Improving Reliability of Emergency Data Frame Transmission in IEEE 802.15.6 Wireless Body Area Networks

Kayiparambil S. Deepak and Anchare V. Babu

***Abstract*—Wireless body area networks (WBANs) are formed by tiny and intelligent sensor devices that are implanted within the tissue or attached on the surface of the human body to acquire both periodic as well as emergency physiological data. WBANs should be capable of reporting physiological emergency events to the doctors and care-givers reliably and as quickly as possible. In this paper, we propose and analyze an efficient channel access scheme for nodes carrying emergency data frames so as to improve the reliability of emergency data frame transmission. We also present an analytical model to compute the average delay and reliability experienced by emergency data frames, under the proposed scheme. Extensive analytical and simulation results are presented to establish that the proposed emergency handling scheme leads to significant improvement in reliability over the default scheme specified by IEEE 802.15.6.**

***Index Terms*—Emergency data transfer, IEEE 802.15.6 wireless body area networks (WBAN), reliability and average delay, superframe structure.**

I. Introduction

WIRELESS body area networks (WBANs) consist of a number of low-power sensor nodes implanted within the tissue or attached on the surface of the human body, that monitor vital physiological parameters and transmit the information to a central device known as hub. In addition to healthcare service, WBAN is a promising technology in many different domains that include consumer electronics and sports [1]–[5]. When used for health monitoring applications, WBANs are required to report both periodic and emergency events. A summary of the data rate and latency requirements of different types of data traffic handled by a WBAN is given in Table I [6], [7]. Compared with periodic traffic, the data rate of event-driven emergency traffic is generally very low; however, such applications have stringent delay and reliability requirements [7]. The occurrence of an emergency event due to a physiological abnormality can trigger multiple emergency events. It is essential to design an efficient channel access mechanism for nodes having emergency data frames, to meet the reliability requirements.

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K. S. Deepak is with the Department of Applied Electronics and Instrumentation, Government Engineering College, Kozhikkode 673005, India (e-mail: deepakptm@gmail.com).

A. V. Babu is with the Department of Electronics and Communication Engineering, National Institute of Technology, Calicut 673601, India (e-mail: babu@nitc.ac.in).

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TABLE I
Medical Monitoring Applications [6], [7]

Application	Data Rate	Delay
ECG (12 leads)	288 kbps	250 ms
ECG (6 leads)	71 kbps	250 ms
EMG	320 kbps	250 ms
EEG (12 leads)	43.2 kbps	250 ms
Blood saturation	16 bps	250 ms
Temperature	120 bps	250 ms
Glucose monitoring	1600 bps	250 ms
Cochlear implant	100 kbps	250 ms
Artificial retina	50–700 kbps	250 ms
Emergency data	–	125 ms

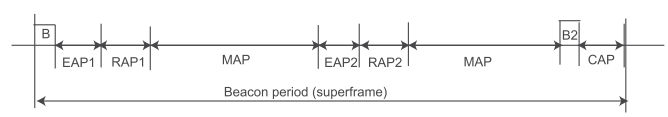

Fig. 1. Superframe structure: beacon mode with beacon superframe access [8].

IEEE 802.15 Task Group 6 has recently approved the physical (PHY) and medium access control (MAC) layer specifications for WBANs [8]. The standard defines a MAC layer in support of three PHY layers, i.e., narrowband (NB), ultrawideband (UWB), and human body communications (HBC). At the MAC sub layer, it supports both contention access and contention free access. The contention access phase is based on either slotted ALOHA or carrier sense multiple access/collision avoidance (CSMA/CA) mechanism. The contention free access phase supports a scheduled uplink/downlink access scheme as well as an improvised polling/posting-based access scheme [8].

In IEEE 802.15.6, time is divided into superframe structures. In the beacon mode with superframe boundaries, beacons are transmitted by the hub in each beacon period. Fig. 1 shows the superframe structure specified by 802.15.6, which is divided into exclusive access phases (i.e., EAP1 and EAP2), random access phases (i.e., RAP1 and RAP2), managed access phases (MAP1 and MAP2), and a contention access phase (CAP). In EAP, RAP, and CAP, nodes contend for resource allocation using either CSMA/CA or slotted ALOHA protocol depending on the PHY, i.e., slotted ALOHA for UWB and CSMA/CA for NB PHY. Both EAP1 and EAP2 are used for the transmission of highest priority traffic (i.e., emergency events), while RAP1, RAP2, and CAP are used for regular traffic only. During MAP,

either scheduled, unscheduled, or improvised access scheme can be used. In scheduled access, node obtains allocation intervals consisting of allocation slots based on advance reservation using connection request and connection assignment frames exchanged with hub. In one-periodic allocation, nodes exchange data frames with the hub every superframe, whereas for m-periodic allocation, data frames are transmitted in every mth superframe.

Under CSMA/CA, the nodes access the channel using predefined user priorities (UPs). The UPs are determined by the size of the minimum and maximum contention window (i.e., $\mathrm{CW}_{\min}$ and $\mathrm{CW}_{\max}$, respectively). According to the legacy IEEE 802.15.6 WBAN specifications, the transport of highest priority data (i.e., emergency) shall be carried out during EAP (i.e., EAP1 or EAP2) by categorizing the traffic as UP_7 [8]. However, as the number of simultaneously contending UP_7 nodes (i.e., nodes with UP_7 frames) increases, they experience very high collision probability during EAP. The legacy protocol also specifies that, if UP_7 nodes suffer transmission failure during EAP, such nodes are required to contend along with nodes of UP less than 7 (i.e., UP_0–UP_6) during the immediate RAP which is also CSMA/CA based [8]. If the tagged UP_7 node fails to get successful channel access during RAP, the emergency data frame will be dropped from its queue. Even though the transport of emergency life-saving data is very critical, the protocol proposed by the legacy 802.15.6 cannot meet the reliability requirements. The focus of this paper is on the design and analysis of an efficient scheme for improving the reliability of emergency data transfer in WBANs. The main contributions of the paper are as follows.

1) An adaptive superframe structure-based scheme has been proposed for improving the reliability of emergency data frames in WBAN.
2) Analytical models have been developed to compute average delay and reliability experienced by the emergency data frames under the proposed scheme.
3) An analytical model has been proposed to compute the average energy consumed for the successful transmission of an emergency data frame under the proposed scheme.
4) Through analytical and simulation investigations, it is established that the proposed scheme can meet the reliability requirements of emergency traffic in WBAN in the presence of periodic and aperiodic medical traffic.

This paper is organized as follows. Section II describes the related work. Section III describes the superframe structure for the proposed scheme. Analytical model is presented in Section IV for computing the average delay and reliability experienced by emergency data frames under the proposed scheme. Section V describes the results and the paper is concluded in Section VI.

II. Related Work

Recently, several papers have considered the design of MAC protocols for QoS provisioning in WBAN [9]–[24]. Most of these studies are based on IEEE 802.15.4 standard [27]. Among these, a few researchers have focused on the design of efficient schemes for emergency message dissemination. In [11], Shu *et al.* propose an interrupt MAC protocol that uses a long superframe structure with interrupt slots to break the running superframe for transferring emergency data. Work in [12] describes an adaptive beaconing MAC which uses standby slots to deliver event-driven emergency data. In [15], Ali *et al.* propose urgency-based MAC based on IEEE 802.15.4 in which emergency data is given priority over nonemergency data. In PNP-MAC [16], IEEE 802.15.4 structure is modified to handle different traffic classes; however, the authors do not consider QoS constraints for diverse traffic streams. In [19], a certain portion of the time slot is provided for the emergency data transfer. However, such preallocated slots will remain unused when emergency events do not occur for a long time. In [20], Rezvani and Ghorashi propose an adaptive MAC protocol in which an emergency TDMA duration is set for emergency data transmissions. The emergency handling schemes for WBANs proposed in [21]–[23] require additional wakeup mechanism for the sensor nodes and hence incur significant delay. In [24], Huq *et al.* propose medical emergency body MAC that inserts listening windows dynamically within MAP1 and MAP2 for the transmission of emergency data. Otgonchimeg and Kwon [25] propose HBC MAC, in which an emergency guaranteed time slot is provisioned for handling emergency traffic. In [26], Hossain *et al.* adopt the EAP phase of IEEE 802.15.6 for highest priority data transmission in WBAN, which is similar to that specified by IEEE 802.15.6 [8]. Apart from these papers, the works reported in [28]–[31] analyze the performance of IEEE 802.15.6 WBAN for the contention-based access scheme. In this paper, our focus is on improving the reliability of emergency data frame transmission in WBANs.

