Wireless Netw (2017) 23:1249–1266
DOI 10.1007/s11276-016-1199-x

Delay and energy consumption analysis of priority guaranteed MAC protocol for wireless body area networks

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Published online: 11 February 2016

Abstract Wireless body area networks are captivating growing interest because of their suitability for wide range of applications. However, network lifetime is one of the most prominent barriers in deploying these networks for most applications. Moreover, most of these applications have stringent QoS requirements such as delay and throughput. In this paper, the modified superframe structure of IEEE 802.15.4 based MAC protocol is proposed which addresses the aforementioned problems and improves the energy consumption efficiency. Moreover, priority guaranteed CSMA/CA mechanism is used where different priorities are assigned to body nodes by adjusting the data type and size. In order to save energy, a wake-up radio based mechanism to control sleep and active modes of body sensors are used. Furthermore, a discrete time finite state Markov model to find the node states is used. Analytical expressions are derived to model and analyze the behavior of average energy consumption, throughput, packet drop probability, and average delay during normal and emergency data. Extensive simulations are conducted for analysis and validation of the proposed mechanism. Results show that the average energy consumption and delay are relatively higher during emergency data transmission with acknowledgment mode due to data collision and retransmission.

Keywords Wireless body area networks · Slotted CSMA/CA protocol · Inter-arrival time · Wakeup radio mechanism

1 Introduction

Recent years have witnessed tremendous research interest in wireless body area networks (WBANs) because of their suitability for wide range of applications such as medical (e.g., continuous health monitoring) and non-medical (social networking, information exchange, entertainment). These networks employ low-cost, tiny sensing devices (i.e., body nodes) that sense vital physiological body parameters (e.g., temperature, brain activity, heart rate) and transmit it to end stations. Continuous monitoring of patients suffering from different diseases such as electrocardiogram (ECG), blood pressure, and obesity require a special body monitoring system. In this regard, development of small, and wearable sensors that can be alternative to hospitalization has attracted researchers [1]. The main reason for the attraction of these sensor nodes is its low duty cycle, data rate, and energy consumption. Depending on the type of application, body nodes (BNs) are either affixed on-body or implanted inside the body. Data rates and power consumptions of implanted BNs are very low as compared to that of on-body nodes (games and mp3). A list of devices and their energy consumption along with data rates are given in Table 1. Figure 1 shows the data transmission phases in WBANs.

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Table 1 Body nodes and parameters used in WBAN [12]

Sensor type	Parameters	Energy consumption	Data rate
On-body sensors	EEG	Low	Low
	ECG	Low	Low
	Heart rate	Low	Low
	Blood pressure	Low	Low
	MP3 player	High	Medium
	Games	High	High
Implemented sensors	Glucose	Low	Low
	Brain liquid pressure	Low	Low
	Drug delivery capsules	Low	Low
	Deep brain simulator	Low	Low

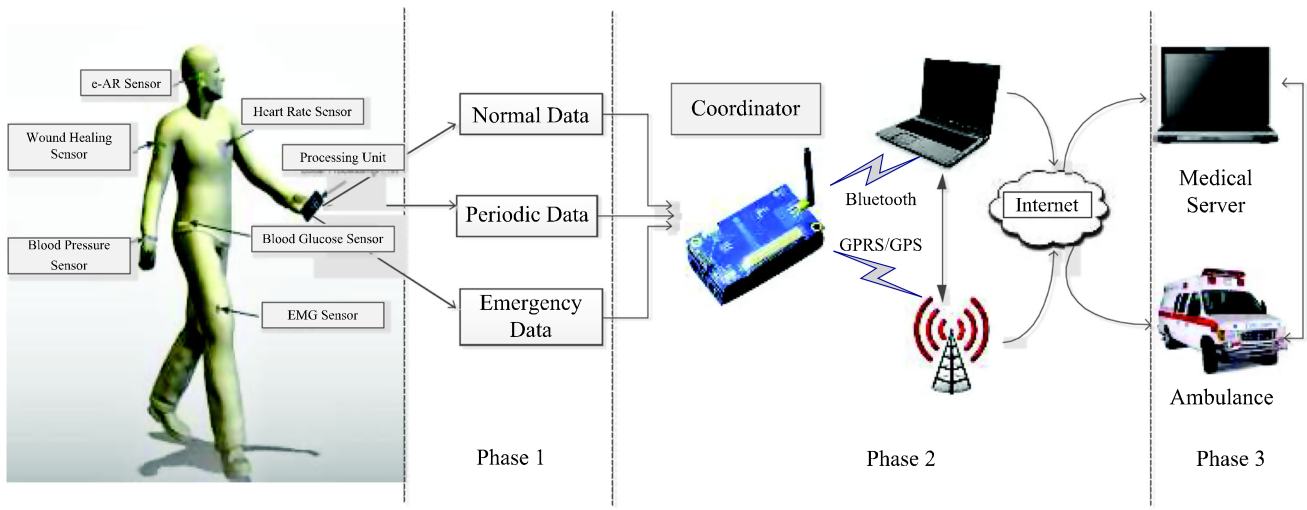

Fig. 1 Data transmission phases in WBANs

Different network topologies are used in WBAN. However, star topology having a transmission range of 3–6 m with different data rates is more appropriate [2, 3]. Traditional medium access control (MAC) protocols consider bandwidth utilization, throughput enhancement, energy consumption and delay minimization. However, emergency handling mechanisms are still need to be explored at MAC layer. The main sources of energy consumption in MAC protocols are; idle listening, packet retransmission, clear channel assessment (CCA), packet inter-arrival time and collision. Different schemes using MAC layer play significant role to overcome these problems which ultimately prolong network lifetime. IEEE standard for MAC layer is widely used due to its low duty cycle and data rate. The Superframe structure of IEEE 802.15.4 standard has three periods: contention access period (CAP), contention free period (CFP) and an inactive period (IP) [4]. In CAP, nodes contend with equal probability to get access to the channel for data transmission. Each node has equal probability to access the channel. However, CAP mechanism is inefficient for emergency data delivery due to more control overhead and energy consumption during packet retransmission and CCA. Moreover, this mode does not guarantee data delivery due to packets collision. In CFP period, the coordinator allocates time division multiple access (TDMA) based guaranteed time slots to nodes having periodic data. Each node transmits its data during its own time slot. However, this mode is not suitable for emergency data. In addition, node consumes more energy during synchronization if the sensed data require more transmission time in comparison to the fixed allocated TDMA based interval.

Most of the existing WBAN MAC protocols do not provide energy efficient data transmissions due to packet drop and varying delays. Development of these protocols is a challenging task because they must fulfill the requirements of right decisions at the right moment of time by different algorithms irrespective of unexpected traffic load, congestion, and network failure. Delays and packet loss are very influencing performance metrics which ultimately decrease the networks lifetime and stability. Depending on these parameters, development of an energy efficient system based on BNs depends on how MAC protocols can be optimized to meet these constraints under limited resources.

Due to low data rates and energy consumption, IEEE 802.15.4 standard for MAC layer has gained significant attraction in WBAN applications. Many applications require that packets must be delivered to the destination with high probability. On the other hand, some applications require timely delivery of data packets. While reliable data delivery with minimum delay needs a significant energy which ultimately reduces the network lifetime. So, network lifetime and delay are key parameters that need to be properly addressed. Recent studies [5, 6] demonstrated that improper configuration of MAC parameters in IEEE 802.15.4 can leads to poor performance in terms of energy efficiency and delay. In order to enhance the performance of MAC protocols, there needs to be a significant improvement in the existing superframe structure. So, the prime requirements while designing WBAN are: low energy consumption, minimum transmission delay, and maximum throughput. For increased throughput, packet drop due to buffer overflow and collision must be reduced. One of the main reasons for packet drop is more packet arrival rate as compared to service time. Due to the limited buffering capacity of BNs, packets will be dropped that will need to be retransmitted. This phenomenon ultimately reduces the network lifetime.

In this paper, we propose a modified superframe structure of IEEE 802.15.4 standard for emergency data (ED) handling. IP of traditional superframe structure is modified in which BNs transmit ED. If more nodes have ED then Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism is used to transmit data to the coordinator. Low power wake-up radio chip is attached with BN which is used to switch on or off the main radio. To model node states, discrete time finite state Markov model is used. This work classifies data into three categories; normal data (ND), ED, and periodic data (PD). BNs transmit ND using CSMA/CA mechanism in CAP. During PD, the coordinator assigns TDMA based time slots to the nodes expected to share a common time. Nodes only transmit data during allocated TDMA time slots. While, during emergency condition, the coordinator broadcasts extra beacons to handle ED. IP is efficiently utilized for emergency data transmission. In case when nodes do not have any data to transmit, they switch to sleep mode to save energy. Nodes can also switch into sleep, idle, active, transmit, and receive modes based on data requests, respectively. We propose a Markov model having a finite buffering capacity to store incoming requests. According to this model, probability of going from one state to another state is the sum of all transition probabilities and their frequencies.

