i-MAC: In-Body Sensor MAC in Wireless Body Area Networks for Healthcare IoT

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***Abstract*—The application of Internet-of-Things (IoT) technology in modern healthcare environment has given rise to a new paradigm known as healthcare IoT. The wireless body area network (WBAN) is one of the basic building blocks of IoT-based healthcare system, comprising many wearable (on-body) and implant (in-body) sensors placed in or around patient body connected to a hub for physiological signal monitoring. In in-body sensor-based WBAN, guaranteeing quality-of-service and prolonging network lifetime are major impediments due to the sensor location and limited battery capacity. In this article, we propose a novel energy-efficient medium access control (MAC) protocol for IEEE 802.15.6 standard complaint in-body sensor-based WBAN. Typically, the in-body sensor-based WBAN communication is hub-initiated; however, in case of an emergency event, the in-body sensor node transmits an emergency frame arbitrarily without sensing the channel. This inadvertent in-body sensor-initiated transmission has a very high probability of collision with the ongoing hub-initiated transmission, and/or another in-body sensor-initiated emergency frame transmission. This results in emergency frame retransmission and consequently affects the node's energy consumption and lifetime. To alleviate this issue, we propose a modified superframe structure, in which separate access phases are introduced for the emergency event and regular event. In case of an emergency event, a novel emergency event handling scheme and a ranking and priority assignment protocol is proposed to detect and address the critical event of in-body sensors. To minimize the collision, a scheduled access mechanism is proposed according to the criticality of the node. Performance analysis of the proposed in-body sensor MAC is done in terms of latency and overall power consumption, in case of both emergency and regular events.**

***Index Terms*—Delay, emergency event, healthcare, implant sensor, medium access control (MAC), power consumption, wireless body area network (WBAN).**

I. Introduction

WITH the rapid increase in chronic patients worldwide in recent years, wireless body area networks (WBANs) are receiving great attention for critical patient remote monitoring and providing real-time ubiquitous healthcare services [1]–[3]. The recent advancements of the Internet of Things (IoT) technology in healthcare domain guarantees cost-effective and ubiquitous healthcare facilities to patients situated in remote areas [4]–[6]. Typically, an IoT-enabled WBAN consists of both wearable (on-body) and implant (in-body) sensors placed in or around human body to sense and collect data from a patient's body and forward it to the healthcare center for further analysis. To support IoT-enabled body area network-centric wireless communications, IEEE proposed a new communication standard—namely the IEEE 802.15.6 standard [7], which supports separate physical and medium access control (MAC) layer for on-body and in-body sensors.

In typical in-body sensor-based WBAN, the in-body sensors (e.g., pacemaker, neuro-stimulator, insulin pump, gastric electric stimulator, etc.) placed inside the human body sense and collect data from respective organs and transmit through the wireless medium to a hub placed outside of the human body. The wireless channel between in-body sensors and the hub is highly dynamic and time-varying in nature and varies with the placement of the sensor node, unlike the conventional on-body sensor-based WBAN [8], [9]. The signal attenuation in case of on-body sensor WBAN mainly occurs due to human body shadowing, whereas, in case of in-body sensors sever attenuation occurs due to the depth of various tissues and muscle below which the sensor is placed which is different for every human body [10], [11]. As the implant sensors are handling very critical physiological parameters, so delaying or missing of any data due to packet collision or packet drop has severe detrimental effect [12], [13]. In addition to that, sensor node should operate in ultra-low power as recharging or replacing an implant sensor node is a very cumbersome process. In our work, we use the term in-body and implant sensor interchangeably.

For sophisticated implant communication, the Federal Communications Commission has allocated a separate MICS band (402–405 MHz) for implant communication. According to the IEEE 802.15.6 MAC protocol [7] for the MICS band communication, except for an emergency event, the communication is always initiated by the hub employing the scheduled access method. The hub first transmits a polling frame to the particular sensor node and provides immediate uplink allocation interval for data transmission. However, in case of a medical implant event report, i.e., emergency event, the node abruptly transmits emergency frames, having no payload, without sensing the channel condition. Upon failing to receive the instant

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acknowledgment from the hub the node retransmits the frame up to retransmission limit is achieved. The hub transmits the acknowledgment frame once it receives the emergency frame and assigns instant uplink allocation interval to the node for further data transmission.

The arbitrary transmission of emergency frames, in case of a medical event report, without sensing the channel, results in a very high probability of collision at the hub end with the current frame transmission or with the emergency frames from the other nodes [14]. This results in a delay in the emergency event detection and leads to a more critical situation. An increased number of collisions results in an increase in retransmission and leads to energy depletion in the implant node. As energy is a vital constraint for battery-driven implant sensors, therefore, in this article, a new energy-efficient MAC layer is proposed for implant sensor-based WBAN. The hub periodically collects the emergency data by employing a scheduled access method to avoid the energy waste due to collision and retransmission. The main *contributions* of this article are listed as follows.