TABLE II
Traffic Types

UP	Traffic class	Nature of data	Access phase	$\mathrm{CW}_{\min}$	$\mathrm{CW}_{\max}$
7	T0	Emergency	EAP2	1	1
7	T0	Alarm	RAP2	1	4
6	T1	Periodic High priority	MAP1,H	–	–
6	T1	Aperiodic High priority	RAP2	2	8
5	T2	Periodic Lower priority	MAP1,L	–	–
5	T2	Aperiodic Lower priority	RAP2	4	8
4-0	T3	Nonmedical	CAP	16	32

III. Design of Superframe Structure and Emergency Handling Scheme

In this section, we describe the superframe structure for the proposed scheme. We classify various data traffic in WBAN into distinct UPs as shown in Table II. Depending on the physiological event being monitored, the medical traffic could be either periodic or aperiodic, having either low or high priority. Emergency data frames are categorized as highest priority, i.e., UP_7. In a WBAN, the hub chooses and enables an access mode. We assume that the beacon mode with superframe is selected by the hub. We suggest that the superframe structure for regular health monitoring applications (i.e., no emergency events) be as shown in Fig. 2(a), which consists of beacon period and different access phases: MAP1, EAP2, RAP2, B2 frame, and CAP. The access phases used for the transport of various traffic classes and UPs are listed in Table II.

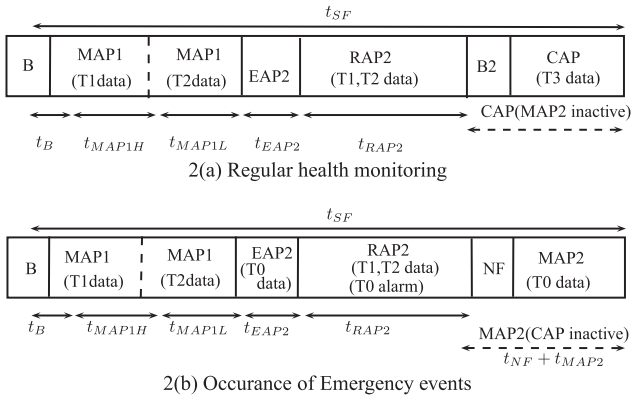

Fig. 2. Superframe structure.

A. Handling Emergency Data Frames

The superframe structure that is applicable when emergency events occur is shown in Fig. 2(b). Nodes with periodic data wake up at slots assigned to them by the hub in MAP1 and transmit their data frames. The nodes with emergency data frames (i.e., traffic class T0) access the channel in EAP2 with UP_7. Since EAP2 is set exclusively for the transport of emergency data frames, we fix its duration as equal to one allocation slot, which is computed as [8]

$$t_{\mathrm{allocSlot}} = \mathrm{AllocationSlotMin} + \mathrm{l.AllocationSlotResolution} \tag{1}$$

where AllocationSlotMin and AllocationSlotResolution are 500 μs [8], and l is the allocationslotlength field defined in the beacon frame. Notice that longer duration for EAP2 may lead to wastage of resources since emergency data is occasional and event driven. Successful delivery is indicated by the receipt of an immediate ACK (i.e., IAck) frame. We select the transmit limit for UP_7 data frames in EAP2 as equal to one (i.e., $L = 1$), so that EAP2 duration is effectively useful if and only if there is only one emergency data frame at a time. When two or more sensor nodes have emergency data simultaneously, they suffer collision in EAP2.

The emergency node tries to recover from collision by transmitting an alarm frame (with zero payload) to the hub during the immediate RAP2 with UP_7, that reports an emergency situation and the emergency data frame size (specified in the MAC header of the alarm frame). The length of the alarm frame has been set as equal to 9 bytes consisting of 7 bytes of MAC header and 2 bytes of FCS. On successful reception of the alarm frame, the hub will allocate reserved TDMA slots in subsequent MAP2 of the current superframe for emergency data frame transmission. However, as indicted in Table II, nodes with aperiodic medical data (i.e., with UP_6 and UP_5) also contend for transmission opportunity during RAP2 based on CSMA/CA with L transmission attempts (we call this as one CSMA/CA cycle). To improve the reliability of alarm frame transmission during RAP2, we provide two additional CSMA/CA retransmission cycles, for the alarm frames, i.e., an alarm frame is dropped only when all the three CSMA/CA cycles, each consisting of L transmission attempts, are unsuccessful. The allocation of TDMA slots in MAP2 is computed by the hub based on the size of the emergency data reported by the alarm frames and is communicated through a notification frame. Nodes with emergency data wake up in the notification period which corresponds to the RAP2 END given in beacon. The details of the proposed scheme is described in Algorithm 1.

Algorithm 1: Emergency data transfer along with scheduled access/contention access.

```
Data frame ready for transmission ;
if priority < 7, then
    Step 1:Normal data transmission;
    if Scheduled access node then
        transmit data in MAP1,L/MAP1,H;
    else
        transmit data in RAP2/CAP;
    end
else
    Step 2: Transmit data frame in EAP2;
    if Ack recd then
        Data frame Txn sucess
    else
        Step 3:Tx Alarm frame in CSMA0
        if Ack not received then
            Step 4:Tx Alarm frame in CSMA1
            if Ack not received then
                Step 5: Tx Alarm frame in CSMA2;
                if Ack not received then
                    Alarm frame Transmission fail;
                else
                    Alarm frame Txn sucess, go to step6;
                end
            else
                Alarm frame Txn sucess, go to step6;
            end
        else
            Alarm frame Txn sucess, go to step6;
        end
        Step 6: Wake up in NF slot, receive Slot number ;
        Step 7: : Transmit Data frame in MAP2 ;
        if Ack received then
            Data frame Txn sucess;
        else
            Data frame Txn fail;
        end
    end
end
```

According to IEEE 802.15.6 specifications, any of the access phases specified by the protocol can be disabled by the hub depending on the requirements of the applications [8]. Accordingly, we have made minor modifications for the original superframe structure of IEEE 802.15.6 where MAP1 succeeds EAP1 and RAP1 (see Fig. 1). In the proposed design, we avoid the use of EAP1 and RAP1 and the superframe always begins with MAP1. This can be explained as follows: As mentioned before, we rely on EAP2, RAP2, and MAP2 for the emergency data frame transmission. The duration of MAP2 will depend on

the number of alarm frames successfully received by the hub during RAP2 and the amount of emergency data available. This leads to a variable length MAP2. However, it does not upset the scheduled allocation for periodic traffic during MAP1 since, in our proposed design, MAP1 appears before MAP2. Now let us consider that EAP1, RAP1, and MAP1 are used for emergency data transmission instead of EAP2, RAP2, and MAP2 as proposed in this paper, and MAP2 for the scheduled transmission of periodic traffic. In this case, MAP1 duration becomes a variable since it depends on the number of alarm frames successfully received at the hub during RAP1. The variable length MAP1 will upset the scheduled transmission in MAP2 since it affects the preassigned wakeup arrangement between the nodes and the hub in MAP2. Furthermore, as shown in Fig. 1, CAP which is used for the transmission of data with lower UP (i.e., UP_0–UP_4), is always preceded by a B2 frame. We suggest that, for regular monitoring applications, both B2 frame and CAP durations are available as shown in Fig. 2(a). However, when emergency data frames are present, we suggest that both B2 frame and CAP durations shall be allocated to MAP2, i.e., the B2 frame which activates the CAP is not transmitted by the hub; instead the hub transmits the notification frame containing allocation details for emergency data frame transmission in MAP2.

IV. Analytical Model

In this section, we present analytical models for computing the average delay and reliability experienced by the emergency data frames under the proposed scheme. We consider a single hop WBAN with star topology. The data frames are categorized into distinct UPs by the respective sensor nodes and are transmitted during various access phases as described in Table II. Nodes that monitor periodic medical traffic are classified as UP_6 and UP_5 (i.e., high and low priority applications); they send data in MAP1 according to a scheduled allocation announced by the hub. Let the total number of nodes with data frames of UP_k having scheduled allocation be $n_{k,p}$ and the number of UP_k nodes that use contention-based access be denoted by n_k. Nodes that monitor aperiodic medical traffic are classified as either UP_6 or UP_5 (high and low priority, respectively) and all these nodes try to access the medium in RAP2. Furthermore, nodes that are used for monitoring nonmedical data traffic categorized as UP_4-UP_0 access the medium in CAP. Let the total number of medical nodes with data frames classified as UP_6 and UP_5 be $n_{6,\mathrm{tot}}$ and $n_{5,\mathrm{tot}}$, respectively. Out of the $n_{6,\mathrm{tot}}$ number of UP_6 nodes, a total of n_6 nodes use contention-based access and $n_{6,op}$ nodes use one-periodic scheduled allocation in MAP1, i.e., $n_{6,\mathrm{tot}} = n_6 + n_{6,op}$. Similarly, out of the $n_{5,\mathrm{tot}}$ number of UP_5 nodes, n_5 nodes use contention-based access and $n_{5,mp}$ nodes use m-periodic scheduled allocation in MAP1, i.e., $n_{5,\mathrm{tot}} = n_5 + n_{5,mp}$.

