BodyMAC: Energy Efficient TDMA-based MAC Protocol for Wireless Body Area Networks

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Abstract—**Wireless Body Area Networks (WBANs) enable placement of tiny biomedical sensors on or inside the human body to monitor vital body signs. The IEEE 802.15.6 task group is developing a standard to optimize WBAN performance by defining the physical layer (PHY) and media access control (MAC) layer specifications. In this paper an energy efficient MAC protocol (BodyMAC) is proposed. It uses flexible bandwidth allocation to improve node energy efficiency by reducing the possibility of packet collisions and by reducing radio transmission times, idle listening and control packets overhead. BodyMAC is based on a Downlink and Uplink scheme in which the Contention Free Part in the Uplink subframe is completely collision free. Three types of bandwidth allocation mechanisms allow for flexible and efficient data and control communications. An efficient Sleep Mode is introduced to reduce the idle listening duration, especially for low duty cycle nodes in the network. Simulation results show superior performance of BodyMAC compared to that of the IEEE 802.15.4 MAC.**

I. INTRODUCTION

Whilst wireless technology continues to evolve for a broad range of new applications, applications like human body monitoring have led to the development of Wireless Body Area Networks (WBANs) bringing with them challenges associated with their unique requirements [1-3]. WBANs are targeted for wireless networking of wearable and implantable body sensors which monitor vital body signs such as heart-rate, temperature, blood pressure, ECG, EEG, etc. WBANs are of particular interest to the healthcare sector to provide efficient healthcare services and ongoing clinical management.

Although WBANs have many similar challenges as other wireless networks, they have many specific design requirements. Batteries in sensor nodes are low density because of the size limitation and in most cases are not rechargeable and replaceable. Thus, efficient energy usage is an important part of the MAC protocol design. WBANs use primarily a star topology with a communication range of around 3 meters. A WBAN has fewer than 256 nodes, which is smaller than general Wireless Sensor Networks (WSNs). These new challenges impose new specifications on WBANs. Current wireless technologies for short-range communications of low to moderate data rates, such as IEEE 802.11 WLAN, and IEEE 802.15.4 WPAN [4] are not capable of meeting WBAN requirements.

In this paper, we propose a TDMA-based MAC, BodyMAC. The primary design goal of BodyMAC is to be energy efficient and flexible in terms of bandwidth allocation and supporting a sleep mode by exploiting specific characteristics of WBANs. We assume that WBANs would use a star topology, especially for implanted devices. How to prolong the lifetime of a WBAN is the first high priority to make it practical. A WBAN also has to support different types of applications. These include life critical and non life critical applications, as well as low duty cycle low data rate and high data rate multimedia applications. We address the MAC protocol design for WBANs, including MAC frame structure, bandwidth management and sleep mode mechanisms by taking the above considerations into account. Our contributions are as follows:

- We define a TDMA-based MAC frame structure with uplink and downlink subframes. The MAC frame is adaptive and flexible in terms of the uplink and downlink configuration facilitating the sleep mode design and improving the efficiency of the sleep mode.
- Considering the characteristics of data transmission in BodyMAC, we propose three bandwidth management schemes: *Burst Bandwidth*, *Periodic Bandwidth* and *Adjust Bandwidth*, which deal with different types of data communications such as periodic data sensing and important event reporting. The flexibility of bandwidth allocation also improves efficiency of MAC control packets transmission.
- An energy efficient sleep mode is proposed to turn off the node's radio during Beacon, Downlink and Uplink periods. The sleep mode is especially efficient for the nodes supporting low duty cycle applications.

The rest of the paper is organized as follows. In Section II we review the related work. In Section III we describe the BodyMAC design including its frame structure, bandwidth management and sleep mode schemes. In Section IV, we evaluate the performance of BodyMAC by simulations and compare it with the IEEE 802.15.4 MAC. Finally, we conclude the paper in Section VI.

II. RELATED WORK

Although there are a few types of short-range wireless networks, such as IEEE 802.11 WLAN and IEEE 802.15.4 WPAN, which may be used to form a WBAN, they cannot meet the requirements of WBANs in terms of energy efficiency, flexible bandwidth management. IEEE 802.11 WLAN

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has been designed for wireless networks with coverage from 10 to 100 meters and high bandwidth requiring power of hundreds of milliwatts and resulting in battery life of only a few hours of operation.