The rest of the paper is organized as follows. Sections 2 and 3 include the related work and motivation, respectively. Detailed description of our protocol is given in Sect. 4. Section 5 provides Markov model for different transition states of BN. Expressions for average energy consumption and delay of the node during ND and ED is given in Sect. 6. Section 7 presents the simulation results and detailed description about the average delay, throughput, packet drop probability, and impact of the total number of nodes. Conclusion and future work is given at the end of this paper.

2 Related work

Extensive research has been conducted in the development of energy efficient and reliable MAC protocols for WBANs. Different researchers use IEEE 802.15.4 and IEEE 802.15.1 standards for Personal Area Networks (PANs) [7]. IEEE 802.15.4 standard is especially designed and used for low rate PANs. In the last few years, IEEE 802.15.4 standard has also been widely adopted for WBANs. Another main reason for its use is the superframe structure to increase the quality of service (QoS) in WBANs. One of the major drawbacks of IEEE 802.15.4 standard is high energy consumption of nodes due to the periodic listening of beacon messages. A comprehensive survey to look into deep the existing technological advancement in device manufacturing as well as paradigm shift towards reactive and proactive management of patient monitoring system is given [8–10]. Moreover, the authors conducted a comprehensive survey on different WBAN technologies and mathematical expressions are formulated in order to analyze the impact of channel access probability. CSMA/CA mode of IEEE 802.15.4 (slotted and unslotted) is inefficient due to high packet collisions and large energy consumption during channel sensing and CCA. To overcome this problem, TDMA based protocols are developed. However, TDMA mechanism is not suitable for ED transmission due to fixed time slot allocation in superframe. To overcome these problems, authors in [11], proposed an efficient RFID-enabled MAC protocol for WBANs. They use separate control channel along with main data channel to reduce the energy consumption. In this protocol, nodes transmit ND according to pre-scheduled mechanism, and emergency events are handled by using RFID methods. When a node has ED, it transmits control signal via RFID control channel to the coordinator. The coordinator then transmits emergency beacons to that node for channel contention. If the channel is found busy, the node waits for a unit backoff time and will contend again after this time interval. The node switches to sleep mode when it has no data to send.

In [12], authors investigated and handled normal, emergency, and on demand traffic by using traffic information of nodes. This traffic information is saved in a traffic wake up table which is maintained by the coordinator as per data pattern. In order to save energy, duty cycles of nodes are adjusted according to the data patterns. A wakeup radio is also used to send control signals to the coordinator during emergency situations. Nodes transmit normal routine data to the coordinator based on prescheduled mechanism. If more than one node has ED, then the channel is allocated to the highest priority node. Unlike this work, we assign priorities based on data type and packet size. In addition, IP of superframe structure is employed for ED transmission. So, ND and PD transmissions are not affected during ED handling situations. To counter the problems of idle listening, control overhead and collision, the authors in [13, 14] analyzed the wakeup radio mechanism with separate control channels. The wakeup radio chip is cheap and can easily be attached with normal sensor nodes. Nodes switch into the sleep mode when they have no data to send. Otherwise, the wakeup radio transmits control signals to the main circuit of the BN for data transmission. In [15], authors provide energy consumption analysis of slotted CSMA/CA algorithm of IEEE 802.15.4 standard. Nodes consume more energy while using CSMA/CA mechanism due to backoff periods during busy channel, packet retransmissions, and CCAs. However, this mechanism increases the reliability in terms of data delivery. Message retransmissions and CCA procedure consume more energy and introduce extra delay which is not feasible for WBANs. Moreover, authors do not provide any mechanism for data transmission in emergency situations. Performance comparison of different MAC protocols and IEEE 802.15.4 standard for WBANs is presented in [16, 17]. In order to evaluate the performance in terms of energy efficiency and delay, analytical expressions of different performance parameters: delay, throughput, collision, low power listening and energy minimization are derived. Authors also provide path loss analysis for in-body, on-body and off-body communications. Authors provide a hybrid MAC protocol in which different priorities are used to accommodate time critical data in WBANs [18]. Priorities are adjusted according to contention window time period during CAP. In order to handle large amount of data, CFP is used. Energy efficient and reliable MAC protocols provide control over channel access along with a reliable link level communication. Superframe structure is also modified during network operation based on channel status and traffic nature [19]. Markov chain based analytical model of IEEE 802.15.4 standard including acknowledgment and retry limits is proposed. To minimize the energy consumption and delay for reliable data delivery, a novel MAC algorithm is used. To validate the results of the proposed protocol, a real time test bed implementation with the Contiki operating system and TelosB node was made. The proposed MAC algorithm is capable enough to accommodate different sensors and topologies at run time without degrading its performance. Authors also analyzed the effect of improper channel and carrier sensing failure on system performance which greatly depends on the limited range of the control parameters and data payload [20]. In order to provide QoS to several applications, advantages of random access schemes with contention period and TDMA of IEEE 802.15.4 standard can be combined. For this purpose, clear understanding of delay, throughput, and energy are major requirements to optimize the controlled parameters.

In [21], authors investigated the analytical performance of a hybrid MAC protocol which is not accurately analyzed yet. One of the main reasons for this analysis is the probabilistic as well as the random behavior of MAC protocols. Performance in terms of average packet delay, queuing delay, and throughput is evaluated mathematically and using simulation. One of the recent advancements in remote health monitoring technology is the integration of cloud computing with traditional health monitoring solutions in order to provide facilitation to all kinds of patients. The integration of the cloud computing technology is inevitable due to the limitations such as handling and processing of large amount of real time data, mobility of outdoor patients, and network coverage. So, the cloud computing technology is helpful in providing the solutions to overcome these types of problems associated with WBANs. In [22, 23], authors propose cloud based health monitoring system for outdoor patients. Authors divide cloud into two parts, one for patients and doctors and other for the outer world. Results show the performance of the cloud based health monitoring system in terms of lower network congestion, reliable data delivery and mobility of the patients. Cloud based techniques are efficient in terms of lower congestions and interference however, they can create extra delay during critical data transmissions. So, we use the superframe structure based scheme especially for ED. This paper is an extended version of the published work in [24] in which energy consumption during ED, ND, and PD is analyzed. Moreover, the effect of beacon interarrival time on the energy consumption is also shown. In the proposed work, following contributions are made; (1) average delay analysis during ND and ED, (2) network lifetime and throughput analysis, (3) packet drop, (4) transition states modeling through Markov chain.

3 Motivation

One of the key requirements in WBANs is to prolong the network lifetime which is significantly affected by sleep and wake-up modes of sensor nodes. Traditional approaches such as duty cycling or channel polling are inefficient due to packet collisions, idle mode listening and control overhead. Due to the limited energy of BNs, efficient utilization of resources and error free operation is needed for WBANs. There are different issues listed below that must be carefully addressed. However, energy efficiency and delay are the main challenges during the design of WBANs. For more reliability, MAC protocols should meet the requirements listed below [13, 18].

- Minimization of energy consumption
- Network lifetime prolongation
- Delay minimization during retransmission and CCA
- Increasing the throughput
- Reduction of packets drop

In this work, we aim to prolong the network lifetime by reducing the average energy consumption and delay of BNs. Thus, we propose an IEEE 802.15.4 based MAC protocol which uses on-demand wakeup radio to avoid idle mode listening and packet collisions. Moreover, the control overhead is also reduced by adjusting sleep and backoff time periods of BN. To estimate and model different transition states, a generalized Markov model is used. Detailed description of our proposed protocol is given in upcoming section.

3.1 Wake-up radio

A wake-up radio is a special kind of circuit that can be attached with main circuit of a BN. The main purpose of this device is to trigger the main radio off when there is no data to transmit. A wake-up radio can detect control signals from an external device and generate interrupt to turn off or on the main radio. Different researchers explored and used the concept of wake-up radio in sensor networks. The energy consumption of different wake-up radios is given in the Table 2. The cost of adding an extra wake-up radio with main BN is very low. Moreover, a wake-up radio does not use the energy of the main BN, thus avoiding an extra energy cost. A normal wake-up radio has 1–15 ft range. Thus, it is suitable for short range applications such as WBANs. There are different advantages of using a wake-up radio device as given below;

Table 2 Power consumption of different wake-up radio chips

Wake-up radio model	Power used (μW)
On-CMOS [25]	75
Ansari [26]	12.53
Basic [27]	84
Van doom [28]	171

- A wake-up radio hardware is simple and easy to implement
- It does not interrupt during ND transmission and does not wake-up the BN without external request
- It extracts and uses the energy from radio signals. So, external energy supply is not required

4 Proposed MAC protocol

In this section, a priority guaranteed MAC protocol with modified superframe structure of IEEE 802.15.4 standard is proposed. Dynamic superframe structure depends on the variation of data loads. Based on the energy and delay constrains of data payloads, we made a data classifications. These classifications are further used to calculate backoff time periods and data priorities. These priorities are used by the coordinator during node's contention process. Backoff time periods are used by the BNs before transmitting the data packets.

