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TDMA BASED DELAY SENSITIVE AND ENERGY EFFICIENT PROTOCOL FOR WBAN

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Abstract

The fundamental function of Wireless Body Area Network (WBAN) is to convey information over short distances. Because of their tremendous potential in medical and home applications, WBANs have raised tremendous research interests in recent years. This paper presents an energy-efficient and delay sensitive medium access control (MAC) protocol suitable for communication in a WBAN for remote monitoring of physiological signals such as EEG, ECG etc. In the proposed scheme, sensors are allowed to interrupt the PDA in case of emergency so that immediate action may be taken to avoid any causality, hence provides support to deal with emergency data along with the normal data. For performance analysis viewpoints the proposed scheme is simulated and compared with IEEE 802.15.4 standard. The simulation results shows that the proposed scheme is better in QoS for emergency (higher priority) data and gives better performance in terms of the average transmission time and energy efficiency.

Keywords: PDA, Interrupt, Slot adjustment, Emergency data.

1. Introduction

Recent developments in the wireless sensor technologies have brought the emergence of low-cost short transmission wireless devices and this has led to the expansion in Wireless Body Area Networks (WBANs). The network architecture of WBAN is designed for a conceptually simple wireless network like home automation system with short range operation, low data-rate, low power consumption and low cost of deployment using inexpensive portable fixed or moving devices [1]. Unlike Bluetooth (IEEE 802.15.1), which is designed for applications with high quality-of-service (QoS) requirements [2], WBANs are designed for applications with low data-rate and low-latency requirements. WBAN

Nomenclatures

C_{rn}	Communication range of Relay Node
C_{sn}	Communication range of Sensor Node
$d_{i,j}$	Distance between i^{th} and j^{th} device
f_{c1}	Transmission rate of Sensors in bits per seconds
f_{c2}	Transmission rate of PDA in bits per seconds
N	Total number of devices (i.e., Sensor Nodes & Relay Nodes)
N_{ack}	Number of ACK/NACK bits
N_{BE}	Number of back-off period
$Nbr_i[\ ]$	Neighbourhood list of i^{th} Sensor Nodes
N_e	Number of SN with emergency medical data
N_i	Number of bits sampled by i^{th} Sensor in one time frame
N_{oh}	Number of overhead bits
N_{sn}	Number of Sensor nodes
P_{Idle}	Overall power consumption when idle
P_{Rx}	Overall power consumption at receiver
P_{Tx}	Overall power consumption at transmitter
T_{frame}	Duration of one TDMA time frame
T_g	Time required by sensors nodes to turn on/off their transceiver, ms
T_{ms}	Duration during which PDA delivers data to MS

Abbreviations

CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CSMA/CA	Carrier Sense Multiple Access With Collision Access
GTS	Guaranteed Time Slot
MAC	Medium Access Control
MS	Medical Service
PDA	Personal Digital Assistant
QoS	Quality of Service
TDMA	Time Division Multiple Access
WBAN	Wireless Body Area Network

applications can be broadly classified into home automation, commercial, industrial, emergency response applications and medical health care. Home Automation is one of the largest WBAN applications aimed at creating smarter homes with low-rate data communications and self-organizing capability [3]. Some common applications of WBAN involve deploying the sensor nodes to monitor the heart rate of a person or to report to emergency services if a person is injured in a blast. So, in these applications a timely response is more critical than saving energy for the sensor nodes.