A. Average Delay Experienced by an Emergency Data Frame

Let the probability that an emergency data frame from a tagged node suffers transmission failure in the first attempt (i.e., during EAP2) be denoted as $p_{f,\mathrm{EAP2}}$. In the proposed scheme, after the first transmission failure, the node transmits an alarm frame during RAP2, which occurs with probability $p_{f,\mathrm{EAP2}}$. Furthermore, let $p_{f,\mathrm{RAP2}}$ represent the probability that the alarm frame suffers transmission failure in RAP2. The total average delay experienced by the emergency frame can be expressed as follows:

$$D_{\mathrm{total}} = t_{\mathrm{EAP2}} + p_{f,\mathrm{EAP2}} t_{\mathrm{RAP2}} + (1 - p_{f,\mathrm{RAP2}}) \left(t_{\mathrm{NF}} + \frac{t_{\mathrm{MAP2}}}{2} \right) \quad (2)$$

where t_{EAP2}, t_{RAP2}, and t_{MAP2} denote the length of the access phases EAP2, RAP2, and MAP2, respectively; and t_{NF} represents the time duration of the notification frame.

1) Finding t_{EAP2} and $p_{f,\mathrm{EAP2}}$: The EAP2 phase is selected exclusively for emergency data transfer, and nodes having emergency data frames contend for channel access using CSMA/CA with UP_7. As described in Section III, we select EAP2 length (i.e., t_{EAP2}) as equal to one allocation slot of the superframe i.e., we set $t_{\mathrm{allocSlot}} = 3.5$ ms, which is sufficient for a node to transfer an emergency data frame of maximum size, i.e., 255 bytes, at a data rate of 971.4 kbps [8]. For transmission in EAP2 with UP_7, we keep maximum transmit limit to be equal to 1 (i.e., we set $\mathrm{CW}_{\min} = \mathrm{CW}_{\max} = 1$, $L = 1$ for UP_7 in EAP2). The transmission failure probability $p_{f,\mathrm{EAP2}}$ is equivalent to the probability that more than one sensor node generate emergency data frame in a superframe. Let $n_{5,\mathrm{tot}} + n_{6,\mathrm{tot}} = N$ represent the total number of medical nodes in the network. The probability that exactly one node generate emergency data frame during a superframe duration is $N_{c_1} txp_7 (1 - txp_7)^{N-1}$. Here txp_7 is the probability that a sensor node generate an emergency data frame during a superframe. Assuming that emergency data is generated according to a poisson process of rate λ_7, $txp_7 = \lambda_7 t_{\mathrm{SF}}$, where t_{SF} is the superframe duration. The probability that none of the nodes generate an emergency data frame is given by $(1 - txp_7)^N$. Thus, $p_{f,\mathrm{EAP2}}$ is computed as follows:

$$p_{f,\mathrm{EAP2}} = 1 - N\, txp_7 (1 - txp_7)^{N-1} - (1 - txp_7)^N. \quad (3)$$

2) Delay Experienced by an Alarm Frame in RAP2: If a tagged node fails to transmit the emergency data frame successfully during EAP2, an alarm frame is transmitted (with UP_7) during RAP2 to the hub. However, for getting channel access during RAP2, the nodes carrying alarm frames have to compete with nodes carrying aperiodic medical data frames classified as either UP_6 or UP_5, based on the CSMA/CA procedure. As discussed in Section III, to improve the reliability of alarm frame transmission, we allow such nodes to contend for three CSMA/CA cycles, each consisting of L transmission attempts.

IEEE 802.15.6 standard specifies the procedure for a UP_k ($k = 0, 1, \ldots, 7$) node to contend for channel access using CSMA/CA as described below: A single hop network is considered consisting of a hub and n_k number of UP_k nodes and thus the hidden terminal problem is ignored. Furthermore, we assume that there is only uplink traffic from the nodes to the hub. A node will choose a back-off counter by sampling an integer from a uniform distribution over the interval (1,CW) where CW is the contention window. The CW is chosen depending on the UP of the frame to be transmitted as given in Table II. For a UP_k node, the value of CW for yth back-off stage (i.e., $W_{k,y}$) is related to the minimum CW (i.e., $W_{k,0}$) as follows.

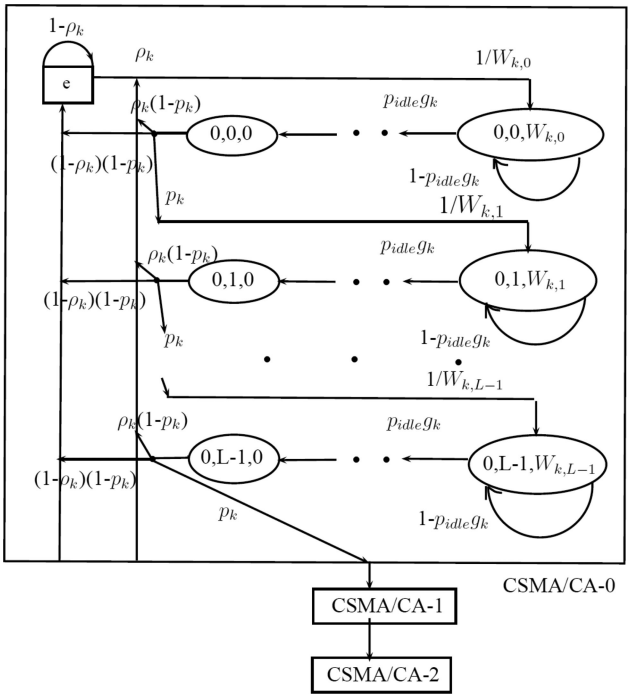

Fig. 3. Discrete time Markov chain for node of UP_k.

1) $W_{k,y} = W_{k,\min}$, the minimum value of CW if the node had succeeded in the last contended allocation or did not obtain any contended allocation, previously.
2) For the yth back off, if previous transmission was a failure, then $W_{k,y} = W_{k,y-1}$ for y odd and $W_{k,y} = 2W_{k,y-1}$ for y even, $y = 0,1,.....L-1$, where L is the transmission limit.
3) If $2W_{k,y-1}$ exceeds the maximum CW size $W_{k,\max}$, then $W_{k,y} = W_{k,\max}$.

The back-off counter of a tagged node is frozen if any of the following events occur.

1) Channel is sensed as busy due to ongoing frame transmission.
2) Current time is outside any of the contention-based access phases, i.e., EAP/RAP/CAP.
3) Difference between current time and end of the current access phase is not sufficient for a successful frame transaction. The back-off counter is unlocked when the medium is idle for SIFS and none of the above conditions are met. The counter is decremented by one for every idle CSMAslot [8].

We use the theory of discrete time Markov chain (DTMC) to model the back-off procedure of a UP_k node in RAP2 [29]. Assume nonsaturation condition for each node in the network with Piosson arrivals. Let λ_k denote the arrival rate for a node of UP_k. We consider a tagged UP_k node and let $\{C_k(t), S_k(t), B_k(t)\}$, respectively, denote the stochastic processes representing the CSMA/CA cycle, the back-off stage corresponding to a CSMA/CA cycle, and the back-off counter, respectively, at time t. We assume the frame collision to be Bernouli [32], so that the state of each node of UP_k can be described by the triplet $\{C_k(t), S_k(t), B_k(t)\}$. The state transition diagram is shown in Fig. 3, that describe the back-off decrement and frame transmission process. Define the stationary distribution of the DTMC corresponding to a tagged UP_k node as follows:

$$b_k(x,y,z) = \lim_{t\to\infty} P(C_k(t) = x, S_k(t) = y, B_k(t) = z);$$
$$x \in (0,1,2), y \in (0,1,..L-1), z \in (0, W_{k,y}). \tag{4}$$

The three CSMA/CA cycles for alarm frame transmission during RAP2 are denoted as CSMA/CA-0, CSMA/CA-1, and CSMA/CA-2 in Fig. 3. Let τ_k and p_k, respectively, represent the conditional frame transmission and the conditional collision probability experienced by tagged UP_k node. Furthermore, let ρ_k be the probability that a frame of UP_k is generated during the mean service time of the node; otherwise, the node enters the empty state. As shown in Fig. 3, the back-off counter is chosen by sampling an integer from uniform distribution over the interval [1, $\mathrm{CW}_{k,\min}$]. Let n_7, n_6, and n_5, respectively, be the number of nodes corresponding to UP_7, UP_6, and UP_5. Let p_{idle} be the probability that a tagged UP_k node, while residing in the back-off stage sense the channel to be idle. Then, p_{idle} is computed as follows:

$$p_{\mathrm{idle}} = (1-\tau_7)^{n_7}(1-\tau_6)^{n_6}(1-\tau_5)^{n_5}. \tag{5}$$