4.1 Data types

We assume three types of data; ND, PD, and ED. BNs transmit ND using the slotted CSMA/CA mechanism [29]. If the medium is found idle, the BNs perform CCA for more reliability. However, if the medium is found busy, the node waits for a random amount of time according to IEEE 802.15.4 standard. Soon after, the node senses the medium again and transmits the data after a successful channel access process. The PD corresponds to data that a medical specialist needs after some regular intervals of time. This type of data does not have any delay constraint and nodes transmit it during CFP of superframe. The coordinator assigns TDMA based time slots to the nodes having PD. Both CSMA/CA and TDMA mechanisms have some drawbacks. They do not provide ED handling mechanism. To overcome the problem of ED, we assign different priorities according to data payload and nature of data.

4.2 Priority classification

In this section, BNs are assumed to have assigned their data types and payloads with different priorities. We differentiate these priorities on the bases of ED, ND, and PD that are defined in Sect. 4(a). Based on these priorities, the nodes and coordinator take decisions during resource allocation and transmission. Priorities are calculated by using the following formula;

$$Priority = \frac{D_{Type}}{\lambda_t \times P_{size}}, \quad (1)$$

where λ_t is the traffic generation rate and P_{size} is the length of the packet generated by the BN. ED packets with lower traffic generation rate and smaller packet size have the highest priority and need to be transmitted timely with a high reliability. Data packets with medium and normal priorities must also be delivered timely, otherwise, the node buffer will overflow and data packets would be dropped.

4.3 Superframe structure

Modified superframe structure of IEEE 802.15.4 standard for WBAN consists of four periods: CAP, CFP, IP and Extended Period (EP) in which ED is transmitted. Superframe structure starts with a beacon message which contains all the information about time slots, coordinator, BNs, and start and end of this period. In CAP, all nodes contend to access the channel for ND transmission. Nodes requiring fixed time slots and having PD, transmit their data during CFP. During emergency, BN generates a request for coordinator to immediately transmit data without any delay. The coordinator then transmits an emergency beacon message to handle ED in EP. During this situation, ND and ED transmissions will not be interrupted. If a node does not have any data, it switches to sleep or idle listening mode accordingly. Modified superframe structure is shown in Fig. 2.

4.4 Backoff periods calculation

Priority based random backoff process is performed in CAP. Each node performs a random backoff process before transmission of data packets. The value of the backoff period can be calculated using $[0 - 2^{D_{type}} + 2]$, where D_{type} is the data type. Thus, the ED has less delay during transmission as compared to the ND. During transmission, if the channel is found busy, nodes perform random backoff process in CAP. The random backoff period is based on the amount and priority of data as mentioned in Eq. 1. A smaller backoff period is assigned to a node with less amount of data and high priority. Nodes having large amount of data with low priority wait for more time to avoid collisions. However, this adds extra delay and increases the energy consumption. Figures 3 and 4 show the channel access mechanism for normal and ED, respectively. During no data, the node can switch into a sleep or an idle listening mode.

4.5 Wakeup radio implementation

In some protocols, energy efficiency can be achieved at the cost of extra delay. Wakeup radio is another possible and widely used mechanism in WSNs. Nowadays, different low power radio based tags are available in the market. These tags are energy efficient and can be used to switch on the main radio channel whenever required. It is mentioned in [30, 31], that wakeup radio consumes only 50 µW which makes this implementation useful for WBAN. Energy consumption of a node with wakeup radio is much lower than traditional duty cycling schemes. However, it also depends on the nature of data. In our proposed work, both coordinator and sensor nodes are equipped with wakeup radios to reduce the energy consumption during idle listening. BNs in the sleep mode to save energy and wakeup radio monitors the environment to hear the coordinator request.

4.6 Analyzing average delay

BNs can create delay during retransmissions of data packets while channel is found busy. To overcome the extra delay problem, different mechanisms can be used including packet inter-arrival time adjustment, fixed time

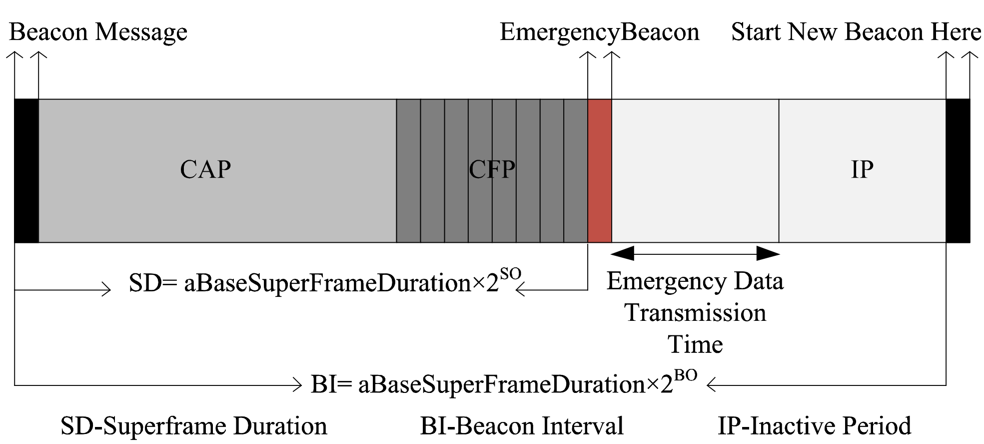

Fig. 2 Modified superframe structure

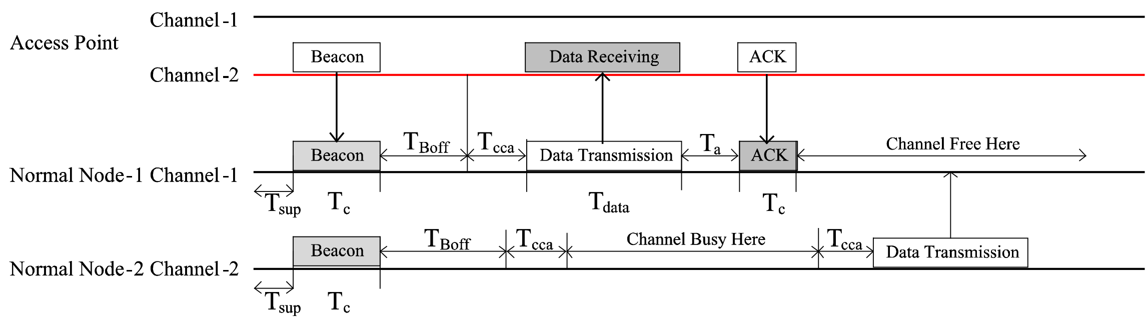

Fig. 3 Channel access mechanism during ND

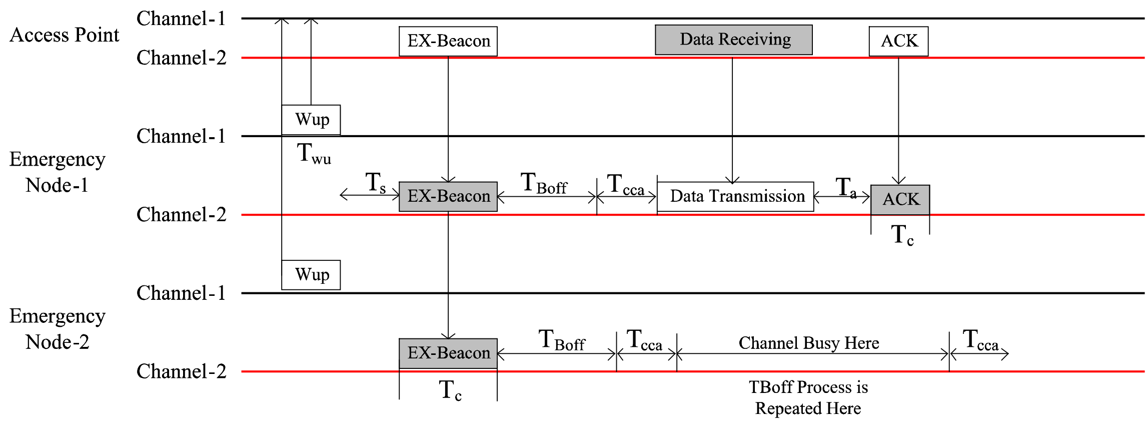

Fig. 4 Channel access mechanism during ED

slots allocation, priority based data transmissions, etc. Fixed time slot allocation technique cannot handle the ED which is the basic need in WBANs. This is due to the fact that, nodes can create ED at any time during the network operation time while, in fixed time slot allocation, nodes transmit data during their allocated time slot. MAC protocols that use only CAP and CFP are also unable to handle ED. So, in our proposed protocol modified superframe structure is used which efficiently handle the ED on the basis of data priority class. For improved quality of service and reliable data delivery, packet interarrival time plays a significant role. So, with proper packet inter-arrival time adjustment, packets drop due to collision can be avoided which ultimately increases the average throughput.

