

# An Adaptive Energy Efficient MAC Protocol for the Medical Body Area Network

N. F. Timmons\* and W. G. Scanlon\*\*

\*WiSAR Lab,  
Letterkenny Institute of Technology  
Letterkenny, Donegal  
Email: nick.timmons@lyit.ie

\*\*School of Electronics, Electrical Engineering and Computer Science  
Queen's University, Belfast  
Email: w.scanlon@qub.ac.uk

**Abstract**—Medical body area networks will employ both implantable and bodyworn devices to support a diverse range of applications with throughputs ranging from several bits per hour up to 10 Mbps. The challenge is to accommodate this range of applications within a single wireless network based on a suitably flexible and power efficient medium access control protocol. To this end, we present a Medical Medium Access Control (MedMAC) protocol for energy efficient and adaptable channel access in body area networks. The MedMAC incorporates a novel synchronisation mechanism and initial power efficiency simulations show that the MedMAC protocol outperforms the IEEE 802.15.4 protocol for two classes of medical applications.

**Keywords**—BAN, wireless, sensor, network, protocol, MAC.

## I. INTRODUCTION

The rapid expansion of wireless technology has inevitably led to the possibility of widespread un-tethered medical and health monitoring. Health monitoring systems which use cable as a medium can now be replaced with wireless connections. Point to point wireless links such as with the Medical Implant Communication Service (MICS) [1], MedRadio, and single sensor biotelemetry have been deployed over the last few years. However, thinking has moved on to the benefits of a body-centric communication networks. In the medical domain there are potentially a multitude of ultra low power wireless sensor networks (WSN) and body area network (BAN) applications with data rates ranging from 0.01 bps to 10's Mbps. While medical BAN applications could support both in-patient and out-patient care, it is convenient to distinguish between implantable and wearable sensing activities (Table 1).

TABLE I. SENSING ACTIVITIES IN MEDICAL BANs.

Wearable BAN devices	Implanted BAN devices
EEG	Glucose sensor; Cardiac arrhythmia: pacemaker, cardiovertor, defibrillator
ECG	Intracranial pressure sensing
SpO <sub>2</sub> pulse oximeter,	Wireless capsule drug delivery
Glucose	Deep brain stimulation:
Fall detection	retinal sensors, Parkinson's, epilepsy
Emergency call	Insulin pump
Performance assessment	

## A. Medical BAN Technical Requirements

The main challenge in medical BANs is to balance the demands of the hard energy constraint associated with low power wireless sensor devices, with the quality of service (QoS) demands of the wide range of sensing and control applications. For example, a battery powered implanted medical device ideally must have a lifetime of up to 10 years. Unlike other wireless networks, it is generally impractical to charge or replace exhausted batteries, and therefore battery lifetime defines node lifetime. Since the transceiver communication operations consume much more energy than the processing operations, it is a primary objective to minimise transmit and receive operations to maximise node lifetime. Therefore, the medium access control (MAC) protocol in a BAN must be highly energy efficient. The main energy saving features that must be exhibited by a well designed MAC protocol are: collision avoidance, overhearing, control packet overhead, receiver idle listening, and transmitter over-emitting. Important attributes such as latency, throughput, and bandwidth utilisation, may be secondary in priority in generalised WSNs. However, in medical BANs life critical applications will place a priority on latency, security and guaranteed throughput.

Unlike a WSN, a BAN will have a limited number of nodes, typically 10–15. The demands of scalability, which are a feature of many WSN applications, are not an issue, and multi-hopping will be limited to 2 or 3 hops at most. Multi-hopping is used to overcome harsh propagation conditions in and around the body [2] and is required to link ultra-low power devices. This affects the topology, which for a BAN, is most suited to a hybrid STAR network.

