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Reliable Energy-Efficient Dynamic-TDMA MAC Protocol for Wireless Body Area Networks

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Abstract

Time Division Multiple Access (TDMA) is a reliable and proper channel access mechanism for Wireless Body Area Networks (WBAN). In this paper a dynamic-TDMA Medium Access Control (MAC) protocol for WBANs is presented. To achieve a high rate of reliability, a novel dynamic channel allocation mechanism is introduced This mechanism uses a novel collision-free field, called Basic Time Slot (BTS) to control communications in the network. Using BTS field, different conditions e.g. emergency, on-demand and regular traffic transmission are distinguished and handled properly. To investigate the performance of the protocol, analytical equations and regarding simulation results for power consumption, duty cycle, packet delivery delay and channel utilization are presented. Existence of reserved time slots and reallocation mechanism in case of packet failure keeps packet delivery delay at a minimum value which is an important metric in evaluation of network reliability. It is shown that proposed protocol keeps power consumption and duty cycle of sensor nodes at a low value and increases channel utilization rate, compared to static-TDMA protocols.

Keywords: Wireless Body Area Network, MAC Protocol, Dynamic-TDMA, Reliability, Energy Efficiency.

1. INTRODUCTION

Within the last few years, pervasive health monitoring has become a wide area of research interest. On one side, continues and intangible monitoring of physiological parameters, quick detection of emergency situations, improvement in quality of patient health status log and online surveillance of patient health status, improve patient's Quality of Life. On the other side, application of modern tiny, low-power and inexpensive technologies along with modern wireless technologies result in a huge decrease in healthcare expenses. Thus, WBAN is turned into a promising healthcare system for near future [1].

A WBAN is a set of tiny sensor nodes that operate in, on, or in close vicinity to human body, aimed to collect its biomedical information. Sensor nodes are wirelessly connected to a coordinator and form a wireless network with star topology. The number of medical sensor nodes in a WBAN is typically 5-6 nodes and regarding data rates range from a few kbit/s to 1 Mbit/s while their communication range is limited to 1-2 m. A number of nonmedical sensor nodes e.g. forgotten things monitoring, may also join the network [2]. Because of the critical applications of WBAN, design of this network type should assure its proper operation in different situations with a high rate of network reliability.

Sensor nodes in a WBAN, especially implanted nodes, are small in size with small batteries while they are expected to operate at least for a few years. This imposes high energy constraints on them. Since radio transceiver is the most power consuming module in a sensor node, energy efficient methods should be hired to reduce duty cycle of this module. This would further reduce power consumption of sensor nodes and lengthen their lifetime [3], [4].

Due to the broadcast nature of communications in a WBAN, challenges arise on design of proper MAC protocols which directly affect the duty cycle and power consumption rate of transceiver modules. So far, there has been a large number of MAC protocols considered in design of WBANs. Among them, many of early MAC protocols hired methods used for Wireless Sensor Networks (WSN), while more recent works proposed MAC protocols specific to WBANs and their requirements [3], [5]. The small number of sensor nodes in a WBAN compared to WSNs, absence of node redundancy, strict power constraints and necessity of high reliability rate distinguish WBANs from WSNs. Thus, it is necessary to design MAC protocols specific to WBANs, their limitations and requirements.

Two diverging channel access mechanisms are common schemes in design of WBAN MAC protocols; Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) and Time-Division Multiple Access (TDMA). A comparison of these two mechanisms is presented in Table 3. According to fundamental requirements of WBANs, TDMA mechanism is the better solution for this type of networks [6]. Because of small number of nodes in a WBAN, Traffic level and Scalability are not an issue in this network type. Channel allocation predictability is the most important advantage of using TDMA mechanism which not only helps with reduction of duty cycle of sensor nodes and their power consumption, it also provides the network designer with an accurate estimation of packet transmission delay. Power consumption reduction and delay limitation which results in a semi Real-Time operation of the network, are important metrics in reliability evaluation [3], [6].

Table 3: CSMA/CA vs. TDMA Mechanism

Performance Metric	CSMA/CA	TDMA
Power Consumption	High	Low
Traffic Level	Low	High
Bandwidth Utilization	Low	Maximum
Scalability	Good	Poor
Effect of Packet Failure	Low	Latency
Synchronization	Not Applicable	Required

So far, there have been a number of TDMA and Hybrid MAC protocols designed for WBANs. In [7] a hybrid MAC protocol, BodyMAC, is proposed. BodyMAC hires CSMA/CA mechanism for channel allocation while taking advantage of TDMA mechanism for data transmission. The protocol divides Superframe into two parts; downlink and uplink. Downlink period is used for transmission of control information from network coordinator to sensor nodes. Uplink period is divided into Contention Access Period (CAP) and Contention Free Period (CFP). In CAP, sensor nodes content to acquire slots in CFP for data transmission [7].