5 Discrete time finite state markov model

In order to determine different states of BNs, we use a well-known discrete time finite state Markov queuing model [32]. According to this model;

- Requests (control, data) arrive at each node independently.
- Nodes have a capability to buffer a finite number of packets.
- Due to limited queue capacity, packets can be dropped. So, retransmission mechanism is supported.
- There is only one packet reception and transmission capability of each node at the same time. A node does not have transmission as well as reception probability simultaneously.
- All nodes have different probabilities to transmit data packets according to their priority class.

In the proposed Markov model, there are finite number of states which represent the different status of a node, i.e., during idle or transmitting modes, different queue lengths. Each node can change its status at every instance of time corresponding to the transitions between all possible states. Figure 5 shows the proposed Markov model with transition probabilities for all possible states. In case when the buffer of a node is not empty, the node attempts to access the medium for data transmission. After a successful transmission, a data packet is removed from the buffer. While, in case of a collision, nodes will retransmit data packets up to a maximum retries limit. After this limit, packets are dropped.

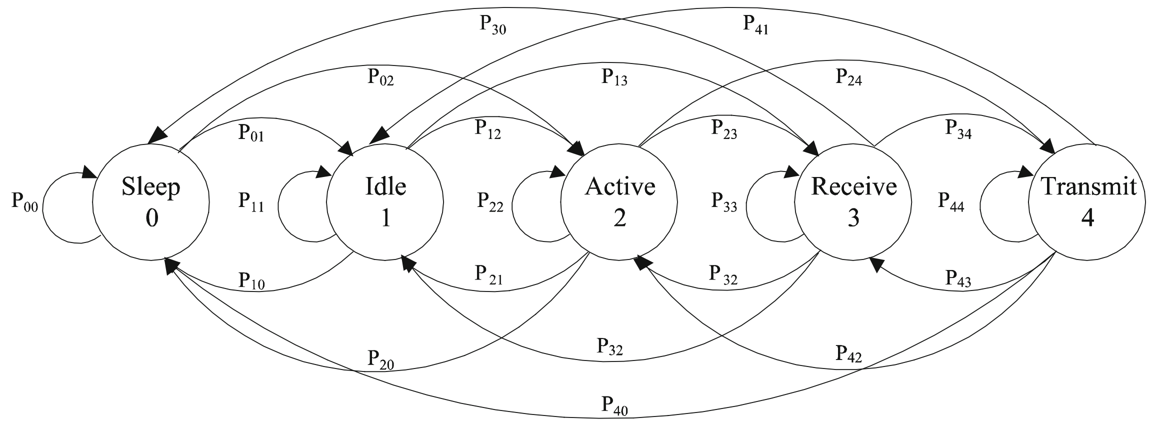

Fig. 5 State transition diagram of proposed MAC protocol

5.1 Markov parameter assumption

In this model, we are interested in finding the following;

- Model all possible states
- Determine the possible transitions
- Identify all possible transition probabilities

According to the Markov property, future states can be identified based on the current state. Past states do not matter in future predictions as well as how one state reaches the current state. However, past states can be helpful in finding the future states more accurately. Generally, in Markov processes past states do not get involved. Discrete time is used which is denoted by n, where, n = 0, 1, 2, …, ∞. Request arrivals are modeled by Bernoulli p distribution for a random variable. Geometrical distributed service time is denoted by q. X_n is the state of the system after n number of transitions. Here, n can be used as a transition or time alternatively. X_o is a state from where systems start which could be a random or a given variable. Now, the probability of transmitting from one state to another state is given as;

$$p_{ij} = P_r\left(X_{(n+1)} = j | X_n = i\right), \quad \forall\, n = 0, 1, 2\ldots \tag{2}$$

$$p_{ij} = P_r(X_{(n+1)} = j | X_n = i, X_{(n-1)} = i-1, X_{(n-2)} = i-2\ldots X_0), \forall n \geq 0, i, j, i-1\ldots \in S. \tag{3}$$

Equation 3 shows the probability of landing at state j after n + 1 number of transitions for all past transitions. S is set of all sample spaces.

All possible transitions are calculated as:

$$P_{r,00} = p(1-p). \tag{4}$$

where, p denotes any arrival request (control or data) and q is the service time which is a geometrically distributed random variable.

$$P_{r,21} = q(1-p) \tag{5}$$

$$P_{r,12} = p(1-q). \tag{6}$$

$$P_{r,44} = pq + (1-p)(1-q). \tag{7}$$

In Eq. 5, one service is completed and no request arrival. Equation 7 shows the probability of remaining at the same state in which one arrival and one service completion or no arrival and no service completion occur at the same time. Initially, the system is at state i and the transition probability at time n = 0 is given below;

$$r_{ij,n} = P_r(X_n = j | X_0 = i). \tag{8}$$

where, X_n is the final state after n number of transitions while the initial state is X_{no}. There might be different transition states between source i and destination j. In order to find the destination state j, we must find the state just before the destination state. It is not important here that how many transitions involved to reach the $n-1$th state. Here, X_o is the initial state from where the system starts, not the $n-1$th state.

$$r_{ij,0} = \begin{Bmatrix} 1; & if\ i = j \\ 0, & otherwise \end{Bmatrix} \tag{9}$$

The one step transition probability is given by;

$$r_{ij,1} = P_{ij}. \tag{10}$$

According to Fig. 6, the transition probability of returning to its own state is given as;

$$r_{ii} = 1. \tag{11}$$

Using the law of total probability [33], n − step transition probability can be calculated.

$$r_{ij,n} = \sum_{a=1}^{m} r_{ia}(n-1)P_{aj},\ \forall\, i,j \in S. \tag{12}$$

Equation 12 is known as the recursion equation which states that once state n − 1 reached, one will ultimately

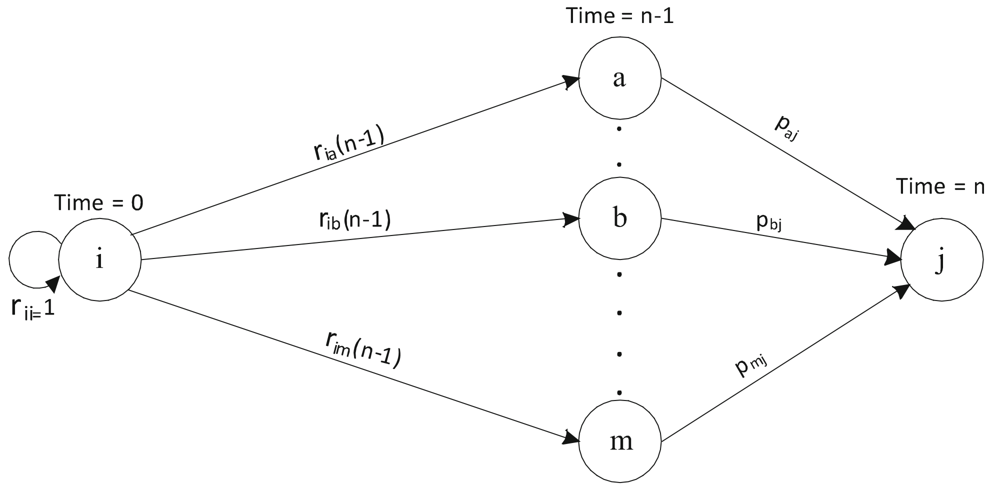

Fig. 6 State transitions at different time intervals

calculate the final state. This formula gives the initial state X_o = i and after r_{ij}(n) number of transitions, one could find the final state which is X_n = j. The random initial state is defined as;

$$P(X_n = j) = \sum_{i=1}^{m} P(X_0 = i) r_{ij}(n). \tag{13}$$

The total number of transition states after the first state is given as:

$$r_{ij,n} = \sum_{i=1}^{m} P_{i1} r_{1j}(n-1), \ \forall \ i,j \in S. \tag{14}$$

5.2 Convergence probability

Now, we will calculate the convergence probability of Markov chain [32]. What is the probability that Markov chain with some initial state $X_{ij,n}$ after n number of transitions converge to some steady state π_j value. Where, steady state value does not depend on the initial state of the process. In the proposed Markov model, we have only one recurrent state class in which each state can returns to its own state from any other state. However, in the case of more than one recurrent state classes, initial state really does matter. One key point to calculate the steady state probability is that recurrent state class must not be periodic. Otherwise, the state will oscillate with regular intervals of time.