## B. Existing Asynchronous and Synchronous MACs

The main approaches for accessing the media in an energy efficient manner in WSNs are *asynchronous*: Low Power Listening (LPL), or *synchronous*: Scheduled Contention or TDMA slot allocation. The shortcomings of these protocols when applied to a medical BAN application can be

summarised below:

- TDMA schemes are contention free but are not flexible, adaptive and scalable. Synchronisation mechanisms are an overhead cost in terms of energy used.
- LPL schemes are scalable, flexible and adaptive but are susceptible to high energy cost in transmitter and receiver due to extended preamble mechanisms.
- Scheduled contention MACs are scalable, flexible, adaptive, however require maintenance of a schedule to reduce collision cost overhead control. Scheduling overhead has a cost in terms of energy consumption.

The IEEE 802.15.4 [3] standard has been examined as a platform for BANs however there are some limitations in meeting the requirements of IEEE 802.15.6 (BAN group [4]), in terms of power consumption [5] and also, as this paper will show, in flexibility and adaptability. The IEEE 802.15.4 is not adaptive to channel quality variation, not optimised for heterogeneous devices, or adaptive to multiple applications, and there is no guarantee for life-critical transmissions. Its beacon mode has an overhead cost in energy whereas the

non-beacon mode has better energy consumption at the expense of reduced flexibility [5]. Its rigid superframe size and beacon interval leads to over-provisioning (higher energy) or under-provisioning (poorer QoS delivery).

A medical BAN will have to accommodate two types of data which are characteristic of medical services: periodic and non-periodic. Periodic data is traditionally best suited to a TDMA type protocol, i.e., monitoring temperature, glucose levels etc., whereas non-periodic data is best suited to a contention style MAC, i.e., medical emergency.

The key driver for this new work is that no wireless standard has yet been adopted which governs medical BANs incorporating implantable and wearable devices. The proposed MedMAC solution attempts to provide flexibility, scalability, and adaptability, combined with ultra low power consumption. Section II will set out the proposed architecture for the MedMAC, while Section III will compare its power efficiency with the IEEE 802.15.4.

## II. MEDICAL MEDIUM ACCESS CONTROL PROTOCOL (MEDMAC)

### A. Scope

The key features of this protocol include: contention free channel access over a variable number of TDMA channels; energy efficient and dynamically adjustable time slots; a novel adaptive and low-overhead TDMA synchronisation mechanism; optimised energy efficiency by dynamically adjusting the QoS requirements using ongoing traffic analysis; and optional contention period used for low grade data, emergency operation, and network initialization procedures.

All devices will sleep or run idle to save power when not transmitting or receiving. Within each superframe (period between beacon transmissions), slots will be allocated to devices by the coordinator and will be given up by the device

when not in use. The most appropriate topology for the medical BAN is a STAR topology with the central coordinator worn outside the body or fixed in a bedside position. The main features of MedMAC are summarised below:

- device synchronisation maintained without waking for regular beacon;
- maximises energy/bandwidth efficiency by dynamically adjusting QoS provision based on traffic analysis;
- a single adaptable superframe structure to facilitate three classes of QoS, combining contention and dynamic slot reservation e.g.:
  - Class 0: Low grade data, asymmetric, < 1000 bps e.g. temp monitoring, respiratory, pulse sensor.
  - Class 1: Medium grade data, asymmetric/symmetric -  $\leq 250$  kbps, e.g.: ECG, EEG, blood pressure,  $S_pO_2$ .
  - Class 2: High grade data up to 10 Mbps. asymmetric/symmetric; medical imaging, video, EMG, Capsule Endoscope;
- dynamic and adaptive bandwidth allocation - number of devices from 2–256 with a dynamic slot duration;
- flexible delivery of data while maintaining device sleep time of > 99%;
- adaptive packet size depending on channel quality, and traffic and QoS analyses;

### B. Proposed MedMAC Architecture

TDMA is an attractive solution for medical BAN applications as it is suited to periodic data. Guaranteed timeslots for each device removes the possibility of collisions from other nodes in the network and the resultant waste in energy. The novel aspect of this proposal is that each device will have the exclusive use of the channel for a fixed timeslot, without the synchronisation overhead normally associated with the TDMA mechanism. Another novel aspect of the MedMAC is the capability to accommodate variable slot sizes simultaneously for heterogeneous applications.