1) We have proposed a modified superframe structure with separate allocation intervals amenable to IEEE 802.15.6 standard for in-body sensor regular and emergency event communication.
2) We have introduced a novel emergency handling scheme to avert the critical situations that occur in the case of in-body sensors. An emergency event detection mechanism is proposed based on the implant sensed data to separate the emergency event from the regular event.
3) A novel priority assignment scheme is proposed based on the criticality of the in-body sensor collected data, which takes into account both the number and the criticality of the emergency event encountered by the node.
4) Both latency and power consumption analysis is done for both regular and emergency event in case of implant communication using the in-body sensor medium access control (i-MAC) protocol.

II. Related Work

A survey on design challenges in the case of in-body sensor communication MAC is presented in [15]. The work summarizes the issues occur in case of power consumption while using the existing wireless standard (Wi-Fi, IEEE 802.15.4) MAC protocol for implant communication. In [16], IEEE 802.15.4b and IEEE 802.15.4a-chirp spread spectrum is used for implant sensor communication. According to the authors, the limited sensing range in the case of implant sensors results in unreliable idle channel access operation. However, the IEEE 802.15.4 standard may not be suitable in practice for an implant communication system.

A link quality aware MAC protocol for implant-based WBAN using IEEE 802.15.6 standard while considering various human activities is presented in [17]. Both carrier sense multiple access/collision avoidance (CSMA/CA) and scheduled access mode are used for the communication based on the wireless link quality. However, obtaining channel quality information frequently in the case of implant-based WBAN is challenging to obtain. Along with that, this increases the communication overhead and overall energy consumption. In [18], an adaptive energy-efficient emergency packet transmission scheme is proposed for the emergency event according to the subchannel transmission success probability. A modified IEEE 802.15.6 standard specified superframe structure for implant communication is proposed in [19]. A separate access phase termed as an emergency access phase (EAP) is proposed for emergency data packet during which CSMA/CA medium access mechanism is employed. However, there is no provision of an emergency event handling scheme for implant sensors which may have catastrophic effects on critical patients.

All the above-mentioned MAC protocols for implant-based WBAN lack in emergency handling event and proposed CSMA/CA based channel access mechanism for emergency data transmission which is energy inefficient. In addition to that, CSMA/CA mechanism in case of implant communication is unreliable due to the placement of sensor nodes inside the tissues which shrinks the sensing range and makes the collision inevitable. In this article, we propose an energy-efficient MAC protocol for implant communication with scheduled access mechanism for emergency of data transmission. A novel emergency handling scheme is proposed for detection of emergency event in the implant node and schedule the node for transmission according to its criticality.

III. System Model

The IEEE 802.15.6 standard supports both one-hop and two-hop star topology for in-body and hub communication. In our work we assume an one-hop star topology based communication architecture between implant nodes and hub. The maximum number of in-body sensors that can be connected to hub is up to 64 as specified by the standard [7].

The wireless channel state of implant communication is lossy and highly time-varying in nature due to the presence of various tissue layers with different thicknesses above it and for the different movements of the human body. Let $P_L(d)$ is the received signal power at hub places at a distance d from the implant, then the path loss model for the in-body communication over the MICS band can be expressed as

$$P_L(d) = P_L(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) + \Gamma[dB] \quad (1)$$

where $P_L(d_0)$ is the reference path loss at distance d_0, n is the path loss exponent, and $\Gamma \sim (0, \sigma^2)$ is normal distributed random variable with variance σ^2. The values of channel parameters n and σ^2 depend on the location of the implant inside the human body such as near deep tissue or near the skin surface, i.e., $n = 4.22$ and $\sigma = 6.81$ [11].

IV. Design of i-MAC

In this section, we illustrate the proposed i-MAC (in-body sensor medium access control) for the implant sensor communication in the MICS band. The time axis of the hub is divided into repetition intervals known as superframe as shown in Fig. 1. At the beginning of each superframe, the hub broadcasts a beacon frame to each implant sensor for synchronization. Each superframe is divided into five allocation intervals followed by

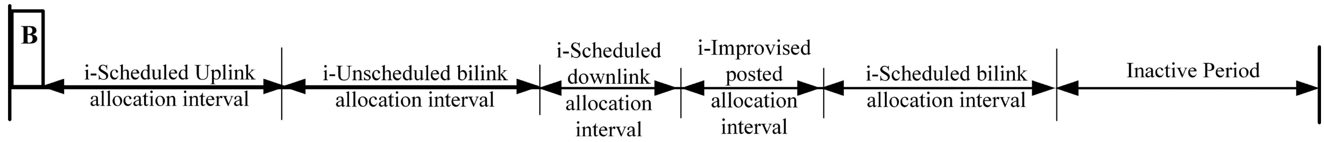


Fig. 1. i-MAC superframe structure.

an inactive period. The first two allocation intervals are meant for emergency event handling and the rest three are for a regular event. Note that, in the proposed i-MAC protocol, periodic check of an emergency event is done in every superframe for each node. The lengths of allocation intervals may have zero value, except the i-Scheduled uplink allocation interval, i-Unscheduled bilink allocation interval, and the i-Scheduled bilink allocation interval. The detailed analysis of all the allocation intervals is presented below.

