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AT-MAC: Adaptive MAC-frame Payload Tuning for Reliable Communication in Wireless Body Area Networks

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***Abstract*—In wireless sensor networks, adaptive tuning of Medium Access Control (MAC) parameters is necessary in order to guarantee the QoS requirements. In this paper, we propose an adaptive MAC-frame payload tuning mechanism for wireless body area networks (WBANs) to maximize the probability of successful packet delivery or reliability. The proper tuning of MAC parameters of IEEE 802.15.4 MAC protocol, increase reliability of sensor nodes based on real-time situation. The enabling algorithm, Adaptively Tuned MAC (AT-MAC), has been proposed to tune the MAC-frame payload of a WBAN sensor node. AT-MAC prioritizes sensor nodes the seriousness of the health parameters that are being measured by the sensors. Further, we consider a Markov chain-based analytical approach that acknowledges the slotted CSMA/CA backoff mechanism with retry limits, as described in the IEEE 802.15.4 protocol. We derive expressions for reliability, power consumption, and throughput, which are the key metrics to evaluate the network performance of the proposed protocol, and analyze the impact of MAC parameters on them. Finally, results indicate that the low rate and low power IEEE 802.15.4 can be used effectively in case of WBANs if the payload is tuned properly through the proposed algorithm. The proposed AT-MAC algorithm yields around 70% increase in reliability of a critical node in a WBAN.**

***Index Terms*—Wireless Body Area Network, IEEE 802.15.4 standard, Markov chain model, Adaptive payload tuning, Critical sensor node, Criticality Index.**

I. Introduction

A WBAN, as the name suggests, is a network of wireless and wearable computing entities that sense and transmit the measurements of the physiological parameters of a patient [1]. WBANs find applications in diverse domains such as physiological and medical monitoring, and human-computer interaction [2]. The last decade has witnessed a dramatic increase in the number of such wearable computing devices. Examples include wearable heart-rate monitors, glucose-monitors, blood-oxygen saturation (SpO_2) monitors, accelerometers, ECG sensors, and medical implants [3].

A. Motivation

Most of the modern era e-Health applications, which are being used for pervasive and ubiquitous healthcare of patients, are based on WBANs [4]–[6]. Data (or packet) loss due to collisions and network problems such as non-idle channel, and channel errors are the primary reliability-centric limitations in WBANs. Moreover, in case of WBANs, data loss by an abnormally behaving physiological sensor node, when some part of the physiological system malfunctions, is more crucial than that of the traditional wireless sensor networks (WSNs), as it concerns human health monitoring. Thus, maximizing reliability of a sensor node is an important concern in WBANs, in order to increase the chance of successful reception of packets to the destination node.

The *motivation* behind the proposed work is to increase the rate of successful packet delivery of the sensors, so that it can be used in any WBAN application. In this work, we introduce the concept of *Criticality Index* (CI) to identify the most critical physiological parameter and the concerned sensor node. The sensor node with maximum CI is termed as the *critical node*, at a particular time. Furthermore, we propose an algorithm – *AT-MAC* – to tune the MAC-frame payload, which is the length of data in the transmitted frame, in order to maximize the probability of successful packet delivery (reliability) of the critical node. Consequently, we achieve that the information from the most critical node reaches the destination node or the Local Processing Unit (LPU) with the least possible delay and maximum reliability.

B. Contribution

The specific *contributions* of this work are as follows:

- In order to quantify the severity of a WBAN sensor node, we introduce the term CI.
- The Markov chain-based analytical model proposed in this work achieves much better reliable communication with less delay and less power consumption.
- We optimize the MAC-frame payload of the critical node in order to maximize the reliability of that node.

II. Related Work

In this Section, we categorically discuss the pros and cons of the existing literature that are focused on the IEEE 802.15.4 protocol [7]. We categorize the works based on their nature, and analyze their pros and cons.

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A. Simulation-based Works

In spite of the deficiency of MAC payload tuning-based works for IEEE 802.15.4, there have been several simulation-based studies [8], [9] to investigate the delay, throughput and power consumption of this protocol. Koubaa et al. [8] simulated the performance of slotted CSMA/CA for different network settings to analyze the impact of protocol attributes such as superframe order, beacon order and backoff exponent on network performance. Zheng and Lee [9] further consider several other issues such as association through tree formation, coordinator relocation, and guaranteed time-slot allocation in their simulation-based study. On the other hand, Vishnevsky et al. [10] studied the problems of beacon collisions in case of simultaneous joining of multiple devices to a piconet at the same time. Pang et al. [11] and Ko et al. [12] proposed TCP-like window adjustment mechanisms for IEEE 802.15.4 to maximize network throughput and the proposed algorithms in these works adapt the contention window size depending on the successful packet transmission, packet collision, and channel sensing state. A fair backoff algorithm is also proposed by Fang et al. [13]. However, the authors did not consider any health specific parameters in their works. Further, physiological severity measured by the individual sensors is not considered in these works. The primary focus of some of these works [11]–[13] are maximizing network throughput. Though, in case of health monitoring applications, maximum throughput cannot guarantee the reliability of packet transmission. Moulik et al. [14] considered the severity of health data in their recent work. The payload tuning scheme described in this work categorize the total payload into three schemes and assign them on the physiological sensors based on health priority. However, the tuning of payload is not sufficiently adaptive, and the detailed analysis of reliability, delay, throughput, and other network parameters are not addressed in this work.

B. Analytical Works

Inspired by Bianchi's work [15], different authors contributed by developing analytical models for IEEE 802.15.4. For instance, Misic et al. [16] proposed a three-dimensional Markov chain considering a non-saturated network. The authors considered M/G/1/K queues to acknowledge the uplink transmission. In a similar approach, Sahoo and Sheu [17] derived an analytical model for IEEE 802.15.4 CSMA/CA based on a three-dimensional Markov chain considering the packet retry limits. Pollin et al. [18] provided a detailed analytical evaluation for both uplink and acknowledged traffic, based on a two-dimensional Markov chain. However, none of these studies realized the necessity of tuning protocol parameters in order to achieve better network performance. Park et al. [19] proposed a three-dimensional Markov chain model for IEEE 802.15.4 protocol, while taking into account reliability, delay and energy consumption. In another work, Park et al. [20] presented an analysis and optimization of the performance metrics on reliability, delay and power consumption for the IEEE 802.15.4 protocol. These works do not consider the severity of health parameters which are monitored by specific physiological sensor nodes. Moreover, these works are mostly analytical in nature, and from the hardware implementation perspective, the direct tuning of the considered MAC parameters in these works is difficult to achieve.

C. Application-based Works

Among the application-based works, the ones by Rodrigues et al. [21] and Pereira et al. [22] are prominent. Rodrigues et al. [21] addressed the issue of processing of raw biosensor data to achieve appropriate and medically relevant visualization of monitored physiological parameters. The authors setup a completely functional health-monitoring platform that runs on a Java and Bluetooth-enabled phone. Extending the previous approach, Pereira et al. [22] presented a mobile-based biofeedback monitoring system that operates on major smartphone platforms such as Symbian, Windows Mobile, Android, and iPhone. Another interesting work by Anjum et al. [23] proposed a priority-based load aware MAC protocol for body sensor networks. In this work, the data packets are served based on some priority that depends on the data-type and the generation rate. However, these works lack tuning of MAC parameters, specifically the tuning of frame payload, which is necessary to optimize QoS attributes such as reliability of the critical-most sensor node in a WBAN.

