Design of an ultra low power MAC for a heterogeneous in-body sensor network

Ashutosh Ghildiyal
ELA Medical, Parc d'affaires Noveos
4 Avenue Réaumur,
Clamart,
France
Ashutosh.ghildiyal@sorin.com

Balwant Godara
Institut Superieur d'Electronique de Paris
28 Rue Notre Dame des Champs,
Paris, France
bgodara@isep.fr

Amara Amara
Institut Superieur d'Electronique de Paris
28 Rue Notre Dame des Champs,
Paris, France
Amara.amara@isep.fr

ABSTRACT
This paper presents an ultra low power MAC designed for in-body implant network. We show how an in-body implant network, has its own unique set of requirements (priority, latency, throughput etc.) which are not addressed by generic BAN(body area network) protocols which are designed assuming identical sensors. By choosing a particular use case, we demonstrate how we can exploit disparities inherent in a typical implanted BAN to enable ultra low power operation which also meets other (often) competing requirements. We present a new MAC scheme, which allows ultra low power operation by handling the nodes in accordance to their power and latency requirements. We present a new scheme for deriving analytically the power-optimised TDMA frame parameters like beacon interval and discuss solutions to manage synchronisation overhead. Equations for deriving the duty-cycling efficiency are presented and the packet error rate is calculated for the in-body wireless channel. Our results and simulations show that the protocol outperforms best of reported MACs and for low data rate sensors (typical of BAN) our MAC allows close to standby limit power consumption.

Categories and Subject Descriptors
C.2.2 **[Computer-Communication Networks]:** Network-Protocols

General Terms
Design, Experimentation, Performance, Standardization

Keywords
Link protocols; Biomedical implants; Body area networks; IEEE 802.15.6; Media Access Layer; Power optimisation; MAC

1. INTRODUCTION
Unprecedented advancements in medical technology have improved health care by leaps and bounds. Medical devices today are faster, more perfomant and smaller [1]. At the heart of these medical devices are sensors. A typical implanted medical device like pacemaker contains 6-7 different types of sensors which monitor various physiological parameters of a patient.

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This sensor information is collated to not only render therapy but to also enable early and timely detection of maladies [1][2]. The sensor data needs to be exchanged either between peer sensors or a central controller. RF technology is generally used for this data exchange. In early 2002, FCC permitted the use of a set of frequencies to be used exclusively by medical implants, under indoor conditions. These frequencies form the Medical implant service band (MICS) and are in the range of 402-405MHz. FCC has not specified the access mechanism, protocols etc. for these frequencies [3]

Recently IEEE has constituted a task group, TG6 which is developing standards for the generic body area networks [4]. The TG6 is in the process of finalizing the MAC and PHY layers for body area network communication scenarios. Apart from IEEE TG6, lot of work has been done in developing efficient MAC protocols by the wireless sensors community and the body area network community[6][7][8].

While the WSN community has developed very energy efficient protocols, the nature of WSN applications, which are typically distributed, de-centralized, co-operative and event detection based, is very different from the typical nature of BAN networks[3]. BAN networks are inherently centralized and have periodic data traffic nature. Furthermore they have peculiar characteristics which make them different from WSNs [4][13]. Therefore the BAN community has taken a different approach to addressing the MAC design as we shall discuss in this paper. However, still, these protocols have been designed assuming *a set of identical/similar sensors, each having the same data rate and priority requirements which makes the protocols sub optimal*.

In a typical implant network however all nodes have different set of requirements, priorities, data rates etc. and these disparities cannot be addressed effectively by adopting a uniform, "one size fits all approach". In this paper we consider these varying requirements and present the design of one such protocol which addresses these varied needs. Our MAC has been designed for an implanted cardiac network for distributed pacemaker applications, one of the most important medical implant use cases. The design principles we present in this paper however are generic and can be applied without little or no modification to any such disparate network.

This paper is organized as follows, in section 2 we presented related work done by BAN and WSN community. In section 3 we present our use case, the implanted cardiac network and its requirements. In section 4 we present the design of MAC for such a network and in section 5 we discuss the results and compare our work to the other ultra low power MACs.

2. RELATED WORK

Since power consumption is a major concern in both senor networks and BANs, the MAC protocol design has centered around ways to reduce power consumption. The WSN communities have identified the key sources of energy wastage to be *idle listening, overhearing, collision and overhead* [7],[8]. In these four sources, idle listening is reported to dominate the power consumption [7]. Idle listening occurs because the data rates in WSN applications are low and WSN traffic is sporadic, hence nodes have to waste power listening for transmission, even when there is no intended transmission. WSN protocols tackle idle listening by duty-cycling the receiver and hence trading off power for latency. In order to make sure, that transmission takes place, neighboring nodes wake-up at the same time. Other approaches such as low-power listening also exist [6],[9]. They operate by trying to shift the burden on the transmitter by making it transmit a long preamble and letting the nodes maintaining their own duty cycled intervals.