1) i-Scheduled uplink allocation interval: The total i-Scheduled uplink allocation interval is divided into the scheduled uplink slots, one for each node. The ordering of the slots is randomly decided by the hub and informed to nodes in the beacon frame. In each uplink slot, the node transmits the emergency event data (EED) frame to the hub which consists of sensing data collected by the node by periodic sensing during the inactive period of the previous superframe. After the reception of the EED frame from a particular node, the hub transmits an instant acknowledgment (I-Ack) frame to the node. At the end of this allocation interval, the hub prioritizes the critical nodes.

2) i-Unscheduled Bilink Allocation Interval: After the reception of the EED frame, the hub undergoes an emergency handling process and sort the nodes according to their criticality level. In this allocation interval, the hub initiates the frame transaction with the node according to the criticality order. The hub transmits a polling frame to the particular node and allocates immediate polling interval. After the reception of the polling frame, the node transmits the immediately sensed data frame to the hub in the allocated polled interval. The allocation interval varies according to the criticality of the node. If the allocated polled interval is not sufficient for the node, the hub provides additional polled allocation by sending another polled frame. The frame initiation is always done by the hub in this interval. The node transmits I-Ack or block acknowledgment (B-Ack) according to the requirement of the hub and vice versa.

3) i-Scheduled Downlink Allocation Interval: In this interval, the hub may initiate frame transactions by transmitting the data frame at the start of each allocation interval. During this interval, the node is in the receiving mode. The hub sends the data frames addressing to the particular node. Upon the reception of the data frame, the node transmits I-Ack. If there is any medication/solution need to the sensor node, then the hub uses this interval to transmit the instruction to the node.

4) i-Improvised Posted Allocation Interval: The i-Improvised posted allocation is used by the hub if enough time is not left for data transmission in the preceding interval. The hub transmits a polling frame addressed to the particular node to which the last data frame was sent and immediately allocates the posting interval. After receiving the posting frame, the node becomes ready to receive the data frame from the hub.

5) i-Scheduled Bilink Allocation Interval: At the beginning of this interval, the hub chooses a node in a random manner and initiates the frame transaction by transmitting a polling frame. An immediate polling allocation is granted by the hub for the respective node. Upon reception of the polling frame, the node becomes ready to transmit data. The node does not start transmission of its own in this interval. If the allocated polling interval is insufficient for the data transaction, then the node requests for more time. The hub allocates additional slots by transmitting another polling frame at the end of the current polling interval.

V. Emergency Event Handling in i-MAC

In this section, we discuss the emergency event handling scheme, proposed for the i-MAC. The overall process is divided into two parts. The first part is the sensing events with periodic sense sleep (PSS) cycle in the inactive period of the i-MAC superframe. During a PSS cycle, each implant sensor node wakeup and just senses the data from their respective organ and goes to the sleep state. The node senses in a periodic manner for n times and all the sensing data are stored in the node buffer. At the beginning of the i-Scheduled Uplink allocation interval, all implant sensor nodes transmit their EED frame to the hub which consists of a header, data corresponding to n sensing events, and a frame checking sequence. The second part is the emergency event detection which is done at the hub end, in which hub assigns an emergency event index (EEI) to each sensing event and prioritizes the node according to a novel ranking and priority assignment (RPA) algorithm as explained below.

A. Emergency Event Detection

After the reception of the EED frames, the hub decides the criticality level of individual nodes and assigns priority to the nodes. Keeping the energy-constrained characteristics of the in-body sensor in mind, our proposed model facilitates the criticality computation task at the hub. For each sensing instants, the hub decides the emergency level and assigns EEI which can be expressed as EEI $= 1$ for an emergency event and 0 for normal/regular event. Hub stores all the n EEI values in a buffer in such a manner that the first event is stored in the most significant bit (MSB) and the most recent event is stored in the least significant bit (LSB).

B. Ranking and Priority Assignment Algorithm

Critical condition of an individual in-body sensor node is calculated based on the EEIs of the corresponding node. This criticality calculation procedure follows three phases. The first phase arranges the nodes according to their number of critical events. The second phase sorts the nodes according to the effectiveness of critical events. This is determined by the critical events that occurred towards the end of the previous superframe and assigning priority to them, as it is most likely to continue in the critical state in the current superframe too. The third phase ranks and prioritizes the nodes according to the number of critical events and their effectiveness. Details of all these phases are described below.