Synthesis: Most of the existing studies were either conducted in contexts other than IEEE 802.15.4-based WBANs, or overlooked the importance of reliable packet transmission as a significant aspect of QoS. We address this lacuna in this paper, and show how we can exploit the low data rate and the low power of IEEE 802.15.4 for reliable data transmission in WBANs. In this paper, we present AT-MAC, an adaptively tuned MAC protocol for IEEE 802.15.4, to maximize the probability of successful data packet delivery (reliability) of a 'critical' node at a certain time instant, by tuning the MAC-frame payload. Payload tuning can be achieved by varying the sensing time of physiological data, which is much easier to implement in hardware in comparison with the MAC parameters considered by Park et al. in [19], [20]. The proposed adaptive MAC improves the reliability of a critical WBAN sensor node, while guaranteeing less collision probability, power efficiency and delay constraints of the entire system.

III. Framework and Problem Scenario

In this Section, we discuss the overall framework and the problem scenario of the proposed model in an ubiquitous health monitoring [24] context. An end-user is equipped with a WBAN setup that contains different physiological sensors (such as heart rate sensor, accelerometer, pulse oximeter etc.) and one LPU associated with them. These sensors sense physiological parameters and convey the measurements to the LPU, as illustrated in Figure 1. In such systems, it should be ensured that at every turn, the sensor node that shows the maximum abnormality in sensed physiological data, i.e., the *critical* body sensor node must be detected by the LPU in order to improve it's own transmission reliability through MAC-frame payload optimization. However, apart from the payload optimization there is no difference among the critical and the non-critical sensor nodes. They all follow the same protocol

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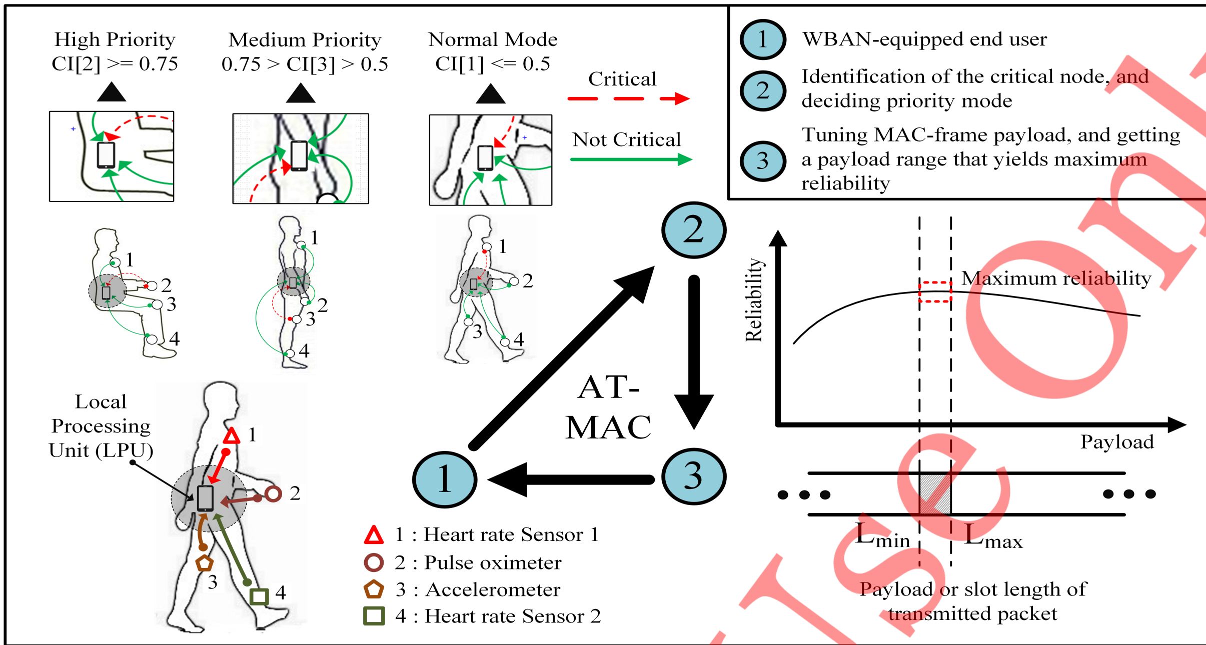

Fig. 1: Overall framework of the proposed AT-MAC algorithm

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for periodically transmitting physiological data. If one of the nodes which was previously a 'non-critical' node, exhibits the maximum health severity, the LPU considers it as the 'critical' node in the current turn, and optimize it's payload. Thus, critical and non-critical notions associated with the sensor nodes are not static, rather changes with time, depending on the severity of the sensed physiological data.

At a particular instant of time, it may be the case that the sensed data have different range of medical severity. Therefore, the default MAC-frame payload of these sensors may not always guarantee optimal satisfaction of QoS attributes, such as reliability of data transmission. For the sake of receiving critical health information reliably it is necessary to grant a privilege to the physiological sensor node that senses the most critical data with respect to the other sensors at that particular time instant. Figure 1 briefly elaborates all the major steps involved in the whole operation. In this work, the proposed AT-MAC algorithm identifies the most critical node at a particular time instant, and then based on the severity value of the measured physiological parameter, i.e., the CI of that node, the system selects a priority mode for it. Three priority modes are envisioned in this work, viz. *High Priority*, *Medium Priority*, and *Normal Mode*. Each priority mode has its own payload range, which is optimized in order to maximize its data transmission reliability. This payload range also depends on the minimum reliability requirement of that mode, i.e., R_{min}^{highP} or R_{min}^{medP} or R_{min}^{normP}. Furthermore, the proposed AT-MAC algorithm handles packet re-transmissions, until the retry limit reaches, through payload tuning within the resultant payload range. All associated calculations such as selecting the maximum CI among a pool of CIs, assigning priority mode based on the value of maximum CI, and optimization of MAC-frame payload of the critical node, are done by the LPU.

However, a case always may exist that re-transmission of packets fails continuously. In such cases, the proposed AT-MAC algorithm considers the approach stated in the IEEE 802.15.4 protocol itself [7], i.e., re-transmitting the packet only a fixed number of times, which is defined by the parameter *re-transmission counter* (r) in this paper. If packet transmission still fails then AT-MAC drops the current packet and chooses a new packet from the buffer, even if the current packet holds information that is sensed from a critical node. It won't be a problem as the next packet, which contains fresh updated information, is picked up immediately. This whole process of transmission, re-transmission, dropping of the current packet, and selection of the next packet for fresh transmission is very fast, approximately in a scale of fraction of seconds. Thus, it is highly unlikely to misjudge a critical node as non-critical, even if the patient faces irregular heart rate, or any such similar health abnormality, as frequent ups and downs in physiological severity is assumed not to occur within fraction of seconds.

IV. Analytical Model

In the proposed work, we consider a WBAN with N physiological sensor nodes that contend to send physiological data to the LPU. As stated earlier, the primary objective of this work is to find the most critical node at a particular time instant and maximize its reliability. The Markov model analysis proposed in this work, is purely based on the principles of slotted CSMA/CA algorithm discussed in IEEE 802.15.4 protocol [7]. Thus the ideas of Clear Channel Assessments ($CCAs$), acknowledged transmission, *macMaxCSMABackoffs* (p), and *macMaxFrameRetries* (r) are used in Markov chain, as it is discussed in the protocol.