Let g_k be the probability that a tagged UP_k node finds the residual time in current RAP2 to be sufficient for a frame transmission, which includes the time for the back-off counter to decrement to zero and the time required for successful data transmission. Assume $t_{\mathrm{BO},k}$ to be the average back-off duration spent by a UP_k node in a CSMA/CA cycle that consists of L back-off stages. Hence, $\frac{t_{\mathrm{BO},k}}{L}$ is the average time duration spent by the node in one back-off stage. Furthermore, assume t_S to be the time required for successful data transmission and t_{RAP2} to be the duration of the RAP2 phase. Then, g_k is computed as

$$g_k = 1 - \frac{\frac{t_{\mathrm{BO},k}}{L} + t_S}{t_{\mathrm{RAP2}}}. \tag{6}$$

Hence, the counter decrement probability is given by $p_{\mathrm{idle}}g_k$. Let t_{Data} represents the time duration for transmission of a frame of length N_{Data}. For NB PHY, t_{Data} can be expressed as [8]

$$t_{\mathrm{Data}} = [N_{\mathrm{phyhdr}} + N_{\mathrm{totalDataPSDU}}]T_s \tag{7}$$

where N_{phyhdr} is the PHY layer header and T_s is the symbol duration. Here, $N_{\mathrm{totalDataPSDU}}$ represents the length of the service data unit passed to the PHY layer from the MAC layer which consists of MAC layer overheads N_{MAChdr} and N_{FCS} and can be expressed as [8]

$$N_{\mathrm{totalDataPSDU}} = N_{\mathrm{MAChdr}} + N_{\mathrm{Data}} + N_{\mathrm{FCS}}. \tag{8}$$

For alarm frames and IAck frames, $N_{\mathrm{Data}} = 0$. The time duration for a successful frame transmission can be written as

$$t_S = t_{\mathrm{Data}} + t_{\mathrm{SIFS}} + t_{\mathrm{Ack}} \tag{9}$$

where t_{SIFS} is the short inter frame duration and t_{Ack} is the time duration of the Ack frame.

As shown in Fig. 3, when the back-off counter becomes zero, the tagged node would initiate the transmission attempt. Successful transmission is indicated by the reception of the Ack frame after which the back off is cleared to zero. Collisions would result if two or more nodes attempt simultaneous transmissions. After each unsuccessful transmission attempt, the tagged node will enter the next back-off stage by doubling the CW size for even numbered attempts and with the same CW

size for odd numbered attempts. After L unsuccessful transmission attempts, the node enters the CSMA/CA cycle-1 and continues the back-off procedure. The alarm frame is discarded if the transmission attempts in all the three CSMA/CA cycles become unsuccessful. The one step transition probabilities of the DTMC corresponding to a UP_k node from time t to $t-1$ are as follows:

$$P(x,y,z|x,y,z+1) = g^{'}; y \in (0,..L-1); \quad 0 \le z \le W_{k,y} \tag{10a}$$

$$P(x,y,z|x,y,z) = 1-g^{'}; y \in (0,..L-1); \quad 1 \le z < W_{k,y} \tag{10b}$$

$$P(x,y,z|x,y-1,0) = \frac{p_k}{W_{k,y}}; y \in (1,..L-1,); \quad z \in (1,..W_{k,y}) \tag{10c}$$

$$P(x,0,z|x,y,0) = \frac{\rho_k p_{k'}}{W_{k,0}}; y \in (0..L-1); \quad z \in (1..W_{k,y}) \tag{10d}$$

$$P(e|x,y,0) = (1-\rho_k)(1-p_k); \quad 0 \le y \le L-1 \tag{10e}$$

$$P(e|e) = 1-\rho_k \tag{10f}$$

$$P(0,0,z|e) = \rho_k \ \frac{1}{W_{k,0}}; 1 \le z \le; W_{k,0} \tag{10g}$$

$$P(x+1,0,z|x,L-1,0) = p_7 \frac{1}{W_{7,0}}; 0 \le x \le 1; \quad 1 \le z \le; W_{7,0} \tag{10h}$$

where $g^{'} = p_{\mathrm{idle}} g_k$, $p_{k'} = 1-p_k$, x $\in$ (0,1,2); for (10a) to (10e). Equation 10(a) accounts for the probability that the back-off counter of a tagged UP_k node gets decremented by one, while 10(b) represents the probability that the back-off counter is frozen. Equation 10(c) accounts for the probability that the node encounters a collision and enters the next back-off stage, while 10(d) represents the probability that the node transmits a frame successfully and starts a new back off for the next frame in the queue. Equation 10(e) represents the probability that after successful transmission of the frame, the node enters the empty state due to nonavailability of a frame in its MAC queue, while 10(f) represents the probability that the node continues to remain in the empty state. Equation 10(g) represents the probability that a new data frame is generated (with probability ρ_k) while residing in the empty state and node starts a new back off. Finally, 10(h) represents probability that a UP_7 node will enter the next CSMA/CA cycle when the maximum retry limit for the current CSMA/CA cycle is reached and frame transmission remains as unsuccessful. By solving the DTMC in the steady state, the following relations can be obtained:

$$b_k(x,y,0) = p_k^y b_k(x,0,0); 0 \le x \le 2; 0 < y \le L-1 \tag{11}$$

$$b_k(x,y,z) = p_k \frac{(W_{k,y}+1)-z}{(W_{k,y}) p_{\mathrm{idle}} g_k} b_k(x,y-1,0); \quad x \in (0,1,2), y \in (0,1,..L-1), z \in (0,W_{k,y}). \tag{12}$$

Notice that above relations exclude the first row of the CSMA/CA cycles. Furthermore, we have the following relations:

$$\sum_{z=1}^{z=W_{k,y}} \frac{(W_{k,y}+1)-z}{W_{k,y}} = \frac{(W_{k,y}+1)}{2} \tag{13}$$

$$1 = \sum_{x=0}^{x=2} \sum_{y=0}^{y=L-1} \sum_{z=0}^{z=W_{k,y}} b_k(x,y,z) + b_k(e) \tag{14}$$

where $b_k(e)$ represents the steady-state probability that the node enters the empty state which can be expressed as

$$b_k(e) = (1-\rho_k)(1-p_k) \sum_{x=0}^{x=2} \sum_{y=0}^{y=L-1} b_k(x,y,0) + (1-\rho_k) b_k(e) + p_k(1-\rho_k) b_k(2,L-1,0). \tag{15}$$

In (15), the probability that the node enters the empty state due to three events are considered.

1) Transmission from the node is successful and no data arrived in the queue of the node, which happens with probability $(1-\rho_k)(1-p_k)\sum_{x=0}^{x=2}\sum_{y=0}^{y=L-1} b_k(x,y,0)$.
2) The node remains in empty state with probability $(1-\rho_k) b_k(e)$.
3) Transmission from the node fails after the three CSMA/CA cycles, the current data frame is dropped and no data frame is available in the queue of the node, which happens with probability $(1-\rho_k) p_k \ b_k(2,L-1,0)$.

As given in Appendix A, this probability can be simplified as

$$b_k(e) = \frac{1-\rho_k}{\rho_k} b_k(0,0,0). \tag{16}$$

We define f_1 as the probability to start the first attempt of CSMA/CA cycle 0. This probability can be expressed as the sum of three terms.