Another important application of a WBAN involves remote sensing by deploying thousands of low-cost sensors in battlefields or dense forests in an ad-hoc fashion where the nodes sense and transmit the data to a central coordinator in the network, which in turn performs computation on the received data and transmits the result to a data centre. Sometimes, the devices are deployed in regions where battery replacement is not feasible. Therefore low power consumption is very critical to increase the lifetime of the network in such applications. During the development phase of WBAN, IEEE 802.15.4 [4] was considered to be the most competitive MAC protocol. The performance evaluation of IEEE 802.15.4 MAC protocol for WBAN is presented in [4, 5]. Figure 1 presents beacon-enabled superframe structure of IEEE 802.15.4 MAC protocol. Sensor nodes use CSMA/CA channel access mechanism in CAP and the CFP is divided into guaranteed timeslots (GTS) on a reservation-based approach. All signals are treated in the same way in IEEE 802.15.4 MAC protocol, which is the main limitation of IEEE 802.15.4 MAC's usage in the WBAN scenario.

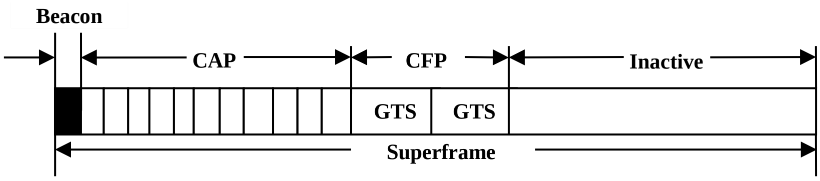

Fig. 1. IEEE 802.15.4 superframe structure.

In case of emergency, urgent medical data should be given higher precedence as compared to the normal medical data and should be delivered immediately to avoid any causality. In this paper, we propose a scheme based on IEEE 802.15.4 MAC protocol which is suitable in case of medical emergency. In this scheme medical data is classified into two categories: normal medical data and emergency medical data. The goal of the proposed scheme is to have following characteristics:

- Low latency for emergency data: In case of emergency, PDA receives emergency data from sensor immediately and delivers it to MS without waiting for remaining sensor data.
- Data Reliability: Sensors retransmit the lost or erroneous data to PDA immediately after receiving negative acknowledgement from PDA.
- Collision free data-transfer: Collisions are one of the major causes for power wastage in sensor network. The proposed protocol overcomes this problem by using TDMA approach to avoid collision.
- Low duty cycle: Sensors wake up during their allocated time period, or to interrupt PDA in case of emergency data, or to receive beacon packet in the beginning of each T_{frame}. Rest of the time, they remain in sleep mode resulting low duty cycle.

Rest of the paper is organized as follows. Section 2 summarizes the motivation factors and related works. In Section 3 System Model of the proposed scheme is presented followed by working of system model including algorithm running at sensors and PDA during communication phase. Simulation results and analysis of the proposed scheme is presented in Section 4 and finally work is concluded in Section 5.

2. Related Work

In WBAN protocols must be designed to achieve energy efficiency, maximum throughput and minimum delay. The energy efficiency may be achieved by avoiding idle listening, overhearing, collision and control packet overhead. The various MAC protocols for WBANs are mainly divided in to two categories, i.e., Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA). The Code Division Multiple Access (CDMA) protocols and Frequency Division Multiple Access (FDMA) are not suitable for WBAN as they requires high computational demands and complex hardware respectively whereas TDMA based contention-free MAC protocols such as LEACH [6] are unable to satisfy WBAN stringent requirements. A comparative study of CSMA/CA and TDMA based protocol is given in [7]. It has been observed after investigating various MAC protocols for WBAN such as Heartbeat driven MAC (H-MAC) [8] that, TDMA is more suitable for static types of network. To achieve maximum network life, maximum throughput and minimum delay, various MAC protocols are designed for WBAN. The following sections give a brief overview of different MAC protocols proposed for WBAN.

To maximize network lifetime a MAC protocol for WBAN, based on TDMA approach is presented in [9], which uses single hop communication. In this protocol idle listening and communication overhead is reduced by using TDMA strategy which is more suitable for static type of networks with limited number of sensors, generating data at the same data rate. The main objective of this protocol is to keep the communication time of each sensor as minimum as possible compared to its power down mode (sleep mode). The protocol tries to optimize the duty cycle which is the key parameter for energy consumption and reliable communication; it uses some extra slots for retransmission in case of communication error. To lower the probability of losing packets, protocol transmits redundant data and sensors are allowed to go in sleep mode for long time to achieve energy efficiency. Low channel utilization is the weakness of the protocol in case of networks having sensors with different sampling rates as sensors with lower sampling rates sends their sampled data after a fixed time interval instead of in every time frame, resulting wastage of time slots allotted to them.