Let α_1 and α_2 be the probability of finding the channel busy during CCA_1 due to data and ACK transmissions, respectively. Hence, the total probability of a channel to be busy during CCA_1 is given by: $\alpha = \alpha_1 + \alpha_2$. Let β denote the probability of finding the channel busy during CCA_2. We consider the default values of *macMaxCSMABackoffs (p)* and *macMaxFrameRetries (r)* as 4 and 3, respectively, as prescribed in the IEEE 802.15.4 protocol [7]. This model holds good for other values of r and p too, and it is verified in Section VI. The slot lengths L_s and L_c represent the slot length for successful packet delivery and the slot length for packet collision respectively. They are defined as, $L_s = L_p + L_{SIFS} + L_{ACK}$, and $L_c = L_p + L_{SIFS} + L_{mACK}$, where L_p is the slot length of the transmitted packet, L_{SIFS} is the slot length of inter-frame spacing after a packet is transmitted, L_{ACK} is the slot length of the acknowledgement frame received by the sensor node, and L_{mACK} is the $macAckWaitDuration$ in terms of slot length. The different terminologies considered in the proposed analytical model, are defined as follows.

Definition 1. ***(Collision Probability):*** *The collision probability (P_{coll}) of a sensor node is the probability that the data packet transmitted from that node encounters a collision with another data packet or ACK packet transmitted by some other node of the network at the same time slot.*

Proposition 1. *If τ is the probability that a node attempts the first carrier sensing CCA_1 in a random time slot, then the collision probability of the sensor node is given as*

$$P_{coll} = 1 - (1-\tau)^{N-1} - (\alpha + (1-\alpha)\beta)^{N-1}$$

Proof: Consider one sensor node (N_1) among N sensor nodes, for which we derive the expression for collision probability. Now, α denotes the busy channel probability during CCA_1 and β is the busy channel probability during CCA_2. Hence, $(1-\alpha)\beta$ is the probability of finding the channel busy during CCA_2, given that the channel is idle during CCA_1. Hence, the probability that the channel is busy for all other sensor nodes, except N_1, is given by

$$P_{idle} = (\alpha + (1-\alpha)\beta)^{N-1} \tag{1}$$

We have, $(1-\tau)$, the probability that a node does not perform carrier sensing. The probability that all $(N-1)$ nodes, other than N_1, do not attempt carrier sensing is $(1-\tau)^{N-1}$. Hence, for the sensor node N_1, the probability that there is no chance of collision, that is other $(N-1)$ nodes are not sensing or they find the channel busy during CCA is given as

$$\bar{P}_{coll} = (1-\tau)^{N-1} + (\alpha + (1-\alpha)\beta)^{N-1} \tag{2}$$

Therefore, for the sensor node N_1, the collision probability is given as

$$P_{coll} = 1 - (1-\tau)^{N-1} - (\alpha + (1-\alpha)\beta)^{N-1} \tag{3}$$

■

Park et al. [19] considered τ as the carrier sensing probability as well as the transmission probability. However, in practice, this may not be the case.

Definition 2. ***(Failure Probability):*** *The failure probability is the conditional probability that a packet is not received by a sensor node, given that it was transmitted successfully from another node.*

The failure probability is primarily affected by channel error (P_{ec}) and collision, and is given as follows:

$$P_f = 1 - (1-P_{ec})(1-P_{coll}) \tag{4}$$

In the simulation of the proposed model, we consider the probability of the channel error (P_{ec}) as a function of received signal strength indicator (RSSI), modulation and channel coding. RSSI depends on the path-loss model, shadowing standard deviation, and Gaussian fading model. We also incorporate the packet error rate for the corresponding modulation scheme in our simulation. Interference due to multiple body sensor nodes is considered in the shadowing and fading model.

Definition 3. ***(Reliability):*** *The reliability (R) of a sensor node is defined as the probability of successful packet delivery by that node* [19].

The expression of reliability of a sensor node is given by

$$R = 1 - (P_{dcf} \cup P_{drl}) = 1 - P_{dcf} - P_{drl} \tag{5}$$

where, P_{dcf} is the probability that the packet is discarded due to channel access failure, and P_{drl} is the packet drop probability due to retry limits.

Definition 4. ***(Payload):*** *The payload (L) of the transmitted data frame by a sensor node is defined as the length of data or message in the transmitted frame.*

From the simulation results obtained, we can express α and β in terms of the MAC frame payload as shown below.

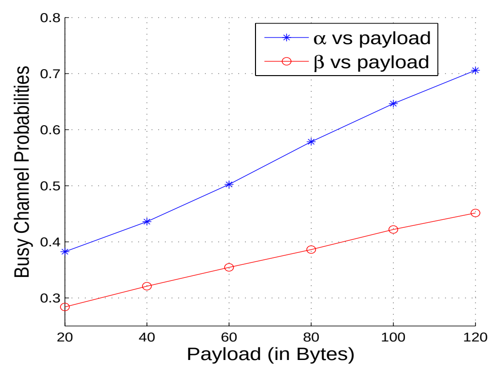

Fig. 2: Variation of α and β with MAC frame Payload (L_p)

Lemma 1. *The expressions of the busy channel probabilities α and β can be approximated as linear functions of the MAC frame payload (L_p).*

Proof: We study the variation of α and β for different values of MAC-frame payload. From Figure 2, it is evident that the variation of α and β with the payload (L) is almost linear. For the sake of convenience, we interpolate the set of obtained values using polynomial fitting. We find that, in the expression of α and β, the coefficients of the higher order terms are negligible in value. The coefficient of the squared term in the expression of α and β is of the order of 10^{-5}. Hence, only the linear term along with a constant is considered for the sake of our calculations in this work. Therefore, the

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expressions of α and β are given as

$$\alpha = c_1 L + c_2 \quad (6)$$

$$\beta = c_3 L + c_4 \quad (7)$$

where, c_1 lies in the range (0.0029, 0.0033), and c_2 lies in the range (0.3051, 0.3428) so that the overall frame payload is less than 127 bytes, as specified in the IEEE 802.15.4 standard [7]. Again, maintaining the above constraint, the range of c_3 is (0.0015, 0.0019) and that of c_4 is (0.1120, 0.1542). ■

Corollary 1. *Let us consider that the payload assigned to a critical node, corresponding to maximum reliability, at an instant be L', and let L_p be the payload assigned to all other sensor nodes. Therefore, using Lemma 1, the normalized equations for α and β are:*

$$\alpha = c_1(\frac{L'}{N} + \frac{N-1}{N} L_p) + c_2 \quad (8)$$

$$\beta = c_3(\frac{L'}{N} + \frac{N-1}{N} L_p) + c_4 \quad (9)$$

Definition 5. ***(Criticality Index):*** *The Criticality Index (CI) of the s^{th} sensor is the measure of seriousness of the health parameter, which is being measured by that physiological sensor at the time instant t [14].*

In crisp set theory, we can only interpret a particular health parameter as 'low', 'moderate', and 'high' compared to its normal value, but cannot quantify how much it is low, moderate or high from its expected measure. Thus, from one recent existing work [14], we incorporate the concept of fuzzy rules, fuzzy sets, and membership functions in order to achieve a justified formulation of CI. Mamdani model [25], the most used fuzzy inference technique is used to derive the criticality of the physiological parameters.

The CI considers the criticality of data collected through different fuzzy sets and membership functions. In the fuzzy rules, along with the internal factors (human physiological parameters), external factors such as age that has influence on health parameters, is considered. Linguistic sets such as 'LOW', 'MODERATE', and 'HIGH' are considered to categorize the severity of each physiological parameter. On the other hand, the external variable, human age, is represented through the sets – 'YOUNG', 'ADULT', and 'AGED'. Next, some rules are considered such as "if temperature = LOW and age = HIGH, then criticality = STAGE 3". The Mamdani model fuzzifies the input variable combinations (such as the combination of temperature and age), evaluates the rules, aggregates the rule outputs, and defuzzifies to get a crisp value, which is considered as the CI of that particular physiological sensor. The value of CI strictly ranges between 0 and 1. The mathematical expression of the CI is given as follows.

$$CI = \frac{\int_0^1 \mu_{R,t}(c).c \, \mathrm{d}c}{\int_0^1 \mu_{R,t}(c) \, \mathrm{d}c} \quad (10)$$

where, $\mu_{R,t}(c)$ represents the aggregated output of all the fuzzy rules that are stored in a rule-base. The details of this mechanism are available in the original published article [14].