While latency vs. power trade-off is central to design of WSN MACs, the BAN MACs resolve this problem by using a TDMA based approach[5][10]-[12]. Since BAN networks are centralized networks, a schedule based approach like TDMA can be easily adopted by them. Furthermore since TDMA eliminates idle listening, overhearing, and collision all major energy wastage sources they can enable the ultra low power operation desired by the BANs[5][10]. The benefits however come with cost of maintaining schedule via periodic resynchronization phase, which adds to the power consumption and wastes network bandwidth.

3. CARDIAC BAN

The given cardiac network consists of six different physiological sensors, subcutaneously implanted inside the human body. These sensors are the physiological inputs to the pacemaker which functions as the master node to these sensors. The pacemaker is generally placed just underneath the chest skin.

We now briefly describe the sensors:

- Electro-gram (EGM): It is closely related to the much better-known electro-cardiogram (ECG). While ECG is the potential of the electrical signal generated by the human heart measured on chest surface, EGM is the same signal measured inside the heart;
- Peak endocardial acceleration (PEA): It is essentially a micro-accelerometer implanted inside the tip of a pacemaker lead;
- Bio-impedance (Bioz): Measures the change in the impedance of heart over time. A change implies that the medium inside the heart is changing;
- Minute-ventilation (MV): It is one of the most important rate-adaptive sensors. Minute ventilation is the product of ventilatory rate and tidal volume. The changes in MV accurately reflect oxygen uptake, which is the most accurate measure of human energy expenditure;
- G2D: Another accelerometer sensor implanted inside heart;
- Temp: Measures the temperature of the human body. Variation in temperature is known to signify increased immune-system activity.

Table 1. Cardiac BAN sensors: data rates and priorities

Sensors	Data rates	Priority
PEA	10kbps	High
EGM	5kbps	High
G2D	2kbps	Moderate
BioZ	1.28 kbps	Moderate
MV	80bits/second	Low
Temperature	.2 bits/second	Low

Table 1 gives the corresponding data rate of each of these sensors. Note that is a substantial disparity between the data rate requirements of these sensors. While the PEA sensor generates data at tens of kb/seconds the temperature sensor has very low data rate requirements. Furthermore even in terms of priority, the PEA and the ECG signal have high priorities and need to be monitored every few cardiac cycles, so as to provide the pacemaker the feedback of cardiac operation, while signals like temperature etc. have lower priority and are not needed that often.

Therefore the requirements and hence the MAC strategies which are suitable for a high data rate, low latency sensor lie PEA cannot be applied to a low data rate, high latency sensor like temperature. Furthermore, the master pacemaker has much larger power and computation resources at its disposal than the sensor nodes; hence the reduction of power consumption inside sensor nodes is of far greater importance than in the master node. This relative disparity between the power budget and computational resources of the master and the slave nodes makes our network asymmetric, hence amenable to certain optimisations as we shall discuss in the next section. Table 2 summarizes the key design requirements of implanted BAN networks.

In the next section we discuss the design challenges and choices in designing a MAC for such an implanted cardiac network.

4. DESIGN OF MAC

4.1 Choice of multiple access scheme

Reliability and quality of service are of prime concern in applications like cardiac networks. Critical medical data of high priority sensors like electrical signal (EGM) or pressure signal (PEA) cannot be delayed unpredictably or be dropped due to insufficient buffer space or collisions. A CSMA based scheme, does lead to collisions which not only implies re-transmissions (hence increased power consumption) but also unpredictable delay. For sensors transmission during emergency situations or high priority sensors, this could potentially have catastrophic consequences. To ensure that the high priority sensor (transmission) get a collision free and predictable latency, data transfer, TDMA scheme seems to be the natural choice.

Furthermore even in the case moderate priority but high throughput sensors like (G2D/BioZ), a TDMA slot based transmission is preferable. Since high throughput sensors have larger packets and data transfer needs, collisions on such packets would lead to increased power consumption and waste network bandwidth. While TDMA ensures fixed QoS, an important performance metric, it needs a periodic synchronization phase to make sure that nodes transmit in their respective slots. This synchronization could be cumbersome for sensors which have little data to transmit (like the temperature sensors). Such sensors would have to spend energy each "frame period" just to remain synchronized with master. The ideal scheme for such low latency, low priority and low data rate sensors would be a contention based scheme, where they just transmit data when they intend to.

Table 2. Requirements of an implanted BAN

Parameters	Choices
Reliability	High
Topology	Star(centralized)
Nature of traffic	Uplink (mostly)
Power	Ultra low power
Latency	Low and predictable
Priority	Needed
Asymmetry	Between master and slave

We are therefore faced with two contradictory multiple access schemes for different situations, one scheme(TDMA) guarantees reliability and latency and collision free transfer (at a cost of power consumption and complexity) and the other scheme on the other hand is simple and eliminates the periodic synchronization (contention), at the cost of erratic QoS and collisions.