1) Phase-I: In the first phase, the hub first sorts the nodes according to the maximum number of 1's. This indicates that the node has encountered a critical event maximum number of times during sensing. Nodes having the same number of 1's are sorted according to their node ID value. The output of Phase-I is denoted by a vector $\varphi = [\varphi_1, \varphi_2, \ldots, \varphi_N]$, where $\varphi_b = \sum_{i=1}^{n} E_b[i]$ is the sum of all the EEIs of the bth implant node. To avoid the ambiguity occurring due to nodes having the same φ_b values, a *dense ranking* procedure is used, in which the nodes having the same φ_b values are assigned the same ranks and the next node has immediately next rank number. The vector of the rank of nodes is denoted by $R_\varphi = [R_\varphi[1], R_\varphi[2], \ldots, R_\varphi[N]]$.

2) Phase-II: In this phase, the nodes are sorted according to the occurrence of critical events. The nodes having emergency events occurring during the last phase of sensing are more critical than the nodes having critical events in the first phase of sensing. The criticality of a node increases as the position of 1's goes from MSB to LSB. To sort the nodes according to the position of 1's, the bitwise sorting method is used. In this method, the EEI vector of the corresponding node is first reversed using right circular shift and then its decimal equivalent is calculated. The node having the highest decimal equivalent will be at the top of the priority list and sorted in descending order.

Let the right circular shift of EEI vector is denoted by a vector $\tilde{E}_b = [\tilde{E}_b[1], \tilde{E}_b[2], \ldots, \tilde{E}_b[n]]$. The decimal equivalent of $\tilde{E}_b$ is denoted by a vector $\psi = [\psi_1, \psi_2, \ldots, \psi_N]$, where $\psi_b = \sum_{i=1}^{n} \tilde{E}_b[i] * 2^{n-(i+1)} \quad \forall b \in \{1, 2, \ldots, N\}$. A general ranking procedure is followed in this phase to sort the nodes. The vector of rank of all nodes in this phase is denoted by $R_\psi = [R_\psi[1], R_\psi[2], \ldots, R_\psi[N]]$.

3) Phase-III: A hybrid Phase-III sorting procedure is followed for final selection. Priority is assigned to nodes having more number of 1's in EEI and more number of 1's towards LSB part of the emergency bank. To achieve that, the sum of the rank of both phases are taken for each individual node. The output vector after Phase-III is denoted as $\chi = [\chi_1, \chi_2, \ldots, \chi_N]$, where $\chi_b = R_\varphi[b] + R_\psi[b], \forall\, b \in \{1, 2, \ldots, N\}$ calculated from Phase-I and Phase-II, respectively. For the nodes having the same χ values, priority is assigned to the node having the lowest R_ψ, because nodes having more number of critical events towards the end of the sensing event are more critical than those having a higher number of 1's. If both nodes have the same χ and R_ψ values then it is concluded that both nodes have the same EEIs. So, priority is given according to their node ID.

The final ranks of nodes are stored in a vector denoted as $R_\chi = [R_\chi[1], R_\chi[2], \ldots, R_\chi[N]]$, where R_{χ_b} is the final rank assigned to node $S[b]$ and $R_\chi[b] \in \{1, 2, \cdots, N\}$ $\forall b \in \{1, 2, \ldots, N\}$. The complete RPA algorithm is provided in Algorithm 1.

Algorithm 1: RPA algorithm

Input: Each sensor node ID
Output: Sorting of node according to critical event
begin
  for $i = 1 : N$ **do**
    Calculate φ_b ▷ Phase-I
  end
  Calculate R_φ vector
  for $i = 1 : N$ **do**
    Calculate ψ_b ▷ Phase-II
  end
  Calculate $R_\psi^{(i)}$ vector
  for $i = 1 : N$ **do**
    $\chi_b[i] = R_{\varphi_b}[i] + R_{\psi_b}[i]$ ▷ Phase-III
  end
  Calculate $R_\chi[i]$ vector
end

VI. Performance Metrics

A. Latency Analysis

In i-MAC, the overall latency analysis is divided into two parts: 1) Emergency event and 2) normal event. Details of these two events are demonstrated below.

1) For Emergency Event: In the *i-Scheduled uplink allocation*, the total time required from the generation of EED frame in the implant node to the reception of the I-Ack frame is divided into three parts. The first part corresponds to the transmission duration of nodes scheduled ahead of the tagged node. The second part is for the time required for successful transmission of EED frame i.e., T_{EED}. The last part is the time required for the reception of the I-Ack frame from the hub denoted as $T_{I-\text{ACK}}$.

Let there are total N number of nodes connected to the hub and among them j number of nodes is scheduled ahead of the bth tagged node in the current allocation interval. Let T_b^e be the total time elapsed from generation of an EED frame to the successful reception near hub for the bth in-body node, given that j of the given $b-1$ nodes are scheduled before bth node transmit. Then the value of T_b^e is $T_b^e = j * (T_{\text{EED}} + T_{I-\text{ACK}}) + T_{\text{EED}} + T_{I-\text{ACK}}$. In this case, T_{EED} and $T_{I-\text{ACK}}$ are constant and the same for all sensor nodes. As the hub can assign a node to any uplink slot out of N slots uniformly with probability $1/N$ therefore the random variable j follows an uniform distribution $U[1, N]$ with mean $N/2$. Averaging over j, the *average waiting time of an EED frame* in the i-Scheduled uplink allocation interval is calculated as $\mathbb{E}[T_b^e] = \frac{N+2}{2}(T_{\text{EED}} + T_{I-\text{ACK}})$.