For collision free communication in the network another protocol is presented in [10], which separates the control channels from data channels. This protocol consists of two periods, i.e., CAP and CFP where the CAP is used by control channel and CFP is used by data channel. The control channels are used for uplink control of emergency medical traffic and CE traffic whereas the data channels are reserved for periodic traffic and busty traffic. Randomized slotted ALOHA is used as random access mechanism on the control channels to improve the resource efficiency. The protocol demonstrates significant improvements on throughput and energy efficiency. The access latency and power consumption for the emergency traffic is also minimized.

To achieve both, i.e., to avoid idle listening and collision in the network a MAC protocol based on master-slave architecture is presented in [11] where master node coordinates with all its slaves. In this protocol clear channel assessment avoidance with time division multiplexing (CCA/TDMA) is used to avoid idle listening and collision the network. The collisions due to common time slots resulting from alarm conditions or other interference is reduced. Maximum number of slaves that can join to the cluster is 8 and only one slave node can join to the network at a time, which causes large setup time for the network.

The scheme presented in [12] is an improvement over [11] as it also reduces radio state switching times, packet collisions and control packets overhead along with idle listening and collision the network. To achieve its aim an energy efficient sleep mode is proposed to turn off node's radio during Beacon, Uplink and Downlink periods. This protocol also supports time critical event reporting by a node during its sleep mode. In this protocol bandwidth allocation is flexible, adaptive, energy efficient and offers better performance in terms of the end-to-end delay and energy saving compared to the IEEE 802.15.4 MAC. The CAP in Uplink part is based on CSMA/CA which consumes high energy due to Clear Channel Assessment (CCA) and it is difficult for the nodes to be precisely synchronized to the gateway.

A priority-based adaptive timeslot allocation (PTA) scheme is presented in [13]. The scheme classified the data on priority basis to achieve quality of service (QoS) and is able to cope with dynamically changing network size. To achieve energy efficiency, MAC level acknowledgement is disabled in the scheme. Under PTA scheme, the slot allocation request for continuous traffic is sent in Contention Access Period (CAP) and actual traffic is delivered in Contention Free Period (CFP) of next superframe. The emergency data or busty data are delivered during CAP period through CSMA/CA approach.

In none of the above mechanism precedence is given to emergency medical data except [13], but priority must be assigned to such kind of data, to avoid any causality. The objective of our work is to develop a scheme for timeslot allocation and management in WBAN to deal with emergency data.

3. Proposed Scheme

3.1. System model

Figure 2 shows the system model of the proposed scheme. The proposed model consists of SNs, RNs and PDA deployed manually at specified locations on human body to record the physiological signal and report to MS for further action.

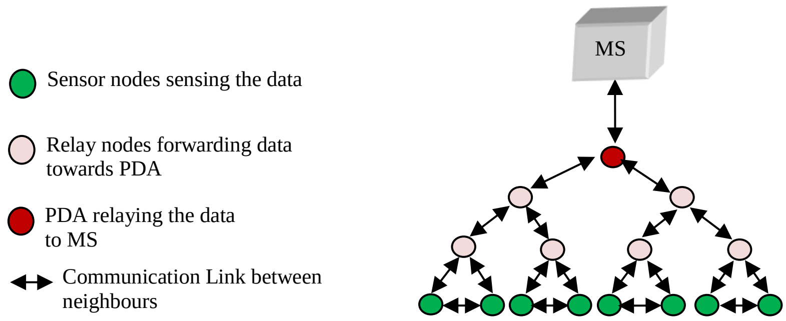

Fig. 2. System model of the proposed scheme.