Authors in [8] proposed a static-TDMA MAC protocol for WBAN. In this protocol every sensor node has a Granted Time Slot (GTS) in every superframe. To prevent GTS overlap, caused by limited accuracy of sensor clock, guard time (T_g) is applied between time slots. Nodes are required to receive resynchronization packets in certain intervals. The maximum number of TDMA frames that can pass before a sensor node needs resynchronization is represented with N_R and is calculated using Equation (1), where θ and T_{frame} represent the sensor clock accuracy and superframe duration, respectively. A number of extra GTS slots are considered to provide proper service in case of packet failure. These slots are dynamically dedicated to sensor nodes whose packets fail to deliver successfully [8]. This protocol supports regular operation of the network with minimum duty cycle and power consumption using assignment of GTS slots to sensor nodes in every superframe. Application of a static-TDMA structure and existence of extra slots to handle packet failure conditions in this protocol reduces packet deliver delay to the minimum value achievable for TDMA mechanism.

$$N_R \leq \frac{1}{2}\left(\frac{T_g}{T_{frame}\theta}\right) \qquad \textbf{(1)}$$

Although the protocol proposed in [7] shows limited delay and high channel utilization rate due to application of dynamic slot allocation procedure, it uses CSMA/CA mechanism which is not a reliable scheme for WBAN due to collision possibility and unreliable CCA procedure. The protocol proposed in [8] is a suitable protocol for WBANs with a majority of sensors having a high sampling or reporting rate e.g. ECG, EMG or Motion Sensors. But in case of a regular WBAN with heterogeneous network traffic as stated in [9], [10] and [11], application of this protocol results in a low channel utilization rate. The protocol presented in [8] performs a tradeoff between channel utilization, power consumption, packet delivery delay, and networking simplicity.

In this paper a dynamic-TDMA MAC protocol is proposed. Application of TDMA mechanism in a dynamic manner eliminates all discussed problems while maintaining the profits, at the cost of a slight increase in processing requirements of network coordinator which already is available since network coordinator has relatively rich processing and storage resources. Proposed protocol uses energy efficiency, low delay rate, predictability and reliability of TDMA mechanism, but hires this mechanism in a dynamic manner to handle various medical and network-related critical conditions and achieve high channel utilization rates. A novel field, called Basic Time Slot (BTS), is considered for control packets and three different data types i.e. regular, emergency and on-demand packets are distinguished and handled properly.

The rest of paper is organized as follows. In section 2 proposed MAC protocol and superframe structure are presented. Section 3 provides performance analysis of the protocol in terms of duty cycle, power consumption, packet delivery delay, and channel utilization rate. Section 4 concludes the paper.

2. PROPOSED PROTOCOL AND SUPERFRAME STRUCTURE

TDMA mechanism is a predictable and reliable scheme for channel allocation in WBANs. Application of a dynamic-TDMA MAC protocol enables dynamic and flexible slot allocation in a collision-free manner, increases channel utilization rate and helps the network adapt better with heterogeneous traffic. This approach can also address a large number of fundamental requirements of a WBAN including limited power consumption in sensor nodes, limited packet delivery delay and high rate of reliability. Small number of sensor nodes, single-hop communication links and semi-static topology of WBAN are metrics that support the dynamic-TDMA MAC protocol have a more efficient operation compared to larger and multi-hop networks e.g. WSNs. The main issues considered in design of the proposed dynamic-TDMA MAC protocol are as follows:

1. Proper respond to various conditions e.g. regular traffic, emergency and on-demand conditions.
2. Support for heterogeneous traffic from nodes with diverging sampling and reporting rates.
3. Proper respond to operational dynamics of the network, in terms of addition and demission of nodes, especially nonmedical nodes, and change in their operational parameters e.g. change in sampling and reporting rate.
4. Keeping power consumption of sensor nodes and their duty cycle at a minimum value and hence lengthening their lifetime.
5. Minimization of successful packet delivery delay.
6. Improvement of channel utilization rate, using dynamic channel allocation.

In the following, in subsection 2.1 the proposed MAC protocol is introduced and its following subsections describe packet format of each field of the protocol, in detail.

2.1 Proposed MAC Protocol

The proposed frame structure is developed for WBANs with a single-hop star topology. It is assumed that sensor nodes stay in sleep mode, as long as no resynchronization or data transfer is being performed by them. As shown in Figure 6, proposed superframe introduces two novel fields; Basic Time Slot field (BTS) and Dedicated Time Slot field (DTS). Communications in both BTS and DTS fields are TDMA-based and collision-free, except for an optional Contention Access Period (CAP) field.

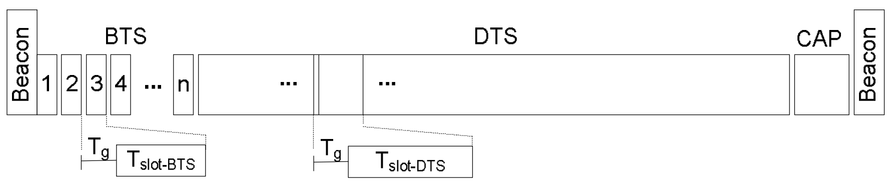

Figure 6: Proposed superframe structure including Beacon, Basic Time Slot field (BTS), Dedicated Time Slot field (DTS) and optional Contention Access Period (CAP) period

BTS field is composed of a number of time slots, one for each sensor node ($node_1$ – $node_n$). These slots have the duration of $T_{slot\text{-}BTS}$ and are used for transferring control packets e.g. DTS slot request and emergency status reporting. DTS field is also composed of time slots which are dynamically assigned to sensor nodes and are used for transmission of data or control packets. The number of time slots in DTS field is much greater than the number of time slots in BTS field.