In the *i-Unscheduled bilink allocation interval*, the hub transmits polling frames according to the priority assigned by the RAP algorithm. The hub may allocate more number of slots to the node when needed. Let T_b^w be the waiting time of a node b before transmission. Then, the average waiting time of a node b is calculated as

$$\mathbb{E}[T_b^w] = R_\chi[b] * T_{\text{poll}} + \sum_{l=1}^{R_\chi[b]-1} \mathbb{E}[T_l^{\text{act}}] \tag{2}$$

where $R_X[b]$ is the *rank of bth node* calculated by the RAP algorithm. T_{poll} is the polling frame duration. $\mathbb{E}[T_l^{\text{act}}]$ is the average active time duration of a node l, in which the total number of data frame transmission and reception takes place between hub and node. Mathematically

$$\mathbb{E}[T_l^{\text{act}}] = \mathbb{E}[T_b^{\text{poll}}] + \mathbb{E}[T_b^D] + \mathbb{E}[T_b^{HD}] + \mathbb{E}[T_b^{I-\text{ACK}}] \quad (3)$$

where T_b^{poll} and $T_b^{I-\text{ACK}}$ be the overall duration of polling and I-Ack frames in a bilink communication between node b and hub, respectively. T_b^D and T_b^{HD} are the total transmission duration of node and the hub data frame, respectively. As the hub can assign multiple allocation intervals to node according to its criticality because the more critical nodes may have to transmit data with a high sampling rate. If ϵ is the probability of a node transmitting data more than one allocation slot and α the probability of a hub transmitting more than the allocation interval to node. The expressions of $\mathbb{E}[T_{D,b}]$, $\mathbb{E}[T_{h-\text{Data}}]$, and $\mathbb{E}[T_b^{I-\text{ACK}}]$ are given as

$$\mathbb{E}[T_b^D] = T_{\text{payload}} \sum_{l=1}^{a_1} l\epsilon^{l-1} \quad (4)$$

$$\mathbb{E}[T_b^{HD}] = T_{\text{payload}} \sum_{l=1}^{a_2} l\alpha^{l-1} \quad (5)$$

$$\mathbb{E}[T_b^{I-\text{ACK}}] = (a_1 + a_2)T_{I-\text{ACK}} \quad (6)$$

where T_{payload} is the transmission time of the payload data frame. a_1 and a_2 are the maximum number of allocation intervals occupied by the node and hub, respectively, for bilink communication.

2) For Regular Event: The *i-Scheduled bilink allocation interval* is assigned for regular normal event, during which the data transmission is always initiated by the hub. The transmission scheme followed in this allocation interval is identical to the implant communication described by the IEEE 802.15.6 standard. The hub transmits polling frames to a random node and allocates time slots for it. The node transmits its data packet and waits for I-Ack. At the end of a polling allocation interval, the node goes to sleep state. If T_b^{Reg} is the duration of node b during an assigned polling allocation interval, during which both the hub and the node transmit data. Then, the value of $\mathbb{E}[T_i^{\text{Reg}}]$ is given by

$$\mathbb{E}[T_i^{\text{Reg}}] = \mathbb{E}[T_b^{\text{poll}}] + \mathbb{E}[T_b^D] + \mathbb{E}[T_b^{HD}] + \mathbb{E}[T_b^{I-\text{ACK}}] \quad (7)$$

where $\mathbb{E}[T_b^D]$ and $\mathbb{E}[T_b^{HD}]$, are the average transmission duration of node and the hub data frame, respectively, as explained in (4) and (5). Let T_b^{wt} be the waiting time of a node b in the i-Scheduled bilink allocation interval then, the average waiting time of a node b in i-Scheduled bilink allocation interval. Then the *average waiting time* of a node b in i-Scheduled bilink allocation interval is expressed as

$$\mathbb{E}[T_b^{wt}] = \mathbb{E}[T_{\text{poll}}] + \sum_{i=1}^{r[b]-1} Pr[A_i|A_X]\mathbb{E}[T_i^{\text{Reg}}] \quad (8)$$

where $r[b]$ is the order wise rank of poll reception for node b during the ongoing bilink allocation interval. The event A_i denotes the reception of polling frame by the node at the ith attempt. The event A_X denotes the reception of polling frame by the node within the Xth attempt. X is the total number of nodes that can be accommodated within the complete i-Scheduled bilink allocation interval. The value of X is $0 \leq X \leq N$. If within the i-Scheduled bilink allocation interval, each node has an equal probability of receiving poll frames from the hub, then we can write the probability of receiving a polling frame given the total Xth attempt is $Pr[A_i|A_X] = \frac{B^i - B^{i-1}}{B^X - 1}$, where $B = 1 - \frac{1}{N}$ and N is the total number of in-body sensor nodes.

