A Novel TDMA-Based MAC Protocol for Mobile in-vivo Body Sensor Networks

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Abstract—**With the development of sensor and wireless communication technologies, the concept of body sensor networks (BSNs) is proposed in recent years. BSNs are used to measure a large number of vital signs of the human body. Body sensor devices are typically powered by batteries and difficult to replace, so energy efficient medium access control (MAC) protocols, which can perform medium access mechanism with less energy are necessary. In this paper, we propose a novel energy saving MAC protocol for mobile BSNs based on time division multiple access (TDMA). An uplink, downlink asymmetric network architecture is introduced. A changeable access and sleep frame format as well as a routing algorithm are proposed. Simulation results show that the proposed MAC protocol achieves lower energy consumption than IEEE 802.15.6.**

***Index Terms*—Body sensor networks, MAC, TDMA, energy efficiency**

I. Introduction

Body sensor networks (BSNs) is becoming a popular research field in recent years after wireless sensor networks (WSNs). It is able to measure a large number of vital parameters of the human body. Because the size of the sensors limits the energy resources, normally there is a coordinator attached to the human body. Figure 1 shows a simple architecture of typical BSNs.

The body sensor devices are usually powered by batteries and difficult to be replaced, so efficiently utilizing the limited battery power and prolonging the lifetime of the network is an important issue. As the transceiver of the device consumes a large part of the energy budget, a good medium access control (MAC) protocol can efficiently reduce the energy consumption of the device, therefore prolong the network lifetime. Many MAC protocols have been proposed for WSNs [1-4]. However, BSNs have their own attributes like smaller network area and higher limitations in energy and processing resources, which make them different from WSNs. The IEEE 802.15.6 group concentrates on body area networks for medical devices and a draft was released in 2010 [5]. It is a time division multiple access (TDMA) based MAC protocol. In this protocol, the hub is responsible for coordinating channel access. There are three modes for accessing: beacon mode with beacon period superframe boundaries, non-beacon mode with beacon period superframe boundaries and non-beacon mode without beacon period superframe boundaries. IEEE 802.15.6 provides macroscopic and microscopic power management schemes named hibernation and sleep. To hibernate, the sensor nodes can sleep for n consecutive beacon periods by setting the wakeup period field in its last connection request frame an integer n and set the Wakeup Phase field a value identifying the intended next wakeup beacon period. Within the beacon frame, a node should wake up to receive and transmit packets in its scheduled allocations. Outside the expected allocations, the node goes into sleep for energy conservation.

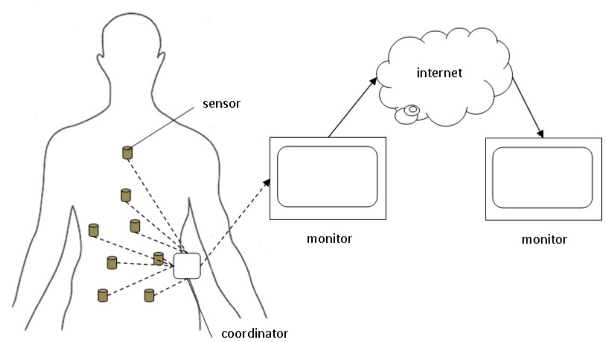

Figure 1. A simple architecture of body sensor networks.

Many energy efficient MAC protocols are proposed for BSNs by researchers. These protocols can be classified as distributed and centralized in terms of topology. The distributed topology like [6], offers the advantages of lower power consumption and self organization. However, coordinating the network is not easy and the protocols for distributed topology are always complex. For the centralized topology which is widely adopted by the current MAC protocols [7-10] proposed for BSNs, there is a coordinator node which coordinates among all the sensor devices. These protocols are easily implemented but consume more energy at the coordinator.