Each SN in the deployment area directly communicates with one of the RNs to deliver its data to PDA through multi-hop communication. Each RN on receiving the data from SNs and RNs at the lower level, forward it immediately to higher level RN on the path from SNs to PDA. Finally PDA sends the aggregated data to the MS.

The working of the Model is divided into the following four phases:

3.2.1. Pre-deployment phase:

Doctor or medical practitioner identify number of locations on human body for the deployment of various devices, i.e., SNs, RNs and PDA, compute distance between these locations (i.e., distance between various devices to be deployed) and feed the identified locations & distance between these locations within PDA memory; set their communication range to C_{sn} , C_{rn} and C_{PDA} respectively, register various devices to PDA and deployed these devices on the identified locations. Thereafter PDA takes over the charge and find neighbourhood list for each devices depending on their communication range using Algorithm 1 and construct the network graph. From the network it finds the communication path for each device and fed it into their memory.

Algorithm 1: *Running at PDA to compute neighbourhood list*

For i = 1 to N do
  k = 1
  If i < N_{sn} // ith device is SN
    For j = 1 to N do
      If j = = i no-operation;
      Else
        $d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$
      If $d_{i,j} \leq C_{sn}$ $Nbr_i[k]$ = j; k++;
  else
    For j = 1 to N do
      If j = = i no-operation
      Else
        $d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$
        If $d_{i,j} \leq$ Crn $Nbr_i[k]$ = j; k++;

3.2.2. Slot allocation phase:

To avoid collision during data communication proposed scheme uses TDMA scheme. The PDA computes slot for each SN and allocates to them. Various packets exchange in this phase is shown in Fig. 3. The PDA initiated the operation by broadcasting Hello packet to advertise itself; in response, sensors in the deployment area send Request Packet for slot allocation to the PDA using CSMA/CA medium access method. In case of collision, sensors wait random amount of time and repeat the process. The PDA_Id field in the Request packet is the Id of the PDA in the corresponding BAN. On receiving the response, PDA compute duration of TDMA frame and TDMA slot duration for each SN using equation (1) and equation (2) respectively, construct Beacon packet containing TDMA frame and broadcast in the deployment area, thereafter network enters into the communication phase. The structure of TDMA frame is given in Fig. 4. As shown in Fig. 4, in each TDMA frame (T_{frame}), fixed time slot is allocated to each sensor (S1 to Sn) in which they send their sensed data to selected RN. Data is aggregated and processed by PDA and further delivered to MS in the remainder of T_{frame}. Guard time (Tg) is inserted between consecutive time slots to prevent transmission overlapping from different sensors due to clock drift.

Hello Packet	PDA_ Id	Hello message	
Request Packet	PDA_ Id	Sensor_ Id	Data sampling rate
Beacon Packet	PDA_ Id	TDMA Frame	

Fig. 3. Packets used in registration and slot allocation phase.

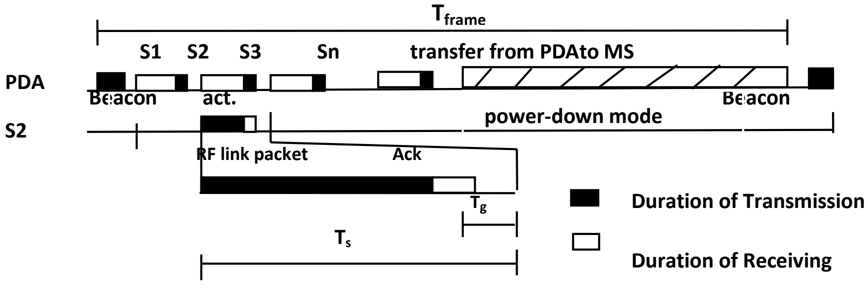

Fig. 4. Structure of TDMA frame of the proposed scheme.