B. Power Consumption

The overall power consumption of an implant node within a superframe interval time duration depends on two factors. The first one is due to the PSS cycle performed during the inactive period of a superframe (explained in Section V) and the second one is due to the overall operation occurring during different allocation intervals in i-MAC. The power consumption during i-MAC is further divided into power consumption during an emergency event and that during a regular event.

1) Power Consumption Due to PSS-Cycle: The implant nodes wake up on a certain duration, sense data, and then go for the sleep duration during a PSS-cycle. Let P_{sense} and P_{idle} be the power consumption by implant node for sensing data and during idle state, respectively. For a given n number of PSS-cycle events before the starting of the next superframe, and τ and t_s are the sense and sleep duration during a PSS-cycle. Therefore, the overall power consumed is given by $P_{\text{PSS}} = n(\tau P_{\text{sense}} + t_s P_{\text{idle}})$.

2) Power Consumption During Emergency Event: During the i-Scheduled uplink allocation interval, the node transmits the sensing data accumulated during PSS-cycle in the form of the EED frame. After successful transmission of the EED frame, the node goes to the idle state and refrains itself from further activities until the end of the current allocation interval. If $P_{\text{avg}}^{i-\text{up}}$ is the average power consumed by the node during this allocation interval, then it can be expressed as $P_{\text{avg}}^{i-\text{up}} = T_{\text{EED}}P_{Tx} + T_{I-\text{ACK}}P_{Rx}$, where P_{Tx} and P_{Rx} are the power consumed during the transmission and receiving state of the sensor node.

During the *i-Unscheduled bilink allocation interval* the node transitions through the three different states. The first one is the idle state before the reception of the polling frame. After the reception of the polling frame, the node starts transmitting the present data to the hub and waits for the reception of the I-Ack from the hub. The average power consumption during i-Unscheduled bilink allocation interval is $P_{\text{avg}}^{i-bl} = \mathbb{E}[T_b^w]P_{\text{idle}} + \mathbb{E}[T_b^D]P_{Tx} + (\mathbb{E}[T_b^{HD}] + \mathbb{E}[T_{I-ACK}])P_{Rx}$. The expressions of $\mathbb{E}[T_b^w]$, $\mathbb{E}[T_b^D]$, $\mathbb{E}[T_b^{HD}]$, and $\mathbb{E}[T_{I-\text{ACK}}]$) is described in (2), (4), (5), and (6), respectively.

3) Power Consumption During Regular Event: Power consumption in each node during the *i-Scheduled bilink allocation interval* is the power consumed due to idle listening of a node during the waiting time and the transmission power during the active duration of the node. If P_{avg}^{i-sbl} is the average power consumption during the i-Scheduled bilink allocation interval, then $P_{\text{avg}}^{i-\text{sbl}} = \mathbb{E}[T_b^{wt}]P_{\text{idle}} + (\mathbb{E}[T_b^D] + \mathbb{E}[T_{I-\text{ACK}}])P_{Tx} + (\mathbb{E}[T_b^{HD}] + \mathbb{E}[T_{I-\text{ACK}}])P_{Rx}$. The expressions of $\mathbb{E}[T_b^{wt}]$ is shown in (8).

TABLE I
SIMULATION PARAMETERS

Parameters	Values	Parameters	values
Payload size [7]	0-255 Bytes	Reception current [19], [20]	5 mA
Sensing duration	50 μs	P_{sense}	6 μW
P_{Tx}	22 μW	Idle current	250 nA

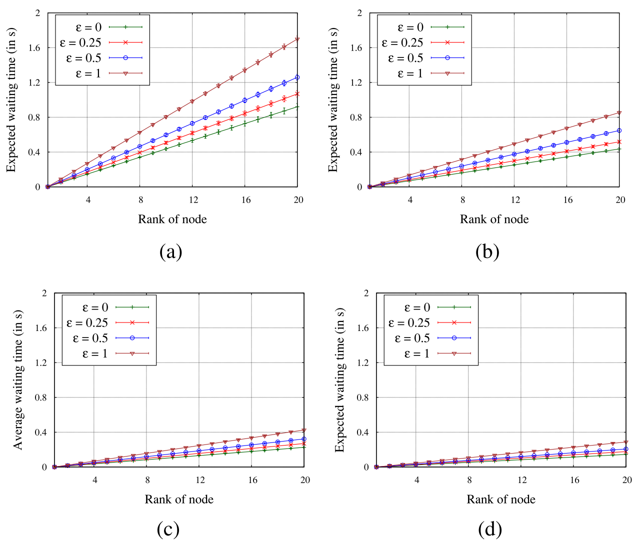


Fig. 2. Average waiting time versus rank of node during emergency event for different MICS band data rates. (a) Data rate = 75.9 kb/s. (b) Data rate = 151.8 kb/s. (c) Data rate = 303.6 kb/s. (d) Data rate = 455.4 kb/s.