1) Probability that a data frame arrives when node is in empty state.
2) A data frame is available after a successful transmission.
3) When the current data frame transmission fails and the packet is dropped after three CSMA cycles, a fresh data frame is available in the queue

$$f_1 = b_k(e) \ \rho_k + (1-p_k) \sum_{x=0}^{x=2} \sum_{y=0}^{y=L-1} b_k(x,y,0) + \rho_k p_k b_k(2,L-1,0). \tag{17}$$

Using (16) and (11), we can simplify (17) to obtain the following:

$$f_1 = b_k(0,0,0). \tag{18}$$

Define f_2 as the probability to start the first attempt of CSMA/CA cycle 1 or 2. This probability can be expressed as

$$f_2 = p_k \ b_k(x-1,L-1,0), 1 \le x \le 2. \tag{19}$$

Specific to the first row of the CSMA/CA cycles, i.e., for $y = 0$; we can obtain the following relations by solving the DTMC:

$$b_k(x,y,z) = \frac{(W_{k,y}+1)-z}{(W_{k,y})\, p_{\text{idle}} g_k} f_1; x = 0, y = 0, 0 < z \le W_{k,y} \tag{20}$$

$$b_k(x,y,z) = \frac{(W_{k,y}+1)-z}{(W_{k,y})\, p_{\text{idle}} g_k} f_2; 1 \le x \le 2, \quad y = 0, 0 < z \le W_{k,y}. \tag{21}$$

The probability conservation relation given in (14), for a UP_7 node, can be rewritten as the sum of five terms as

$$1 = b_k(e) + \sum_{x=0}^{x=2}\sum_{y=0}^{y=L-1} b_k(x,y,0) + \sum_{z=1}^{z=W_{k,y}} b_k(0,0,z) + \sum_{x=1}^{x=2}\sum_{z=1}^{z=W_{k,y}} b_k(x,0,z) + \sum_{x=0}^{x=2}\sum_{y=1}^{y=L-1}\sum_{z=1}^{z=W_{k,y}} b_k(x,y,z). \tag{22}$$

The first term of (22) represent the probability of the empty state, the second term represents the sum of the steady-state probabilities of the states having back-off counter value zero for the different CSMA cycles, the third term is the sum of the steady-state probabilities of zeroth back off of CSMA-0, the fourth term is the sum of the steady-state probabilities of zeroth back off of CSMA-1 and 2, the last term is the sum of steady-state probabilities of other back-off stages of CSMA-0, 1, and 2. These terms are expressed in terms of $b_k(0,0,0)$ as given in Appendix B as

$$1 = b_k(0,0,0)\left[\frac{(W_{k,0}+1)}{2p_{\text{idle}}g_k} + \frac{(W_{k,0}+1)(p_k^L + p_k^{2L})}{2p_{\text{idle}}g_k} + \frac{1}{p_{\text{idle}}g_k}\left[\sum_{y=1}^{y=L-1}(p_k)^y\frac{(W_{k,y}+1)}{2}\right] \times (1+(p_k)^L+(p_k)^{2L}) + \frac{(1-(p_k)^L)(1+p_k^L+p_k^{2L})}{(1-p_k)} + \frac{1-\rho_k}{\rho_k}\right] \tag{23}$$

For a UP_7 node $W_{k,0} = 1$ so that $b_7(0,0,0)$ can be written as (24), shown at the botom of this page. Since a UP_7 node that transmits emergency alarm frame in RAP2 is allowed to use three CSMA/CA cycles, the conditional frame transmission probability of the UP_7 node can be computed as $\tau_7 = \sum_{x=0}^{x=2}\sum_{y=0}^{y=L-1} b_7(x,y,0)$. From (11) and (24), the transmission attempt probability of UP_7 node can be determined as (25), shown at the bottom of this page. For UP_6 and UP_5 nodes, only one CSMA/CA cycle is allowed and hence the transmission attempt probability can be computed as $\tau_k = \sum_{y=0}^{y=L-1} b_k(0,y,0); k = 6, 5$. Furthermore, analysis similar to that given in Appendix B for a UP_6 node having $W_{k,0} = 2$, gives τ_6 as given by (26), shown at the bottom of this page. Similarly for UP_5 nodes, $W_{k,0} = 4$ so that τ_5 is given by (27), shown at the bottom of this page.

The conditional collision probabilities experienced by a tagged UP_k node is given by

$$p_k = 1 - (1-\tau_k)^{n_k - 1}\prod_{i=5, i\neq k}^{7}(1-\tau_i)^{n_i}; k = 5, 6, 7. \tag{28}$$

Next, we compute the mean service time experienced by the data frames of a UP_k node. This includes the total average back-off delay and the time required for successful transmission of the frame. The probability that a tagged UP_7 node while in the back-off stage finds a successful transmission from the remaining nodes is given by

$$p_{S,o,7} = n_5\tau_5(1-\tau_5)^{n_5-1}(1-\tau_6)^{n_6}(1-\tau_7)^{n_7-1} + n_6\tau_6(1-\tau_6)^{n_6-1}(1-\tau_5)^{n_5}(1-\tau_7)^{n_7-1} + (n_7-1)\tau_7(1-\tau_7)^{n_7-2}(1-\tau_5)^{n_5}(1-\tau_6)^{n_6}. \tag{29}$$

In (29), the first term is the probability that there is atmost one transmission from a UP_5 node and no transmissions from UP_6 and UP_7 nodes, the second term is the probability that there is atmost one transmission from a UP_6 and no transmissions from UP_5 and UP_7 nodes, and the third term is the probability that atmost one among the remaining UP_7 nodes transmit and no transmission from UP_5 and UP_6 nodes. Generalizing (29), for a given UP_k node, the probability that a tagged UP_k node, while staying in the back-off stage, finds that there is a successful

$$b_7(0,0,0) = \frac{2p_{\text{idle}}g_7\rho_7(1-p_7)}{\rho_7(1-p_7)2(1+(p_7)^L+(p_7)^{2L})(1+p_7+(p_7)^2\frac{3}{2}+(p_7)^3\frac{3}{2}+(p_7)^4\frac{5}{2}) + 2p_{\text{idle}}g_7(1-p_7+\rho_7p_7-\rho_7p_7^{3L})} \tag{24}$$

$$\tau_7 = \frac{2p_{\text{idle}}g_7\rho_7(1-(p_7)^L)(1+(p_7)^L+(p_7)^{2L})}{\rho_7 2(1-p_7)(1+(p_7)^L+(p_7)^{2L})(1+p_7+(p_7)^2\frac{3}{2}+(p_7)^3\frac{3}{2}+(p_7)^4)\frac{5}{2} + 2p_{\text{idle}}g_7(1-p_7+\rho_7p_7-\rho_7p_7^{3L})} \tag{25}$$

$$\tau_6 = \frac{2p_{\text{idle}}g_6\rho_6(1-(p_6)^L)}{\rho_6(1-p_6)6(1+p_6\frac{3}{2}+(p_6)^2\frac{5}{2}+(p_6)^3\frac{5}{2}+(p_6)^4\frac{9}{2}) + 2p_{\text{idle}}g_6(1-p_6+\rho_6p_6-\rho_6p_6^L)} \tag{26}$$

$$\tau_5 = \frac{2p_{\text{idle}}g_5\rho_5(1-(p_5)^L)}{\rho_5(1-p_5)10(1+p_5\frac{5}{2}+(p_5)^2\frac{9}{2}+(p_5)^3\frac{9}{2}+(p_5)^4\frac{9}{2}) + 2p_{\text{idle}}g_5(1-p_5+\rho_5p_5-\rho_5p_5^L)} \tag{27}$$

transmission from any of the other nodes in the network is given by

$$p_{S,o,k} = \frac{1}{1-\tau_k}\sum_{i=5}^{i=7}(n_i - I_k)\tau_i \frac{1}{1-\tau_i} p_{\text{idle}}; k = 5, 6, 7 \quad (30)$$

where $I_k = 1$ for $i = k$ and zero otherwise, p_{idle} is the probability that none of the nodes transmit during a slot time. The average time duration spent by a node of UP_k in the freeze state during a back-off stage can be expressed in terms of $p_{S,o,k}$ as

$$t_{\text{lock},k^{(y)}} = (p_{S,o,k} t_S + (1 - p_{S,o,k} - p_{\text{idle}}) t_f)\frac{W_{k,y}}{2}. \quad (31)$$

In (31), t_S is computed using (9). Furthermore, t_f the time duration for unsuccessful transmission attempt is calculated as follows:

$$t_f = t_{\text{Data}} + t_{\text{SIFS}} + t_{\text{preamble}} + t_{\text{timeout}} \quad (32)$$

where t_{preamble} is the time to receive the preamble and t_{timeout} is the time out duration and is equal to 30 μs [8].

The total average back-off duration spent by a tagged UP_k node in a CSMA/CA cycle ($t_{\text{BO},k}$) depends on the number of attempts made till successful transmission or packet dropping. The mean back-off delay experienced by a UP_k node per CSMA/CA cycle can be expressed as follows:

$$\begin{aligned} t_{\text{BO},k} = & \left(t_{C\text{slot}}\frac{W_{k,0}}{2} + (1-g')t_{\text{lock},k^{(0)}} + g' t_{\text{SIFS}}\frac{W_{k,0}}{2}\right) \\ & + p_k\left(t_f + t_{C\text{slot}}\frac{W_{k,0}}{2} + (1-g')t_{\text{lock},k^{(1)}}\right. \\ & \left. + g' t_{\text{SIFS}}\frac{W_{k,0}}{2}\right)\cdots \\ & + p_k^{L-1}\left(t_f + 2^{\lfloor \frac{L-1}{2}\rfloor}\frac{W_{k,0}}{2}(t_{C\text{slot}} + g' t_{\text{SIFS}})\right. \\ & \left. + (1-g')t_{\text{lock},k^{(L-1)}}\right) \end{aligned} \quad (33)$$

where $g' = p_{\text{idle}} g_k$ and $t_{C\text{slot}}$ is the CSMA slot duration. In (33), the first term represents the average back-off duration in the first transmission attempt. The three components in this term are as follows.