To accommodate emergency or life-critical scenarios, low grade data applications and network set up procedures, the MAC will also have an optional adaptable contention period. In a life-critical scenario TDMA slots can be overridden with contention access giving priority to emergency messaging. The novel aspect of this will be the flexibility in the ratio of the slotted period to the contention period, which can vary depending on applications and associated traffic demand.

#### 1) Beacon Period and Multi-Superframe

The MedMAC will incorporate a multi-superframe structure for all three classes of MAC and is shown in Fig. 1. The basic unit of the structure is a dynamic and programmable period (superframe) bounded by a beacon frame sent at regular intervals by the coordinator. The beacon period consists of an optional contention period and a contention free period made up of timeslots. The contention free period and the contention period make up a total number of timeslots ranging from 2 to 256; the proportion of time slots in each period is dynamically

adjustable and dependent on the number of devices and associated applications. The durations of the superframe and the timeslots are also programmable and dependent on the application requirements including sleep/power saving demands.

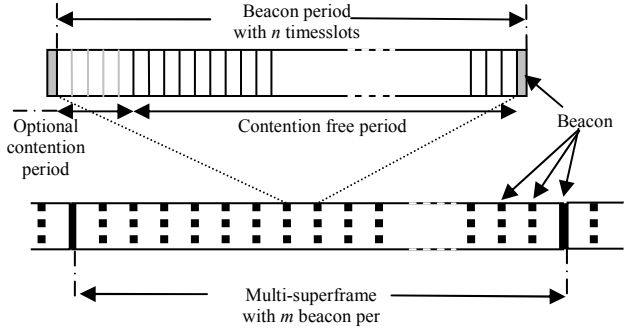


Figure 1. Multi-Superframe structure for the MedMAC protocol.

The MedMAC protocol relies on synchronisation between the coordinator and other nodes to maintain timeslot synchronisation. In low power wireless networks waking up the receiver every superframe to listen for a beacon is a significant drain on energy. The MedMAC protocol incorporates a novel synchronisation mechanism where a node can sleep through a number of beacon periods without losing synchronisation. The duration of the multi-superframe is defined by this synchronisation scheme and is equal to the number of beacon periods through which the node can sleep. The node receiver is only activated to listen for the beacons bounding the multi-superframe and can ignore all other beacons (Fig. 1).

## 2) Adaptive Guard Band Algorithm

Maintaining synchronisation of devices while sleeping through beacons can be achieved by using a combination of timestamp scavenging and an Adaptive Guard Band Algorithm (AGBA).

In timestamp scavenging, synchronisation can be maintained using an updated timestamp field as long as there are regular packets from the coordinator to a node (e.g., Data, Ack, and Beacon). However, if there is an interruption in the regular delivery of packets from the coordinator, or simply that an application requires a very low throughput then the node cannot rely on scavenging packets from the coordinator to maintain its timing. In this case, the AGBA allows the node to sleep through many beacon broadcasts without losing synchronisation with the coordinator. It does so by introducing a guard band for each of the timeslots which can be dynamically adjusted to track the actual drift of local time bases. The Drift Adjustment Factor (DAF) minimises the waste of bandwidth using guard bands. The nodes can sleep through many beacon periods and need only be refreshed with new timing corrections by capturing the beacon at the beginning of the next multi-superframe.

Upon start-up the AGBA introduces a guard band to each

timeslot which allows for the maximum possible drift of the combined coordinator and node timing crystals. All nodes will be informed by the beacon when the AGBA is initially invoked at the start of a multi-superframe. The beacon packet will also contain information which defines slot allocation, beacon period, and multi-superframe duration. At the start of the multi-superframe all nodes are brought into synchronisation by the timestamp from the coordinator. After this point the algorithm will be invoked to calculate the guard band for each node. This calculation is based on the maximum drift of the crystals and the time elapsed from start of multi-superframe to the end of the timeslot (see Eqn. 1). The time elapsed depends on the timeslot number allocated to the node, the timeslot duration, and the beacon period. These results are known as the default guard band (GB) values.

$$GB = (time\_elapsed) \times (crys\_tol\_TX) \times (crys\_tol\_RX) \quad (1)$$

The default GB values can be calculated and stored in the coordinator during the device registration period. From the default GBs the coordinator calculates the values for the associated timeslot start times for each node with reference to the beacon start time for the current multi-superframe. These values will be transmitted to each node during the initialization phase of the network where they will be stored as default values.