Table 3 presents the ideal scheme for each of our nodes/data-transfer situations.

Table 3. Multiple access schemes for different priorities and throughputs

	High throughput	Low throughput
High Priority	TDMA-Slots (PEA/EGM)	TDMA-Slots (emergency messages)
Low/Moderte Priority	TDMA -slots (Bioz/G2D	Contention(CSMA) (Temperature)

Given the diversity of our sensors and the relative merits/demerits of each of the multiple access schemes and the need to optimise power consumption we choose the multiple access scheme to be a mix of the two contention and scheduled based schemes as shown in Fig 1.

Our TDMA frame has beacon for synchronizing, slots for high priority and high throughput transmission and a contention period for low priority transmission. Additionally it has an optional inactive part where both master and slaves can sleep. Such a frame structure thus combines the best of both CSMA and TDMA schemes. Notice that the contention period is not slotted and nodes which intend to transmit during this period, should still have some notion time keeping, so as to deduce the starting and the end of contention period. We remark that even though there are some similarities between the chosen frame structure and the frame structure of IEEE 802.15.4 (like the mixed TDMA-CSMA approach) [22], it is in a) the determination of the *frame-*

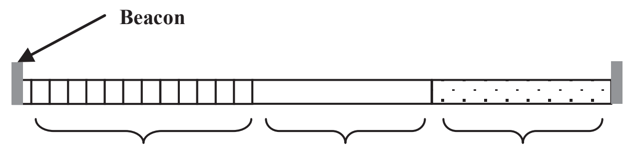

Figure 1 Frame structure description

parameters , b) the internal structure of frame (as we shall see in the next sub-section) that our innovations primarily reside.

Having chosen the multiple access scheme, we now proceed to determine the key *frame-parameters* of this scheme, namely the slot sizing, the beacon interval etc. in the next section. The combination of above two factors thus forms the core of our contribution.

4.2 Choosing the frame parameters

Since the higher priority nodes in our MAC transmit their data during their assigned slots each frame and sleep, the beacon interval (or the frame period) controls the latency of the high priority nodes. Furthermore this interval also has a direct effect on the power consumption. In order to conserve power we would like to increase the sleep period (frame duration) as much as possible and then transmit rapidly during our slot and sleep again. This means that while power consumption requirements favor a large beacon interval, the latency requirements favor a small beacon interval. We must therefore take into consideration this tradeoff in choosing the appropriate beacon interval.

However, in BAN unlike the WSN, sensor events are periodic. Therefore the longer the nodes sleep, the more data-samples it has in the buffer. It would then have to wake up for a proportionately longer time to send the buffered data to the master. Hence duty cycling the node to reduce power consumption would have only a finite advantage. This implies that if we consider power consumption to be most crucial parameter of optimisation, *there would be a point beyond which sleeping leads to no advantage in power but leads to increase in latency*. We now proceed to determine this point analytically and then present the results for each sensor node of our use case.

4.2.1 Duty cycle interval determination

Let us consider a duty-cycled system having a current consumption of I_{on} and I_{sl} for on and sleep times respectively.

We define t_{sl}, t_{su} and t_{trx} as the radio sleep, start-up and transmission times respectively. Then, the average current drawn over the duty cycling period would be:

$$I_{avg} = [(t_{su}+t_{trx})*I_{on}+ I_{sl}*t_{sl}] / (t_{su}+t_{trx}+t_{sl}) \quad (1)$$

milliseconds [16]. Transmission time, however, depends not only on the rate at which the sensor is sampling the signal, but also on the rate at which data can be sent over the physical layer. We define 'R' to be the sampling data rate (in bits-per-second, bps) and 'DR' to be the data-rate over physical layer.

So, after sleeping for t_{sl}, the amount of data to be sent and the time to send it are:

Data to send = $(t_{su}+t_{sl})*$ R bits, R is the data sampling rate;

Time to send the data = $t_{trx} = (t_{su}+t_{sl})*(R/DR)$ (2)

Substituting (2) in (1) we get:

$$I_{avg} = \frac{[t_{su} + (t_{su} + t_{sl}) \times (R/DR)\ ] \times I_{on} + I_{sl} \times t_{sl}}{(t_{su} + (t_{su} + t_{sl}) * (R/DR)\ + t_{sl})} \quad (3)$$

We see that for high-rate sensors (high 'R'), the time taken to send the data increases as sleep time t_{sl} increases. Hence the duty cycling efficiency of the sensor node is related to the sampling rate of the inherent sensor. That is, if we have a very high-rate sensor which samples data at a rate comparable to transmission rate, the inherent gains of sleeping for long might offset the large time needed to transmit data. t_{su}, R, DR, I_{on}, I_{sl} are either hardware-defined or sensor-dependent. The values of t_{su}, R, DR, I_{on}, I_{sl} were taken from the data sheets of the TI-Chipcon CC2420, a popular low power radio [16].