1) Average time spent by the back-off counter to decrement to zero.
2) The average time spent by the counter in the locked state.
3) The SIFS duration spent when the counter unlocks and then resumes back off.

The second term represents the average time spent in back off when the first transmission attempt fails. This term includes an additional time duration of the failed transmission. Similarly, the last term is the average back-off duration of the Lth back-off stage. It may be noted that the contention window size remains same for odd number of failures and doubles for even number of failures. The time for a successful transmission is accounted in (34) in the computation of the mean service time.

The mean service time for successful transmission of a data packet of a UP_k node is

$$t_{k,\text{mean}} = t_{\text{BO},k} n\text{CSMA} + t_S \quad (34)$$

where $t_{\text{BO},k}$ is the average back-off duration of one CSMA/CA cycle, nCSMA is the number of CSMA/CA cycles. The delay experienced to transfer an alarm packet in RAP2 is given by $t_{k,\text{mean}}$. With poisson arrivals, ρ_k, which is the probability that a data frame arrives during the mean service time of the UP_k node, is given by

$$\rho_k = 1 - e^{\lambda_k t_{k,\text{mean}}}. \quad (35)$$

3) Delay Experienced by an Emergency Data Frame in MAP2: Let t_{MAP2} be the total duration of MAP2. Notice that t_{MAP2} depends on the number of alarm packets successfully received at the hub during a superframe and the size of the available emergency data. Assuming that the transmission instant of a tagged node is uniformly distributed over (0, t_{MAP2}), the average delay experienced by emergency data frame in MAP2 can be computed as $(1 - p_{f,\text{RAP2}})(t_{\text{NF}} + \frac{t_{\text{MAP2}}}{2})$ as described in (2). Here, $p_{f,\text{RAP2}}$ is the probability that alarm frame transmission in RAP2 results in a failure and is given by $p_7^{n\text{CSMA}*L}$, t_{NF} is the time duration of notification frame. Let the total number of emergency nodes be n_7 and the fraction of nodes that successfully transmit alarm frames in RAP2 be $n_7' = \lceil (1 - p_{f,\text{RAP2}})n_7 \rceil$. Thus, the time duration t_{MAP2} can be computed as

$$t_{\text{MAP2}} = t_{\text{allocSlot}} \sum_{i=1}^{i=n_7'} \left\lceil \frac{(t_{\text{Data}}^i + t_{\text{SIFS}} + t_{\text{Ack}})}{t_{\text{allocSlot}}} \right\rceil. \quad (36)$$

B. Reliability Calculations

The probability that an emergency data frame suffers transmission failure in EAP2, i.e., $p_{f,\text{EAP2}}$ is given by (3). The probability that an alarm frame suffers transmission failure in RAP2 is computed as p_7^{3L}, where p_7 is the collision probability corresponding to UP_7 frame. We express the reliability of emergency data frame in terms of packet acceptance rate (PAR), which is computed as follows:

$$\text{PAR}_7 = 1 - p_{f,\text{EAP2}} p_7^{3L}. \quad (37)$$

Now, the reliability of UP_k $(k = 6, 5)$ frame in RAP2 is given by

$$\text{PAR}_k = 1 - p_k^L. \quad (38)$$

C. Average Energy Consumed for an Emergency Data Frame Transmission

Let the power consumption of a node in the transmit, receive, and idle states be P_T, P_R, and P_{idle}, respectively. The energy consumed for the successful transmission of a data frame (E_s) is related to the time required for transmitting the data frame t_{Data}, the SIFS duration t_{SIFS} and the time to receive the Ack, i.e, $E_s = P_T t_{\text{Data}} + P_{\text{idle}} t_{\text{SIFS}} + P_R t_{\text{Ack}}$. When the frame transmission is unsuccessful, the energy consumed can be computed as $E_f = P_T t_{\text{Data}} + (t_{\text{SIFS}} + t_{\text{preamble}} + t_{\text{timeout}}) P_{\text{idle}}$.

1) Energy Consumed by Emergency Data Frame in EAP2: The total energy consumed for the successful transmission of an emergency data frame in EAP2 (i.e., $E_{\text{EAP2},s}$) consists of energy consumed for the back-off process and that required for successful frame transmission. Since $\text{CW}_{\min} = \text{CW}_{\max} = 1$ for EAP2, the node spends in the back-off stage for one CSMA slot duration. Hence, $E_{\text{EAP2},s}$ is given by

$$E_{\text{EAP2},s} = P_{\text{idle}}\, t_{\text{CSMAslot}} + E_s. \quad (39)$$

The total energy consumption for unsuccessful transmission attempt can be expressed as

$$E_{\mathrm{EAP2},f} = P_{\mathrm{idle}}\ t_{\mathrm{CSMAslot}} + E_f. \tag{40}$$

The transmission of emergency data frame in EAP2 is unsuccessful with probability $p_{f,\mathrm{EAP2}}$ and the total average energy consumption in EAP2 phase can hence be expressed as

$$E_{\mathrm{EAP2}} = (1 - p_{f,\mathrm{EAP2}})E_{\mathrm{EAP2},s} + p_{f,\mathrm{EAP2}}E_{\mathrm{EAP2},f}. \tag{41}$$

2) Energy Consumed by the Alarm Frame in RAP2 (E_{RAP2}): The average energy consumed for the successful transmission of an alarm frame in RAP2 consists of energy consumed by the corresponding node in the idle state, failed attempt states, and that required for the successful transmission. Energy consumed in the idle state depends on the time spent by the node in the back-off stage in RAP2. For a single CSMA/CA cycle, this time duration $t_{\mathrm{idle},7}$ can be written similar to (33) and the average amount of energy consumed by the node while residing in the back-off stage corresponding to three CSMA cycles is given by $E_{\mathrm{BO}} = 3t_{\mathrm{idle},7}P_{\mathrm{idle}}$. The total energy consumed for failed transmission in one CSMA/CA cycle is given by

$$E_{f,\mathrm{avg}} = E_f + p_7E_f + p_7^2E_f + \cdots + p_7^{L-1}E_f \tag{42}$$

Now, E_{RAP2} is given by

$$E_{\mathrm{RAP2}} = E_{\mathrm{BO}} + 3E_{f,\mathrm{avg}} + (1 - p_{f,\mathrm{RAP2}})E_s. \tag{43}$$

3) Energy Consumed by Emergency Data Frame in MAP2: The energy consumption in MAP2 consists of energy consumption for a successful transmission as well as energy to receive the notification frame

$$E_{\mathrm{MAP2}} = E_s + P_R\ t_{\mathrm{NF}} \tag{44}$$

where t_{NF} is the time duration of the notification frame. The total average energy consumed for the successful transmission of an emergency data frame can be expressed as

$$E_{\mathrm{total}} = E_{\mathrm{EAP2}} + p_{f,\mathrm{EAP2}}E_{\mathrm{RAP2}} + (1 - p_{f,\mathrm{RAP2}})E_{\mathrm{MAP2}}. \tag{45}$$

In the next section, we describe the performance evaluation of the proposed scheme with the help of analytical and simulation results.

V. Analytical and Simulation Results

This section describes the analytical and simulation results. The Levenberg–Marquardt algorithm [34], [35], which is a combination of steepest descent and the Gauss-Newton method, is used to solve the system of nonlinear equations. The various system parameters used for getting the results are listed in Table III. The length of the superframe duration is selected as 100 ms and the RAP2 duration is set as equal to 20 ms [7]. The CSMA slot duration in EAP2 and RAP2 (i.e., $t_{C\mathrm{slot}}$) is selected as equal to 0.145 ms [8]. For MAP, the duration of an allocation slot is equal to 3.5 ms, so as to accommodate transaction of a frame having maximum size, i.e., 255 Bytes [8]. Furthermore, we consider six nodes with one-periodic allocation during MAP1, H. We have allocated the same number of slots, i.e., six slots, for m-periodic nodes in MAP1, L also. The proposed scheme was implemented using Castalia-3.2 [36] which works on the OMNET++ platform. Castalia implements baseline MAC proposed by the IEEE 802.15 Task Group 6. The structure of the proposed scheme has been realized by making suitable modifications to the baseline MAC. A single hop network has been set up with variable number of nodes sending uplink traffic to hub. A UP_k node generates data traffic according to a Poisson process of rate λ_k frames/s. The initial energy of the nodes corresponds to a battery of capacity 560 mAHr, which is equivalent to 6048 J. The reported simulation results are obtained by averaging the observations for 5000 superframe durations.