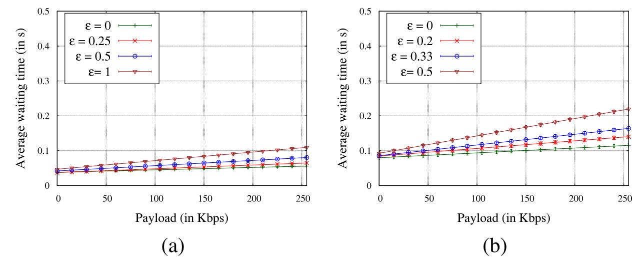


Fig. 3. Average waiting time versus payload. (a) Number of nodes = 16. (b) Number of nodes = 32.

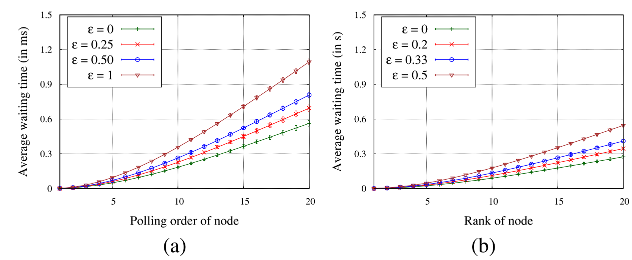


Fig. 4. Average waiting time versus polling order of node. (a) Data rate = 75.9 kb/s. (b) Data rate = 151.8 kb/s.

4) Overall Power Consumption: Finally, the overall power consumption in an in-body sensor node is given as $P_{\text{total}} = P_{PSS} + P^{i-up}_{\text{avg}} + P^{i-bl}_{\text{avg}} + P^{i-sbl}_{\text{avg}}$.

VII. Performance Analysis

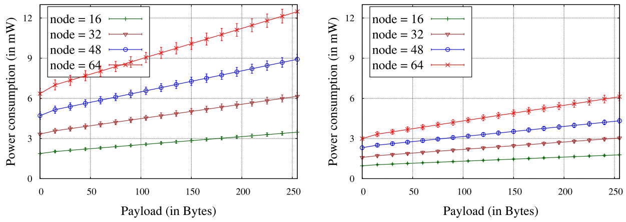
A. Simulation Setup

The system parameters used for the analysis are presented in Table I. We use MATLAB simulator to simulate the proposed scheme. It may be noted that the magnitude of α, i.e., the probability of the hub transmitting more than one data frame during the *i-Unscheduled bilink allocation interval* (for emergency event reporting) or the *i-Scheduled bilink allocation interval* (for regular event reporting) is assumed to be randomly chosen from within [0,0.5]. Also, as IEEE 802.15.6 supports four distinct data rates at 75.9, 151.8, 303.6 and 455.4 kb/s, for the MICS band [7]. In our work we assume homogeneous tissues and homogeneous human body with in-body sensors placed on the near surface of each patient, i.e., $n = 4.22, \sigma = 6.81$, and $d_0 = 30$ mm. Further, the distance d varies between 100 and 300 mm. All results are taken with 95% confidence.

B. Analysis of Latency

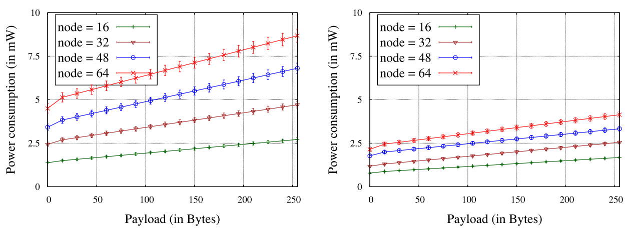
1) Latency for Emergency Event Reporting: First, the latency of the in-body sensor nodes during the *i-unscheduled bilink allocation interval* is analyzed based on the rank of the node assigned as per the RPA algorithm, as shown in Fig. 2. The magnitude of ϵ, i.e., the probability of the node transmitting more than one data frame during the *i-Unscheduled bilink allocation interval* is chosen as discrete values 0, 0.2, 0.33, and 0.5. The number of in-body nodes in the network is considered to be 20, while the frame payload is taken to be maximum, i.e., 255 B. In Fig. 2(a), we observed that, as the priority of the node decreases, the expected latency during frame transmission increases linearly. This comes as a straightforward observation, as lower rank of a node indicates more number of nodes transmitting prior to the said node. Also, an increase in the magnitude of ϵ corresponds to higher transmission latency as it indicates longer transmission duration for the nodes. Similar patterns are observed for the plots corresponding to the other data rates. However, from the comparison of the two subgraphs shown in Fig. 2, it is evident that an increase in the data rate diminishes the frame transmission delay. This observation is an evident one, as frame transmission delay is inversely proportional to the bit rate of the channel, by definition.