The minimum value of I_{avg} is the point where:

$$d(I_{avg}/dt_{sl}) = 0. \quad (4)$$

Figures 2 show the graphical description of change in I_{avg} with increase in duty cycle period (up to 5s). The different lines correspond to the sensors of our use-case (as table II above shows, their sampling rates are widely different from one another). Figure 2 shows clearly the finite effects of duty cycling.

Table 4 presents the results for easier comprehension. We see that for high-rate sensors, sleeping beyond 5 or 10 seconds does not lead to any significant reduction in consumption. On the other hand, for low-rate sensors (MV and Temp), the energy minimum is achieved around 100s. Hence, we see that each sensor has a different energy minimum point. Now, how do we incorporate these different ideal duty-cycle intervals of each sensor in the TDMA scheme? We propose to do so by choosing the beacon-cycle interval such that it meets the latency and power requirements for the higher- rate and priority sensors. In our case, the high-rate sensors are also those that have higher priority: EGM and PEA. We thus choose a the beacon interval according to these two sensors, and then make the other sensors wake up after every 'N' beacon intervals. For example, if we choose a beacon interval of 5s, the MV and Temp sensors, which have the ideal beacon interval of 100s, wake up after every 20 (100/5) beacons

The analysis in this section gave us an idea of how far can power consumption decrease if we increase latency. In the next subsection we discuss the crucial problem of synchronization.

4.2.2 Synchronization

The more nodes sleep, the more time drift they accumulate. So, nodes that wake up after (100s) would have much higher time uncertainty about their transmission. Hence it's important that nodes respect their respective slots and durations (high/low priority durations) inside the frame and do not transmit out of their turn.

The beacon frame transmitted by the master serves this purpose of synchronizing the nodes to the master. In a typical TDMA scheme all nodes wakeup and listen to beacon and adjust their clocks according to the time-stamp of the master's clock. Note that the timing information conveyed by the beacon is important not only for the high priority or high throughput sensors which have to transmit data during slots, but also for low priority sensors which transmit their data during the contention period. This is because the low priority sensors do need an estimate of the starting of the contention duration inside the frame.

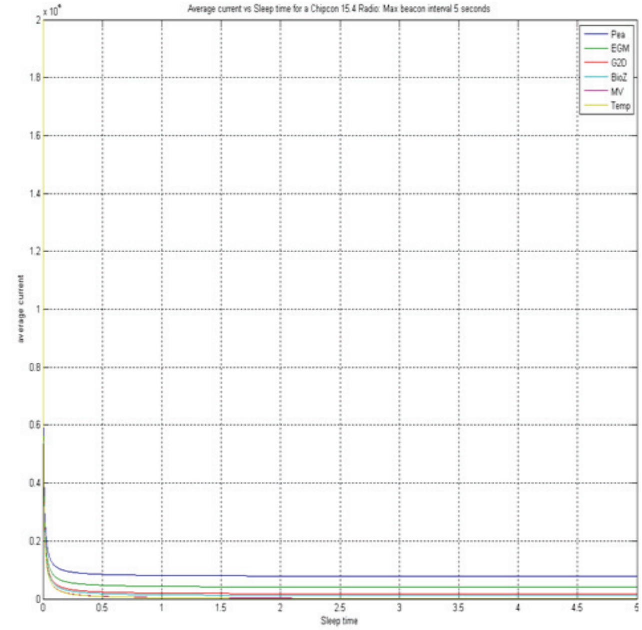

Figure 2 Decrease in average current as duty cycle increases for all sensors

Table 4. Cardiac BAN sensors: data rates and priorities

	Duty cycle interval				
Sensors	.5s	1s	5 s.	10 s	100s
PEA	847	808	777.9	774	770
EGM	471	432	401	397	393
G2D	238	198	167	163	160
BioZ	182	142	110.8	106	103
MV	87	47	15.39	11	7.99
Temp.	80	40	8.997	4.99	1.4

Moreover since the ideal sleep duration is different (duty cycle interval) for different sensors, the corresponding timing error accumulated by the sensors will be different. We can express this analytically as follows:

If we have a crystal of tolerance 'ε' ppm, the amount of timing accuracy 'δ' over the duration of ideal duty cycle interval (sleep interval) 'T' will be:

$$\delta = \pm \varepsilon \times T \quad \text{seconds} \quad (5)$$

Typical timing inaccuracies are given in terms of parts per million (ppm). For example, a 100ppm crystal will lose 100 time units over a total of 1 million units [15]. Over one second, the crystal drift would be 100µs. Since the drift could be both forward and backward, the timing inaccuracy is specified as both positive and negative. We remark that, the value specified by δ are the boundary values i.e. the maxium/minimum possible drift. In practise the drift can be anything between 0 and δ.