Definition 6. ***(Critical Node):*** *A Critical Node (sensor) in a WBAN is defined as that node, which has the maximum CI at a certain time slot.*

In this paper, we ensure that the critical node is able to send data with maximum reliability, at any instant of time.

A. AT-MAC: The Proposed Algorithm

The proposed algorithm, AT-MAC, tunes the MAC-frame payload adaptively, as the name suggests. Algorithm 1 governs the whole procedure of AT-MAC by sequentially calling the functions - *FindCritical*, *SetPriority*, and *ACKSensing*.

Algorithm 1 AT-MAC Algorithm

Input: Sensed physiological data from each sensor node.
Output: Assignment of payload that leads to maximum reliability for the critical node.

In a WBAN, N number of nodes communicate with the LPU at fixed MAC parameters.
critical node = $FindCritical(N)$
Mode = $SetPriority(CI[CriticalNode])$
$ACKSensing(Mode)$

Algorithm 2 Algorithm for determining the critical node

Input: Sensed physiological data from N sensor node.
Output: The sensor node that senses critical physiological data at that time instant.

function $FindCritical(N)$
  temp = 0
  for all i = 1 to N **do**
    Compute CI as described in [14]
    if CI[i] $>$ temp **then**
      temp = CI[i]
      CriticalNode = i
    end if
    $i \leftarrow i + 1$
  end for
  return(CI[CriticalNode])
end function

Algorithm 2 identifies the critical body sensors node in the entire network. The function *FindCritical* returns the CI of that critical node whose payload scheme is to be optimized, and the function *SetPriority* described in Algorithm 3, assigns a particular priority mode for data transmission to that node, depending on its CI. We envision three priority modes: *high priority*, *medium priority*, and *normal* mode. After selecting the priority mode, the most critical sensor node starts data transmission using the slotted CSMA/CA algorithm. The payload range varies between modes, and is set depending on the reliability requirement of each mode – such as R_{min}^{highP}, R_{min}^{medP}, and R_{min}^{normP}. These additional constraints represent the minimum reliability requirement for the high priority, medium priority, and normal mode respectively. This

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Algorithm 3 Algorithm for assigning the priority mode

Input: CI of the critical node.

Output: The suitable priority mode and MAC-frame payload for the critical node.

function $SetPriority(CI[CriticalNode])$
  if CI[CriticalNode] > 0.75 **then**
    Assign $Mode \leftarrow$ High Priority
    Set minimum reliability requirement as R_{min}^{highP}
    Assign $L' \leftarrow L_{max}$, $r \leftarrow 3$
  else
    if CI[critical-node] > 0.5 **then**
      Assign $Mode \leftarrow$ Medium Priority
      Set minimum reliability requirement as R_{min}^{medP}
      Assign $L' \leftarrow L_{max}$, $r \leftarrow 3$
    else
      Assign $Mode \leftarrow$ Normal Mode
      Set minimum reliability requirement as R_{min}^{medP}
      Assign $L' = L_p$, $r \leftarrow 3$
    end if
  end if
  return($Mode$)
end function

Algorithm 4 Algorithm for Acknowledgement sensing of the transmitted health data

Input: The operating mode of the critical node.

Output: No output. It handles retry counter depending on the status of packet transmission.

function ACKSENSING(*Mode*)
  if success **then**
    Critical sensor node goes to idle state.
  else
    while $r \neq 0$ **do**
      if r = 1 **then**
        $L' \leftarrow L_{min}$
      else
        $r \leftarrow r - 1$
        $L' \leftarrow Rand(L' - 1, L_{min} + 1)$
      end if
    end while
  end if
end function

threshold can be varied in application level, depending on the requirement, and accordingly the MAC-frame payload will be tuned. The function *ACKSensing* finally assigns the payload, as explained in Algorithm 4. This algorithm is repeated till successful transmission occurs, or the retry limit r becomes zero; whichever is earlier. For the case, $r = 0$, the packet is dropped. However, it is highly undesirable and should not occur for a high or medium priority critical node. Hence, the payload is tuned in order to ensure highest reliability. The values of L_{max} and L_{min} are derived from Markov chain analysis of the data transmission on the critical node.

B. Markov Chain Model for Critical Node

In this paper, Markov chain has been used for analytical modeling, from which we derive the expression of *reliability*, which, in turn, helps to derive the range of payload for maximum reliability of the critical node. Using the Markov model we efficiently consider different steps of the slotted CSMA/CA algorithm, and deduce corresponding expressions for *power consumption*, and network parameters such as – *throughput* and *delay*, for further analysis.

We propose a Markov chain model considering the MAC PIB attributes $macMaxCSMABackoffs = p$ and $macMaxFrameRetries = r$ for each packet transmitted by the critical node, which follows slotted CSMA/CA algorithm and acknowledged transmission. We design the Markov model with three variables $s(t)$, $l(t)$ and $r(t)$ representing the backoff stage, payload of the transmitted data frame, and the value of re-transmission counter at time t, respectively, as illustrated in Figure 3. The transition to any of the three priority mode considered in the Markov model, is a stochastic process. Hence, we assign P_1, P_2, and P_3 as the transition probabilities respectively for high priority, medium priority and normal mode data transmission, such that $P_1 + P_2 + P_3 = 1$. We consider τ as the stationary independent probability that a node performs carrier sensing in a randomly chosen time slot. The tuple $(s(t), l(t), r(t))$ represents each state in the proposed three dimensional Markov chain. We do not include the Markov model states for the normal mode data transmission as it is the trivial case and payload tuning is not necessary for this case. We consider $(0, 0, 0)$ as the idle state, when the node has no packet to transmit or receive and is waiting for new packet arrivals. In every scheme, the node, initially, performs Clear Channel Assessment (CCA_1 and CCA_2), and if the channel is idle, data transmission starts. $(i, 0, 0)$ and $(i, L_{max}, 0)$ represent CCA_1 and CCA_2 respectively. States (p_s, 0, 0) and (0, 0, r) consider the successful transmission and failure (packet drop) respectively. The stationary distribution of the proposed Markov chain model is given by,

$$S_{i,j,k} = \lim_{t\to\infty} P(s(t) = i, l(t) = j, r(t) = k),$$
$$\forall i \in [0, p], j \in [L_{min}, L_{max}], k \in [0, r] \quad (11)$$

The state transition probabilities in Fig. 3 are,

$$P(p, 0, 0 \mid 0, 0, 0) = P_x\tau, \forall x \in [1, 3] \quad (12)$$

$$P(i, L_{max}, 0 \mid i, 0, 0) = 1 - \alpha, \forall i \in [1, p] \quad (13)$$

$$P(i, L_{max}, r \mid i, L_{max}, 0) = 1 - \beta, \forall i \in [1, p] \quad (14)$$

$$P(p_s, 0, r \mid i, j, k) = (1 - P_{coll}) \sum_{x=0}^{k-1} P_{coll}^{x} = 1 - P_{coll}^{k},$$
$$\forall i \in [1, p], j \in [L_{min}, L_{max}], k \in [1, r] \quad (15)$$

$$P(i, j_2, k - 1 \mid i, j_1, k) = P_{coll},$$
$$\forall i \in [1, p], k \in [2, r]; j_1, j_2 \in [L_{min}, L_{max}] \quad (16)$$