The state transition probability of n number of transitions is.

$$r_{ij,n} = \sum_{a=1}^{m} r_{ia}(n-1) P_{aj}, \ \forall \ n = 0, 1, 2.\ldots \tag{15}$$

To calculate the steady state probability, take the $lim_{n\to\infty}$ to both sides of the Eq. 15.

$$\lim_{n\to\infty} r_{ij,n} = \lim_{n\to\infty} \sum_{a=1}^{m} r_{ia}(n-1) P_{aj}, \ \forall \ n = 0, 1, 2.\ldots \tag{16}$$

$$\pi_j = \sum_{a=0}^{n} \pi_a P_{aj}, \forall j. \tag{17}$$

where, π describes the transition frequency from all possible states to state j. It is a general equation for steady state probability. You can calculate the steady state probability of any state by changing the value of j. According to Fig. 5, $\pi_1 P_{40}$, $\pi_2 P_{20}$, $\pi_3 P_{10}$, $\pi_4 P_{30}$ and so on are different transition frequencies to state 0. The total frequency of transition to the state 0 is.

$$\pi_0 = \sum_{m=0}^{n} \pi_m P_{m0}, \ \forall \ n = 0, 1, 2.\ldots \tag{18}$$

6 Energy and delay analysis of the proposed protocol

This section provides the average energy consumption and delay analysis of the proposed protocol. After the network initialization, the coordinator broadcasts a beacon message containing all the information of superframe duration, BNs, and Guaranteed Time Slots (GTS). During CAP, nodes contend to access the medium using CSMA/CA mechanism. In superframe structure, ACK mode is an optional. However, to achieve high reliability in terms of data delivery, ACK mode can be used which consumes more energy as compared to non-ACK mode which is shown in Fig. 7.

6.1 Energy consumption analysis of ND

The average energy consumption during transmission, reception, ACK, and control packets is given below;

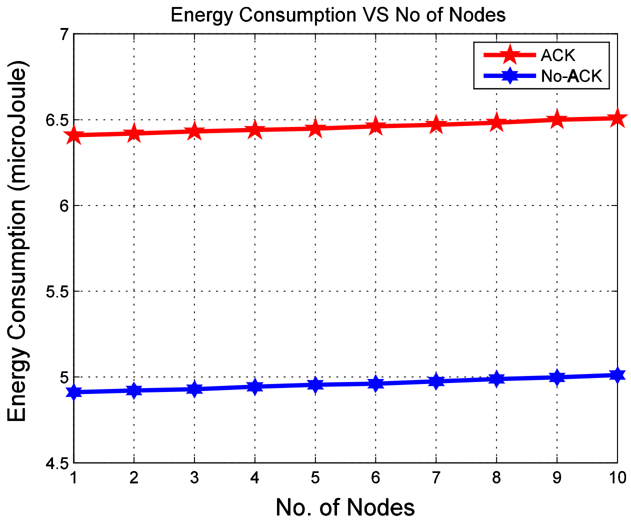

Fig. 7 Average energy consumption during ACK and Non-ACK mode

$$E_{total} = E_{normal} + E_{bwait} + E_{rec} + E_{tran}. \quad (19)$$

where, E_{total} is equal to the sum of energies during normal, backoff, receive, and transmit modes, respectively.

$$E_{normal} = P_i(\lambda p - (T_{sup} + T_{bn} + T_{cca} + T_{data} + T_{ACK} + T_b\tau)), \quad (20)$$

$$E_{bwait} = P_{rec} \times T_b\tau, \quad (21)$$

$$E_{rec} = P_{rec} \times (T_{sup} + 2T_c + 2T_p), \quad (22)$$

$$E_{tran} = P_{tran} \times T_{data}, \quad (23)$$

$$E_{total} = P_i(\lambda p - (T_{sup} + T_{bn} + T_{cca} + T_{data} + T_{ACK} + T_b\tau) + (P_{rec} \times T_b\tau) + (P_{rec} \times T_{sup} + 2T_c + 2T_p) + P_{tran} \times T_{data})/\lambda p, \quad (24)$$

$$E_{extra} = P_i(\lambda p - (T_{sup} + T_{bn} + T_{cca} + T_{data} + T_{ACK} + T_b\tau) + (P_{rec} \times T_{EXb}\tau) + (P_{rec} \times T_{sup} + 2T_c + 2T_p) + P_{tran} \times T_{data})/\lambda p. \quad (25)$$

where, P_i, P_{rec}, and P_{tran} are powers consumed in idle, receive and transmit modes, respectively. T_{sup} is the setup time from the idle state to the transmit or listen state. T_{bn} is the beacon transmission time. T_{cca} and T_{data} are CCA and data transmission times, respectively. The average beacon inter-arrival time is denoted by T_b which defines the time between two beacons. T_c and T_p are control packet transmission and propagation time of the packet. λp denotes the packet inter-arrival time and τ denotes the busy channel probability. T_{EXb} describes the extra beacon transmission time and energy consumed during this phase is shown in Fig. 8.

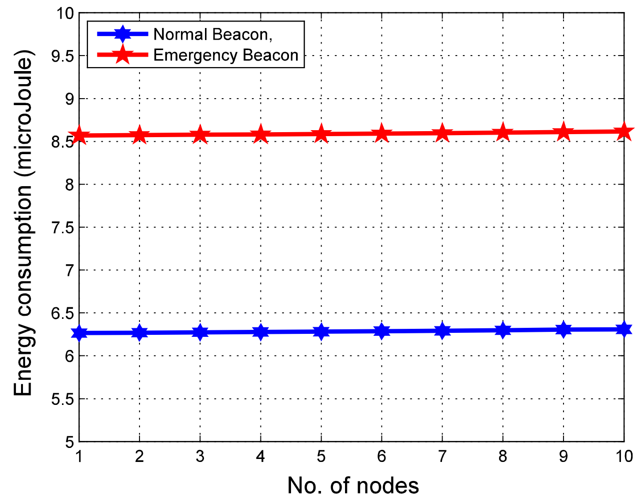

Fig. 8 Average energy consumption of the proposed MAC protocol due to emergency data

In case of emergency, the coordinator transmits a short beacon message to receive time critical data. This does not affect the normal and PD transmission because BN uses IP for ED transmission. After the reception of emergency beacon, BNs transmit data to the coordinator. However, if more than one node has ED, the coordinator broadcasts a beacon message to all nodes. In this case, BNs transmit their data using the CSMA/CA mechanism. Here we can also modify the CAP, CFP, and IP durations in case of more nodes having ED. In order to avoid packets drop, packet inter-arrival time must be optimal. If the packet inter-arrival time is more than the service time, nodes wait due to limited queue size. To reduce packet drop ratio and energy consumption, packet inter-arrival time needs to be adjusted according to data rate and payload. For stability, the service time should be less than the packet inter-arrival time otherwise the queue will overflow. After contending, node transmits data if the channel is free. Otherwise, the node will wait for a unit backoff time period and will contend again after this time. If again the channel is found busy, the node will wait for a unit backoff time however, the wait time will be doubled. This process continues up to macMAX backoff limits. Upon every failed attempt, node consumes extra energy while in backoff state. The energy consumption with different backoff periods during the busy channel is shown in Fig. 9.