For each subsequent beacon period the node will recalculate the guard band required based on the increasing value of time elapsed. A revised timeslot start time based on the new guard band will be calculated for each new beacon period. This can continue until the end of the multi-superframe when all nodes will receive a beacon which corrects the timing of each node to the coordinator. The size of the multi-superframe is dictated by the permitted maximum size of GBs. The larger the GB allowed, the larger the multi-superframe. For the experiments reported in this paper an arbitrary 50% rule is used which limits the maximum GB size to 50% of the timeslot. In subsequent multi-superframes the AGBA and DAF mechanisms will be deployed unless one of the following conditions occurs: timestamp scavenging; initial multi-superframe following device registration; or default GB conditions.

The individual default GB duration for each slot is calculated using the following equations. The GB for the first slot in the first beacon period will only have a single guard band given by:

$$GB_{n,m} = (SD).(X\_tol) \quad (2)$$

For the remaining slots in the first beacon period the following equation will determine the GB for each slot. This equation is iterative and incorporates the GBs of previous slots into the time elapsed:

$$GB_{n,m} = \frac{X\_tol(n.SD + GB_1 + 2GB_2 + \dots + 2GB_{n-1})}{1 - X\_tol} \quad (3)$$

Now to calculate the GBs in the subsequent beacons of the multi-superframe the following generic equation can be used:

$$GB_{n,m} = \frac{X\_tol(n \cdot SD + (m-1) \cdot BP + GB_1 + 2GB_2 + \dots + 2GB_{n-1})}{1 - X\_tol} \quad (4)$$

Alternatively, GB values can also be calculated by using:

$$GB_{n,m} = GB_{n,m-1} + BP \cdot (X\_tol) \quad (5)$$

From the GB values the new slot start times (SST) can be determined for each node:

$$SST_{n,m} = SST_{1,m} + (n-1)SD + 2GB_{1,m} + 2GB_{2,m} + \dots + 2GB_{n-1,m} \quad (6)$$

$$\text{and } SST_{1,m} = SST_{1,1} + (m-1)BP - GB_{1,m} \quad (7)$$

Where  $n$  indicates slot number in a beacon period and its range is  $1 \leq n \leq SN_{\max}$  where  $SN_{\max}$  is the maximum number of slots;  $m$  is beacon period number in a multi-superframe and its range is  $1 \leq m \leq BPN_{\max}$  where  $BPN_{\max}$  is the maximum number of beacon periods in the multi-superframe;  $SD$  is the slot duration measured in seconds;  $X\_tol$  is the combined tolerances (ppm), of the coordinator and the device time base crystals;  $BP$  is the beacon period measured in seconds and  $SST_{1,1}$  is the beacon start time.

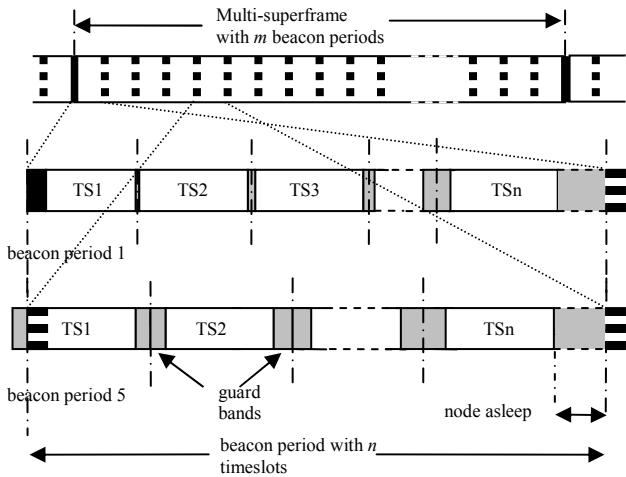


Figure 2. Multi-Superframe with beacon frame, timeslots and guard bands.