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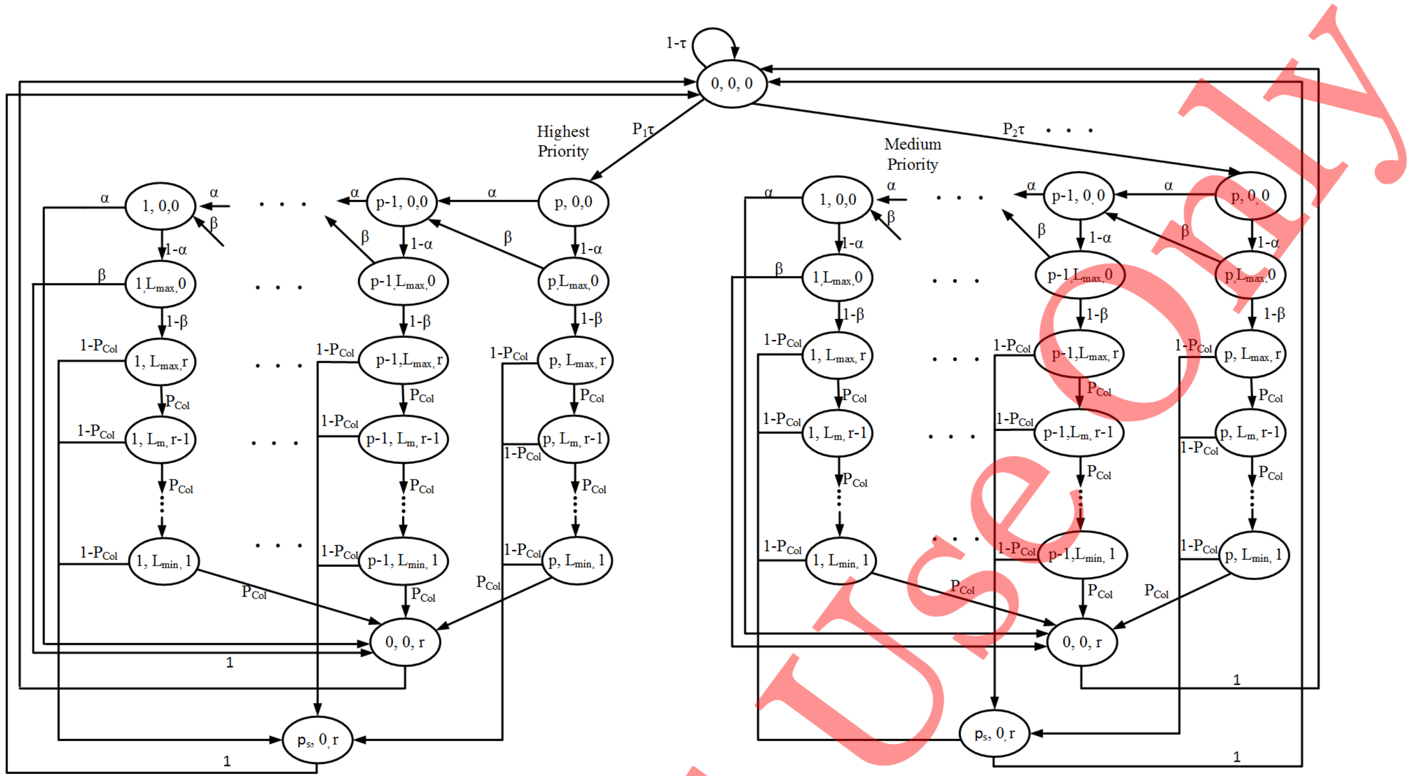

Fig. 3: Markov chain model for the IEEE 802.15.4 - based AT-MAC algorithm

$$P(0,0,r \mid i,j,k) = P^k_{coll}, \\ \forall i \in [1,p], j \in [L_{min}, L_{max}], k \in [1,r] \tag{17}$$

$$P(0,0,0 \mid i,j,k) = 1, \\ \forall i \in [1,p], j \in [L_{min}, L_{max}], k \in [1,r] \tag{18}$$

$$P(i-1,0,0 \mid i, L_{max}, 0) = \beta, \forall i \in [2,p] \tag{19}$$

$$P(i-1,0,0 \mid i,0,0) = \alpha + (1-\alpha)\beta, \forall i \in [1,p] \tag{20}$$

$$P(0,0,r \mid 1,0,0) = \alpha \tag{21}$$

$$P(0,0,r \mid 1,L_{max},0) = \beta \tag{22}$$

Eq. 12 derives the probability that the sensor node selects either of the three modes, as decided by the LPU. Eq. 13 shows the probability of transition to the CCA_2 state from CCA_1. Eq. 14 denotes the probability that the sensor node finds the channel idle in CCA_2 and goes to the next state (i, L_{max}, r), where maximum payload is assigned to the transmission data frame of the critical sensor node, depending on the priority mode. When the CI of the critical node is less than 0.5, we choose normal mode of data transmission, and set the maximum payload to L_p, a fixed optimal value. Eq. 16 denotes the decrement of retransmission counter due to collision of transmitted data packet, and the size of payload is set randomly between the previous payload value and the minimum payload for that scheme.

$$L' = Rand(L'-1, L_{min}+1) \tag{23}$$

Eq. 17 derives the packet failure probability after finding the channel idle in both CCA_1 and CCA_2 due to r successive packet collisions. Eq. 18 derives the probability of reaching the idle state from the transmitting state, which is unity. Eq. 19 denotes the probability of finding the channel busy in CCA_2, and of selecting the next state in the backoff stage of CCA_1. Eq. 20 represents the transition from one backoff state to another backoff state. Eqs. 21 and 22 denote the total probability of packet drop due to channel access failure in CCA_1 and in CCA_2 respectively.

Proposition 2. *The idle state $S_{0,0,0}$ is expressed as*

$$S_{0,0,0} = \Bigg((\alpha + (1-\alpha)\beta)^p + (1 - (\alpha+(1-\alpha)\beta)^p) \\ ((1-P^r_{coll})(1+\frac{1}{1-P_{coll}}) + P^r_{coll} + \frac{1}{1-\beta}(1+\frac{1}{1-\alpha})) \Bigg)^{-1} \tag{24}$$

Proof: The proof is given in the Appendix. ■

C. Maximization of Reliability

In a WBAN, we must ensure the successful data transmission from the critical body sensor node and reception at the LPU, so that the reliability is maximum and collision probability, delay, and failure probability of the critical node is minimum. Hence, we develop a mathematical model for tuning the payload of the critical node, in order to find the range of payload for which the reliability of that node is maximum. The critical node in the WBAN is determined using the CI, as mentioned earlier in this Section.