Optional CAP period is considered to let new sensor nodes join WBAN and uses CSMA/CA mechanism as channel access method. In regular operation conditions, addition and demission of medical sensor nodes occurs rarely, since each sensor node is added to the network only once and stays in the network during its lifetime. Thus, optional CAP field is mainly used by nonmedical sensor nodes. If the network in used in medical environments e.g. hospitals, CAP field is considered in more frequent superframes to let various temporal medical sensor nodes join the network.

In Beacon field, network coordinator broadcasts a beacon packet which contains information about superframe duration, BTS field boundaries, BTS and DTS slot durations and CAP field period. This packet is also used for resynchronization of sensor nodes with network coordinator.

All sensor nodes transmit or receive control packets in their BTS slots, transmit data in their DTS slots, listen to Beacon packet once in every resynchronization interval and stay in sleep mode in other times. In the presented superframe, each field has a specific packet format, based on its application. The main novelty of proposed superframe structure lies in BTS and DTS fields. Beacon frame is designed to deliver resynchronization and superframe structure-related information to sensor nodes. In the following subsections packet format of each field is introduced.

2.2 BTS and DTS Packet Formats

In proposed MAC protocol, BTS field is dedicated to control packets while DTS field is used for data transmission. Packet format of these fields is shown in Figure 7. MAC Protocol Data Unit (MPDU) field does not exist in BTS packets. In both BTS and DTS fields, each Packet is started with a “Preamble” of 2 bytes followed by MAC header. BTS field has a MAC header of 4 bytes while DTS field uses a MAC header of 3 bytes. MAC header is followed by MPDU of 0 upto 248 bytes in DTS packets. In both packet types, the last 2 bytes of packet is a field of Frame Check Sequence (FCS) code. We consider FCS to be a 16-bit Cyclic-Redundancy-Check (CRC-16) code.

The total packet length is 8 bytes in BTS field and limited to 255 bytes in DTS field which is indicated using an 8-bit “Frame Length” in MAC header. “Node ID” is the 8-bit ID of each sensor node. Network coordinator is assumed to have an ID of “00000000”. “Field ID” is set in BTS packets and is reset in DTS packets and is used to distinguish BTS packets from DTS packets.

“Field Control” is 15 bits in BTS packets and 7 bits in DTS packets. In BTS Field Control, “Control Type” indicates whether the frame is a request, response, acknowledge or not-acknowledge frame using the encoding presented in Table 4. “Frame Type” may vary from one WBAN to another according to specific network requirements. A set of useful “Frame Types” and “Subtypes” are presented in Table 5, which may be modified for each patient case. In DTS header, “Packet ID” is a 4-bit ID to specify each data packet and is used as sequence number. Acknowledge and Not-Acknowledge packets from network coordinator use the Packet ID to specify the reference of their response.

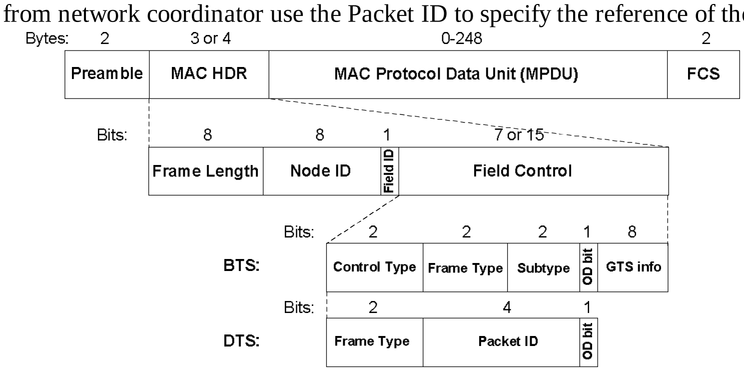

Figure 7: Proposed Packet Format for BTS and DTS fields

In BTS MAC header, On-demand bit, i.e. OD-bit, is used for two purposes; first, to inform the sensor node about available on-demand control packets from physician. Second, to respond to a sporadic report from the sensor node e.g. report of a low battery status or report of emergency condition. “OD-bit” is valid only in downlink packets from network coordinator to sensor nodes. When “OD-bit” is set in a downlink packet, the receiver sensor node has to listen in its BTS slot in next superframe to receive on-demand control data. In the next BTS slot the coordinator will dedicate a DTS slot to the sensor node. In this response packet, if the “OD-bit” is set, the sensor node is supposed to listen in the assigned DTS slot to receive on-demand information and if the “OD-bit” is reset, the sensor node may send its sporadic report packet to the network coordinator. In this case, the sensor node has access to the dedicated GTS slot only in current superframe.

