor network. For example, the electrical property changes of the heart caused by the heart contraction are recorded by the electrocardiogram (ECG). The sounds and murmurs produced by the heart and associated great vessels can be picked up by phonocardiography (PCG). With each heartbeat, the blood volume changes of different blood vessels can reflect ambulatory blood pressure (ABP) and be observed in many peripheral parts of the body, such as the fingertip or ear lobe using techniques like piezoplethysmography and photoplethysmography (PPG).

Artifact-resistant power-efficient PPG ring sensors have been developed recently [11]. Periodical blood oxygen saturation (SpO₂) fluctuation can also be detected by PPG sensors. Fig. 2 shows several simultaneously recorded biosignals from the MIT-BIH multi-parameter database MIMIC. Therefore, the naturally synchronized and easy-access heartbeat rhythm can be used to replace the traditional periodically broadcast timing information for performing network synchronization between various biosensors in body sensor networks.

C. Rhythm Representation

Many biosignal waveforms tend to possess the same periodic peaks or valleys as shown in Fig. 2, because they are impelled by the same source, the heartbeat pulsation. We choose waveform peaks to represent the biosignal rhythm information in our algorithm because of the following reasons. First, peaks are the most significant characteristic of biosignal waveforms. They are easy to identify and relatively immune to potential noise interferences, so that the algorithm robustness can be improved. Second, many peak detection algorithms with good performance are already available. For example, there are numerous QRS complex detection algorithms reported to be able to achieve over 99% sensitivity (SE) and positive predictivity (PP). Waveform peaks detection algorithms are also integrated with many signal processing toolboxes. Third, the waveform peak information is often required by other signal processing algorithms as an initial (sometimes the only) input, such as ECG ST segment analysis, data compression, cardiac arrhythmia detection and hypertension early alarm algorithms. Therefore, peak extraction will not be a heavy burden in terms of energy cost since it is often available as a byproduct from other algorithms. Last, peaks appear periodically in biosignals and the length of the interval between peaks is suitable for a time slot in TDMA. The heart beat rate of human beings, defined as the times per minute (bpm) that the heart contracts, is usually within 60-200 bpm, which makes the peaks interval fall in the range of 300-1000ms, which is an appropriate length for TDMA time slots. In this paper, the ECG QRS complex detection algorithm proposed in [12] and an automatic beat detection algorithm in [13] are used to extract peaks information from the biosignal database. The peak detection results of ECG and blood pressure are shown in Fig. 3. The detection results are also compared with the annotations made by medical experts.

D. Time slot scheduling

H-MAC considers time slot scheduling for one-hop star topology body sensor networks. Since the traffic pattern in
body sensor networks is data logging and the network coordinator is the common receiver of the transmissions, only one sensor node is allowed to transmit in a time slot to avoid collisions.

As discussed before, represented by biosignal waveform peaks, biological rhythm information of humans can be used for timing synchronization. Although peaks are not perfectly aligned due to the propagation delay of the human circulatory system, they appear periodically along with each heartbeat. The interval between two biosignal waveform peaks is very close to the interval of two heartbeats. In H-MAC, we use the peaks as synchronization beacons and use peak intervals as time slots for data transmission. By introducing a peak counter in each biosensor, we can assign dedicated time slots to each biosensor for collision free network transmission.

One external device will be chosen as the BSN coordinator, which is responsible for broadcasting network control messages, including time slot scheduling message and synchronization recovery beacons. The coordinator itself can also access the heartbeat rhythm information via its own sensors. After the network association, the coordinator calculates the length of the frame cycle and time slot assignment scheme based on the biosensor numbers and their data rate requirement. Then when the first peak is detected by the coordinator, the control packets will be sent out.

Two kinds of control packets are introduced. One is very short and used for synchronization/resynchronization (noted as CS thereafter). It only includes the coordinators current peak counting number and one bit indicating whether there are changes in time slot assignment scheme. The other is longer and used for time slot scheduling (noted as CL thereafter). CL includes the H-MAC frame length (total peak number in a frame), time slot assignment scheme (sensor id, transmission start/stop peak number), and mandatory radio wake up cycle (peak number). The control packets will be sent out repeatedly during the first three peak intervals with the only difference in CS. CS is sent out before CL for synchronization recovery and energy efficiency purposes, which will be discussed later. After receiving the control packets, each biosensor in the body sensor network may start their own peak counter and transmit during their assigned peak intervals. An illustration of H-MAC time slot scheduling is shown in Fig. 4.