At the end of each TDMA frame PDA broadcast a Network Control (NC) packet for frame synchronization in alarm conditions or while network is forming. The maximum number of TDMA cycles that can pass before the sensor needs to resynchronize using the NC packet, depends on the slot guard time and the clock accuracy of the sensor.

$$T_{frame} = \sum_{i=1}^{n} T_{s(i)} \tag{1}$$

$$T_{s(i)} = \frac{N_i}{f_{c1}} + \frac{N_{oh}}{f_{c1}} + \frac{N_{ack}}{f_{c1}} + T_g \tag{2}$$

3.2.3. Communication phase

In this phase, PDA broadcasts beacon packet at the beginning of each T_{frame} and SNs in the network uses Algorithm 2 to send their data to the PDA, in the slots allocated to them in each TDMA frame. Each SN wakes up to send its data to nearby relay on the communication path to PDA, to interrupt PDA in case of emergency and to receive Alarm message from the PDA, rest of the time it remains in the sleep mode. Alarm message is sent by PDA when it is interrupted by any SN in the network, to stop other SNs from transmitting their data until interrupt is handled and, to give immediate attention to emergency data. Each SN enters into the sleep mode after sending its data successfully till the beginning of new T_{frame} to receive beacon packet or its allocated slot in the next T_{frame} or in case of any emergency data. Various packets exchanged in this phase are shown in Fig. 5. The control packet is of two types, i.e., transfer control (TC) and network control (NC) packet and, both are used by PDA. The TC packet is used to inform the SNs about the status of the received packet, i.e., whether the received packet is intact or not and the NC packet is used to send Alarm to SNs in the network.

Algorithm 2: *Running at Sensors during communication phase*

```
while (true)
    if Received Beacon
        for i = 1 to N do // extract its own slot info. From beacon
            if Sensor_id = = device_id
                slot_begin:= GTS starting slot
                slot_end:= slot_begin + GTS length
                timer:= 0;
                break;
        while (timer != slot_begin )//wait for its own slot
            timer:=timer + 1;
        send  data
        while (timer != slot_end) // wait for acknowledgement
            timer:=timer + 1;
    if received NACK
        interrupt PDA &wait for next Beacon
    if received alarm signal
        wait for next Beacon
```

Data /Interrupt packet

PDA_ Id	Sensor_ Id	Type	Packet_ ID	Data	CRC

TC Packet

Sensor_ Id	ACK/NACK	Packet _ID	CRC

NC Packet

PDA_ Id	Alarm	CRC

Fig. 5. Packet used in communication phase.

The PDA broadcasts NC packet whenever it is interrupted by any sensor either in case of emergency or in case of NACK received by any sensor in the network. Data/Interrupt packet is used by SN, either to send data to PDA or to interrupt the PDA in case of emergency data or in case of damaged/lost data. The Type field in the packet is used by PDA to identify whether the packet is interrupt packet or it's a data packet. In the proposed scheme, the value 0 in the Type field represents Data packet and value 1 represents Interrupt packet. If the value of Type field is 1, other fields in the packet are ignored by PDA and to give immediate attention it broadcast NC packet. The Alarm field in the packet gives signal to the sensors in the network, to wait for next Beacon from PDA. The PDA reconstructs the TDMA frame using Algorithm 3 and broadcasts it in the network. After receiving data from all Sensors, the PDA uses some high data rate protocol like Bluetooth or Zigbee (so that $f_{c2} >> f_{c1}$) and transmit gathered data to MS in last slot at the end of TDMA frame. During the communication phase if sensor has some emergency data, it immediately send it by interrupting the PDA. After receiving emergency data, PDA uses wakeup radio to send it to the MS immediately without waiting for remaining sensors data, which ensures low latency for the emergency data. Retransmission allows more data reliability even in case of poor channel conditions when packet error rate is quite high. Dynamic allocation of slots ensures efficient bandwidth utilization thus making more space for data retransmission.