Table 4: Proposed MAC frame Control Types

Control Type	Control Type Name
00	Request (Req)
01	Response (Resp) + Ack
10	Acknowledge (Ack)
11	Not Acknowledge (NAck)

Table 5: Proposed Frame Types and Subtypes

Frame Type	Type Name	Subtype	Subtype Definition
00	Emergency	00 01 10 11	Life Critical State HW Error Battery < 10% Battery < 5%
01	Data GTS	00 01 10 11	Periodic GTS Request Periodic GTS Dismiss Single GTS Request Notification of Invalid Interval
10	On-Demand	00 01 10 11	Data request Threshold change Report interval change Node shut down
11	Reserved	XX	Reserved

The last byte in BTS MAC header, “GTS info”, contains permanent DTS slot allocation information and is used only in GTS data frame types. When a sensor node requests a Granted Time slot (GTS) in DTS field, “GTS info” of the request packet contains the reporting interval requested by the sensor node. In order to simplify allocation procedures, only intervals of 1, 2, 4 and 8 superframes are considered. For instance, if a sensor node requires a maximum reporting interval of 20 superframes, it may request an interval of 8 superframes to satisfy its QoS requirements. Using GTS info, each sensor node requests for a permanent time slot in DTS field with a specific interval. In the response packet from coordinator, “GTS info” indicates the number of the time slot that is dedicated to the sensor node in current superframe. Thus, the sensor node acquires a permanent time slot in DTS field and this allocation is valid in current superframe and every further superframe with the requested interval.

Using this mechanism, sensor nodes have permanent access to a time slot, according to their requirements, as in static-TDMA mechanism. But, this access is valid only in specific superframes which will let more than one sensor node use the same time slot without collision possibility. This is the key feature that helps the network to achieve high rates of channel utilization. Consider a WBAN in which 4 sensor nodes have a reporting interval of 4 seconds. In a dynamic-TDMA procedure as proposed here, only one DTS time slot in DTS field is dedicated to these sensor nodes. The first sensor node uses this time slot in superframe 1, 5, 9..., the second sensor node uses this slot in superframe 2, 6, 10…, and so on. Thus, the dedicated slot is used in every superframe, as opposed to static-TDMA procedure where 4 time slots are dedicated to sensor nodes and each slot is used only once in every 4 superframes.

Another important use of OD-bit is to postpone GTS allocation. In a situation where a sensor node requests for a specific interval and there is a possible free slot for the sensor node, but not in current superframe, the coordinator sets the OD-bit in response packet. With the OD-bit set, the GTS info field in response packet is not valid and the sensor node is requested to listen in its next BTS slot. This will be repeated until the proper superframe arrives and then the slot will be dedicated to the sensor node.

For instance, in previous example, consider a situation where the 3 first sensor nodes are assigned the specific DTS slot in superframe 1, 2 and 3. If the fourth sensor node requests for a DTS slot with an interval of 4 superframes and the request is submitted in the first superframe, the response will have the OD-bit set to ‘1’, meaning that the sensor node has to listen in its BTS slot in next superframe i.e. 2^{nd} superframe. This will be repeated in 2^{nd} and 3^{rd} superframes too. Finally in the 4^{th} superframe, where the slot is free, it will be dedicated to the sensor node. Since the number of medical sensor nodes in a WBAN is limited, the number of BTS slots with OD-bit set, in which the sensor node should be listening before it is dedicated a time slot, is small and in worst case, limited to 3 or 4.

2.3 Beacon Packet Format

The proposed beacon packet format is shown in Figure 8. “Coordinator ID” is the 8-bit ID of network coordinator, considered to be “00000000”. Coordinator ID is used in CAP period. The sequence of “00000000” after preamble is also used for distinguishing beacon packets –as it does not occur in other packet formats–. “Length” indicates beacon packet length in bytes. “SF Duration” is used for indicating the duration of the superframe. “BTS Slot Duration” and “DTS Slot Duration” indicate single slot duration is BTS field and DTS field, respectively. “BTS Information” has a length of (3+k+2N) bytes where k is calculated using Equation (2) and N represents the number of sensor nodes in the network. In the field of “BTS Information”, after indication of first and last BTS field slot numbers and number of sensor nodes, 17 bits are dedicated to each sensor node, including 8 bits for “Node ID”, 8 bits for indication of it BTS slot number and one as OD-bit. Redundancy of OD-bit in BTS, DTS and beacon packets helps the network to have a quick response to on-demand requests from physician. This also assures the network designer that each sensor node will be informed about available on-demand information with a delay of resynchronization interval or less.