Networking technologies for general WSNs are mostly concentrated on solving issues coming from distributed ad-hoc networks. MAC protocols for WSNs can be classified into two categories, Contention-based (CSMA) and Contention-free (TDMA). CSMA contention-based MAC protocols such as S-MAC [5], T-MAC [6], B-MAC [7] and WiseMAC [8], are not energy efficient for WBANs since the majority of applications in WBANs, such as body monitoring, have constant periodic bandwidth requests. Furthermore, WBANs need to support real-time applications such as important event reporting. TDMA based contention-free MACs, such as PACT [9] and LEACH [10], try to organize the WSN as a clustering hierarchy with the cluster heads cooperating to allocate the time slots to the nodes to avoid collisions.

The IEEE 802.15.4 standard has been designed for low-rate wireless personal area networks. It can support up to 250kbs data rate with possible 10 meters of coverage. The data rate is not high enough to support WBANs' required rates of up to 10Mbps, according to IEEE 802.15.6. According to IEEE 802.15.4, MAC control packets are transmitted in the Contention Period. This may introduce long delays for real-time critical applications. The network scale (maximum 256 nodes) [11] in a WBAN will make this even worse. IEEE 802.15.4 uses WPAN ID and Coordinator ID to differentiate different nodes from different WPANs. When different WPANs come together, all the nodes compete for the contention based slots resulting in doubling of the actual network size. There is also no efficient power saving scheme to support very low duty and energy constrained nodes in IEEE 802.15.4 standard. The proposals for IEEE 802.15.6 so far concentrate on channel models for WBAN and no efficient MAC proposals have been presented to the Task Group. Research into MAC for WBANs is only beginning to be reported in the literature [12].

Since in general, WBANs have specific requirements in terms of network topology, network scale, energy consumption, cost and complexity constraints, a new MAC protocol needs to be defined to meet the system requirements.

III. BODYMAC

In this section, we describe the BodyMAC from its' MAC frame structure, bandwidth allocation schemes and sleep mode.

A. MAC Frame Structure

The main aim of BodyMAC is to reduce packet collisions, radio state switching times, idle listening duration and control packet overhead. TDMA-based MACs are much more flexible and efficient in terms of bandwidth allocation and QoS guarantee. Since nodes and gateway are synchronized in time, energy constrained nodes, e.g., implant nodes, can enter into sleep mode and only wake up when they have data to send to the gateway. The short transmission distance and the star topology in a WBAN make it possible to achieve more precise network synchronization between the nodes and the gateway.

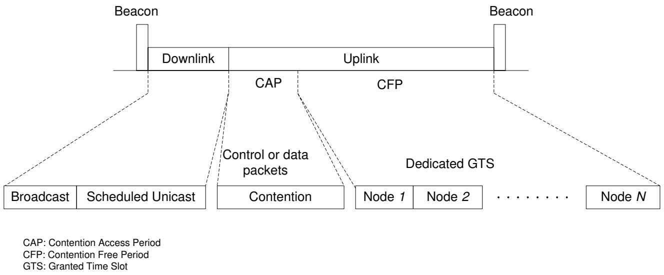

Fig. 1. BodyMAC Frame Structure.

The MAC frame in BodyMAC has three parts: Beacon, Downlink and Uplink as shown in Figure 1. Beacon is used for MAC layer synchronization and description of the MAC frame structure, including many slots are allocated for downlink and uplink, respectively. It also contains network information that needs to be broadcast to nodes periodically. The Downlink part is reserved for the transmission from the gateway to the nodes. It can be either unicast data for a specific node or broadcast data for all the nodes in the network. The Uplink part has two sub-parts: Contention Access Part (CAP) and Contention Free Part (CFP). CAP is based on CSMA/CA, and the nodes contend in CAP for the transmission of MAC control packets. Small size MAC data packets can also be transmitted in CAP. The gateway controls the allocation of slots in CFP. The Granted Time Slot (GTS) in CFP is dedicated to one Node. The duration of Downlink, CAP and CFP are adaptively configured by the gateway based on the current traffic characteristics.

Since frequent state switching of radio states costs extra energy and bandwidth in terms of transmission gaps, the Uplink and Downlink MAC frame structure in Fig. 1 can save node's energy by reducing the times of switching between the transmission state and receiving state of the radio. The dedicated slot allocation in CFP is completely collision free. This improves the successful packet transmission possibility and hence saves energy. Bandwidth allocated in CFP can be changed in each MAC frame to meet the dynamic requirements of nodes. Since bandwidth allocation is decided at the beginning of the MAC frame or even few MAC frames ahead, nodes that do not have bandwidth allocated in each frame can go into sleep mode even without listening to the beacon. This is done using the Sleep Mode described in Section IIIC.