MAC protocols can also be classified as contention based and schedule based protocols. The advantages of contention based MAC protocol include simplicity, small overhead, small latency, etc. Compared with contention based MAC protocol, schedule based MAC protocols are more often used for BSNs. They can avoid collisions, idle listening and overhearing very easily. Table I shows the comparison of contention based and schedule based MAC protocols. For non-dynamic types of networks like BSNs, schedule based MAC protocol is a better choice since it can gives less energy consumption and maximum bandwidth utilization [7].

TABLE I. Comparison of contention based and schedule based MAC protocols

	Contention based	Schedule based
Simplicity	Good	Poor
Maintain states	No	Yes
Overhead	Small	Big
Collision	Yes	No
Idle listening	Yes	Little
Overhearing	Yes	Little

In this paper, we propose an energy saving MAC protocol for mobile BSNs based on TDMA. In the BSNs, the radio of the coordinator can cover the entire network area easily. This paper uses an uplink, downlink asymmetric network architecture. For downlink, the coordinator sends data directly to sensor devices, while for uplink communication the data is sent in multi-hop mode to the coordinator, which helps the sensor nodes to conserve energy. The TDMA scheduling is given in details. Each sensor periodically collects the neighboring information and passes it to the coordinator. The coordinator calculates the routing and time slot schedules, and then sends them back to the sensor devices. A changeable frame format is proposed for saving energy. Adaptive power control is used in our proposed MAC protocol to further reduce the energy consumption. The simulation results show that the proposed MAC protocol achieves better performance than IEEE 802.15.6 in terms of energy consumption.

The rest of the paper is organized as follows: Section II introduces the details of energy efficient MAC protocol design for mobile BSNs. The performance evaluation is presented in Section III and Section VI concludes the paper.

II. Energy Efficient MAC Protocol for Mobile BSNs

A mobile BSN is composed of a coordinator and a number of static/mobile sensors. It has several unique attributes. The assumptions of mobile BSNs are listed below:

1. The power and data processing resources are very limited on the sensor nodes, as the sensor nodes are small in size.
2. The power of the coordinator is not an issue because the coordinator is typically outside the human body without strict size limitation.
3. The path loss of the human body is large due to the different electrical properties of the body tissue [11], therefore the communication through the human body is much more difficult than through the air.
4. The sensors periodically send the data to the coordinator.
5. The sensors are heterogeneous with different sampling rate and sample data size.
6. Some sensors are mobile. This influences the routing and the transmit power.
7. BSNs are within the body area. Thus, every sensor node will be within radio range of the coordinator.
8. This paper assumes that the coordinator knows the number of sensor devices in the networks. This is a reasonable assumption for health care applications.

Based on the above assumptions, the details of the MAC protocol for mobile BSNs are given.

A. *Uplink, downlink asymmetric network topology*

Multi-hop communication has been widely used in WSNs, as it can reduce the total energy consumption compared with single hop communication. In this paper, an asymmetric topology is introduced. It is different from the pure star topology which is used in mobile telecommunication networks, and also different from the pure mesh topology which is used mostly for WSNs. It has an uplink, downlink asymmetric topology.

For downlink data transmission, the network follows a centralized topology that the coordinator sends the data directly to the sensor devices. This is because the coordinator is outside the human body with no strict constraint of its size, so it can carry enough energy. The total energy consumption that the coordinator sends some data directly to certain sensor device can be calculated as the receiving energy consumption of the sensor node, E_r. If the coordinator sends data using a mesh topology, then the total energy consumption is equal to $E_r + \sum_K (E_{r_i} + E_{t_i})$. E_{r_i} and E_{t_i} are the receiving energy consumption and the transmit energy consumption of node i respectively, $i \in K$. Multi-hop communication achieves larger energy consumption than single hop transmission for downlink communication.

For uplink data transmission, the multi-hop communication is adopted. The sensor devices relay the data in a multi-hop way to the coordinator. The total energy consumption for multi-hop communication would be smaller than single hop communication when circuitry power is smaller enough [12]. The smaller the circuitry power is, the more significant the multi-hop communication is for energy saving. Transmit and receive circuitry power consumptions are becoming smaller and smaller as the new technologies come out. J. Pandey et al. proposed a 90 μW MICS/ISM band transmitter [13]. The simulation in this paper uses 100 μW as the TX/RX circuitry power.