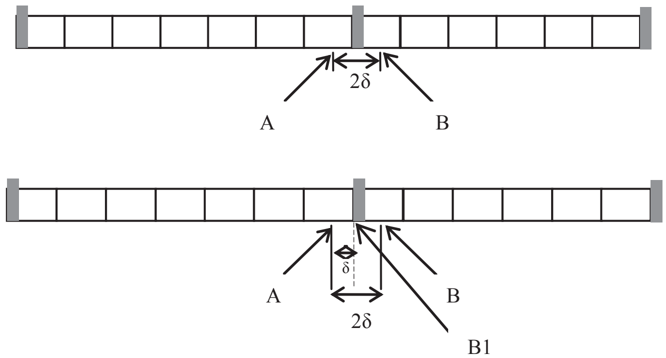

Figure 3 Decrease in average current as duty cycle increases for all sensors

So, if we have a local digital clock at the node, which wakes up at a programmed time to receive beacon, it could in the worst case wake up either before the beacon (A in figure 3a) or after the beacon (B in Fig 3a), assuming that the beacon occurs after fixed clock cycles. Note that if the radio wakes up at point A and turns its receiver on for the beacon, it will receive the beacon after time 'δ'. The penalty would be in terms of the additional energy of keeping the receiver on for 'δ' seconds. However, if time drift is positive and the receiver wakes up at point 'B' our receiver will end up missing the beacon and hence accumulate more drift thereby causing collisions. These are the boundary conditions and time drift could be anything between A and B. If we for the moment assume that higher consumption due to radio start-up before the beacon can be tolerated, the only problem which we are left with is the radio start-up after beacon.

We propose to resolve this as follows. Since we analytically know ε, and the maximum timing error that we can encounter (δ), we can avoid missing the beacon by forcing the radio start-up at (BI-δ) instead of BI, as shown in figure 3b. Hence if we wake up, the radio at (BI-δ), which in the worst-case would have woken up at point B, it will now wake up at point B_1 and receive the beacon (Fig. 3b). We call this the 'cost of synchronising' with the beacon. .Table 5 shows the cost of synchronising with beacon in terms of current for different sensors for the minimum-energy points of table 4 for a standard 40ppm Chipcon radio and a time drift accumualated over 1 beacon interval. Note that for low-rate sensors (Temp. And MV), the relative cost is insignificant (2μA). For the higher-rate sensors, it is still significant (~20 μA) especially for power constrained medical implants which have to last years inside human body. If we can avoid this additional cost of synchronization each beacon interval (~20 μA), we can use this scarce energy resource to carryout useful physiological computation inside the implant.

We note that we can reduce this cost of synchronization for high priority/high throughput sensors, by completely eliminating the beacon based synchronization. Because these nodes transmit data each frame, they interact with the master node each frame. Therefore this interaction during a slot can be used to remain synchronized with master. If the master transmits the timing information of its local-clock by time-stamping the acknowledgement packets, the slave nodes can remain synchronized with the master [23]. However these nodes do accumulate some drift during the frame duration after they finish their transmission and sleep. This drift can be compensated by incorporating guard duration (guard band) inside slots to account for the timing error accumulated each frame period. (Figure 4)

Table 5. Cardiac BAN sensors: data rates and priorities

Sensor: data rate	Original Iavg (μA)	Iavg with early start (μA)	Additional cost
PEA:	777.9	800.3	22.4 μA
EGM	401	423.8	22.8μA
G2D	167	190.76	23.7μA
BioZ	110.8	134	23.2μA
MV	7.99	9.4	1.41μA
Temp	1.4	3.0	1.6μA

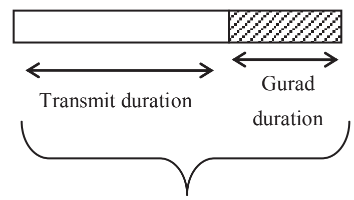

Figure 4 Guard time at the end of each slots

Hence by making the sure that the timing uncertainty accumulated over each beacon doesn't exceed the guard duration and getting synchronized with the master each beacon interval via time-stamped acknowledgements, we can avoid the cost of synchronization.