Since the waveform peaks of different biosignals are not perfectly aligned and appear with different sequences varying from time to time, there exist overlapped peak intervals between different sensor nodes, as the shaded area shown in Fig. 5. If the time slots between peak $A_{k-n}$ (not shown in the figure) and $A_k$ are assigned to sensor node $A$, assigning time slots from $B_k$ to node $B$ may cause collisions when node $B$ is scheduled to transmit after node $A$. To solve this problem, we introduce a guard period between $A_k$ and $B_{k+1}$ to compensate for the peak misalignment. As shown in Fig. 5, the time between peak $A_k$ and peak $B_{k+1}$ is the guard time interval, which eliminates possible collisions caused by overlapped peak intervals. The next available time slot that can be assigned to node $B$ will begin at peak $B_{k+1}$, instead of $B_k$. Guard periods are used by the network coordinator to transmit control packet CS to help the nodes who lost synchronization recover as soon as possible.

### E. Synchronization recovery

We also consider the synchronization recovery scheme when a certain biosensor loses synchronization. A sensor may lose synchronization when the peak detection algorithm fails and the heart rhythm information is lost. This could happen when the biosignal is temporarily unavailable or very noisy due to a bad connection. Therefore, a synchronization recovery mechanism is necessary.

In H-MAC, an active resynchronization scheme is introduced. Each sensor predicts the possible lost of synchronization by analyzing their sensory data and looking for abrupt changes of peak intervals. The human heartbeat is regulated by the inherent rhythmicity of cardiac muscle. In order to maintain appropriate oxygen supply to the body, the heart
rate may change with various external stimuli, such as daily activities, physical and mental stress, and even environmental changes (temperature, air pressure, etc). However, the heart rate change, as well as the peak interval changes in other biosignals caused by it, should be smooth and continuous under normal situations. Abrupt changes of peak intervals may indicate possible peak detection mistakes, either missing a peak or counting a false peak. H-MAC triggers synchronization recovery procedures by monitoring abrupt changes of peak intervals, which may result in lost of synchronization.

Algorithm 1 Synchronization recovery

```
SET APC = 0, PC = 0
While no stop command do
  Power off radio
  If Peak is true then
    SET PC = PC + 1
  End if
  If CPI > API > T1 then
    SET APC = APC + 1
  End if
  If APC > T2 then
    Wake up radio
    While CS not received do
      Listen to the channel for CS
      If get CS then
        Adjust PC according to CS
        SET APC = 0
      End if
    End while
  End if
  If T2 ≥ APC > 0 and PC = T then
    Wake up radio
    While CS not received do
      Listen to the channel for CS
      If get CS then
        Adjust PC according to CS
        SET APC = 0
      End if
    End while
  End if
End while
```

As shown in Algorithm 1, a predefined threshold $T_1$ is used to identify abrupt peak interval changes. $T_1$ can be represented either by the number of samples or time interval between current peak interval ($CPI$) and average previous peak interval ($API$). Once an abrupt peak is detected, the abrupt peak counter ($APC$) is increased and compared with a predefined threshold $T_2$. $T_2$ is set to one in this paper. Synchronization recovery/resynchronization will be triggered when $T_2$ is above zero because it indicates the peak counting is not reliable any more.

Two kinds of recovery mechanism will be used according to whether APC exceeds the threshold $T_2$. In the previous section, the control packets $CS$, which contains the accurate peak counting number of the coordinator, will be sent out repeatedly during the three peak intervals at the beginning of a frame. Therefore, if only one abrupt peak is detected, the sensor only needs to wake up the radio at the end of a frame. No matter if the sensor peak counter leads or lags one peak interval, it can receive the resynchronization control packets which are sent out periodically at the beginning of each frame and adjust its own peak counter to get synchronized again. When APC exceeds $T_2$, since the sensor can not guarantee to wake up at certain time to receive $CS$, it will turn on the radio immediately until a $CS$ is received. The block diagram of H-MAC resynchronization scheme is shown in Fig. 6.

IV. EXPERIMENTAL TESTING AND SIMULATION

To verify the rationality and correctness of H-MAC, we used real-world data from the MIT-BIH multi-parameter database MIMIC (Multi-parameter Intelligent Monitoring for Intensive Care). MIMIC includes 100 patient records, each typically containing between 24 and 48 hours of continuous data recorded from patient monitors in the medical, surgical, and cardiac intensive care units. Each record is also accompanied by detailed clinical data derived from the patient’s medical record and from the hospital’s on-line medical information systems.

The patients in the database are intentionally selected to be hemodynamically unstable during the planned recording period. This helps us to better investigate the performance of H-MAC in real-world everyday life, in which many body sensor network users may have various cardiovascular diseases leading to fluctuations in physiologic parameters. The records used in the paper are listed in Table 1. The signals include ECG (electrocardiograph), ABP (arterial blood pressure), PAP (pulmonary arterial pressure), CVP (central venous pressure), and PLETH (fingertip plethysmograph).