B. Bandwidth Management

The main characteristic of data transmission in BodyMAC is that Downlink and Uplink are asymmetric. Normally sensors in nodes collect data and then send it to the gateway through Uplink data paths. Uplink has much more data than Downlink, so the duration of Downlink is usually much smaller than that of Uplink. Downlink is only used for control commands and some system broadcast information from the gateway to the nodes. The bandwidth resource allocation algorithm in the gateway decides how long the Downlink period should be and how to share the bandwidth resource, i.e., time slots, among the nodes. The bandwidth resource allocation result for Downlink is sent as part of the Beacon's payload.

For Uplink, it is also the gateway that controls bandwidth allocation among the different nodes. After nodes become synchronized with the gateway, they send bandwidth requests to the gateway during the CAP period using CSMA/CA. There are two types of bandwidth requests: control bandwidth requests and data bandwidth requests.

A *Control Bandwidth* request is sent from a node to the gateway to apply for dedicated bandwidth for MAC control packets. This procedure is necessary when a node needs to send a lot control packets to the gateway for control purposes. This can accelerate network control procedures, for example, network entry and association processes, saving energy by reducing packets collision in CAP. The dedicated bandwidth requested by the control bandwidth request can then be recycled by the gateway after a period of time.

Data Bandwidth requests bandwidth in the Uplink period for data transmission from nodes to the gateway. Each node sends a bandwidth request MAC control packet to the gateway in the CAP period or using dedicated control bandwidth based on the type of application and QoS requirements placed on the node. The resource allocation algorithm in the gateway can allocate different types of resources to the nodes based on the characteristics of the data traffic from the node to the gateway. We defined three types of data resources, i.e., *Burst Bandwidth*, *Periodic Bandwidth* and *Adjust Bandwidth*.

Burst Bandwidth defines a temporary period of bandwidth which only lasts for several MAC frames and will be recycled gradually by the gateway. BURST-LENGTH is the initial bandwidth that a node requests from the gateway within a MAC frame. If the gateway finds that *Burst Bandwidth* is not used in a frame, then BURST-LENGTH in the next fame will become half of that in the previous frame. An ACK will be sent from the gateway to the node to indicate that *Burst Bandwidth* is not used in the current frame when the Gateway did not receive any data from the dedicated node. In this case, both the gateway and the node will reduce BURST-LENGTH to half of the current length.

Periodic Bandwidth allows a node to have access to the channel exclusively within a portion of each MAC frame or few MAC frames. *Periodic Bandwidth* is also allocated by the gateway based on the node's QoS requirements and current availability of the bandwidth. *Periodic Bandwidth* may be recycled by the gateway whenever necessary, for example, a node requests to release its *Periodic Bandwidth* or a node disassociate from the network. The data transmitted in *Periodic Bandwidth* can either be data packets or control packets. The node itself decides how to use the allocated *Periodic Bandwidth*.

Adjust Bandwidth defines the amount of bandwidth to be added or reduced from the previous *Periodic Bandwidth*. An *Adjust Bandwidth* request control packet can be sent in the CAP or using dedicated bandwidth as defined by *Burst Bandwidth* and *Periodic Bandwidth* above. The gateway will generate an *Adjust Bandwidth* in response to the control packet containing the information about the bandwidth adjustment result for the node. When the gateway determines that the remaining bandwidth is available for the applied extra bandwidth defined by *Adjust Bandwidth* or when *Adjust Bandwidth* is asking to reduce the bandwidth, the gateway informs the node about the new updated *Periodic Bandwidth* allocation result.

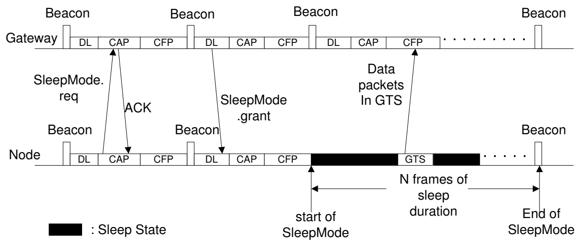

Fig. 2. Sleep Mode Procedure with Normal Completion.