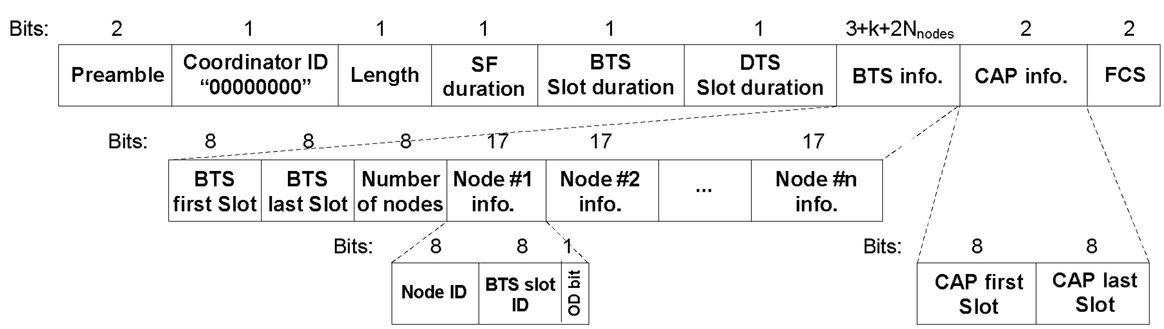

Figure 8: Proposed Beacon packet format

$$k = \lceil \log_8 N_{nodes} \rceil \tag{2}$$

CAP first slot and last slot indicate the starting and ending Time slots of the CAP field. Based on the contention-access nature of this field, the slot limits of TDMA mechanism and the guard time, T_g, are ignored in CAP field. Since existence of CAP field is optional, both first and last slot numbers of CAP field are set to "00000000" in superframes where no CAP period in considered. CAP info is followed by a 2-byte FCS code, which is considered to be a CRC-16 code in this protocol.

3. Analysis and Simulation Results

In this section, performance analysis and regarding simulation results are proposed for a network that uses proposed protocol. Network performance is studied in terms of power consumption, duty cycle, packet delivery delay, and channel utilization rate. In order to model channel distortion and body movement effect on network performance, we considered various Bit Error Rates (BER) in our calculations and computer simulation.

3.1 Bit Error Rate Analysis

WBAN is a network with short-range wireless communication links in, on and around human body. When communicating through body, tissues absorb a considerable portion of signal power and distort the signal. Thus, packet error and packet loss rate in a WBAN is relatively higher that open-air communication channels. In order to model the effect of non-ideal communication medium on packet transmission in a WBAN, we apply BER and PER to our calculations. PER is calculated using BER of a channel as presented in Equation (3). A BER of 0.002% is a reasonable rate for WBAN when the receiving end of a packet is in the line of sight (LOS) of the sending node. In order to model non line of sight (NLOS) communication paths which may come up due to body motion, we also apply much higher BERs (0.01% and 0.02%) to our simulation model, aside from modeling the network using typical BER value of 0.002% and the ideal error-free condition.

$$PER = 1 - (1 - BER)^{Packet-Size} \tag{3}$$

3.2 Network Synchronization

Application of TDMA mechanism for channel allocation requires synchronization of network nodes with the network coordinator. As discussed before and as presented in [8], sensor nodes in a WBAN with TDMA channel access mechanism need to receive resynchronization packets periodically, because of the limited accuracy ratio of their internal clock. As shown in Equation (1) having superframe duration, Guard time duration and clock accuracy of sensor nodes, we can calculate the maximum number of superframes that can pass, before the sensor node needs to receive resynchronization information i.e. beacon packet. Each sensor node will need to listen to beacon packet with an interval of N_R superframes in order to stay synchronized with the network coordinator.

3.3 Duty Cycle and Power Consumption Analysis

In order to study duty cycle and power consumption of sensor nodes in a WBAN, first the active period of transceiver module of each sensor node must be specified. In a WBAN that uses the proposed MAC protocol, after a sensor node acquires a GTS time slot in DTS field, its transceiver module always remains in sleep mode, also called power-down mode, unless in one of the following Conditions:

1. Transmitting data packets in its dedicated time slot, with the reporting interval I_R.
2. Receiving beacon packet for resynchronization, with an interval of N_R superframes.
3. Retransmission of failed packets.
4. Receiving on-demand control or data packets.
5. Transmitting or receiving other control packets.

It should be mentioned that after a sensor node is dedicated a GTS slot in DTS field for regular data transmission, its BTS time slots will be used only in special conditions e.g. emergency and on-demand conditions with control purposes. Since these conditions arise rarely, compared to regular data transmission, we can consider situations 4 and 5 as sporadic and non-frequent situations, and thus, we can waive them from our calculations for duty cycle and power consumption. Abbreviations used in the following calculations are declared in Table 6. Simulation results are also presented to study the effect of BER on duty cycle and power consumption of sensor nodes that communicate using proposed protocol. Transceiver specifications used in our model are adapted from Nordic nRF24L01, an ultra-low power transceiver module operating in ISM band of 2.4 GHz [12]. Transceiver specifications are presented in Table 7.