TABLE III
Parameters [8], [33]

Parameter	value	Parameter	value
I_{RX}	13.1 mA	I_{idle}	26 μA
I_{TX}	7.5 mA	N_{Beac}	15 Bytes
N_{MAChdr}	7 Bytes	N_{FCS}	2 Bytes
N_{IAck}	Nil	T_S	1/1 200 000 s
N_{Data}(MAX)	255 Bytes	AlocSltmin	500 μs
AlocSltResln	500 μs	N_{PLCPhdr}	31 bits
SIFS	75 μs	time out	30 μs
N_{preamble}	90 bits	CSMA slot	0.145 ms

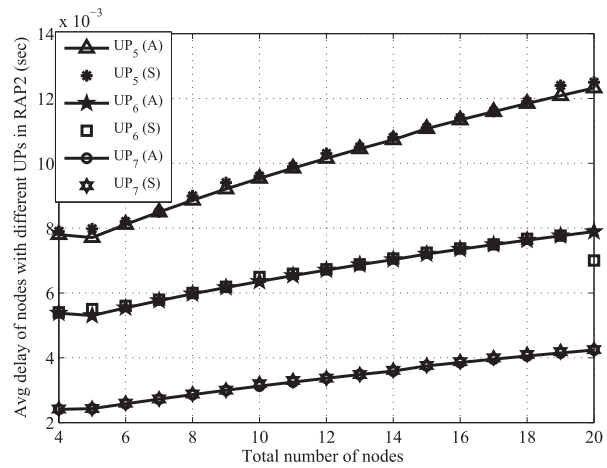

Fig. 4. Average delay in RAP2 of nodes with different UPs versus total number of nodes ($\lambda_5 = \lambda_6 = \lambda_7 = 16$ frames/s; A: analysis; S: simulation).

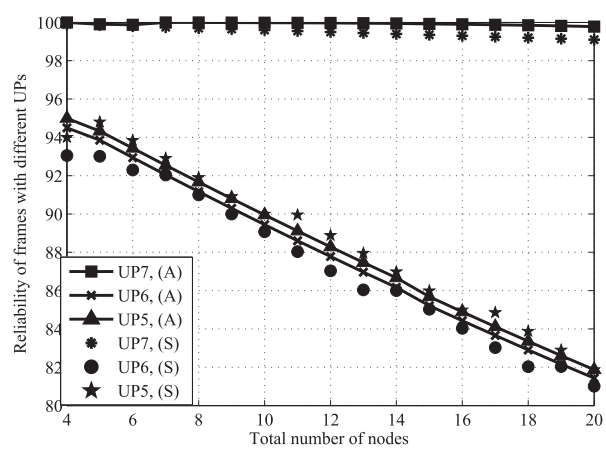

Fig. 5. Reliability of nodes with different UPs in RAP2 versus total number of nodes ($\lambda_5 = \lambda_6 = \lambda_7 = 16$ frames/s; A: analysis; S: simulation).

Fig. 4 and 5, respectively, show the average delay and reliability experienced by nodes with different UPs in RAP2. These quantities are plotted against the total number of nodes accessing the medium during RAP2 that include nodes corresponding

TABLE IV
AVG DELAY AND RELIABILILTY; SAT VERSUS NONSAT

UP	Total Nodes	Avg delay (s) Sat	Avg delay (s) Nonsat	Reliability Sat	Reliability Nonsat
5	20	0.012699	0.010879	80.997	86.325
6	20	0.007937	0.007018	80.747	85.933
7	20	0.004309	0.004193	99.745	99.989

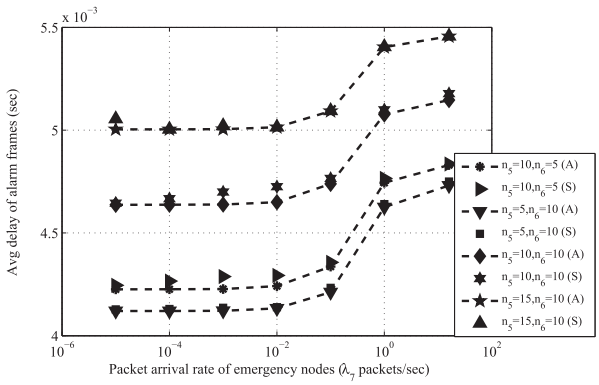

Fig. 6. Total average delay of an alarm frame versus frame arrival rate of emergency nodes ($\lambda_5 = \lambda_6 = 16$ frames/s, $n_7 = 4$; A: analysis; S: simulation).

to UP_5, UP_6, and UP_7. The number of UP_5 (i.e., n_5) and UP_7(i.e., n_7) nodes are equal to 2 each, and the number of UP_6 nodes (i.e., n_6) is increased. Notice that alarm frames (i.e., UP_7 frames) experience the lowest delay since, in RAP2, $\mathrm{CW}_{\min}$ of UP_7 nodes is set as unity. Furthermore, alarm frames are just used for signalling emergency and thus do not carry payload. At the same time, the delay experienced by the UP_5 and UP_6 nodes increases at a higher rate as compared to UP_7 nodes when the total number of nodes in the network is increased. As shown in Fig. 5, alarm frames experience very high reliability as compared to that experienced by frames of UP_5 and UP_6. Furthermore, the reliability of alarm frame is unaffected by the increase in number of UP_5 and UP_6 nodes during RAP2. This is because of the modified strategy adopted for the retransmission of alarm frames in RAP2. Table IV gives the results for the saturation case. The value of ρ_k is taken as unity for saturation condition. For the saturated case, the amount of traffic in the network would be very high resulting in higher collision rate which leads to higher average delay and degradation of reliability.

Fig. 6 shows the total average delay incurred by the alarm frames when the frame arrival rate at the emergency node (i.e., λ_7) is varied. Here, we keep the frame arrival rates of UP_5 and UP_6 nodes as follows: $\lambda_5 = \lambda_6 = 16$ frames/s. Two graphs in Fig. 6 are obtained by fixing the number of emergency nodes equal to 4 and varying the combination of UP_5 and UP_6 up to a total number of 25 nodes. For all cases, the delay becomes higher when the frame arrival rate λ_7 is increased. Fig. 7 show the results for reliability of emergency data frames when the total number of nodes is increased to 50. The reliability of the proposed emergency handling scheme has been observed to be significantly higher than that of the default scheme for emergency handling specified by 802.15.6. Specifically, it is observed that the reliability is almost 100% when the total number of nodes

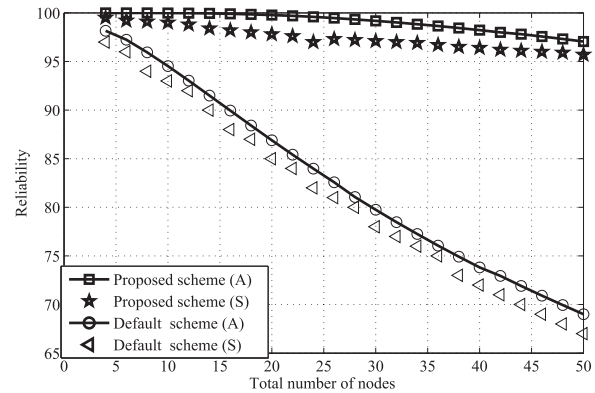

Fig. 7. Reliability of emergency nodes versus total number of nodes: proposed versus default schemes ($\lambda_5 = \lambda_6 = \lambda_7 = 16$ frames/s; $n_7 = 2$; $n_5 = 2$; n_6: 0–46; A: analysis, S: simulation).

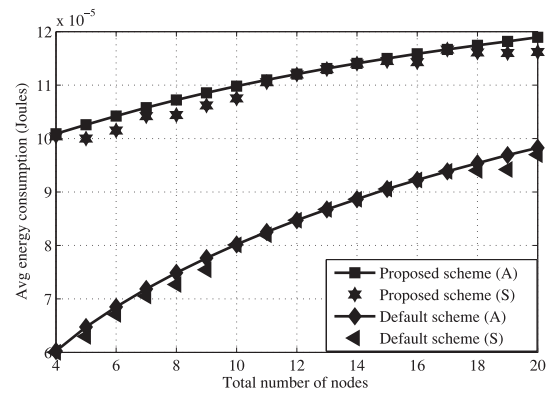

Fig. 8. Average energy consumed for an emergency frame transmission: Proposed versus default scheme ($\lambda_5 = \lambda_6 = \lambda_7 = 16$ frames/s; $n_7 = 2$; $n_5 = 2$; n_6: 0–16; A: analysis, S: simulation).

increases to 25 and thereafter it decreases slightly as the number of nodes is increased to 50. The results further substantiate the scalability of the proposed scheme. Fig. 8 compares the average energy consumed for the successful transmission of an emergency frame under the proposed scheme and the default scheme. Due to additional measures incorporated for enhancing the reliability, the emergency nodes experience higher energy consumption under the proposed scheme as compared to the default scheme.