B. *Scheduling*

Since the coordinator can do synchronization easily, a TDMA based medium access control scheme is adopted. The TDMA scheme can effectively reduce collisions, idle listening, and overhearing. Thus, the stability of the system can be improved.

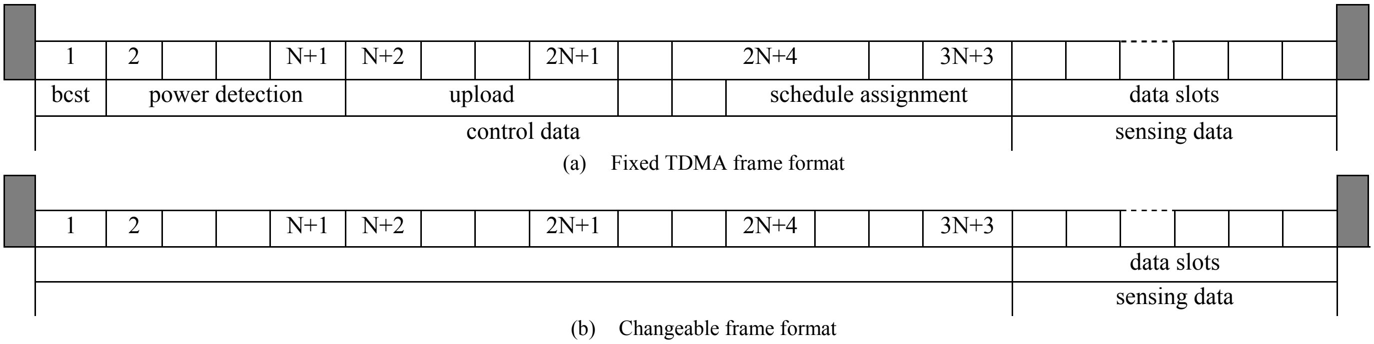

Figure 2. TDMA frame format. The frame is composed of broadcast section, power detection section, information upload section, schedule assignment section and data slots section.

Figure 2(a) shows the TDMA frame format for scheduling. The frame is bounded by the beacon sent by the coordinator. It is composed of mini control slots and data slots. The control slots include broadcast slot, power detection slots, neighboring information upload slots, and scheduling assignment slots. The broadcast information includes the first slot for each control section. All the sensor nodes receive this broadcast information and use it and their own ID to calculate their own transmit time slots for each section. In the power detection section, the sensors share their own information to get a path loss map between each pair of sensors. They upload the neighboring information in the upload section. The coordinator calculates routing and slot schedule pattern and send them to the sensors in the schedule assignment section. The schedule includes transmit/receive time slot and transmit power for the specific sensor in the data slot section (Figure 3). Then, the sensor devices follow the received schedule to complete the communication. The time slot assignment is completely flexible. If a sensor device has a lot of data to send, then it would be given more data slots. If a sensor device has no data to send, then it would not be assigned data slots until next frame. The whole process repeats in the next TDMA frame.

M-periodic power detection is proposed for energy saving. Since the sensor nodes moves very slowly, the power detection and routing update are conducted every *m* frame. The power detection and routing update frame is shown in Figure 2(a), the format for the rest of the frames is shown in Figure 2(b). In these frame formats sensor nodes only have beacon and data slots. They follow the same schedules as in previous frame.