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From Definition 3, reliability is given as $R = 1 - P_{dcf} - P_{drl}$. In this expression, P_{dcf} is the probability of a packet being discarded due to channel access failure. Channel access failure can occur if either of CCA_1 or CCA_2 is unsuccessful. Hence, the overall probability of packet drop owing to channel access failure is given by

$$P_{dcf} = (\alpha + (1-\alpha)\beta)^p \sum_{x=0}^{r-1} [P_{coll}(1 - (\alpha + (1-\alpha)\beta)^p)]^x = \frac{\varphi^p(1-\xi^r)}{(1-\xi)} \tag{25}$$

On the other hand, P_{drl} is the probability of packet drop due to packet collision after finding the channel idle, that is due to retry limits. Hence,

$$P_{drl} = P_{coll}^r (1 - (\alpha + (1-\alpha)\beta)^p)^r = \xi^r \tag{26}$$

Using Eqs. 25 and 26, we get the expression of reliability as

$$R = 1 - \frac{\varphi^p(1-\xi^r)}{(1-\xi)} - \xi^r = 1 - \varphi^p(1 + \xi + \xi^2 + \ldots + \xi^{r-1}) - \xi^r \tag{27}$$

where,

$$\varphi = \alpha + (1-\alpha)\beta \tag{28}$$

$$\xi = P_{coll}(1 - \varphi^p) \tag{29}$$

Let L' be the payload of the critical sensor node, for which reliability of the critical sensor node is maximum. Partially differentiating Eq. 27 with respect to L', we have

$$\frac{\partial R}{\partial L'} = -(r\xi^{r-1} + \varphi^p \sum_{i=1}^{r} i\,\xi^{i-1})\frac{\partial \xi}{\partial L'} - (p\varphi^{p-1}\sum_{i=0}^{r}\xi^i)\frac{\partial \varphi}{\partial L'} \tag{30}$$

Again, using Eq. 28, we obtain

$$\frac{\partial \varphi}{\partial L'} = (1-\beta)\frac{\partial \alpha}{\partial L'} + (1-\alpha)\frac{\partial \beta}{\partial L'} \tag{31}$$

From Eqs. 3 and 29, we have

$$\frac{\partial \xi}{\partial L'} = -(1-(1-\tau)^{N-1}(1-\alpha)(1-\beta))p\varphi^{p-1}\frac{\partial \varphi}{\partial L'} + (1-\varphi^p)(1-\tau)^{N-2}((1-\tau)\frac{\partial \varphi}{\partial L'} - (1-\alpha)(1-\beta)(N-1)\frac{\partial \tau}{\partial L'}) \tag{32}$$

As, the carrier sensing probability τ is independent of payload of the critical node L', we conclude $\frac{\partial \tau}{\partial L'} = 0$. Again, using Eq. 8 and 9 we have, $\frac{\partial \alpha}{\partial L'} = \frac{c_1}{N}$, and $\frac{\partial \beta}{\partial L'} = \frac{c_3}{N}$. Therefore, using Eqs. 31 and 32, we obtain the expression for $\frac{\partial R}{\partial L'}$ as a function of payload (L') of the critical sensor node. For maximum reliability of the critical body sensor node,

$$\frac{\partial R}{\partial L'} = 0 \tag{33}$$

Solving Eq. 33, we obtain the range of payload for which reliability of the critical sensor node is maximum, and it satisfies the minimum reliability requirement of the selected priority mode. Eq. 33 results in multiple solutions, satisfying the desired reliability criteria of different schemes. The minimum payload value for a particular scheme may be obtained from the minimum value of these solutions. Let us consider a WBAN with 20 sensor nodes, that is $N = 20$. Putting $N = 20$ in Eq. 33, and ensuring that the second order derivative is negative, i.e., $\frac{\partial^2 R}{\partial L'^2} < 0$, we have, $L'_{min} = 366.25$ and $L'_{max} = 377.5$. Hence, we need to tune the payload of the critical sensor node in this range for maximum reliability of the critical node.

D. Energy Consumption

Total energy consumption of a sensor node is derived by taking into consideration the different states of a body sensor node, following the Markov chain model. When the node performs CCA, the total energy consumption due to sensing is given as

$$E_{sc,tot} = E_{sc}\sum_{i=1}^{p} S_{i,0,0} + E_{sc}\sum_{i=1}^{p} S_{i,L_{max},0} \tag{34}$$

The first part of the above expression accounts for CCA_1 and the latter part corresponds to CCA_2. The energy consumption when the sensor node is in the idle state is given as

$$E_{i,tot} = E_i(1-P_{coll})(L_s - L_p - L_{ACK})\sum_{i=1}^{p}\sum_{j=L_{min}}^{L_{max}}\sum_{k=1}^{r} S_{i,j,k}) + E_i P_{coll}(L_c - L_p)\sum_{i=1}^{p}\sum_{j=L_{min}}^{L_{max}}\sum_{k=1}^{r} S_{i,j,k} \tag{35}$$

The above equation sums up the energy consumption after successful packet delivery and the energy consumption due to packet drop owing to collision.

In case of successful packet transmission, the sensor node uses L_p slot length for transmitting the data packet and consumes $E_{tx}L_p$ amount of energy in each state. Therefore,

$$E_{tx,tot} = E_{tx}L_p\sum_{i=1}^{p}\sum_{j=L_{min}}^{L_{max}}\sum_{k=1}^{r} S_{i,j,k} \tag{36}$$

Similarly, $E_{rx}LACK$ amount of energy is spent in each state to receive the ACK frame. Thus,

$$E_{rx,tot} = E_{rx}(L_{ACK})(1-P_{coll})\sum_{i=1}^{p}\sum_{j=L_{min}}^{L_{max}}\sum_{k=1}^{r} S_{i,j,k} \tag{37}$$

Adding the Eqs. 34-37, we get the required expression for energy consumption as follows:

$$\begin{aligned} E_{tot} &= E_{sc,tot} + E_{i,tot} + E_{tx,tot} + E_{rx,tot} \\ &= P_x\tau(1-(\alpha+(1-\alpha)\beta)^p)\Big(E_{sc}\frac{1}{1-\beta}(1+\frac{1}{1-\alpha}) \\ &+ E_i\frac{1-P_{coll}^r}{1-P_{coll}}((1-P_{coll})(L_s - L_p - L_{ACK}) \\ &+ P_{coll}(L_c - L_p) + E_{tx}L_p + E_{rx}L_{ACK}(1-P_{coll}))\Big) \end{aligned} \tag{38}$$

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where, E_i, E_{tx}, E_{rx}, and E_{sc} correspond to the average power consumption in the idle state, transmitting state, receiving state, and sensing state, respectively.

E. Throughput and Delay

Throughput is defined as the ratio of product of the slot length (L_s) used by the channel to successfully transmit a packet delay and packet size (L_p), to the total delay in terms of slot length (L_d). The total slot length required to deliver a packet successfully depends on the probability of successful delivery, and the slot length required to determine the successful packet delivery. The delay depends on the busy channel probability and the collision probability. Thus, the probability of successful packet delivery is given as

$$P_s L_s = P_x \tau (1 - P^r_{coll})(1 - (\alpha + (1-\alpha)\beta)^p) L_s \quad (39)$$

where, P_s is the probability of successful packet delivery. Similarly, the delay is given as

$$P_d L_d = P_1 \tau (1 - (\alpha + (1-\alpha)\beta)^p)((1 - P^r_{coll}) L_s + P^{r-1}_{coll} L_c) + (1-\tau) L_0 \quad (40)$$

where, P_d denotes the probability that the packet is neither dropped nor transmitted and L_d is the slot length of delay that can take place before dropping or transmitting the packet.