### 3) AGBA with Drift Adjustment Factor

For increased energy saving the AGBA incorporates a novel optional feature called the drift adjustment factor (DAF). Using AGBA to generate the default GBs means that they are the worst case values and will increase with time until the next time correction at the beginning of the next multi-superframe. However, in practical cases the actual crystal drift may be a lot less than the default GB. The Drift Adjustment Factor (DAF) will assess the relative drift between the default GB and the actual drift (AD) and make an adjustment to the default GB accordingly. If the drift does not grow at the same rate as predicted by the AGBA then the actual GB can be reduced. This adjustment is made at the end of the multi-superframe by

the coordinator based on information received from the nodes during the multi-superframe. The new GBs are calculated and the new timeslot start times are delivered to the nodes by the beacon at the beginning of the next superframe.

Each time a packet arrives at the coordinator from a node it delivers the actual timeslot start time or end time. From this value the coordinator calculates the AD and records the worst-case AD for each node in the multi-superframe. The node with the worst case AD will be the reference for the DAF ( $AD_{ref}$ ). This avoids the possibility of over-correction. The percentage difference between the predicted GB and the AD is calculated for the most recent worst case node. If this is greater than 5% of the timeslot then adjustment is made to the GB value.

$$\text{If } \frac{GB_{n,p} - AD_{n,p}}{SD} > 5\% \text{ of time slot} \quad (8)$$

then invoke Drift Adjustment Factor (DAF). If  $AD_{ref}$  is larger than the corresponding GB in the first beacon period of that multi-superframe, i.e.:

If  $AD_{ref,m,p} > GB_{ref,1,p}$  then invoke default AGBA algorithm.

$$\text{If } AD_{ref,m,p} = GB_{ref,1,p} \text{ then let } GB_{ref,1,p+1} = GB_{ref,1,p}$$

If  $AD_{ref,m,p} < GB_{ref,1,p}$  then apply the following equation to reset the GB for the corresponding timeslot in the first BP of the next multi-superframe:

$$GB_{ref,1,p+1} = GB_{ref,m,p} - \left( \frac{GB_{ref,1,p} - AD_{ref,m,p}}{2} \right) \quad (9)$$

Where  $p$  is current multi-superframe number,  $p+1$  is new multi-superframe number,  $m$  is beacon period number, and  $ref$  is timeslot number of the reference slot.

This effectively allows the GB excess to be divided by 2 in consecutive super-multiframes until the percentage difference between previous GB and current AD is equal to or less than 5. If it is less than 5% then DAF will increase the GB using equation (9).

$$GB_{ref,1,p+1} = GB_{ref,m,p} - \left( \frac{GB_{ref,1,p} - AD_{ref,m,p}}{2} \right) \quad (10)$$

The new GB can be determined for the corresponding time slot in the first beacon period ( $m=1$ ) of the next multi-superframe. This is the reference GB and it is used to extrapolate the remaining GBs for all the timeslots. The difference between the new guard band ( $GB_{ref}$ ) in the first beacon period of the next multi-superframe and the corresponding GB of the first BP in the previous multi-superframe is calculated in order to generate the GB adjustment factor  $R$ .

$$R = \frac{GB_{ref,m,p} - GB_{ref,1,p+1}}{GB_{ref,m,p}} \quad (11)$$

The guard bands for all the nodes in the first beacon period

of the new multi-superframe are then adjusted by this factor:

$$GB_{ref,m,p+1} = GB_{ref,m,p} \times R \quad (12)$$

### III. PERFORMANCE OF MEDMAC COMPARED TO IEEE 802.15.4

Opnet simulation models were used to measure and compare the power efficiency performance of the MedMAC with IEEE 802.15.4. A MedMAC Opnet simulation model was created and used in conjunction with the IPP Hurray IEEE 802.15.4 Opnet model [6]. Ideal channel conditions (no packet errors) were assumed for all the simulations and only the nodes RF transceiver energy use was measured (from the Crossbow MICAZ datasheet [7]: idle 20 uA, sleep 1 uA, transmit 17.4 mA and receive 19.7 mA). To provide a rigorous test of the protocols, simulations were performed using a Class 0 and Class 1 application. The Class 0 application is a health/fitness monitoring BAN with three nodes monitoring respiration (640 bps), pulse (8 bps), and temperature (16 bps). The Class 1 application chosen was an EEG system; EEG requires an overall bit rate of 86.4 kbps from 24 sensors, with 12-bit ADC and a sampling rate of 300 Hz [4]. Each of the 24 EEG sensors can be replaced with a wireless sensor node; each node representing one of 24 channels in a STAR topology. The latency requirement for EEG is less than 250 ms. For a fair comparison the bit rate (250 kbps) and the packet sizes of the MedMAC were made consistent with the IEEE 802.15.4 specification.

#### A. Class 1 Application 24 Node EEG MBAN

##### 1) MedMAC Parameters for EEG Opnet Model

The MedMAC model assigns one timeslot to each sensor, thus using contention free access for each channel. The individual channel bit rate is:

$$\frac{\text{sample size(bits)}}{\text{sample period}} = \frac{12}{1/300} = 3600\text{bps} \quad (13)$$

The number of samples that can be collected and sent together in a single packet depends on the latency value. It is more efficient to send a single packet with many samples than to send each 12-bit sample as a single packet. A bundle of samples can be collected and sent as one packet as long as it is sent before 250 ms have elapsed from the first sample collected. The maximum number of samples that can be collected and transmitted in a single packet can be calculated by dividing the latency time by the sampling period.

$$\frac{\text{latency time}}{\text{sample period}} = \frac{T_L}{T_S} = \text{max no. of samples} \quad (14)$$

The BP must be equal or less than the latency requirement and was set to 240 ms in this example. The minimum slot size for the MedMAC is calculated based on the size of a beacon frame, MAC frame and an ACK frame, i.e., the timeslot must be large enough to receive a beacon frame, send a MAC

frame, and receive an ACK frame. The total number of samples then transmitted in the timeslot represents all the samples collected since the previous transmission in the last beacon period:

$$\frac{0.24}{1/300} = 72 \text{ samples or } 72 \times 12 = 864 \text{ bits}$$

To calculate the minimum slot size add MAC data frame, Beacon frame and ACK frame which is 1192 bits, therefore minimum slot size is

$$1192 \times \frac{1}{250000} \text{ s} = 0.004768 \text{ s}$$

A slot size of 0.005 s was chosen, which for a 240 ms BP allocates 120 ms for the 24 slots, with the remaining 120 ms reserved for timeslot expansion if ABGA is activated. This incorporates the arbitrary 50% rule which limits the maximum GB duration. To calculate the multi-superframe period for a BP of 240 ms and a timeslot size of 0.005 s we use equation 1. We assume that the time base crystal in the transmitter and the receiver both have tolerances of  $\pm 40$  ppm, as suggested in the IEEE 802.15.4 specification [3]. The relative drift between transmitter and receiver will be based on the combined tolerance of  $\pm 80$  ppm. Based on the 50% rule,  $GB_{\max} = 0.0025$  ms, then

$$m = \frac{0.0025}{0.24 \times 80 \times 10^{-6}} = 130 \text{ BPs in the multi-superframe;}$$

Therefore the MedMAC incorporating AGBA only requires that the nodes wake up to listen to a beacon every 130 BPs, or 31.25 s (130 x 0.24). Note that the EEG channel bit rate should be 864 bits in 0.24 s = 3.6 kbps.

##### 2) IEEE 802.15.4 Parameters for EEG Opnet Model

EEG requires 24 channels therefore the GTS option of IEEE 802.15.4 with its seven available timeslots is not sufficient. Each of the nodes in this model will have to use the contention period and CSMA/CA to access the channel.