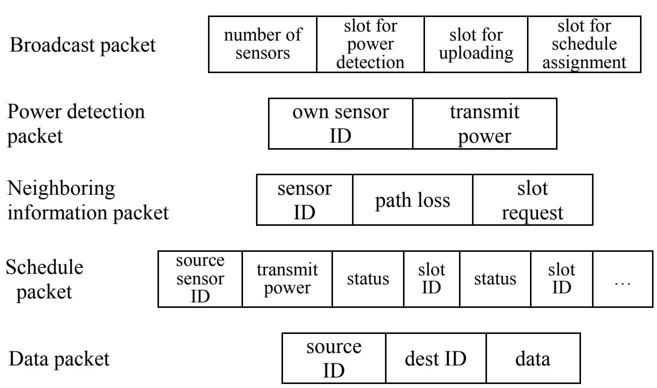

Figure 3. Data packet structure.

C. Routing calculation

The coordinator collects the neighboring information from sensor devices and calculates the routing. It calculates the pathloss PL of any two sensors using the transmit power and received signal strength indication (*RSSI*) according to (1). *Pt* is the transmit power from node *i* to node *j*. *RSSI* is the receiving power of node *j*. It initializes the next hop array and total power array. The total power for node *i* is equal to the power consumption for data transmission from node *i* to the coordinator calculated as (2). $\sum_{\text{route}} Pt_{ij}$ is the summation of transmit power in the route. $\sum_{\text{route}} Pr_{ij}$ is the summation of receive power except the coordinator. For each round calculation, if *TotalPower(i->j->coordinator)* is smaller than *TotalPower(i)*, then the next hop of node *i* becomes node *j*. The corresponding total power is updated. The route calculation is finished until the next hop array does not change. Algorithm 1 shows the route calculation algorithm.

$$PL = Pt - RSSI \quad (1)$$

$$TotalPower(i) = \sum_{\text{route}} Pt_{ij} + \sum_{\text{route}} Pr_{ij} \quad (2)$$

Algorithm 1: Route calculation

```
V: set of all the medical nodes in the networks
SET Nexthop(node i) = BS
SET TotalPower(node i) = TotalPower(i->BS)
WHILE NexthopArray changed do
 WHILE i ∈ V do
       WHILE j ∈ V,j≠i do
        if TotalPower(i->j->BS)<TotalPower(i) Then
          Nexthop(i)=j
          TotalPower(i)= TotalPower(i->j->BS)
        End if
       End While
 End While
 check if NexthopArray is changed
End While
```

III. Performance Evaluation

BSNs with mobile sensor nodes inside the small intestine of human body are simulated in Qualnet 5.0 [14] to evaluate the performance of the proposed protocol for in-vivo applications. The energy consumption of the proposed MAC protocol is compared with IEEE 802.15.6 MAC protocol for BSNs. The results show that the proposed MAC protocol outperforms the

IEEE 802.15.6 in terms of energy efficiency when circuitry power is 100 uW.

The digestive tract is over 6 meters in length [15] and the nodal speed in the digestive tract is around 0.2 mm/s [16]. Table II shows the assumptions to randomly generate the mobility patterns of the digestive tract. The mobility pattern is modeled as multi segment line around 6.3 meters inside a cube of 25 cm × 15 cm × 25 cm. Each segment follows normal distribution with the mean length of 7.4 cm and the standard deviation of 3.1 cm. The angle of each segment line to the coordinate, α and β, follows uniform distribution with the minimum value of 0° and maximum value of 360°. The mobility pattern starts at (7, 11.3, 25) and ends at (0, 0.2, 4).

TABLE II. Assumptions for random mobility pattern generation

Parameters	Value	Parameters	Value
maximum angle	360	mean of distance	7.361
minimum angle	0	standard deviation	3.1229
Length of small intestine	~630cm	border	25*15*25
starting point	(7,11.3,25)	destination point	(0,0.231,4)

This paper refers to 802.15.6 channel model as the path loss model [17]. The proposal defined seven scenarios based on different locations of the communicating nodes. In this paper, only implant-to-implant and implant-to-body surface are involved. The path loss for BSNs is both distance and frequency dependant. (3) shows the statistical model of path loss. d_0 is 50 mm as a reference distance. n is the path loss exponent. S is the variation due to the phenomenon of shadowing. The parameters corresponding to the scenarios of implant-to-implant and implant-to-body surface are expressed in Table III. The parameters used in Qualnet are listed in Table IV.