For a beacon interval of 5s, the drift accumulated for a 40 ppm, crystal will be ±200 μs or ±0.2ms. Notice that just like in Figure 3, this drift can be both positive or negative, which means a node could start transmitting before or after the beginning of its slot. In case the drift is positive and the transmission is delayed, this leads to no problem, since the transmission will extend into the guard duration. However if the drift is negative and the node starts transmitting before its slot boundary, it will transmit in the guard band of its pervious node, potentially causing collisions! However we can avoid collisions, *by choosing guard duration carefully*. We note that the problem only occurs in the case when the delayed transmission of a node (positive timing error) is followed an early transmission its successive node due to (negative timing error). In such a case, the successive node will transmit inside the guard band of its previous node which is active during its own guard band. However if we choose a large enough guard band ensuring that when the successive node transmits during its previous nodes guard band, the previous node has finished its transmission, no collisions will arise. Hence if we choose the guard-band to be 2δ, where δ is the uncertainty during one beacon interval, we make sure that in the worst case, when neighbouring nodes have timing errors of +δ and –δ respectively, no collisions arise.

Thus by choosing guard duration to be 0.4ms (2×200 μs) we will ensure a collision free operation. Recall that this error is not accumulated since, once the data transfer between the master and node begins, master will send the time-stamp of its local clock piggybacked in its acknowledgement packets[23]. Thus by sacrificing some network bandwidth we are able to eliminate this recurring cost of synchronizing with the beacon! We remark that we assume that the master is listening for the node transmission during the guard band, which is not a limitation since master has more relaxed power budget.

Table 6. Slot size determination by considering various factors

	BI	Total Data At BI	Time to Send at 250 kbps	+ Over -head (15%)	+ PER (5%)	+ACK (20%)	# of slots
PEA	5s	50kb	200ms	230ms	242ms	290ms	15
EGM	5s	25kb	100ms	115ms	121ms	145ms	8
G2D	5s	10kb	40ms	46ms	48.3ms	58ms	3
BioZ	5s	6.4kb	25.6ms	29.4ms	30.9ms	37ms	2

4.2.3 Slot size determination

Table 6 shows the time required by each sensor to transmit its data in wireless channel. We have assumed conservative values of PER[19], overhead and retransmission to arrive at the worst-case scenario We chose the slot interval to be 20ms, since 20ms was close to the least common multiple of all these sensors.

5. PERFORMANCE OF MAC

Having designed the protocol and packet structure, we simulated the network in the network simulation software OMNET++, a popular modular, free, open-source, C++ based, discrete event simulator [17]. The MICS channel model as specified by the IEEE 802.15.6 was used to model physical layer behaviour [18]. The channel model specified a randomised Gaussian behaviour for path loss. To gain realistic results, we took the receiver sensitivity to be -90dBm, the same as that of Chipcon and Zarlink biomedical radios [16], [21].

5.1 Performance Results

Since the master only interacts with one slave at a given time, we carried out a packet error rate (PER) analysis of our protocol inside a slot. For a receiver sensitivity of -90dBm, we tried to find out PER behaviour for various distances. This gives us a good idea of the range of our network. Figure 5 shows the plot of PER as we vary the range for MICS band for MICS band (for a transmit power of 0dBm). We obtain acceptable PER (3.1%) for distances upto 25cm inside body.

We now compare our work with the two ultra-low power TDMA-based BAN protocols by Omeni [11] and Marinkovic [10]. Note that a power analysis depends on the underlying hardware, hence radios which are more power-efficient and have faster data rates (hence less 'on' time) tend to give better power consumptions. The radios used by [11] and [10] have much lower data rates (34.56kbps and 50kbps respectively) compared to our solution (250kbps). A direct analysis on the basis of duty cycle or power consumption would automatically favour our implementation. So, we try to provide two analyses by:

- Comparing our scheme "as it is" with these two protocols;
- Adapting our scheme to use the physical radio characteristics of these protocols.

Duty-cycle analysis is generally considered a good figure of merit for any TDMA protocol [11]. It measures how much time one's receiver is 'on'. The protocol published in [10] reports a duty cycle of 4.51% for 1.25kbps sensor and 5.7% for 2.5kbps. [10] reports a far lower (better) duty cycle than [11], SMAC [7] and SCP-MAC [6].

As we discussed in section 4 above, our approach is to first determine the point beyond which duty cycling has no benefit (the energy minimum point). We carried out this analysis for the protocol of [10] and [11] and found that using the same physical and MAC parameters and simply altering the beacon interval, we can reduce the duty cycle from 4.51% to 4.10%, as shown in figure 6. This is the reduction for each frame; the overall gains in the energy over the life-time of sensor would be significant. Using our radio and our MAC scheme, the same data-rate sensor can be duty-cycled to 0.55%, a factor of more than 9 times improvement over and 15.5 times over [10](Fig 7). Figure 8 shows the duty-cycle analysis as we change the data rate over physical layer (use faster radios). We see that our scheme shows greater gains as we move to faster and better radios (the difference between the two curves increases as radio data-rates get higher). These results assume more importance because of the fact that most commercial low-power radios have higher data rates (>200kbps)