We define throughput as follows:

$$\sigma = \frac{P_s L_s}{P_d L_d} L_p \quad (41)$$

Hence, replacing Eqs. 39 and 40 in Eq. 41, we get the expression for throughput as

$$\sigma = \frac{P_x \tau (1 - P^r_{coll})(1 - (\alpha + (1-\alpha)\beta)^p) L_s L_p}{P_x \tau (1 - (\alpha + (1-\alpha)\beta)^p)((1 - P^r_{coll}) L_s) + P^{r-1}_{coll} L_c) + (1-\tau) L_0} \quad (42)$$

TABLE I: Parameters for Simulation

Parameters	**Values**
Maximum CSMA Backoffs	4
Maximum Retry Limits	3
Maximum Length of Payload	127 bytes
macMinBE	3
macMaxBE	5
Multiplicative constant to convert time length of frame to slot length	80 bits/slot
Data Rate	250 kbps
Symbol Rate	62.5 kbps
Length of ACK frame	88 bits

V. Performance Evaluation

In this work we use MATLAB as the simulation tool along with a physical layer modeling in it. For modeling the physical layer in our code, we have incorporated the noise figure (23 dB for our device) and bandwidth, as per the IEEE 802.15.4 standard. Again, our system being low power enabled and having low sensor-LPU distance, we consider the path loss exponent to be 4. Simulations were performed for an intra-WBAN that follows star topology of IEEE 802.15.4 standard, and communicates using the 2.4 GHz ISM band. Simulation results are generated using Monte Carlo simulation where the values of busy channel probabilities (α, β) are randomly generated. Using these values, we obtain the idle state $S_{0,0,0}$. Accordingly, we calculate the throughput, reliability, collision probability and other performance metrics. The system parameters used in our simulation are tabulated in Table I. In this section, we compare the variation of reliability, collision probability, failure probability, power consumption, average delay, and throughput against the offered payload corresponding to the *General IEEE System* [7] and the proposed AT-MAC system. General IEEE system refers to the systems that follow IEEE 802.15.4 protocol but do not tune MAC-frame payload in order to achieve maximum reliability, and also do not consider the severity of physiological data during data transmission. The plots for the proposed AT-MAC system are separately shown in terms of both non-critical nodes and critical nodes. It is observed that the plots corresponding to general IEEE systems and the non-critical nodes in the AT-MAC system vary negligibly. The reason is, our proposed AT-MAC algorithm always focuses on the *critical* node at a certain time instant and tune it's MAC-frame payload.

A. Simulations for Reliability

Figure 4 illustrates the variation of reliability against the offered load (frame arrival rate). For a WBAN system having 20 sensor nodes, we compute the value of payload for maximum reliability by ensuring that the reliability must not be less than the *minimum reliability requirement* for the high priority mode. The range of values of payload to ensure the maximum reliability is obtained in the range (366.25, 377.5) in case of 20 sensor nodes, as mentioned earlier in Section IV C. Figure 4(a) shows the variation of reliability with the offered load, while payload assigned to the critical sensor node (L') = 366.25 bits and the other nodes in the network are assigned payload as 800 bits. Solving Eq. 33, for 30 nodes, we get the range of payload of the critical node as (347.9, 359.1), and similarly for 40 nodes, L' ranges between 338.75 and 349.8 bits. The corresponding offered loads and their effects on the reliability are isillustrated in Figure 4(b) and 4(c), for 30 and 40 nodes, respectively.

Inference: From figure 4, it is evident that the reliability of the critical node is enhanced significantly, compared to the general IEEE systems. Similarly the critical node also exhibits better reliability than the other non-critical nodes in the AT-MAC system. We see that as the offered load increases, the reliability decreases gradually. due to the channel access failure and buffer overflow. We also observe that as the number of nodes increases, the maximum reliability of the critical sensor node decreases, as the collision probability, and thus, the failure probability increases. From the results, it is evident that the proposed AT-MAC algorithm yields average 70% improvement on the reliability of the critical node.

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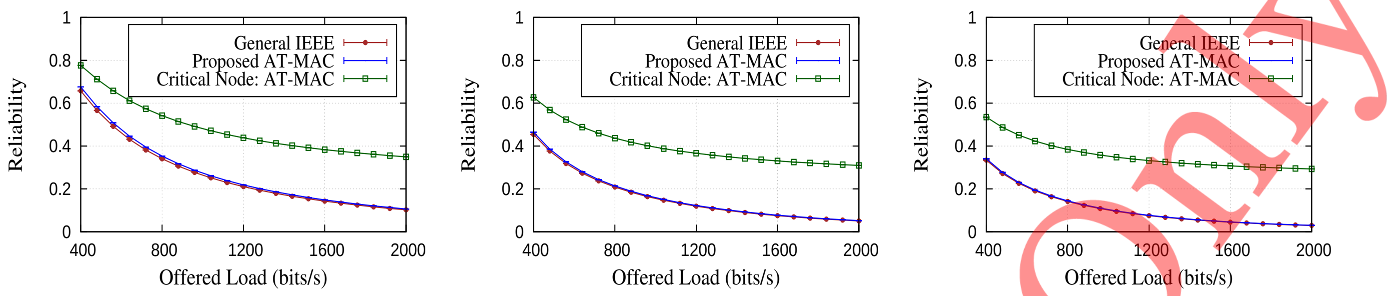
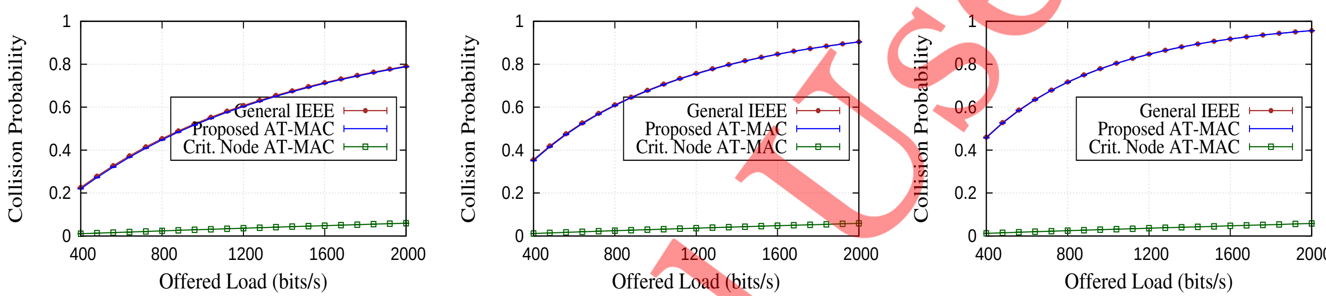


(a) Simulated with 20 nodes

(b) Simulated with 30 nodes

(c) Simulated with 40 nodes

Fig. 4: Variation of Reliability versus Offered Load



(a) Simulated with 20 nodes

(b) Simulated with 30 nodes

(c) Simulated with 40 nodes

Fig. 5: Variation of Collision Probability versus Offered Load

B. Simulations for Collision Probability

Figure 5 shows the variation of collision probability with the offered load, for 20, 30, and 40 sensor nodes. We see that the collision probability is much reduced for the critical node in AT-MAC system, compared to the general IEEE system. Collision probability for the other non-critical nodes in the AT-MAC system is approximately same with the general IEEE system, as the MAC-frame payloads of these sensor nodes are not optimized. The proposed AT-MAC algorithm is able to bound the collision probability of the critical node within a very little value (such as 0.1, in case of analyzing with maximum 40 sensor nodes).

Inference: Negligible collision probability exerts a positive effect to increase the reliability of a node, and it is already verified in Figure 4. For a fixed number of sensor nodes, as the offered load increases, i.e., when the incoming frame arrival rate is high, the transmission rate also increases, and hence, the collision probability increases. However, the rate of increment is much lower for the critical node in the proposed AT-MAC system. In case of general IEEE systems, the rate of increment of collision probability is approximately 6 times larger than that of the critical node in AT-MAC systems. Again, as the number of nodes increases, the collision probability increases for general IEEE systems and the proposed AT-MAC system. However, for the critical node the increment is negligible and mainly carried out by the non-critical nodes in the system.

One of the main reasons that the collision probability of the critical node is much less compared to the rest, and the small rate of increment with the increment in number of nodes in the system, is because of the judicious choice of the payload of the critical node by the proposed AT-MAC algorithm.