6.2 Energy consumption analysis of ED

This section discusses the ED handling and average energy consumption. We use M/M/1/L queuing system to formulate and derive the expression for average delay in emergency situations [32]. The mean service time is defined as the interval from point of packet arrival at the head of the

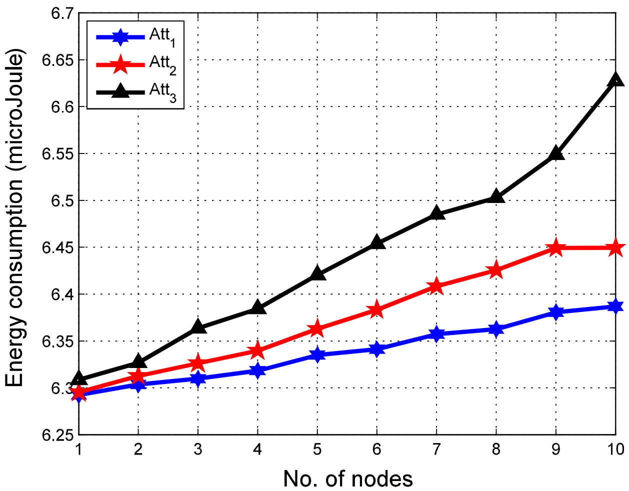

Fig. 9 Average energy consumption of the proposed MAC protocol during busy channel for different backoff attempts (Att)

queue to the point when the packet is successfully transmitted. Let n number of BNs that generate data with an average packet inter-arrival time Lp, where $Lp = \frac{1}{\lambda_p}$. The channel is found busy during CCA1 when other nodes send their data packets. Let T_n denotes the total number of data packets which are served during busy channel.

$$T_n = \frac{1}{1 - T}. \tag{26}$$

In Eq. 26, T denotes the total delay during busy channel which is given as:

$$T = \frac{\left(T_{wup} + E_{Boff} + T_{sup} + 2T_{Td} + 2T_{cont} + T_{data}\right)}{\lambda p} \tag{27}$$

Emergency wakeup time duration is represented by T_{wup}, and E_{Boff} is the average backoff time during busy channel. The time interval during (n − 1) nodes occupied the channel is given as;

$$\begin{aligned} T_{n-1} \quad &= (n-1)E_n\left(T_{wup} + T_{CCA} + T_{suup}\right. \\ &\left. +2T_{Td} + 2T_{cont} + T_{data}\right)(1 - \alpha). \end{aligned} \tag{28}$$

where α defines the packet loss probability. The equation for energy consumption during ED traffic is given as:

$$\begin{aligned} E_{emergency} = &\left[P_i\left[\lambda_p - \left(T_{wup} + \left(T_{sup} + 2T_{Td} + 2T_{cont}\right.\right.\right.\right. \\ &\left.\left.\left. + T_{CCA} + T_{data} + T_{bn}\tau\right)\right] + P_{tran_b}T_{wup} \\ &+ P_{rec}T_{bn}\tau + P_{rec}\left(T_{sup} + 2T_{Td} + 2T_{cont}\right) \\ &\left. + P_{cca}TN_{cca}T_{CCA}\right]/\lambda_p + E_n\left(\tau T_{bn} + E_{Boff}\right). \end{aligned} \tag{29}$$

where, $P_{tran_b}T_{wup}$ is the energy consumed during emergency wakeup packet transmission, P_{cca} is the power used during CCA whose maximum value is 2. TN_{cca} is the total number of CCAs until the data packet is successfully transmitted to the destination node. In our proposed work, we use Pollakzek-Khinchin formula [32] to calculate the average delay during the packet transmission in M/M/1/L queue system.

6.3 Delay analysis during ND and ED

The average transmission delay during the ED transmission is calculated as:

$$\begin{aligned} D_{emergency} = &\tau T_{Boff} + \frac{\lambda E\left[S^2\right]}{2(1-\rho)} \\ &+ \left(E_{bn} + T_{wup} + \left(T_{data} + 2T_{Td} + 2T_{cont}\right)\right). \end{aligned} \tag{30}$$

where, $\frac{\lambda E\left[S^2\right]}{2(1-\rho)}$ represents Pollakzek mean formula. Equation 30 gives the average delay during emergency packet(s) transmission which is due to extra beacon, backoff delay and CCA. During ED transmission, extra energy is used. In case of more than one emergency nodes contending to access the medium, CSMA/CA mechanism is used. To calculate the average transmission delay during normal traffic, the following equation is used.

$$\begin{aligned} D_{normal} = &\tau\left(T_{Boff} + T_{CAP} + T_{CFP}\right) \\ &+ \left(T_{data} + 2T_{Td} + 2T_{cont}\right). \end{aligned} \tag{31}$$

Here, T_{cont} denotes the control packet transmission time including normal beacon and ACK time. In case of normal traffic, nodes continuously contend to access the medium for transmission. In this case, CSMA/CA mechanism is used. During data transmission, other nodes wait for a random time period. After data transmission, the sender node waits for a random time period T_a to receive an ACK. If the ACK is not received during this time, the node assumes that the packet is dropped and the node will retransmit the data packet. This process continues until an ACK is received. It is clear form Eq. 25 that during critical data conditions, the coordinator transmits an extra beacon in the network to inform nodes about the emergency transmission. All nodes having normal as well as PD continue their transmissions.

7 Simulation results and analysis

We implement the IEEE 802.15.4 based MAC protocol to validate the effectiveness of the proposed mechanism. The IEEE 802.15.4 standard defines a unit backoff period as 20 symbols (320 µs for 2.4 GHz). The data generation time used in the proposed protocol is fixed which is different from the PD generation applications commonly used in WBANs. The medium contention criteria of the PD model usually depends on the initial data generation rate and time.

However, the initial data generation rate and time are critical factors to evaluate the different performance metrics such as energy, delay, reliability and throughput. In our proposed protocol, the basic idea is that backoff and CCA time periods can be varied according to the data priority class so that data collisions are reduced. On the other hand, as the traffic generation rate increases, the priority class changes from (ED ↔ ND ↔ PD) which decreases the overall throughput of the network. So, the model allows us to perform a comprehensive analysis of the performance of the protocol.

7.1 Simulation model

We consider a WBAN with a single coordinator and 10 number of BNs. BNs can be varied according to the underlying model and application requirements. BNs sense and transmit the data to the coordinator using a single-hop communication. We use CAP and CFP durations of the proposed protocol as mentioned in Table 3 because there is no specific size mentioned in the literature. The proposed network model is simulated under the conditions of analytical model, message retransmissions, and ACK/non-ACK mode of superframe structure. For MAC, default parameters defined in IEEE 802.15.4 standard (macMAXBE = 5, and macMinBE = 3) are used for fixed length of data [33]. We use WiseNET transceiver [34] for simulation purpose. Simulation parameters along with their values are listed in Table 3.

7.2 Performance metrics and discussion

In the following subsections, different metrics are considered to analyze the performance of the proposed protocol.

7.3 Average energy consumption

In this section, we will discuss the average energy consumption analysis of ND and ED. Figures 10 and 11 show the average energy consumption of the proposed MAC protocol as a function of different backoff time periods and total number of nodes. Extra energy is consumed during ED transmissions due to emergency beacon message. This is because a node first informs the coordinator about ED and then emergency beacon is transmitted in the network containing all the information about the data (node number as well as time duration). Other nodes that perform ND transmissions can also hear extra beacon which is one of the major reasons of increased energy consumption. Critical data is transmitted during IP of the superframe structure. Whereas, during CAP and CFP, nodes perform ND transmission. So, in these periods, energy consumed by the nodes is low as compared to nodes that transmit ED.

Table 3 Simulation parameters

Parameters	Values	Units
Data rate	250	Kbps (2.4 GHz)
Beacon interval (BI)	15,360	Symbols
Superframe duration (SD)	7860	Symbols
Backoff period	20	Symbols
Inactive period	Variable	Symbols
Clear channel assessment (CCA)	8	Symbols
Sensing time	$8 \times 16e^{-6}$	μs
ACK wait time	$120 \times 16e^{-6}$	μs
Turnaround time	$400e^{-6}$	μs
Wakeup time	$800e^{-6}$	μs
Unit backoff time	$20 \times 16e^{-6}$	μs
DIFS	$40 \times 16e^{-6}$	μs
SIFS	$12 \times 16e^{-6}$	μs
Inter-arrival time	0–2	Seconds
Transmission voltage	1.5	Volts
Receiving voltage	0.9	Volts
Receiving power	1.8	Watt
Transmission power	131.5	Watt
Payload	78	Bytes
ACK packet size	13	Bytes
minBackoff exponent (BE)		3
maxBackoff exponent (BE)		5
Beacon order (BO)		4
Superframe order (SO)		3
Nodes		10

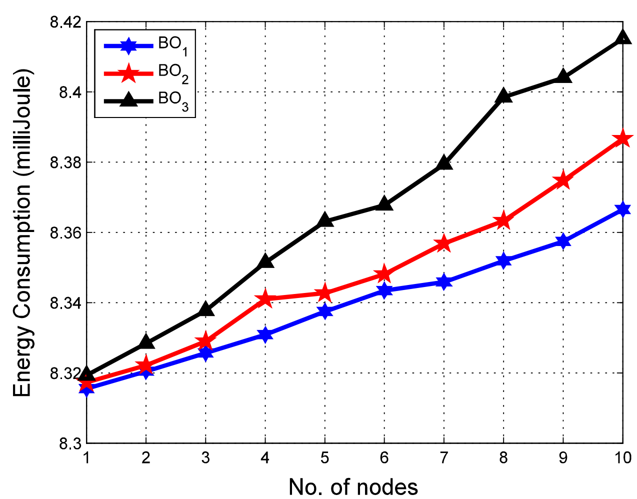

Fig. 10 Average energy consumption for different backoff periods during ND

In the proposed scheme, different priorities are set to handle ND, PD, and ED. More critical data is transmitted with high priority with small backoff time period. During ND, nodes simply use CAP to transmit data. If the channel