Beacon operation is used in the IEEE 802.15.4 model and the beacon period is set to 31.45728 s by selecting a Beacon Order (BO) of 11 to match the MedMAC multi-superframe period. Due to the requirement for a packet to be transmitted every 240 ms there can be no inactive period. Therefore the active portion of the superframe is set to the same dimensions of the superframe, i.e., SO = 11 [3]. As with the MedMAC model 72 samples are collected before a packet is sent every 240 ms. The MSDU frame size is 864 bits.

##### 3) Class 1 Application: 24 Node EEG Simulation

Simulations of 10 minute durations were run on each of the models while increasing the number of nodes in the network from 1 to 24. In the MedMAC model steady state performance is assumed, i.e., full timestamp scavenging applies therefore the timeslots have minimum GBs. AGBA is not invoked and there is no node activity for half the superframe. The energy

consumption of a single node was recorded for each simulation. The results were plotted in Fig. 3 showing the power consumption versus the number of nodes in the network up to a maximum of 24.

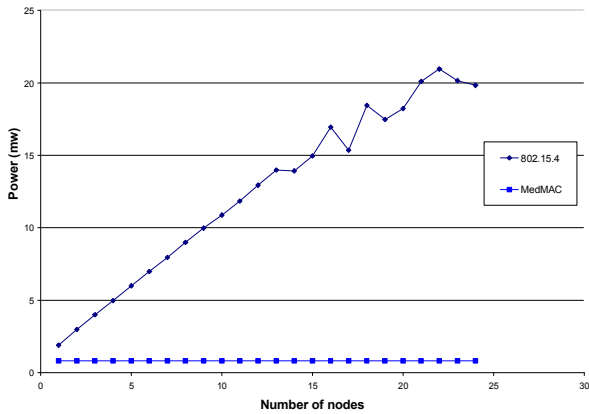


Figure 3. Average power consumption of a single EEG node as number of nodes increased from 1 to 24.

### B. Class 0 Application 3 Node Fitness/Health Monitoring

Typical bit rates and packet sizes are given in Table II [4]:

TABLE II. HEALTH & FITNESS MONITORING DATA REQUIREMENTS.

Application	Data rate (bps)	Packet (bits)
Respiration	640	64
Temperature	16	16
Pulse monitor	8	8

#### 1) MedMAC Parameters for Fitness/Health MBAN Opnet Model

For this simulation one packet is allocated to each timeslot. Each timeslot must be of duration to transmit and receive a beacon, data, and ACK packet. The highest data rate from the respiration monitor requires 10 pkts/s therefore the BP is chosen to be 0.1 s. A BP of 0.1 s consists of 25 slots of 0.004 s duration. Using equation 1 to calculate the number of BPs in a multi-superframe where  $GB_{max} = 0.002$  s:

$$m = \frac{0.002}{0.1 \times 80 \times 10^{-6}} = 250 \text{ BPs in a multi-superframe (a duration of 25 s).}$$

#### 2) IEEE 802.15.4 Parameters for Fitness/Health MBAN Opnet Model

The superframe duration is set by BO. The closest to 0.1 s is achieved by setting BO to 3 which gives a superframe duration of 0.12288 s. This still allows an active and sleep period. By setting the SO to 0, the smallest active period can be realised i.e. 0.01536 s. This means that the nodes are asleep for 87.5% of the time.

#### 3) Class 0 Application: 3 Node Health/Fitness Simulation

Simulations of 10 minute durations were run on each of the

models. In the MedMAC model steady state performance is assumed, i.e., the three active timeslots are set at twice the required duration (0.004 s) which simulates default AGBA Guard Band setting (the worst case). Power consumptions for the three nodes were recorded in Table III for each of the simulations.

TABLE III. COMPARING POWER CONSUMED BY HEALTH/FITNESS NODES FOR MEDMAC AND IEEE802.15.4.