Table 6: Declaration of Abbreviations Used

Abbreviation	Reference
T_{DTS}	Total active time of the radio of a sensor node in DTS field
T_{sync}	Total active time of the radio of a sensor node for resynchronization
T_{SF}	Superframe duration
T_{wu}	Radio wake-up time
T_{sw}	Time to switch the radio state from Idle to RX/TX
T_{data}	Data packet transmission duration
T_{ack}	Acknowledge packet transmission duration
T_{beacon}	Beacon packet transmission duration
I_R	Reporting interval of a sensor node
N_R	Resynchronization interval of a sensor node

Table 7: Power and Timing Specifications of Nordic nRF24L01Transceiver Module

Parameter	Definition	Value
P_{wake}	Radio wake-up power	855µW
T_{wake}	Radio wake-up time	1.5 ms
P_{sw2RX} / P_{sw2TX}	TX2RX / RX2TX switching power	25.2 mw / 24 mW
T_{sw}	Switching time	130 µs
P_{sleep}	Radio sleep power	2.7 µW
P_{TX} / P_{RX}	Radio TX mode / RX mode power	33.9 mW / 36.9 mW

Considering above-mentioned conditions in which the radio of a sensor node is in active mode, duty cycle of the sensor node is calculated as presented in Equation (4) where T_{DTS} and T_{sync} are computed using Equation (5) and Equation (6), respectively. The resynchronization interval, N_R, is calculated using Equation (1). As presented in Equation (4) situations 1, 2 and 3 are applied to the formulation of duty cycle.

$$DC = \frac{\left(T_{DTS} + T_{sync}\right)}{T_{SF}} \times \left(1 + PER\right) \tag{4}$$

$$T_{DTS} = \frac{T_{wu} + 2T_{sw} + T_{data} + T_{ack}}{I_R} \tag{5}$$

$$T_{sync} = \frac{T_{wu} + T_{sw} + T_{beacon}}{N_R} \tag{6}$$

Using the same procedure as for duty cycle, power consumption of each sensor node is calculated as presented in Equation (7), where P_{DTS} and P_{sync} are computed using Equation (8) and Equation (9), respectively. The term [$T_{SF} \times (1-DC)$] denotes the total sleep time of the sensor node in a superframe.

$$P = (P_{DTS} + P_{sync}) \times \left(1 + PER\right) + P_{sleep} \times \left[T_{SF} \times \left(1 - DC\right)\right] \tag{7}$$

$$P_{DTS} = V_{DD}\left(T_{StBy2A} I_{set} + T_{data} I_{TX} + T_{sw} I_{set} + T_{ack} I_{RX}\right) \tag{8}$$

$$P_{sync} = V_{DD}\left(T_{StBy2A} I_{set} + T_{beacon} I_{RX}\right) \tag{9}$$

Figure 9 illustrates variation of duty cycle and power consumption of sensor nodes as a function of reporting interval, for a number of BERs. The nominal value of BER in a WBAN is 0.002% and graphs that represent this BER are indicated with asterisks. It is shown that for the nominal value of BER, A sensor node has a duty cycle of less than 5% and a power consumption rate of 1.5 mW/s for a reporting interval of 1 second. Its duty cycle and power consumption rate fall below 1% and 0.3 mW/s respectively, for reporting intervals more than 5 seconds and they fall below 0.1% and 0.1 mW/s for a reporting interval of 1 minute or more. Since the majority of implanted sensor nodes have a reporting interval of 1 minute or higher to report the accumulated data within the sleep period, proposed protocol enables them to have a rather long operational lifetime.

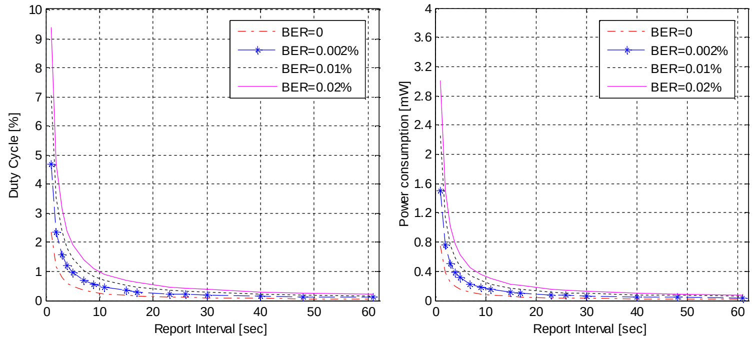

Figure 9: Duty Cycle and Power Consumption as a function of reporting interval, for various BERs

3.4 Delay Analysis

In the proposed protocol, as long as no packet failure occurs, all packets are delivered real-time and packet delivery delay is equal to zero. In case of packet failure, however, retransmission of the failed packet is not immediate and thus, retransmission is delayed. In design of proposed protocol, we have considered two extra time slots in DTS field as reserved slots for the case of packet loss, similar to [8]. When the data packet of a sensor node fails to deliver correctly, the network coordinator sends back a not-acknowledge packet which contains the slot number of the first available extra slot. The sensor node then uses this slot to retransmit its failed packet. If both extra slots are assigned to previous sensor nodes, the coordinator sets the OD-bit in not-acknowledge packet so that the sensor node knows its transmitted packet is not delivered correctly and listens in its next BTS slot to receive a DTS slot for retransmission of the failed packet.