3.2.4. Timeslot adjustment

Sensors are allowed to interrupt the PDA in case of emergency data or in case of damaged/lost data, by sending alarm message containing its own ID and ID of PDA using CSMA/CA channel access mechanism and they can interrupt the PDA only at the beginning of any slot, so that PDA has enough time to receive the interrupt signal, reconstruct the frame and broadcast it in the deployment area before the current transmission is finished. The alarm message contains ID of the PDA so that only PDA responds to the alarm message. If more than one sensor interrupting the PDA at the same time collision occurs and in case of collision participating Sensors waits random amount of time and repeat the process. In response PDA construct new TDMA frame and broadcast it in to the deployment area for resynchronization of timeslot allocated to various sensors. On receiving the response packet from PDA, the corresponding Sensors modify their slot timing accordingly.

As shown in Fig. 6, let m^{th} sensor interrupted the PDA while i^{th} sensor is transmitting its sensed data to PDA and δ is the difference of the Id of the m^{th} sensor to the i^{th} sensor. The value of δ equals to 1 if the interrupting sensor is just next to the transmitting sensor, less than 1 if the Id of the transmitting sensor is less than the Id of the interrupting sensors and the value of δ will be greater than 1 if the Id of the transmitting sensor is greater than the Id of the interrupting sensors. In normal scenario the value of slot beginning ($S_k.beg$) of any sensors k is modified by equation (3) and in case of emergency $S_k.beg$ will be modified using Algorithm 3.

$$S_k.beg = S_k.beg + \sum_{i=1}^{n} d_i \quad (3)$$

where d_i is the duration of i^{th} slot.

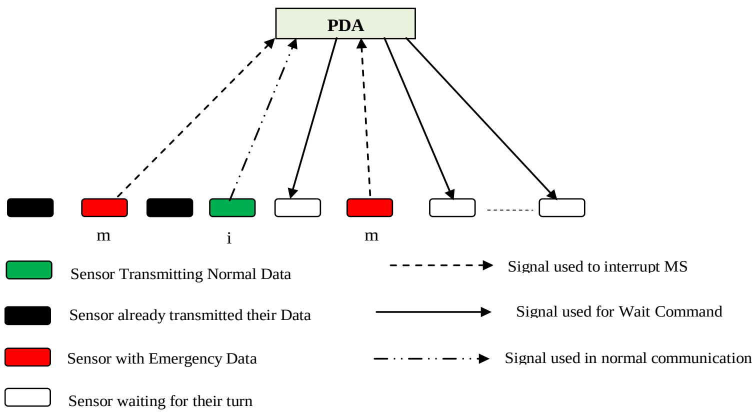

Fig. 6. Time slot adjustment in case of emergency data.

Channel access probability:

In case of normal medical data proposed scheme uses TDMA approach for channel allocation to various devices, so channel access probability is 1, whereas in case of emergency data, it uses CSMA/CA channel access mechanism to interrupt the PDA for resynchronization of time slots allocated to various devices to give immediate attention to the emergency data.

Let P_s is the probability of successful access the channel by any SN in back-off number N_{BE} is given by equation (4).

$$p_s = \sum_{k=0}^{N_{BE}} p_c (1 - p_c)^{\ k-1} \tag{4}$$

where p_c is the probability that the channel is clear at the end of the back-off period. In the proposed scheme only SNs with emergency medical data participate in channel access mechanism. Let Ne is the number of SNs with emergency medical data, the probability p_c that the channel is clear during CCA is given by Eq. (5).

$$p = (1 + q)^{N_e - 1} \tag{5}$$

where, q is the probability that a SN transmits emergency data during CCA and can be calculate by Eq. (6).