We verify the rationality of H-MAC first by showing that all the biosignals follow a same rhythm and analyzing the continuity of the biosignals. Expert annotation files are used to identify the peaks. Samples with huge time differences caused by sensor disconnection are eliminated. We calculate the peak intervals of each biosignal, and then compare their difference beat by beat. The results are shown in Fig. 7(a), in which x axis is the time difference (represented with the number of samples)
between different biosignal peak intervals that are driven by the same heartbeat and the y axis is the peak number.

The result shows that 45.01% peak intervals of different biosignals driven by the same heart beat are exactly the same, having no difference as shown by the peak in the figure. The percentage reaches 99.81%, when we set the difference range to ±5 to ±5 samples, which is perfectly fine for time synchronization since the number of samples between two heartbeats is usually within 5-25 (heart rate 30-150 bpm). Five samples will not cause misalignment trouble in time synchronization. The results justified that various biosignal rhythms driven by the heartbeats are highly correlated and naturally synchronized, so that they could be used for time synchronization.

We also analyze the time difference of adjacent peak intervals in each biosignal to show their continuity. The results are shown in Fig. 7(b), in which x axis is the time difference (represented with samples) between adjacent peak intervals of each biosignal and the y axis is the peak number. Results show that 41.90% adjacent peak intervals have no difference, and 94.69% have difference within ±5 to ±5 samples. This shows that although the heartbeat rate may change from time to time, the adjacent peak intervals of each biosignal change smoothly and continuously. This continuity justifies our active synchronization scheme, which is achieved by monitoring abrupt peak intervals.

We used the discrete event simulator OMNet++ [14] to simulate our H-MAC and compare its performance with a TDMA based L-MAC [5] and S-MAC [1]. The network setup is similar to [5], but the topology used in our simulation is a star environment. Seven nodes are selected to form the body sensor network with the coordinator sitting at the center. The radius of the star network is chosen as 10m, and the transmission range is 15m. Although for a body sensor network, most of the sensors may be located on the human body and work within a limited area, we choose this relatively big transmission range and network size in the consideration of potential increased requirements.

During the simulation, we assumed a single channel transceiver, which has three operational states: transmitting, receiving, standby or sleep. Typically, transmitting and receiving consume more power than standby by a factor 20,000 or more. We found the power consumption parameters from the data sheet of Tmote Sky, as shown in Table II. We use a similar metric as in [5], the network lifetime, to evaluate the energy efficiency of candidate MAC protocols. The network coordinator is given an unlimited energy budget since it is often an external device that can be recharged easily. The body sensor network is considered to be expired when x out of the 1 sensors run out of battery. The simulation result is shown in Fig. 8.

We can observe that H-MAC prolongs the network life over 15% compared with L-MAC and over 300% compared with S-MAC. Part of the improvement comes from the natural features of TDMA protocols, that collisions are completely avoided and idle listening is reduced dramatically. Additional energy savings owe to the elimination of the periodic synchronization overhead, which traditional TDMA protocols suffer from. Here we make a trade-off between the energy consumption of the network coordinator and the lifetime of the network. The periodic network control message is sent out by the network coordinator and the sensors in the network can choose to wake up and receive the control message or not depending on their

<table>
<thead>
<tr>
<th>TABLE I: Experiment data records.</th>
<th>TABLE II: Radio transceiver data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record</td>
<td>Data duration (Seconds)</td>
</tr>
<tr>
<td>No.</td>
<td>55 129600</td>
</tr>
<tr>
<td></td>
<td>216 90000</td>
</tr>
<tr>
<td></td>
<td>225 162000</td>
</tr>
<tr>
<td></td>
<td>230 61200</td>
</tr>
<tr>
<td></td>
<td>248 90000</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Energy consumption: Receiving (Rx)</td>
<td>45 mW</td>
</tr>
<tr>
<td>Energy consumption: Transmitting (Tx)</td>
<td>45 mW</td>
</tr>
<tr>
<td>Energy consumption: sleep</td>
<td>20mW</td>
</tr>
<tr>
<td>Wakeup time from sleep</td>
<td>1ms</td>
</tr>
<tr>
<td>Data rate</td>
<td>250kbps</td>
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</tbody>
</table>

![Fig. 7: Peak interval differences](image1)

![Fig. 8: Relative network life time comparison for S-MAC, L-MAC, and H-MAC](image2)
own abrupt peak counter.

We further consider the energy cost during resynchronization. Although the control packet CS has already been designed to be short and sent out during the guard time period to save the energy of recovering nodes, the idle listening and the cost for receiving control packets CS during resynchronization are still the most important sources of energy wastage in H-MAC. The energy cost for resynchronization and collisions under different abrupt peak detection threshold $T_1$ are shown in Fig. 9. Larger $T_1$ means more tolerance to peak interval changes and less triggered resynchronization recovery. When $T_1$ is low, subtle changes in peak interval may result in unnecessary synchronization recoveries. This eliminates possible collisions caused by losing synchronization, but also introduces longer idle listening. On the contrary, larger $T_1$ can reduce idle listening but increase the probability of collisions.