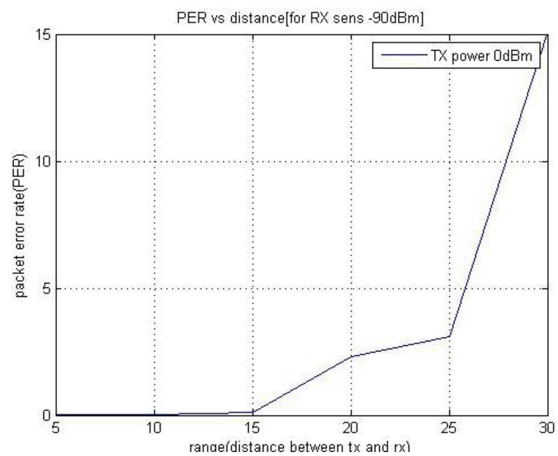

Figure 5 PER vs distance simulation

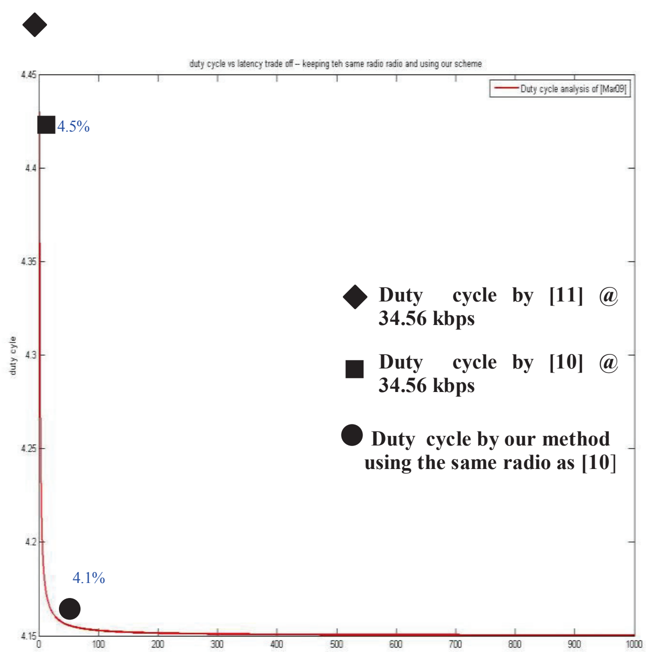

Figure 6 Gain in duty cycle from 4.51% [10] to 4.1% by using the duty cycle scheme described in section 4

[16],[21]. Furthermore, our protocol takes into account retransmission while other protocols permit some packet loss which could be critical for medical data.

6. CONCLUSIONS

In this paper we presented the design of a new MAC layer for Body Area Networks, and illustrated our methodology for a specific use case: cardiac networks which consist of several sensors in or around the heart communicating with the pacemaker. These nodes have vastly different functions; their data has different levels of criticality; their priorities are different; their data-rates vary greatly; as do their power and fidelity requirements. Our MAC design addressed these varying requirements by adopting a TDMA-based approach in which nodes are optimally duty cycled. We also presented a scheme to manage synchronisation and compared our protocol with the best of ultra low power protocols.