$$q = \frac{(T_{frame} - T_{ms})}{N_e} T_s \tag{6}$$

Algorithm 3: *Running at PDA for slot adjustment*

1. if δ = 1 // interrupting sensor is just next to the transmitting sensor
2. no change in slot beginning of any sensor
3. else if δ > 1
4. for k = 1 to n do
5. If m <= k <= i
6. no change in slot beginning of any sensor
7. else
8. Sk.beg = Sk.beg + Sm.duration
9. else
10. for k=i+1 to m-1
11. Sk.beg = Sk.beg + Sm.duration

Energy efficiency:

In the superframe structure of the proposed scheme time slots each allocated to each SN and they remains active only in their own timeslot to transmit the sensed data and to receive the acknowledge. They also become active at the beginning of superframe to receive the beacon for resynchronization purpose due to drift in clock frequency and to interrupt the PDA in case of emergency data. To save their battery energy they remains in the power-down mode rest of the time to avoid idle listening hence prolong the network life. In beacon enabled mode of communication, devices with sporadic data communication introduces a significant part of power consumption in beacon listening process.

4. Simulation and Analysis

A Matlab simulation platform is used to simulate the model presented in Section 3. The average transmission time, channel access probability, average energy consumption and throughput are the metrics used for performance analysis viewpoint. In the simulation 15 nodes generates emergency data in each simulation round. Table 1 shows the simulation parameters used in simulation.

Table 1. Simulation parameters.

Parameter	Value
P_{Tx}	36.5 mW
P_{Rx}	41.4 mW
P_{Idle}	712 μW
Channel Rate	250 kbps
Symbol times	16 μs
Superframe duration	122.88 ms
aUnitBackoffPeriod	20 symbols
macBeaconOrder (BO)	3
macSuperframeOrder (SO)	0
macMaxCSMABackoffs	5
macMinBE	3
macMaxBE	5
Tbeacon	0.36 ms

Figure 7 shows the effect of number of sensors with emergency data, on the number of packets delivered. It is observed from Fig. 7 that

- in the proposed scheme the number of packets delivered are around 95% when the number of sensors with emergency data are 5% and it decreases to 83% when the number of sensors with emergency data are increases to 10%.
- the number of sensors in BAN does not affect the performance of the proposed scheme if the number of sensors with emergency data remains constant, whereas in IEEE 802.15.4 standard as the number of sensors in the BAN increases the packets delivered is keep on decreasing.
- the performance of the proposed scheme is always better than the IEEE 802.15.4 standard.

Figure 8 shows the effect of number of sensors with emergency data on channel access probability. From Fig. 8 it is clear that in both cases (i. e, sensor with emergency data and sensor with normal data) the channel access probability in the proposed scheme is higher than the IEEE 802.15.4 standard as the proposed scheme handles emergency data on priority basis by constructing new Tframe in which beginning slots are assigned to the interruting sensors. We can also observe that in both scheme, the channel access probability decreases as the number of sensors with emergency data increases, due to the multiple number of sensors competing the channel simultaneously which may lead to collisions.

Figure 9 shows the effect of number of sensors with emergency data on avarage transmission time taken by nodes to transmit a packet to PDA. From Fig. 9 it is clear that as the number of nodes with emergency data increases, the average transmission time also increases in both scheme (i.e., in the IEEE 802.15.4 standard and in the proposed scheme) but in the proposed scheme it is very less as compared to the IEEE 802.15.4 standard. This is due to the channel access mechenism (i.e., TDMA) used and priority is given to the emergency data as compared to the normal data.

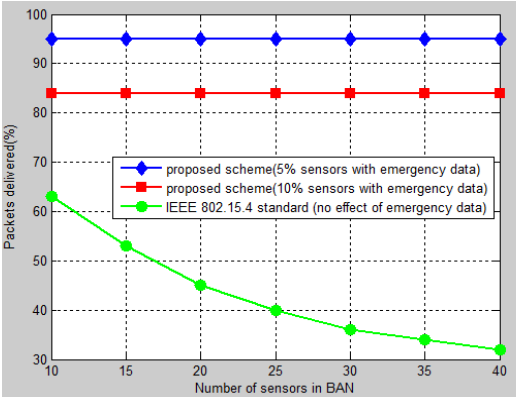

Fig. 7. Number of sensor vs. packet delivered.