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + S \qquad (3)$$

TABLE III. Parameters used path loss estimation

Implant to Implant	$PL(d_0)$(dB)	n	σ_s(dB)
Deep Tissue	35.04	6.26	8.18
Near Surface	40.94	4.99	9.05
Implant to Body Surface	**$PL(d_0)$(dB)**	**n**	**σ_s(dB)**
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81

TABLE IV. Parameters used in simulation

Parameters	Value	Parameters	Value
Area	0.4m×0.4m	Tx/Rx circuitry power	100uW
Number of nodes	3-7	MAC protocol	TDMA
Channel frequency	433MHz	Mobility pattern	Random
Pathloss model	802.15.6	Items to send	12000
Radio type	ABSTRACT	Packet size	512 bytes
Transmission power (dBm)	Adaptive	CBR packet interval	1 s
Energy model	GENERIC	Simulation time	20000s
Inefficiency factor α	1		

Figure 4 shows the simulation results for the fixed frame format (1frame/update) and the changeable frame format (m-periodic). All the simulations obtain a packet delivery ratio of 100%. It can be seen that the changeable frame format can effectively save energy. The less frequent the power detections are conducted, the less the energy is used.

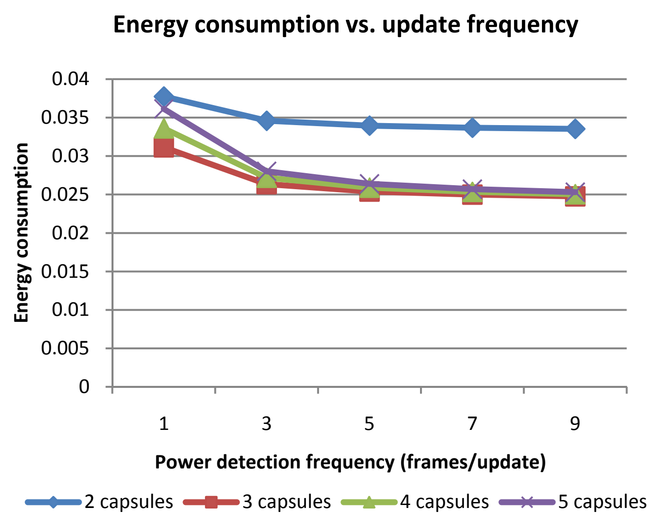

Figure 4. Energy consumption vs. power detection interval. 1frame/update represents fixed frame format. 3 – 9 frames/update represents changeable frame format.

Energy consumptions based on different numbers of sensor devices are simulated as shown in Figure 5. All the simulations obtain the packet delivery ratio of 1. It can be seen that the energy consumption for proposed TDMA is much smaller than that of IEEE 802.15.6. This is because the proposed protocol uses smaller transmit power to send the data and reduces the idle listening and overhearing. For the routing update frequency, it can be seen that the lower the update is conducted, the less the energy is consumed. When the frequency is reduced to 7 or 9 frames/update, the influence of the frequency is not too significant.

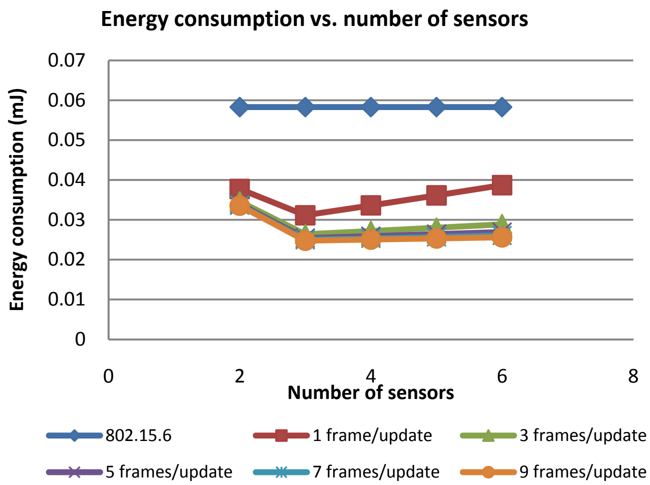

Figure 5. Energy consumption of proposed TDMA with different power detection interval and IEEE 802.15.6.