C. Sleep Mode

Idle listening is a major part of wasted energy when nodes have to stay awake to receive potential data. A well-defined Sleep Mode can put these nodes into the sleep state by turning off their radios when there is no data coming from other transmitters. Since a node in the sleep state is not active, it cannot receive any data and cannot hear broadcast information. A good Sleep Mode mechanism should perform a proper tradeoff between flexibility and energy efficiency. The main ideas for designing the Sleep Mode in BodyMAC come from the observations that some nodes in a WBAN have very low duty cycle applications and there are almost no downlink data or control packets sent from the gateway to the nodes. It is a waste of energy for these nodes to receive Beacon in each frame and to be active in both Uplink and Downlink. The Sleep Mode in BodyMAC tries to turn off the node's radio during Beacon, Uplink and Downlink as much as possible.

According to the definition of the BodyMAC frame structure in Fig. 1, there are three steps involved in the Sleep Mode procedure: Sleep Mode request, Sleep Mode grant and Sleep Mode wakeup. These are shown in Fig. 2. At the beginning of each Sleep Mode process, a node sends the sleep mode parameters to the gateway using CSMA/CA during the CAP period. The sleep parameters are *start frame num* and *sleep duration* in terms of the number of frames. Following the Sleep Mode request, there is an ACK sent from the gateway to the node, indicating if the Sleep Mode request has been successfully received by the gateway. Sleep parameters are decided by the node and are based on QoS requirements and traffic characteristics of the application in the node. A Sleep Mode grant will be sent to the node by the gateway in the Downlink period of the following MAC frame indicating if the Sleep Mode request has been accepted or not and what the sleep parameters eventually are decided by the gateway. The gateway makes the sleep mode decision and chooses the sleep mode parameters based on whether it has some data or

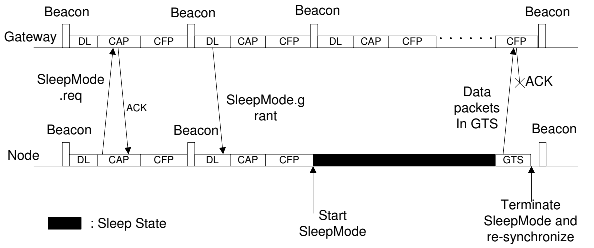

Fig. 3. Sleep Mode Procedure Ending with Data Transmission Error.

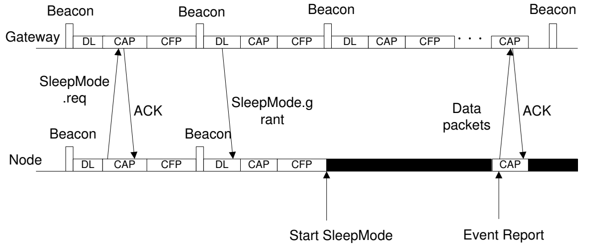

Fig. 4. Sleep Mode Procedure Ending with Event Reporting.

commands to send to the node and the sleep parameters in the Sleep Mode request. The detailed sleep parameters calculation in the Sleep Mode grant is out of scope of the MAC protocol.

As shown in Fig. 2, even during the sleep duration, a node can transmit data packets to the gateway if it has been allocated GTS resources. GTS can also be used as a synchronization procedure. The gateway sends back an ACK after the data packet in GTS. This contains timing information such as frame number and slot number. The node then adjusts its time according to the timing information in the ACK.

Synchronization is a critical issue in a TDMA MAC because the nodes and the gateway have to be precisely synchronized in order to transmit packets successfully. Since the nodes and the gateway have their own clocks, it is difficult for the nodes to be synchronized to the gateway when they wake up after a long period of sleep. So a re-synchronization process is necessary when the possibility of successful packet transmission is low because of loss of synchronization. This possibility is indicated by whether a node can receive the ACK correctly each time after it sends a burst of data to the gateway. Fig. 3 shows that the Sleep Mode is terminated because of data packet transmission failure in GTS. This is followed by the start of the re-synchronization process.

One of the criteria of WBAN MAC design is to support time critical event reporting. Time critical events may come at any time, so the Sleep Mode has to support it. An event report packet can be sent either in CAP or GTS if the node has been allocated GTS in the current frame. As shown in Fig. 4, an event report packet will be send to the gateway in the nearest CAP period using CSMA/CA. After an ACK is received indicating successful reception of an event report packet by the gateway, the node will enter into the sleep mode again. GTS is another option to transmit an event report packet.