We noticed that a fixed $T_1$ leads to different output in Fig. 9. This is due to the individual characteristics of the patients from which the data are recorded. Moreover, an abnormal peak interval, as shown by the shaded area of Fig. 10, may result in an unnecessary resynchronization, since most of the biosensors didn’t actually lose synchronization. This false alarm situation can be improved by introducing an adaptive $T_1$. For example, $T_1$ can be increased, when a sensor performed resynchronization, but found that it didn’t lose synchronization because the content of the control packet CS matched its own peak counting result.

![Fig. 9: Relation between abrupt peak detection threshold $T_1$ and idle listening cost (a), collisions (b)](image)

![Fig. 10: An illustration of a potential false alarm situation for resynchronization](image)

V. DISCUSSIONS AND FUTURE WORK

H-MAC is designed to be conservative in time slot scheduling, making tradeoff between energy efficiency and bandwidth utilization efficiency. An extra guard peak interval is introduced to avoid collisions caused by overlapped peak interval. In the worst scenario, when the peaks of two adjacent assigned time slots happen to be completely aligned, there will be no data transmission during the entire guard time slot. Although bandwidth efficiency is reduced, the guard period can be used by the BSN coordinator to transmit resynchronization control packets to help sensor nodes who lost synchronization recovery promptly. By reducing the idle listening time, precious energy can be saved and the life of the sensors can be prolonged. Since body sensor networks aim to provide low power and low rate communication, the tradeoff is reasonable. The bandwidth efficiency can be improved by assigning time slots in larger chunks to reduce the inserting guard period.

While heartbeat rhythm carried by blood vessels is ubiquitously accessible throughout the human body, some biosensors still have difficulty to directly access the rhythm information, such as accelerometers. This problem can be solved by integrating accelerometers with other biosensors. With the development of micro-electromechanical systems (MEMS) and nanotechnology, more and more miniature sensors are emerging. Integration not only enables more sensors to access heartbeat rhythm, but also makes new BSN applications possible. For example, accelerators embedded in ECG leads could be used to improve the performance of ECG QRS complex detection algorithm, as shown in our previous work [12].

Another way to solve the problems is protocol integration, i.e., introducing a hybrid scheme in the MAC. For the sensors that can’t access heartbeat rhythm, a modified IEEE 802.15.4 MAC could be used. In [2], an adaptive, feedback-based and IEEE 802.15.4-compatible BSN-MAC is proposed. It exploits the feedback information from the deployed biosensors to form a closed-loop control of the MAC layer parameters. A control algorithm enables the BSN coordinator to adjust parameters of the IEEE 802.15.4 super-frame to achieve both energy efficiency and low latency on energy critical nodes, as shown
in Fig. 11. The BSN coordinator can access the heartbeat rhythm as well as send out beacons to regulate the BSN-MAC. Therefore it is able to coordinate the two MAC protocols, although special care is needed to avoid any conflict.

H-MAC may face the so-called single point of failure problem of many central-control based schemes, since both the time slot scheduling and synchronization recovery in H-MAC depend on the BSN coordinator. A possible solution is to integrate more reliable and multiple biosensors in the coordinator to guarantee its signal quality and peak detection performance.

All the peak detection algorithms take time and some depend on historical data. We assume that all the biosensors have buffers to store their sensory data. With the development of electronics, this should not be an issue. A delay may occur at the very beginning for the buffer to be filled. But once the peak detection algorithm starts working, no further latency will be introduced.

VI. CONCLUSION

H-MAC is a novel Time Division Multiple Access (TDMA) based MAC protocol designed for Body Sensor Networks (BSNs). It aims to improve BSNs energy efficiency by exploiting heartbeat rhythm information to perform time synchronization. Heartbeat rhythm is inherent in every human body and reflected in various biosignals, so that biosensors in a body sensor network can extract the heartbeat rhythm from their own sensory data by detecting waveform peaks. All the rhythms represented by peak sequences are naturally synchronized since they are driven by a same source, the heartbeat. Following the rhythm, biosensors can achieve time synchronization without having to turn on their radio to receive periodic timing information from a central controller, so that energy cost for time synchronization can be completely avoided and the lifetime of network can be prolonged. An active synchronization recovery scheme is also developed, in which two resynchronization approaches can be triggered by detected abrupt peak interval changes. The algorithms are verified using real world data from the MIT-BIH multi-parameter database MIMIC.

REFERENCES