With reference to Figure 5, the minimum energy consumption is achieved at a network with 3 sensor nodes. A 2 sensor network has higher energy consumption because the sensors uses large transmit power to send data due to the longer distance between sensor nodes. 4-6 sensor networks have larger energy consumption when compared to a 3-sensor network. This is mainly due to the 100 µW circuitry power used in the simulation. Furthermore, when a packet is routed along the same path, it can be inferred that the same transmit power is used. Since 4-6 sensors also participate in the control section of power detection, information uploading and schedule assignment, extra energy consumption is consumed. When more sensors exist in the network, more energy will be consumed. Thus, the energy consumption for 4-6 sensors increases linearly.

Figure 6 shows the energy consumption vs. packet size from 0.5 KB to 3 KB. The result shows that the proposed TDMA consumes much less energy than IEEE 802.15.6.

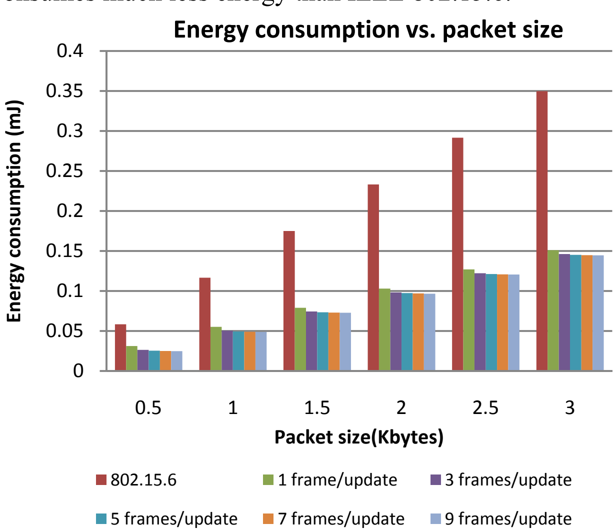

Figure 6. Energy consumption vs. packet size for proposed TDMA with different power detection interval and IEEE 802.15.6.

Figure 7 shows the simulation result of energy vs. CBR packet interval. The proposed TDMA protocol achieves better performance than 802.15.6 for different traffic loads.

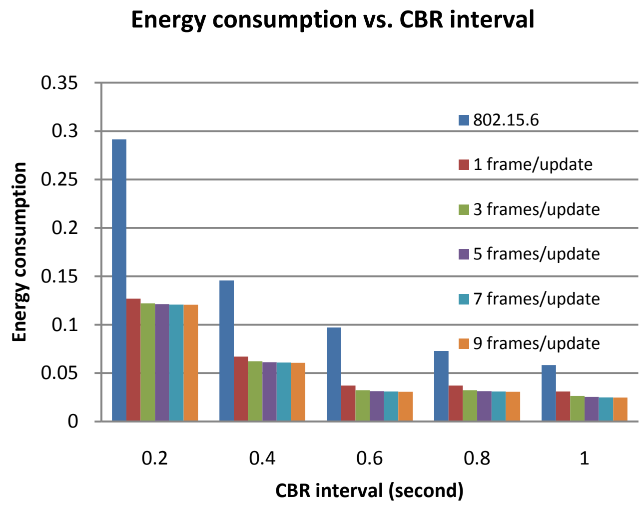

Figure 7. Energy consumption vs. CBR packet interval for proposed TDMA with different power detection interval and IEEE 802.15.6.