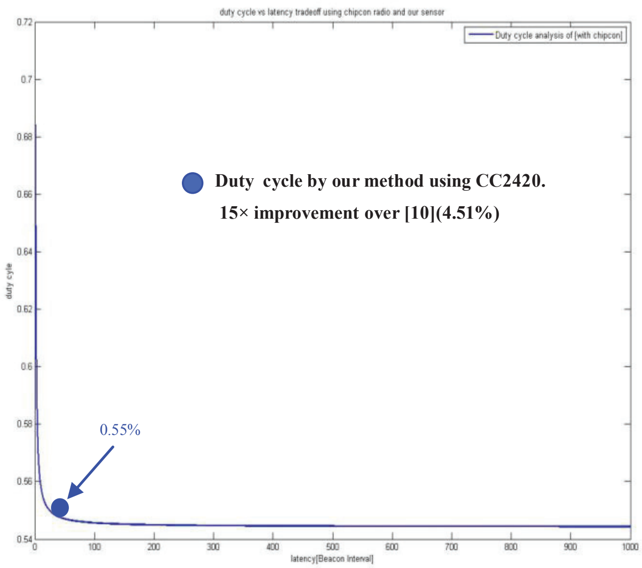

Figure 7 Duty cycle analysis for a 2.5kbps sensor using our radio

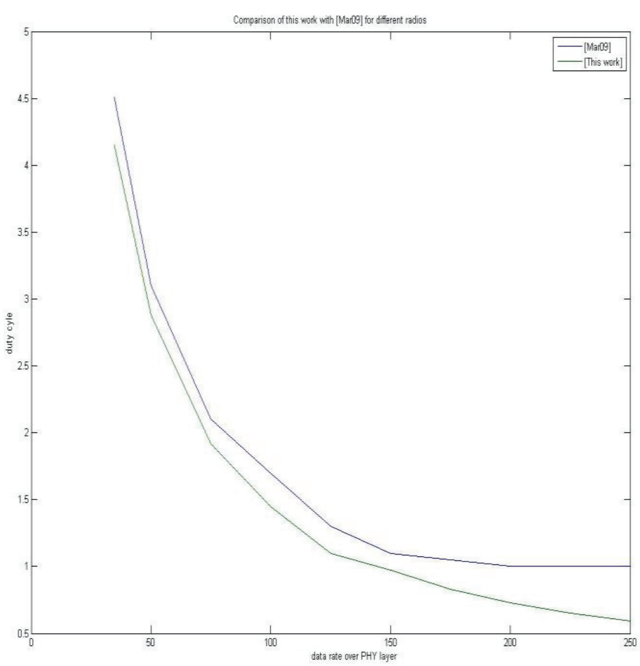

Figure 8. Gain Comparison of our scheme with [10] for different radios: higher gains as radios get faster

7. REFERENCES

[1] The diagnosis for medical electronics. 2009. EE Times special issue. [Online] http://www.nxtbook.com/nxtbooks/cmp/eetimes_medelectronics_20091207/index.php

[2] Chandrakasan, A.P., Verma, N., and Daly, D.C. 2008. Ultralow-Power Electronics for biomedical Applications *Annual Review of Biomedical Engineering,* (Aug. 2008.)

[3] Yang, G. 2005. *Body Sensor Networks*. Springer Science.

[4] [Online]https://mentor.ieee.org/802.15/documents?is_group=0006

[5] Keshav, S. 1997. *Engineering Approach to Computer Networking*. Addison-Wesley Professional.

[6] Ye, W., Silva, F. and Heidemann, J. 2006. Ultra-low duty cycle MAC with scheduled channel polling. *Proc. of SenSys*. (2006).

[7] Ye, W., Heidemann, J. and Estrin, D. 2002. An energy-efficient MAC protocol for wireless sensor networks. *In Proceedings of the IEEE Infocom*. (2002).

[8] Dam, T. V. And Langendoen, K. 2003. An adaptive energy-efficient MAC protocol for wireless sensor networks *Proc. of SenSys*.(2003)

[9] El-Hoiydi, A. et al. 2004. WiseMAC: an ultra low power MAC protocol for the downlink of infrastructure wireless sensor networks Computers and Communications. *IEEE Symposium on Computers and Communications*. (2004)

[10] Marinkovic , S., J. et al. 2009. Energy-Efficient Low Duty Cycle MAC Protocol for Wireless Body Area Networks. *IEEE Trans. on Information Technology in Biomedicine*. (2009).

[11] Omeni, O. et al. 2008. Energy Efficient Medium Access Protocol for wireless medical body area sensor networks. *IEEE transactions on biomedical circuits and systems*.(Dec 2008)

[12] Lee, W.L. et al. 2006. FlexiMAC:A flexible TDMA based MAC Protocol for fault-tolerant and energy-efficient wireless sensor networks. *In Proc. 14th IEEE Int. Conf. Networks.*

[13] Lamprinos, I.E. et al. 2006. MAC design considerations for Patient Personal Area Networks and an Implementation Approach. *Proceedings of the International Special Topic Conference on Information Technology in Biomedicine* .

[14] Tanenbaum, A.S. 1996. *Computer Networks*. Prentice Hall

[15] Schmid T. et al. 2009. On the Interaction of Clocks, Power, and Synchronization in Duty-Cycled Embedded Sensor Nodes. *ACM Transactions on Sensor Networks*.(Aug. 2009)

[16] Texas instruments, Chipcon CC2420 data sheet

[17] [Online]www.omnetpp.org

[18] IEEE 802. 15-08-0783-01-0006, In-body Channel modelling for WBAN with various frequency bands.

[19] Petrova, M. 2006. Performance Study of IEEE 802.15.4 Using Measurements and Simulations. *Proc. Of IEEE Wireless Communications and Networking Conference*

[20] Schmid, T. et al. 2010. High-Resolution, Low-Power Time Synchronization an Oxymoron No More. *Proceedings of the International Conference on Information Processing in Sensor Networks*(IPSN). (Apr. 2010)

[21] [Online]http://www.zarlink.com/zarlink/hs/82_ZL70102.htm

[22] [Online] http://www.ieee802.org/15/pub/TG4.html

[23] Bhaskaran Raman et al. 2010. PIP: A Connection-Oriented, Multi-Hop, Multi-Channel TDMA-based MAC for High Throughput Bulk Transfer. *ACM Conference on Embedded Networked Sensor Systems (SenSys)*, (Nov 2010).