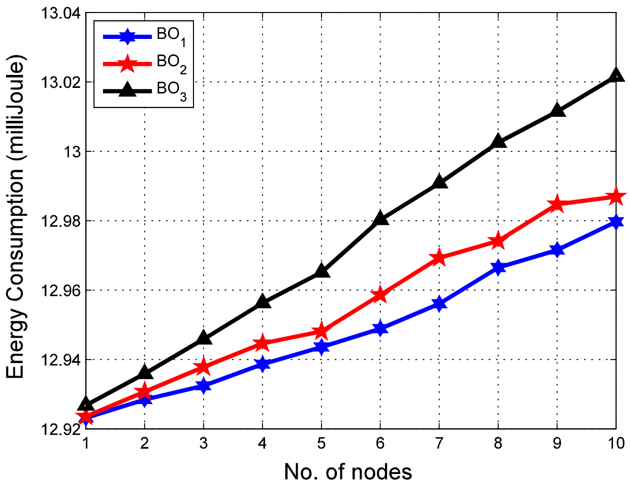

Fig. 11 Average energy consumption for different backoff periods during ED

is found busy, the node waits for a random unit backoff time. The overall energy consumption and delay are increased if we increase the backoff time period. This is because nodes have to wait more time before data transmission. However, by decreasing the backoff time interval, nodes contend more frequently with short intervals of time which ultimately consume more energy during the channel access. In this way, throughput of the network will be increased because the nodes access the channel with more probability is compared to the nodes having long backoff periods. So, the optimal backoff time period based on priority class is used to avoid repetitive attempts during the busy channel. The number of backoff attempts also plays an important role for reliable data delivery. The backoff time period can be fixed or variable size. In order to reduce the average transmission delay, the backoff time should be small. However, in this case nodes consume more energy due to frequent channel access attempts. On the other hand, energy can also be saved by increasing the random backoff time in which nodes switch into idle mode.

7.4 Average delay

Average delay is the time interval from the generation of packets to its reception at the coordinator. Nodes can create delay during backoff time periods, CCA, ACK receiving, turnaround time, etc. Mostly, nodes can create extra delay during contention access process when there is less probability that channel is found free. Furthermore, there is also equal probability at the same time that channel is found idle for data transmission. Upon every failed attempt to access the channel, a unit backoff time is doubled in case of IEEE 802.15.4 standard and extra energy is required to re-access the channel. Ultimately, this process adds extra energy as well as delay during ED and ND transmissions. Moreover, by increasing the packet inter-arrival time, average delay will also be increased. This is because; node has to wait for data packet to be transmitted. However, it increases the reliability and probability of successful data transmission which ultimately increases the overall throughput.

In WBANs, BNs use the beacon enabled slotted CSMA/CA protocol. The key parameters of CSMA/CA based schemes that can increase or decrease the average delay during data transmission are total number of backoff attempts after channel access failure macMaxFrameRetries, MAC minimum number of backoff exponent macMinBE, and maximum number of backoff attempts before the declaration of channel access failure. Figures 12 and 13 show the average delay which is function of backoff time during ND and ED. It is clear that during ED transmission with ACK mode, the average delay is comparatively more as compared without ACK mode. This is because BNs wait for ACK to ensure successful transmission. Otherwise, retransmission process will start until packets successfully delivered to destination point. According to Eq. 31, during ND transmissions BNs create delay only due to CCA and backoff period when the channel is found busy. This is because before data transmission, nodes wait for a unit backoff time period along with an optional CCA for reliable data delivery. In this process, node consumes extra energy which creates delay during ND transmission. In case of ED transmission as given in Eq. 30, extra delay is created due to emergency beacon reception as well as wake-up time. Moreover, in case of ED, we modified superframe structure where the duration of backoff time period is calculated according to the length and criticality of data packet. Whereas, in IEEE 802.15.4 standard, each failed attempt almost double the backoff duration which is not feasible for WBANs. So, the proposed scheme works better in both ND and ED transmission cases (Fig. 14).

7.5 Impact of the total number of nodes

For simulation purpose, we vary the total number of nodes from 1 to 10. First, we calculate the average data transmission delay, the total time needed to transmit data packets to the coordinator. In Figs. 12 and 13, the average data transmission delay with respect to total number of BNs is shown. It is clear that the delay increases by increasing the total number of BNs. This is due to the fact that more the nodes more will be the total number of data packets, collisions and retransmissions. In MAC protocols, where fixed GTS time slots are used, the delay increases when the data load exceeds the total number of time slots. Whereas, in case of our proposed scheme where the length

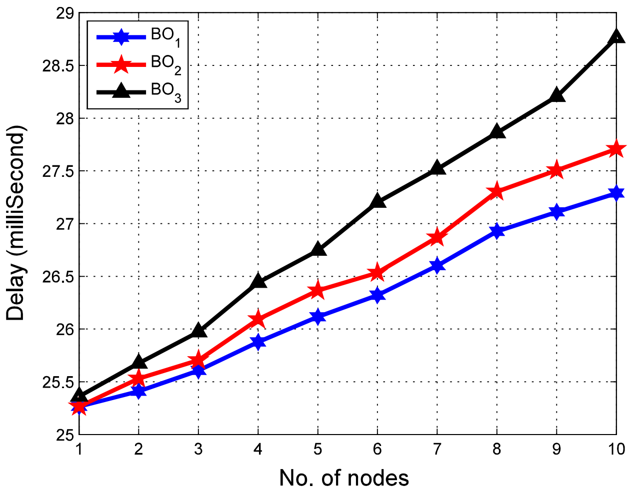

Fig. 12 Average delay for different backoff periods during ED

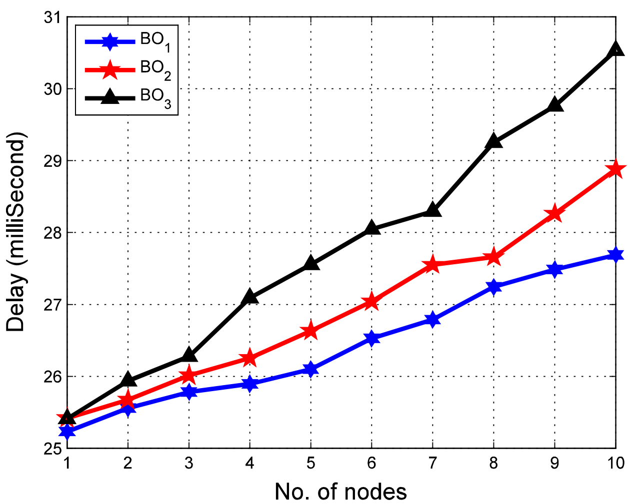

Fig. 13 Average delay for different backoff periods during ED with ACK

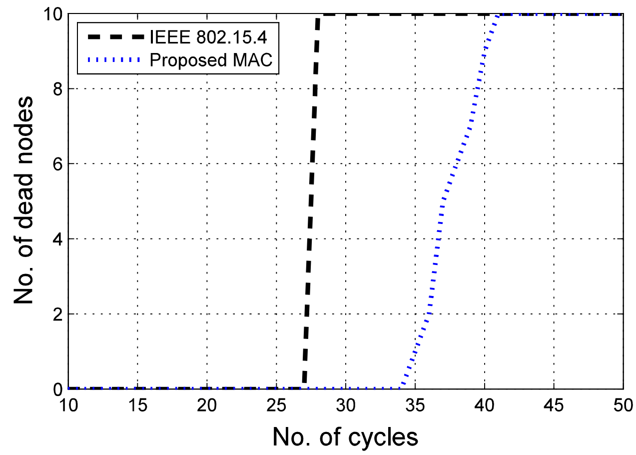

Fig. 14 Lifetime analysis of IEEE 802.15.4 and proposed MAC protocol

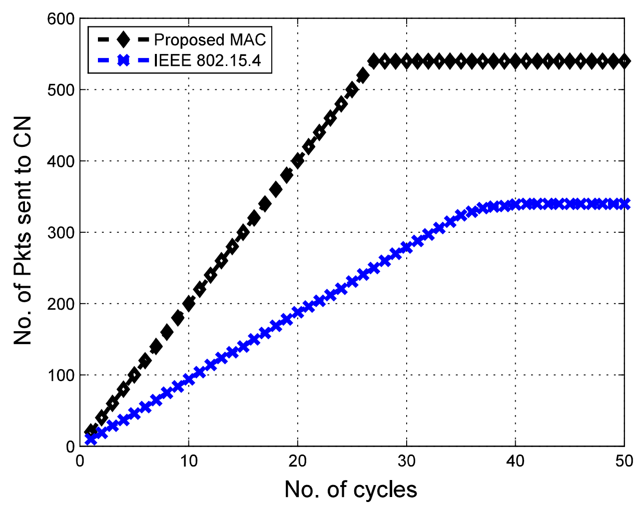

Fig. 15 Throughput analysis of IEEE 802.15.4 and proposed MAC protocol

of backoff time period changes as the data packet changes. So, in this way the total number of data packets successfully received at BS increases which is shown in Fig. 15.