Application	MedMAC Power (mW)	802.15.4 Power (mW)
Respiration	1.81	1.66
Temperature	0.2	0.54
Pulse monitor	0.2	0.54

## IV. DISCUSSION

The graph in Figure 3 shows that as we increase the number of nodes in the Class 1 EEG simulations of the IEEE 802.15.4 model the power consumption of individual nodes increases. With the number of nodes increasing the rate of collisions increases hence the number of retransmissions and power consumption rises. The graph is linear up to 13 nodes where we see the effect of node failure due to collisions i.e. nodes which fail having reached the maximum number of retransmissions without success. Nodes beginning to fail explain the non-linearity in the graph. This is caused by reductions in collisions which in turn means reductions in power consumed. In fact during several simulations it was noted that the IEEE 802.15.4 model consistently had several node failures, and consistently failed to support the 24 node EEG BAN. However, MedMAC shows no variation in average node power as the number of nodes increases. Each node has a dedicated time slot which means there are no collisions. Even with single node operation where there are no collisions in the IEEE 802.15.4 model, MedMAC still shows lower power consumption by a factor of two. This is because of the extra energy required by the CSMA/CA operation of the IEEE802.15.4, with clear channel assessment procedures and back-off algorithms being deployed.

The second set of simulations addressed the lower data rate applications of the Class 0 medical devices. Here collisions were not a significant factor in the IEEE 802.15.4 and as can be seen in Table III the power consumption values were much closer in value as expected. Power consumed by the respiration transceiver was slightly higher in the MedMAC than in the IEEE 802.15.4 model. However, it should be noted that the MedMAC model currently goes into idle mode outside the active timeslots whereas future iterations of the model will incorporate a sleep mode, which would bring this power figure down. The temperature and pulse nodes show much lower power consumption than the respiration node due to the lower bit rate of these two applications. However, the IEEE 802.15.4 values are significantly higher than the MedMAC. Again this indicates the higher overhead penalty integral to the IEEE 802.15.4 specification.

## V. CONCLUSIONS

In this paper we have introduced a new protocol MedMAC for the medical BAN. We briefly describe its main features and, in more detail, the novel synchronisation mechanism (AGBA), which facilitates contention free TDMA channels, without a prohibitive synchronisation overhead.

In particular we focus on the power efficiency of MedMAC using OPNET simulations of medical applications to compare it with IEEE 802.15.4. We found that for a medium data rate medical application (class 1) such as EEG, the MedMAC supported the 24 nodes with less than 10% of the power required by the IEEE 802.15.4 MAC protocol. Also, we found that the IEEE 802.15.4 suffered from consistent node failure due to collisions when more than 13 nodes were introduced to the network.

At lower rate applications our health and fitness monitoring simulation (class 0) demonstrated that MedMAC and IEEE 802.15.4 were much closer in performance. Although at the very low data rate applications, such as the pulse and temperature sensors (< 20bps), IEEE 802.15.4 consumed twice as much power as MedMAC. As collisions were not an issue at these low data rates the extra power consumed is due to the overhead intrinsic in the IEEE 802.15.4 specification.

It can be concluded that MedMAC outperforms IEEE 802.15.4 in terms of power efficiency in low and medium data rate medical applications. Further performance testing of the AGBA synchronisation algorithm and the MedMAC dynamic traffic analysis are on-going with results to be published at a later date.

## VI. REFERENCES

- [1] [http://wireless.fcc.gov/services/index.htm?job=service\\_home&id=medical\\_implant](http://wireless.fcc.gov/services/index.htm?job=service_home&id=medical_implant)
- [2] S. L. Cotton & W. G. Scanlon, "An experimental investigation into the influence of user state and environment on fading characteristics in wireless body area networks at 2.45 GHz," *IEEE Trans. Wireless Communications*, Vol. 8, 1, pp. 6–12, Jan. 2009
- [3] IEEE 802.15.4, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANS), IEEE, Sept. 2006
- [4] <https://mentor.ieee.org/802.15/dcn/08/15-08-0407-06-0006-tg6-applications-summary.doc>
- [5] N. F. Timmons and W. G. Scanlon, "Analysis of the Performance of IEEE802.15.4 for a Medical Sensor Body Area Network," IEEE SECON 2004, October 2004
- [6] IEEE 802.15.4 OPNET Simulation Model, <http://www.open-zb.net/>
- [7] MICAZ Datasheet, <http://www.xbow.com/>