If a packet delivers error-freely in the second transmission, packet delivery delay will be limited to the duration of two superframes. Since PER is a small number, it is unlikely that a packet fails to deliver successfully and error-freely in two consecutive transmissions. The probability of two consecutive failed transmissions is equal to P_F^2, where P_F represents the probability of one failure including the failure of either a data packet or its regarding acknowledge packet. P_F is calculated using Equation (10).

$$P_F = 1-(1-PER_{data})\times(1-PER_{ack}) \tag{10}$$

Figure 10 illustrates the probability of two consecutive failures for various packet lengths with various BERs. The graph shows that even for a packet of 1500 bytes which is a rather large packet in a WBAN, the probability of two consecutive packet failures is ignorable for BERs of 0.002% and 0.007%. According to Figure 10, using the mechanism proposed in this paper, if a packet fails to deliver correctly in its first transmission, it will be delivered error-freely in the second transmission which occurs in the next superframe. Thus, with a probability of more than 99%, a packet will be transmitted correctly within two trials in nominal BER of 0.002%. This probability is higher than 98% for packets with a length of up to 1500 bytes with a BER of 0.007% which is a rather high BER for WBAN. BERs of 0.01% and 0.02% are extremely high error rates that only arise in special conditions. In such conditions, shorter packets have a higher chance of successful delivery.

Based on previous statements, in a WBAN than uses the proposed MAC protocol and the proposed retransmission mechanism, in case of failure, delay of successful packet delivery is limited to two superframe durations with a probability of more that 99% for nominal channel BER of 0.002%.

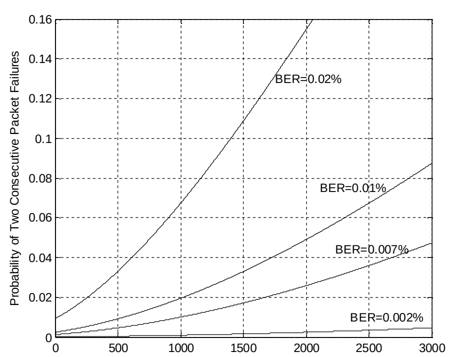

Figure 10: Probability of Two Consecutive Packet Failures vs. Packet Size

3.5 Channel Utilization Analysis

Channel utilization rate, also known as throughput, is defined as the number of successfully delivered bits in their dedicated transmission duration and is calculated using Equation (11), where BFP represents the number of transmitted bits per superframe for each sensor node, TPF represents the total time dedicated to a sensor node in a superframe and n represents the number of nodes in the network.

$$Utilization = \left(\sum_{i=1}^{n} \left[BPF(i) \times \left(1 + BER\right) \right] \right) \Big/ \left(\sum_{i=1}^{n} \left[TPF(i) + \left(\frac{1}{I_R} \times T_{slot} \times PER \right) \right] \right) \quad \textbf{(11)}$$

In order to simplify the comparison of the channel utilization rate in the proposed protocol with static-TDMA protocols, we consider the channel to be error-free i.e. BER=0 and PER=0. Thus, channel utilization equation is simplified to Equation (12) where T_{slot} represents the duration of a DTS time slot and $I_{allocation}$ represents the interval of slot access for each sensor node.

$$Utilization \approx \left(\sum_{i=1}^{n} \left[\frac{L_{Data}(i) + L_{ack}}{I_R(i)} \right] \right) \Big/ \left(\sum_{i=1}^{i=n} \left[\frac{T_{slot}(i)}{I_{allocation}(i)} \right] \right) \quad \textbf{(12)}$$

The nominator in Equation (12) is the same for the proposed protocol and static-TDMA protocols. The denominator, however, is smaller in the proposed protocol, compared to static-TDMA protocols. Considering equal time slot durations in both static and dynamic TDMA mechanisms, in a static-TDMA protocol, each sensor node has a granted time slot (GTS) in every superframe which is used with an interval of I_R. Thus, $I_{allocation}$=1 in static-TDMA protocols. In proposed dynamic-TDMA protocol each sensor node has access to its DTS time slot with an interval of I_R. Thus, $I_{allocation}=I_R$ in dynamic-TDMA protocol. Since in regular and nonemergency conditions, sensor nodes in a WBAN, especially implanted nodes have a reporting interval greater than one second, $I_R>1$, proposed protocol has a channel access interval of $I_{allocation}>I_R$. Thus, proposed dynamic-TDMA protocol has a higher channel utilization rate compared to static-TDMA protocols.

3.6 Reliability Analysis

WBAN is a network of tiny sensor nodes designed to monitor health status and report critical and emergency conditions. Thus, design of a reliable WBAN imposes a wide range of requirements aside from typical reliability requirements of other network types which are low packet delivery delay and low packet loss probability [9]. The extra reliability requirements in a WBAN include correct monitoring of physiological data, real-time recognition of emergency and other critical conditions and a rather long operational lifetime, especially for implanted sensor nodes.