IV. Conclusion

This paper proposed an energy saving MAC protocol for mobile body sensor networks. A novel asymmetric topology is used, which is better than the pure star topology or distributed topology. The TDMA schedules for medium access and sleep are discussed in details. The proposed protocol avoids the idle listening, overhearing problem and most of the processing work is shifted to the coordinator. A changeable frame format is proposed and the power detection frequency is discussed. Simulation results show the proposed TDMA protocol gives better performance than IEEE 802.15.6 on energy consumption when the circuitry power is 100 uW. Future work would focus on the optimization of the time slot assignment algorithm and the power detection frequency.

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References

[1] P. Joseph, H. Jason, and C. David, "Versatile low power media access for wireless sensor networks," in *Proceedings of the 2nd international conference on Embedded networked sensor systems* Baltimore, MD, USA: ACM, 2004.

[2] Y. Wei, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, 2002, pp. 1567-1576 vol.3.

[3] D. Tijs van and L. Koen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *Proceedings of the 1st international conference on Embedded networked sensor systems* Los Angeles, California, USA: ACM, 2003.

[4] V. Rajendran, K. Obraczka, and J. Garcia-Luna-Aceves, "Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks," *Wireless Networks,* vol. 12, pp. 63-78, 2006.

[5] "IEEE P802.15.6/D0 Draft Standard for Body Area Network," *DCN: 15-10-0245-06-0006,* May 2010.

[6] K. HyungTae and L. SuKyoung, "Energy-efficient multi-hop transmission in Body Area Networks," in *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*, 2009, pp. 2142-2146.

[7] S. J. Marinkovic, E. M. Popovici, C. Spagnol, S. Faul, and W. P. Marnane, "Energy-Efficient Low Duty Cycle MAC Protocol for Wireless Body Area Networks," *IEEE Transactions on Information Technology in Biomedicine,* vol. 13, pp. 915-925, Nov 2009.

[8] O. Omeni, A. C. W. Wong, A. J. Burdett, and C. Toumazou, "Energy Efficient Medium Access Protocol for Wireless Medical Body Area Sensor Networks," *IEEE Transactions on Biomedical Circuits and Systems,* vol. 2, pp. 251-259, Dec 2008.

[9] B. Otal, L. Alonso, and C. Verikoukis, "Towards Energy Saving Wireless Body Sensor Networks in Health Care Systems," in *Communications Workshops (ICC), 2010 IEEE International Conference on*, 2010, pp. 1-5.

[10] N. F. Timmons and W. G. Scanlon, "An adaptive energy efficient MAC protocol for the medical body area network," in *Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology, 2009. Wireless VITAE 2009. 1st International Conference on*, 2009, pp. 587-593.

[11] L. C. Chirwa, P. A. Hammond, S. Roy, and D. R. S. Cumming, "Electromagnetic radiation from ingested sources in the human intestine between 150 MHz and 1.2 GHz," *IEEE Transactions on Biomedical Engineering,* vol. 50, pp. 484-92, 2003.

[12] L. Lin, K.-J. Wong, S.-L. Tan, and S.-J. Phee, "Asymmetric Multihop Networks for Multi-capsule Communications within the Gastrointestinal Tract," in *Wearable and Implantable Body Sensor Networks, 2009. BSN 2009. Sixth International Workshop on*, 2009, pp. 82-86.

[13] J. Pandey and B. Otis, "A 90 uW MICS/ISM band transmitter with 22% global efficiency," in *Radio Frequency Integrated Circuits Symposium (RFIC), 2010 IEEE*, 2010, pp. 285-288.

[14] SNT, "QualNet Simulator Version 5.0," *Scalable Network Technologies*.

[15] "Small intestine function," *www.Buzzle.com*.

[16] ""The small intestine"," *becomehealthynow.com*.

[17] "Draft of Channel Model for Body Area Network," vol. IEEE P802.15-08-0780-09-0006, April, 2009.