IV. NUMERICAL RESULTS

In this section, we evaluate the performance of BodyMAC through simulations. Since the IEEE 802.15.4 is the closest protocol designed for short-rang wireless networks, we compare the performance of BodyMAC with that of IEEE 802.15.4 from the point of end-to-end packet delay and energy efficiency.We first briefly introduce the implementation of BodyMAC and then analyze the simulation results as next.

A. Simulation Setup

We developed BodyMAC based on the Open-ZB toolset [13] which is an open source implementation of IEEE 802.15.4. Our implementation of BodyMAC supports only the star topology where communication is established between nodes and a single gateway. The Physical Layer consists of a wireless radio transmitter and receiver compliant with the IEEE 802.15.4 specifications, operating at 2.4 GHz band and a data rate equal to 250 kbps. The transmission power is set to 1 mW and the modulation scheme used is Quadrature Phase Shift Keying (QPSK). The MAC Layer implements the slotted CSMA/CA, GTS and sleep mode mechanisms. The GTS data coming from the application layer is stored in a buffer depending on the bandwidth allocated. Control packets are stored in an unbounded buffer to be transmitted to the network during the active CAP. The Battery Module computes the consumed and remaining energy levels. The default values of the current draws are set to those of the MICAz mote specification [14].

B. Simulation Results

The bandwidth allocation flexibility of BodiyMAC is improved by the dynamic bandwidth allocation mechanisms such as *Burst Bandwidth*. Fig. 5 shows the end-to-end delay produced by CSMA/CA and CSMA/CA plus *Burst Bandwidth*. The average delay of CSMA/CA increases to 62ms when the number of nodes increases to 54, however *Burst Bandwidth* can make the end-to-end delay less than 22ms. In the simulation, we enable *Burst Bandwidth* allocation once the node's average delay is longer than 15ms. Each node requests for *Burst Bandwidth* in the GTS period which is collision free. As can be seen from Fig. 5, the average end to end delay is decreased with the help of *Burst Bandwidth* when the number of nodes is larger than 18. The slight decrease in the end-to-end delay obtained in Fig. 5 when *Burst Bandwidth* is used as the number of nodes is increased from 18 to 42 nodes appears to be an artifact of short simulation times. This behavior will be further investigated in future work.

Fig. 6 shows bandwidth utilisation efficiency of BodyMAC. We compare the performance of pure GTS in IEEE 802.15.4 with the *Burst Bandwidth* allocation mechanism in BodyMAC. The bandwidth utilisation efficiency is calculated as the bandwidth used to transmit packets divided by the total bandwidth allocated. We control the randomness of the packets from applications by increasing the mean packet arrival time which is used by the application module to create data packets. As shown in Fig. 6, GTS in IEEE 802.15.4 has lower bandwidth

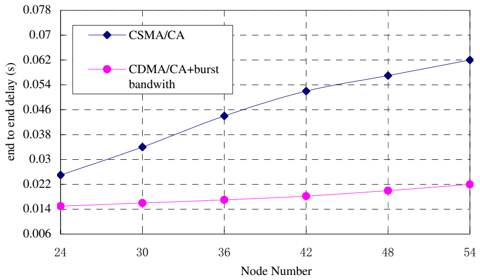

Fig. 5. End-to-end Delay as a Function of Network Size.

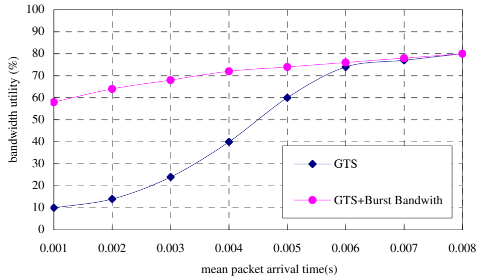

Fig. 6. Bandwidth Utilization Efficiency.

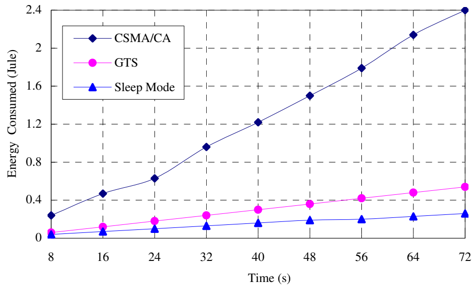

Fig. 7. Energy Consumed by each Node as a Function of Time.

utlisation efficiency than the BodyMAC mechanism, especially when the application becomes more dynamic. The GTS plus *Burst Bandwidth* allocation scheme in BodyMAC has higher efficiency because *Burst Bandwidth* requests bandwidth allocation according to the dynamic requirements of the application.