As studied earlier, proposed protocol keeps the packet delivery delay at the lowest possible value achievable by TDMA mechanism which helps the network to have a semi real-time operation in case of packet failure. Further reduction of delay may be achieved by hiring signal modulation methods that limit BER effectiveness. Application of Forward Error Correction (FEC) techniques may reduce the need to packet retransmission but will add extra overhead bits to transmitted packets and doesn’t agree with strictly limited power resource of sensor nodes [9]. Since data packets in a WBAN are relatively short packets, compared to other network types, packet failure occurs rarely in regular operation conditions. Thus, proposed mechanism suggests a fair tradeoff between power consumption and packet delivery delay.

From a networking perspective, long life-time for sensor nodes can be satisfied using TDMA mechanism. Static-TDMA mechanism enables the lowest power consumption and thus, longest life-time for sensor nodes, compared to other mechanisms. Proposed protocol uses low power consumption and contention-free features of TDMA mechanism in a dynamic manner. Dynamic-TDMA nature of proposed protocol makes it possible to recognize and handle various special conditions properly and increases channel utilization rate without sensible increase in power consumption and duty cycle of sensor nodes, compared to static-TDMA mechanism. All discussed parameters are important metrics in evaluation of the reliability of a WBAN, which are satisfied in the proposed protocol.

4. CONCLUSION

Based on requirements and limitations of Wireless Body Area Networks (WBAN), TDMA mechanism is a proper channel access method for this network type. This mechanism enables sensor nodes to operate with low duty cycle and power consumption rate which is a basic requirement for WBAN sensor nodes, especially implanted nodes. Static-TDMA mechanism however shows low rates of channel utilization rate in case of heterogeneous network traffic and lacks a proper procedure for reduction of packet loss rate and packet delivery delay in case of failure. Since WBAN is a network of sensors with heterogeneous sampling and reporting rates and demands a high rate of reliability due to its critical application, dynamic-TDMA mechanism seems to be a better solution for channel allocation in this network type.

In this paper, a novel dynamic-TDMA MAC protocol for WBANs was presented. Proposed protocol uses dynamic-TDMA mechanism with a flexible allocation procedure to handle different medical and network-related conditions e.g. regular operation, emergency and on-demand conditions. In case of packet failure, proposed protocol hires a reallocation procedure to enable retransmission of failed packet with the lowest retransmission delay possible which is an important metric in reliability evaluation of the network. Network reliability is also improved through dynamic slot allocation for regular traffic transfer, consideration of OD-bit in coordinator frames to handle emergency and on-demand situations and consideration of a novel field for control purposes in superframe, called Basic Time Slot (BTS) field. These considerations help the network coordinator to handle communications of medical and nonmedical sensor nodes efficiently and adapt with various operational conditions, which has been poorly considered in previous WBAN MAC protocols. Proposed protocol also enables medical sensor nodes to operate with ultra-low power consumption and duty cycle and lengthens their operational lifetime which is a basic requirement in WBANs.

References

[1.] B. Latre, et al., "A Survery on Wireless Body Area Networks," Journal of Wireless Networks (WINET), vol. 17, pp. 1-10, Jan 2011.

[2.] IEEE 802.15.6 Standard, "Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs) Used In or Around Body", 2012.

[3.] S. Hayat, et al., "Energy Efficient MAC Protocols," In 5th Int. Symposium Advances on High Performance Computing and Networking (HPCC/AHPCN), Jul 2012, Liverpool, UK.

[4.] Y. Zhang, et al., "RFID And Sensor Networks, Architecture, Protocols, Security and Integrations," CRC Press, Florida, 2010, pp. 227-223.

[5.] S. A. Gopalan, et al.,"Energy-Efficient MAC Protocols for Wireless Body Area Networks: A survey," International Congress on Ultra Modern Telecommunications and Control Systems and Workshops ICUMT, 2010, Moscow, Russia.

[6.] S. Ullah, et al., "A Study of MAC Protocols for WBANs," Journal of Sensors, vol. 10, pp. 128-145, Apr 2010.

[7.] G. Fang, et al., "BodyMAC: Energy Efficient TDMA-based MAC Protocol for Wireless Body Area Networks," 9th International Symposium on Communications and Information Technologies ISCIT, 2009, Incheon, South Korea.

[8.] S. J. Marinkovic, et al., "Energy-Efficient Low Duty Cycle MAC Protocol for Wireless Body Area Networks," IEEE Transaction on Information Technology in Biomedicine" vol. 13, pp 915-925, Jan 2009.

[9.] J. Y. Khan, et al., "Wireless Body Area Network (WBAN) for Medical Applications," In New Developments in Biomedical Engineering, In Tech, China, 2010, pp. 591-627.

[10.] S. M. R. Al Masud, "QoS Taxonomy towards Wireless Body Area Network Solutions," International Journal of Application or Innovation in Engineering & Management (IJAIEM), vol. 2, pp. 221-234, Apr 2013.

[11.] O. Gama, et al., "Towards a Reconfigurable Wireless Sensor Network for Biomedical Applications," International Conference on Sensor Technologies and Applucations (SENSORCOMM); 2007, pp. 490-495.

[12.] "Nordic nRF24L01, Single Chip 2.4 GHz Transceiver", datasheet available on http://www.nordicsemi.com/.