7.6 Throughput

In WBANs, throughput is the total number of data packets that are successfully received at the coordinator node. Data can be transmitted over some logical or physical networks through some intermediate node(s) or directly. In Fig. 15, it is clearly shown that IEEE 802.15.4 standard has lower throughput as compared to the proposed MAC protocol where modified superframe structure is used. This is due to the fact that fixed number of GTS time slots is used in IEEE 802.15.4 standard which are 7. While, in modified superframe structure the length of time slots vary according to the length of data packet. Moreover, lower throughput in case of IEEE 802.15.4 standard is due to its long IP where nodes remain idle or inactive for longer time and transmit minimum number of data packets to the destination point. In our proposed work, the increased throughput is due to the modified superframe structure in which inactive time period is utilized for ED transmission. While in traditional superframe structure, nodes switch into sleep or idle modes during IP which is one of the major reasons for reduced throughput.

7.7 Dead nodes

The network lifetime can be prolonged if energy consumption of nodes is minimized. Subjected to this, traditional schemes where periodic sleep and awake mechanism is used are not efficient in handling idle listening or overhearing problem. In order to analyze the performance of the proposed scheme in terms of network life time, we provide 1.51 J energy to BNs. It can be seen from Fig. 14 that proposed MAC protocol shows enhancement in lifetime as compared to IEEE 802.15.4. This is because in IEEE 802.15.4 standard based schemes, BNs transmit data to the coordinator irrespective of ND or ED. However, in our proposed scheme, ED situation is handled by the coordinator on the request of BN. The node having high priority will get the channel access and transmits data to the coordinator. Moreover, in case of ND if channel is found busy, node will wait for a small amount of backoff time as compared to ND. After successful transmission, nodes switch to the sleep mode which save energy and thus prolongs the network life time. Figure 14 shows the dead nodes versus working cycles (time).

7.8 Packet drop probability

This section discusses the packet drop probability. In reality, the total number of data packets transmitted from source to destination are not equal. Because, there might be probability that all the data packets transmitted from source nodes are not received at destination point. This is due to the fact that packets are dropped due to the following reasons, (1) insufficient power required for data transmission, (2) node's buffer over-flow, (3) interference during multiple data transmissions, etc. To analyze the total number of packet drop during transmission, we use a uniform random packet loss model in which good links' probability is 70 % and probability of bad links is 30 %. Figures 16 and 17 show the total number of data packets sent, received and dropped in IEEE 802.15.4 and our proposed MAC protocols, respectively. It is shown that in case of IEEE 802.15.4 standard where traditional superframe structure is used the length of backoff time period is fixed. Moreover, upon every failed attempt to access the medium this time period will be doubled. So, there is a probability that in next attempt the channel is found busy and then node will wait until successful transmission. Thus, limited number of packets are sent to CN which ultimately reduces the average throughput. On the other hand, the proposed protocol is designed in such a way that the length of backoff time period is adjusted according to the data payload. So that node can access the medium with minimum waiting time. Furthermore, the inactive period of suprframe structure is efficiently utilized for ED transmission. So, due to these modification the average number of packets sent to CN are comparatively greater than IEEE 802.15.4 standard. Figure 18 shows that in case of IEEE 802.15.4 standard, the total number of packets received and dropped are 71.42 and 28.58 %, respectively. While, in the

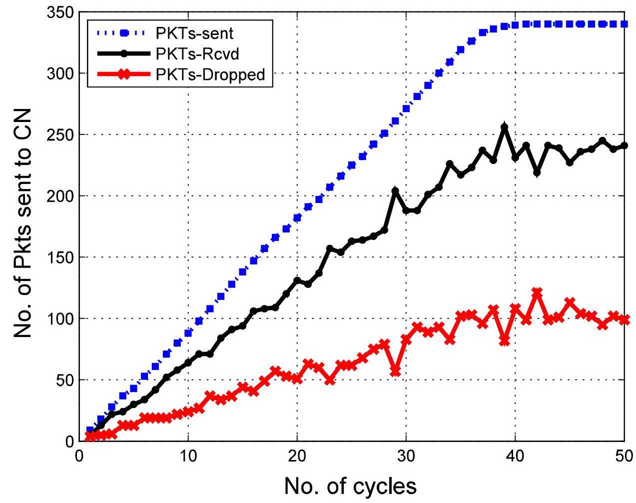

Fig. 16 Packets drop analysis of IEEE 802.15.4 protocol

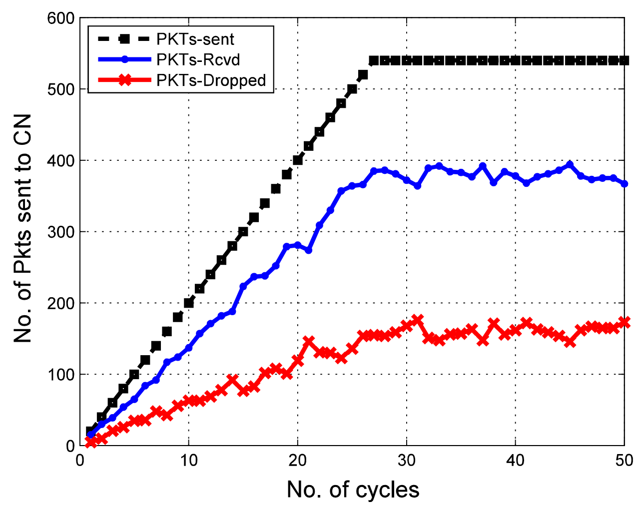

Fig. 17 Packets drop analysis of the proposed MAC protocol

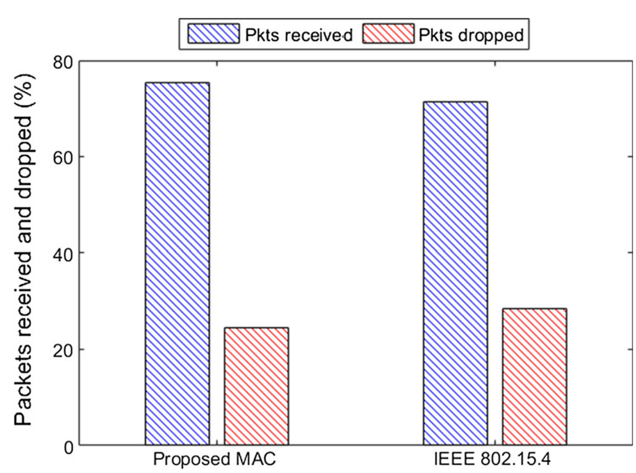

Fig. 18 Total number of packets received and dropped in case of IEEE 802.15.4 standard and the proposed MAC protocol

proposed protocol the total number of packets sent and dropped are 75.47 and 24.53 %, respectively. It is clear that total number of packets received at destination is more in case of proposed technique. Moreover, less number of packets are dropped in the proposed technique.

8 Conclusion

In this paper, analysis of average energy consumption and delay of normal as well as ED is presented. We proposed a pre-scheduled wakeup radio based MAC protocol for periodic and critical data. CSMA/CA mechanism is used for normal traffic whereas, PD is transmitted through TDMA based time slots. In order to handle ED, the coordinator node transmits additional beacon messages. ED is transmitted using IP. However, all periodic as well as normal transmissions are done without any interruption. Nodes transmitting data during emergency phase consume more energy while providing reliability which is one of the main tasks in the development of WBANs.

To analyze node states, a discrete time finite state Markov model is used. This model provides the probabilities of BNs during different states along with their transition probabilities. According to this model, if we know the state just before the last state, we can find the probability of final state more accurately. Simulation results demonstrated the effectiveness of the proposed mechanism in terms of average energy consumption, delay, throughput and packet drop ratio.

In the future, we are interested in implementing the MAC protocol in a real test bed under specific application constraints. Moreover, Hidden Markov model can be used to model different states more precisely. Furthermore, the performance of the patient monitoring solutions using Low Power (LP-WIFI) technology will be investigated and the results will be compared with the widely used WBAN technologies (e.g., IEEE 802.15.4 and IEEE 802.15.6). More importantly, ED transmission is still a main challenge because it is difficult to predict which BN will transmit ED in the next cycle. For this, we are interested in calculating the channel access probability of each BN in order to reduce critical data transmission time.

Acknowledgments The authors would like to extend their sincere appreciation to the Deanship of Scientific Research at King Saud University for funding this research through Research Group Project NO. (RG#1435-051).

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