2) Latency for Regular Event Reporting: The latency analysis for in-body nodes during the *i-Scheduled bilink allocation interval* is analyzed in this section, as shown in Fig. 4. In the *i-Scheduled bilink allocation interval*, the hub is responsible for the random selection of an in-body node and requesting it for data transmission. Clearly, the event of a node being chosen by the hub is stochastic in nature. Analyzing the subgraph shown in Fig. 4(a), we observe that, as the polling order of a node increases, the expected transmission latency during frame transmission rises. The nonlinear nature of the curve can be directly explained by the help of (8). Also, as the magnitude of ϵ increases, the expected transmission latency increases. On the other hand, an increase in the data rate of the channel diminishes the expected latency linearly. Fig. 3 illustrates the variation of expected latency against the payload during the constant data rate. We observe that as the frame payload increases, the



(a) (b)

Fig. 5. Mean power consumption versus payload during emergency event for different MICS band data rates. (a) Data rate = 75.9 kb/s. (b) Data rate = 151.8 kb/s.



(a) (b)

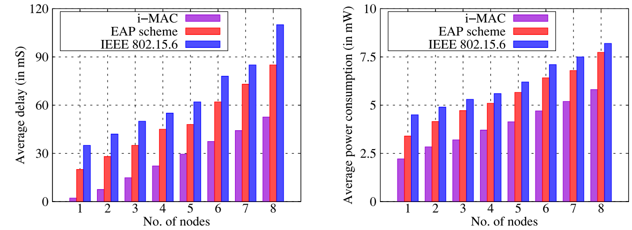
Fig. 6. Mean power consumption versus payload during regular event for different MICS band data rates.

expected latency of node increases. In our case, a constant data rate of 303.6 kb/s is considered, which results in a low slope straight line. As the magnitude of ϵ increases, the number of transmitted bits in the channel increases, which results in the increase of expected latency. Comparing the subgraphs, it is observed that an increase in the number of the in-body nodes in a network leads to an increase in the expected latency.

C. Power Consumption

In Fig. 5, the expected power consumption of a node in a network during the *i-Unscheduled bilink allocation interval* is plotted, while all the network parameters are taken to be variable. In Fig. 5(a), it is observed that, as the data rate of the transmission channel increases, the power consumption decreases. This is because a lower data rate results in prolonged wait duration for a node prior to frame transmission, as well as longer frame transmission duration. Again, a larger number of nodes present in the network indicates longer wait for lower ranked nodes. It is observed that increase in the frame payload results in a monotonic increase in power consumption.

In Fig. 6, the variation of average power consumption of a node for regular event reporting during the *i-Scheduled bilink allocation interval* is shown, while all the system parameters are taken to be variable. With the increase in payload in transmitting the data frame, the average power consumption of a node increases. As the number of nodes in a system increases, the overall power consumption of the system also increases. Comparing the subgraphs, we observe that, as the data rate increases, the average power consumption decreases linearly for regular event reporting.



(a) (b)

Fig. 7. Analysis of average delay and power consumption. (a) Average delay. (b) Average total power consumption.

D. Benchmark Comparison

We have compared average delay and overall power consumption in case of an emergency event between i-MAC, conventional IEEE 802.15.6 [7], and the [19] MAC protocol. In [19], an IEEE 802.15.6 complaint modified superframe structure is proposed for implant sensor communication. A separate EAP in a superframe is used for emergency packet during which CSMA/CA mechanism is employed by the nodes to transmit their data. We denote the scheme as EAP scheme. It can be observed in Fig. 7(a) that the i-MAC i-Unscheduled bilink allocation interval incurs less delay in case of an emergency event than EAP scheme and IEEE 802.15.6 scheme. As there is no provision of collision in the case of i-MAC, the incurred delay is only due to polling order. Therefore, the node with the least priority may have to wait for a longer duration. It can be observed in Fig. 7(b) that due to collision and retransmission in the CSMA/CA-based communication the overall energy consumption of EAP scheme increases, however, scheduled access mechanism based on criticality in case of i-MAC has lesser energy wastage. From Fig. 7 we conclude that the proposed i-MAC scheme is energy efficient and incurs lower average delay for implant-based WBAN than the existing traditional IEEE 802.15.6 and EAP scheme.

VIII. Conclusion

In this article, we proposed a new superframe structure for IoT-enabled in-body sensors based WBAN connected to a single hub for critical patients. The proposed superframe is structured to be a combination of two segments—the first half supports emergency event handling, whereas the latter is designed to facilitate regular in-body sensor-based communication. Periodic emergency event reporting is done by each implant sensor node to avert the abrupt occurrence of an emergency event. Based on the data acquired by the implant nodes, we also rank the node according to their priority of being served in case of emergency event reporting. Grounded in this principle, i-MAC is proposed, which is analyzed thoroughly in the latter half of the work. The performance of the proposed algorithm is then analyzed in terms of latency and power consumption. In the future, we propose to analyze the performance of the slotted ALOHA protocol in case of the in-body sensor nodes. Also, the work may be extended for two-hop extended-star network topology.

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