Fig. 9 shows the reliability of the proposed scheme and the default scheme when the frame arrival rate at the emergency node (i.e., λ_7) is varied. The reliability graphs are drawn for $N = 10$ and $N = 50$. The number of emergency nodes is kept equal to 2 and 10, respectively. The results show that the proposed scheme has significantly higher reliability as compared to the default scheme, and is less sensitive to the variations in packet arrival rate and the number of nodes.

Table V summarizes the average delay incurred by emergency nodes for various combination of n_k (i.e., number of UP_k nodes) and λ_k (frame arrival rate of UP_k nodes). In this experiment, we keep $\lambda_5 = \lambda_6 = 16$ frames/s and two distinct values are considered for λ_7 (i.e., we select $\lambda_7 = 0.016$ frames/s and 1 frames/s). Furthermore, n_7 (i.e., number of UP_7 emergency nodes) is varied. The delay increases as n_7 is increased. However, the delay values reported in Table V are within the tolerable delay limit

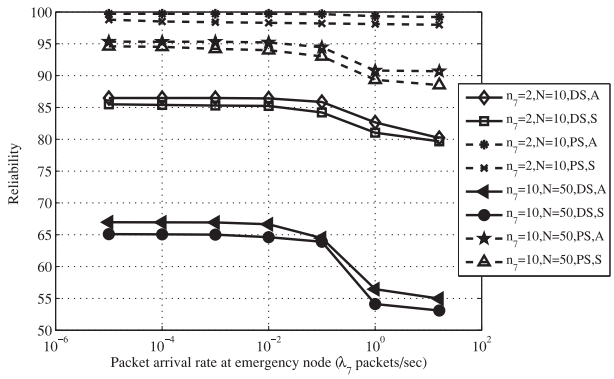

Fig. 9. Reliability of emergency nodes versus frame arrival rate λ_7: Proposed scheme (PS) versus default scheme (DS); $\lambda_5 = \lambda_6 = 16$ frames/s.

TABLE V
AVERAGE DELAY EXPERIENCED BY EMERGENCY NODE

n_7	n_5	n_6	N	λ_7	t_{MAP2}(ms)	Delay(ms)
1	0	0	14	0.016	0	52.5
2	1	0	15	0.016	7	76.2
2	3	3	20		7	76.2
3	1	0	16	0.016	10.5	78
3	3	2	20		10.5	78
4	1	0	17	0.016	14	79.8
4	2	2	20		14	79.8
5	1	0	18	0.016	17.5	81.5
5	1	2	20		17.5	81.5
2	1	0	15	1	7	76.2
2	3	3	20		7	76.2
3	1	0	16	1	10.5	78
3	3	2	20		10.5	78
4	2	2	20	1	14.0	79.8
5	1	0	18	1	17.5	81.9
6	1	1	20	1	21	83.3
8	0	0	20	1	27.9	86.6
10	0	0	22	1	34.6	90.2

for emergency data frames (i.e., 125 ms), specified in [7]. When the total number of nodes in the network is equal to 22 (this includes 10 emergency nodes as well), the maximum value of average delay encountered has been observed to be 90.2 ms. Hence, the proposed emergency handling scheme significantly improves the reliability of emergency data frames; at the same time, the delay experienced is within tolerable delay values. Furthermore, the proposed scheme is strictly based on the superframe structure specified by IEEE 802.15.6 and the scheme requires minor modifications to the legacy protocol.

VI. CONCLUSION

In this paper, we have proposed an efficient channel access scheme for nodes carrying emergency data frames in WBANs to improve the reliability while meeting the end-to-end delay requirements. We have developed analytical models to compute the reliability and average delay of emergency data frames under the proposed scheme. Performance evaluation results have shown that the proposed scheme can improve the reliability of emergency data frames in the presence of other medical and nonmedical applications. Extensive simulation results were presented to corroborate the analytical findings.

APPENDIX A
DERIVATION OF (16)

We can rewrite (15) using (11) as $b_k(e) = \frac{1-\rho_k}{\rho_k}[(1-p_k)\sum_{x=0}^{x=2}\sum_{y=0}^{y=L-1}(p_k)^y b_k(x,0,0) + p_k(p_k)^{3L-1}b_k(0,\ 0,\ 0)]$ $= \frac{1-\rho_k}{\rho_k}[(1-p_k)\sum_{x=0}^{x=2} b_k(x,0,0)\frac{1-(p_k)^L}{1-p_k} + (p_k)^{3L}b_k(0,0,0)] = \frac{1-\rho_k}{\rho_k}[(1-(p_k)^L)\sum_{x=0}^{x=2} b_k(x,0,0) + (p_k)^{3L}b_k(0,0,0)]$ and we can express $b_k(e)$ as

$$b_k(e) = \frac{1-\rho_k}{\rho_k}[(1-(p_k)^L)b_k(0,0,0) \times (1+(p_k)^L+(p_k)^{2L}) + (p_k)^{3L}b_k(0,0,0)] \tag{A.46}$$

which simplifies to (16).

APPENDIX B
DERIVATION OF (23)

The first term of (22) can be written as $\frac{(1-(p_k)^R)(1+p_k^R+p_k^{2R})}{(1-p_k)}b_k(0,0,0)$. Using (11), (18), and (20), the second term of (22) can be written as $\sum_{z=1}^{z=W_{k,y}} \frac{(Wk,y+1)-z}{(Wk,y)\ p_{\text{idle}}g_k} f_1$. $= \frac{(Wk,0+1)}{2p_{\text{idle}}g_k}b_k(0,0,0)$. Using (11) and (21), the third term can be written as $\sum_{x=1}^{x=2}\frac{(Wk,0+1)(p_k\ b_k(x-1,L-1,0))}{2p_{\text{idle}}g_k} = \frac{(Wk,0+1)}{2p_{\text{idle}}g_k}(p_k^L+p_k^{2L}\ )\ b_k(0,0,0)$. The fourth term is expressed in terms of $b_k(0,0,0)$ using (11)–(13) as follows: $\sum_{x=0}^{x=2}\sum_{y=1}^{y=L-1}\sum_{z=1}^{z=W_{k,y}}\frac{(W_{k,y}+1)-z}{(W_{k,y})\ p_{\text{idle}}g_k}(p_k)^y b_k(x,0,0) = \sum_{x=0}^{x=2}\frac{b_k(x,0,0)}{p_{\text{idle}}g_k}\sum_{y=1}^{y=L-1}(p_k)^y\frac{(W_{k,y}+1)}{2}$. The IEEE 802.15.6 specifies $W_{k,y} = 2^{\lfloor \frac{y}{2} \rfloor}\ W_{k,0}$ and we obtain

$$\sum_{y=1}^{y=L-1}(p_k)^y\frac{(W_{k,y}+1)}{2} = \left[\left(p_k\frac{(W_{k,0}+1)}{2}\right)+\cdots + (p_k)^4\frac{(4W_{k,0}+1)}{2}\right]. \tag{B.47}$$

For $L = 5$ and $W_{k,0} = 1$, we obtain

$$\sum_{y=1}^{y=L-1}(p_k)^y\frac{(Wk,y)}{2} = \left[(p_k)+(p_k)^2\frac{3}{2}+(p_k)^3\frac{3}{2}+(p_k)^4\frac{5}{2}\right] \tag{B.48}$$

from (11), we obtain

$$\sum_{x=0}^{x=2}\sum_{y=1}^{y=L-1}\sum_{z=1}^{z=W_{k,y}} b_k\left(x,y,z\right) = \frac{1}{p_{\text{idle}}}\left[(p_k)+(p_k)^2\frac{3}{2}+(p_k)^3\frac{3}{2}+(p_k)^4\frac{5}{2}\right] \times b_k(0,0,0)(1+(p_k)^R+(p_k)^{2R}. \tag{B.49}$$

Hence, the sum of probabilities simplifies to (23).

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Kayiparambil S. Deepak received the Master's degree in communication systems from the Department of Electrical Engineering, Indian Institute of Technology Madras, India, in 2009, and the Ph.D. degree from the Department of Electronics and Communication Engineering, National Institute of Technology, Calicut, India, in 2016.

He is a Faculty of the Government Engineering College, Kozhikkode, India. His research interests include wireless communication networks.

Anchare V. Babu received the Master of Engineering degree in telecommunication from the Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore, India, in 2002, and the Ph.D. degree from the Department of Electronics and Communication Engineering, National Institute of Technology, Calicut, India, in 2008.

He is currently an Associate Professor with the National Institute of Technology. His primary research focus is on wireless networks.