Fig. 7 shows the energy consumed by different channel access schemes. There are in total 24 nodes sending data to the gateway simultaneously in the simulation. The data rate of the application is 8 kbps. As shown in Fig. 7, CSMA/CA has the highest amount of energy consumed. This is mostly because CSMA/CA is contention based and the node has to be in the idle mode before getting the chance for transmission. This becomes worse when the number of the nodes in the network is large. GTS can make a node stay in the active mode only when it has been previously allocated slots. Otherwise the node is in the sleep state to save energy. As can be seen in Fig. 7, this results in the average power consumed by the node to be around 0.006 Watts. From Fig 7 it can also be seen that the sleep mode defined in BodyMAC can further save a node's power consumption by 0.003 Watts. With the help of the sleep mode, the node can be in the active state only when there are packets to be sent. However GTS defined in IEEE 802.15.4 may waste the node's energy when there are no packets to be sent.

V. CONCLUSIONS

In this paper we proposed a new MAC protocol, BodyMAC, for wireless body area networks. BodyMAC uses flexible and efficient bandwidth allocation schemes and sleep mode to meet the requirements of dynamic applications in wireless body area networks. We compared the performance of BodyMAC with that of the IEEE 802.15.4 MAC which is the closest protocol to BodyMAC in structure. Simulation results show that BodyMAC offers better performance in terms of the end-to-end packet delay and energy saving compared to the IEEE 802.15.4 MAC. Further work will be carried out to define the MAC layer control process and to evaluate performance of the protocol by including the effect of control packets. The effect of deep channel fading in WBAN's wireless channel can also be our future work.

REFERENCES

[1] A. Jurik and A. Weaver, "Remote Medical Monitoring," *Computer,* Apr. 2008, pp. 96-99.
[2] T. Zasowski, F. Althaus, M. Stager, A. Wittneben, G. Troster, "UWB for Noninvasive Wireless Body Area Networks: Channel Measurements and Results," *IEEE Conf. Ultra Wideband Systems and Technologies,* Nov. 2003, pp. 285-289.
[3] G.Z. Yang, ed., "Body Sensor Networks," *Springer-Verlag,* 2006.
[4] "Standard for Telecommunications and Information Exchange Between System-Local Area Metropolitan Area Networks-Specific requirements-Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPAN) 2003," IEEE Std. 802.15.4-2003.
[5] W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," *IEEE Infocomm,* New York, USA, 2002.
[6] T. V. Dam and K. Langendoen, "An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks," *SenSys 2003,* Los Angeles, California, USA, 2003.
[7] J. Polastre, J. Hill, and D. Culler, "Versatile Low Power Media Access for Wireless Sensor Networks," *ACM Conference on Embedded Networked Sensor Systems (Sensys),* Baltimore, Maryland, USA, 2004.
[8] A. El-Hoiydi, J. D. Decotignie, and J. Hernandez, "Low Power MAC Protocols for Infrastructure Wireless Sensor Networks," *European Wireless Conference,* Barcelona, Spain, 2004.
[9] G. Pei and C. Chien, "Low Power TDMA in Large Wireless Sensor Networks," *IEEE Military Communications Conference (MILCOM),* 2001.
[10] W.B.Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Wireless Communications,* vol. 1, pp. 660-670, 2002.
[11] B. Zhen et al., "TG6 Technical Requirements Document (TRD)," *IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs),* IEEE P802, 15-08-0rrr-00-0006, Nov. 2008.
[12] Okundu Omeni et al., "Energy Efficient Medium Access Protocol for Wireless Medical Body Area Sensor Networks," *IEEE Trans. On Biomedical Circuits and Systems,* Vol. 2, No. 4, Dec. 2008, pp 251-259.
[13] OpenSource Toolset for IEEE 802.15.4 and ZigBee, http://www.open-zb.net/
[14] Crossbow Technology, Crossbow Datasheet on MICAz, http://www.xbow.com/Products/Products_pdf_files/Wireless_pdf/MICAZ_Datasheet.pdf