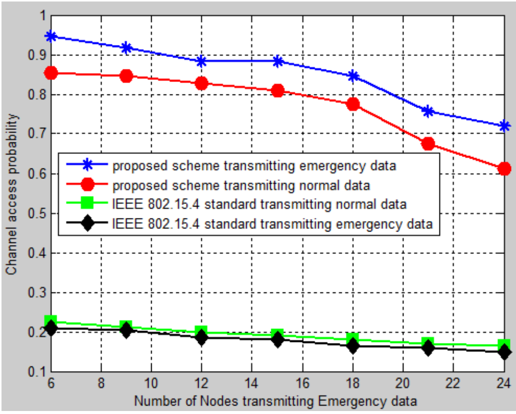

Fig. 8. Number of nodes vs. channel access probability.

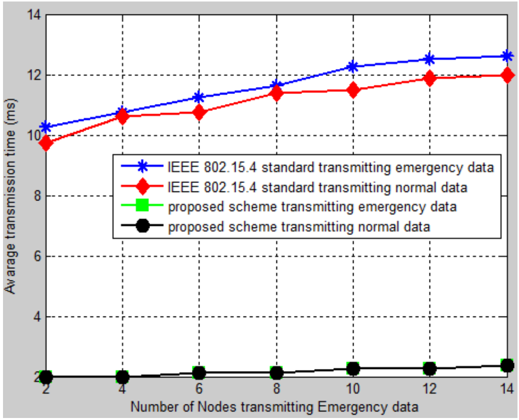

Fig. 9. Number of nodes vs. average transmission time.

Figure 10 shows the effect of varying the total number of nodes in the network on the average energy consumption per bit. From Fig. 10, it can be observed that in the proposed scheme the average energy consumption per bit is very low as compared to the IEEE 802.15.4 standard on the equal number of total nodes. This is due to usage of TDMA approach in the proposed scheme in which, each node transmits its data during its allocated time slot only resulting in no collisions ,which leads to less energy consumption by nodes. But the average energy consumption per bit increases as the total number of nodes increases in both the schemes ; as due to simultaneous transmission by some of the nodes in the network may leads to collision.

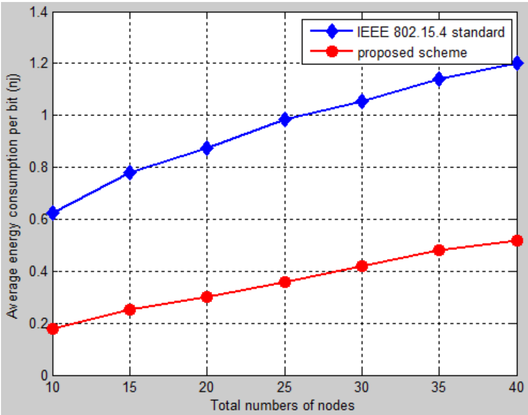

Fig. 10. Total number of nodes vs. average energy consumption.

5. Conclusions

WBAN brings number of requirements and specifications that must be considered during the development of MAC protocol in WBAN. This paper proposed a MAC protocol that has been specifically designed and configured for being used in WBAN. The aim of the proposed MAC protocol is to support various QoS requirements of WBAN. In this medical data is classified into two categories: normal medical data and emergency medical data. The sensors are allowed to interrupt the PDA in case of emergency so that immediate action may be taken to avoid any causality, hence provides support to life threatening scenario. The proposed scheme is simulated and the results are compared with IEEE 802.15.4 MAC protocol on various parameters. Simulation result shows that the proposed scheme is better in terms of number of packets delivered, channel access probability, average energy consumption and transmission delay.

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