C. Simulations for Failure Probability

As defined in Section IV, Definition 4, the failure probability of a sensor node is considered as a function of channel error and collision probability. Thus, similar to the results for collision probability, the failure probability for the critical node is much reduced, compared to that of the general IEEE system, and the non-critical nodes of the proposed AT-MAC system, as illustrated in Figure 6. We observe that the failure probability of the critical node in AT-MAC system lies within $0.2 - 0.3$. It varies from 0.4 to 0.9 in case of the general IEEE system, and the non-critical nodes in the AT-MAC system.

Inference: The chances of failure in end-to-end communication is more than the chances of collision between source and destination, as failure also includes the factor of channel error. Comparison between Figures 5 and 6 further validate the fact. We also observe that, as the number of nodes increases, the failure probability increases. Though the rate of increment is much less in case of the critical node in AT-MAC system. Due to the judicious choice of the critical node and efficient optimization of its MAC-frame payload guided by the proposed AT-MAC algorithm, the failure probability of the critical node reduces to the one-third of it's previous value.

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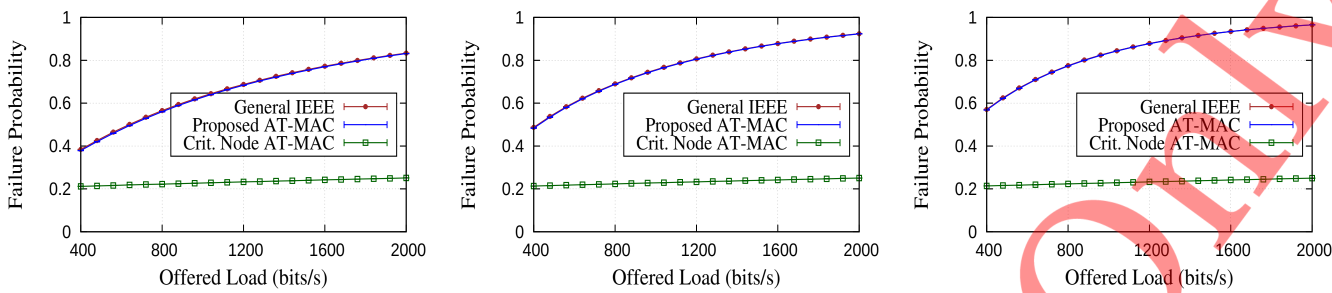
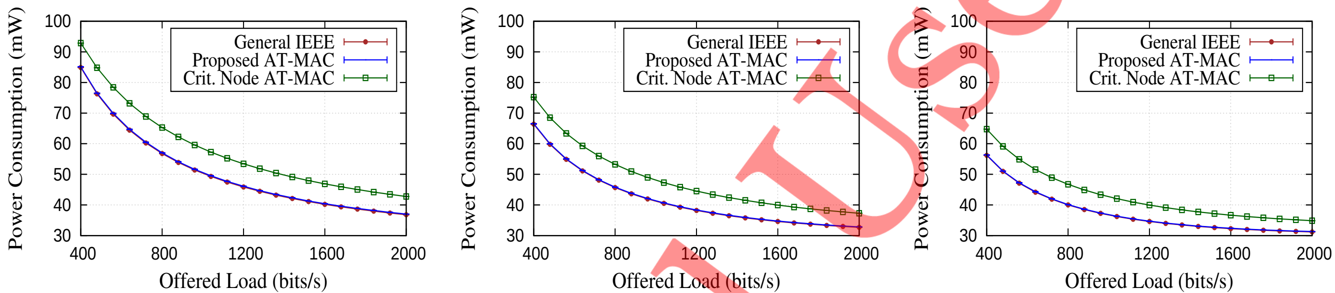


(a) Simulated with 20 nodes (b) Simulated with 30 nodes (c) Simulated with 40 nodes

Fig. 6: Variation of Failure Probability versus Offered Load



(a) Simulated with 20 nodes (b) Simulated with 30 nodes (c) Simulated with 40 nodes

Fig. 7: Variation of Power Consumption versus Offered Load

D. Simulations for Power Consumption

Figure 7 depicts the variation of power consumption (in mW) with the offered load. We observe that the power consumption of the non-critical nodes in AT-MAC system is almost same with the general IEEE standard. The critical sensor node in the AT-MAC system consumes more power, compared to the non-critical nodes and the general IEEE system. Again, as the number of nodes increases, the power consumption of every individual sensor node decreases.

Inference: The approximate increment in the power consumption of the critical node lies within $12\%-16\%$. However, with this little more expense in energy the critical node exhibits low collision and failure probability, and thus, achieves maximum possible reliability. It is appropriate to consider this expense as a trade-off between between energy and reliability. Moreover, when the number of sensors increase, the probability of finding channel idle for data transmission is less. As a consequence, the energy consumption is less, as the share of transmission energy is maximum in the total amount of energy consumption.

E. Simulations for average delay

The critical node in the proposed AT-MAC system attains significant achievement in reducing end-to-end delay. Figure 8 illustrates that the average delay increases with the increment in the offered load, in case of the general IEEE systems along with the non-critical nodes of AT-MAC. However, we observe an interesting phenomena that the average delay of the critical node of AT-MAC system decreases initially upto a certain offered load value, and beyond that it remains almost stable.

Inference: Average delay primarily depends on the channel access failure probability, which in turn is directly proportional to the packet arrival rate. Thus, normally the delay increases with the increase of offered load. However, in case of the AT-MAC critical node we already observe in Figure 6 that the rate of increase of failure probability with the increase of offered load is almost negligible. Thus, the average delay witnesses a different behavior in case of the critical node.

F. Simulations for throughput

Figure 9 depicts the variation of throughput with the offered load. As the offered load increases, throughput for both the general IEEE system and AT-MAC increases. However, in case of general IEEE systems the throughput increase till it reaches the congestion area. Again, with more number of sensors the system throughput gets affected, especially in case of general IEEE systems. In all cases the proposed AT-MAC system yields better throughput than the general IEEE systems.

Inference: The involvement of more sensor nodes increases the failure probability, α, β, i.e., the probabilities of finding channel busy. Thus, it also affects the system throughput. However, in case of AT-MAC system it does not affect much, and the reason is the optimized MAC-frame payload tuning of the critical node. The aim of the proposed algorithm is to

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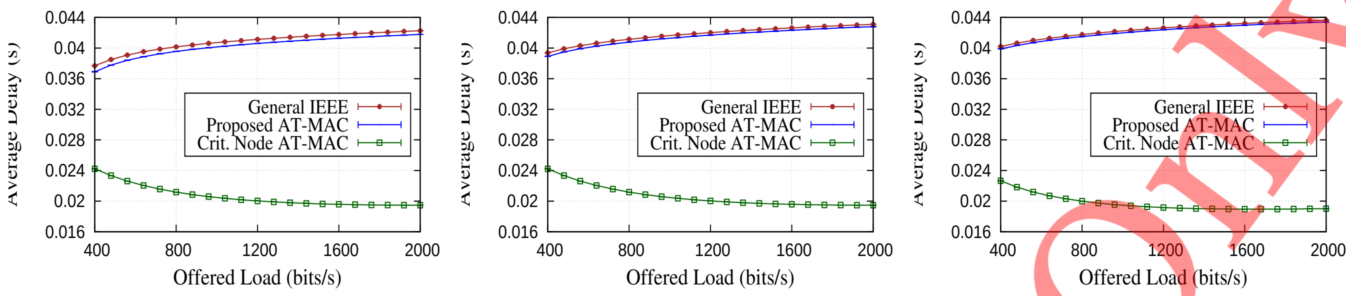
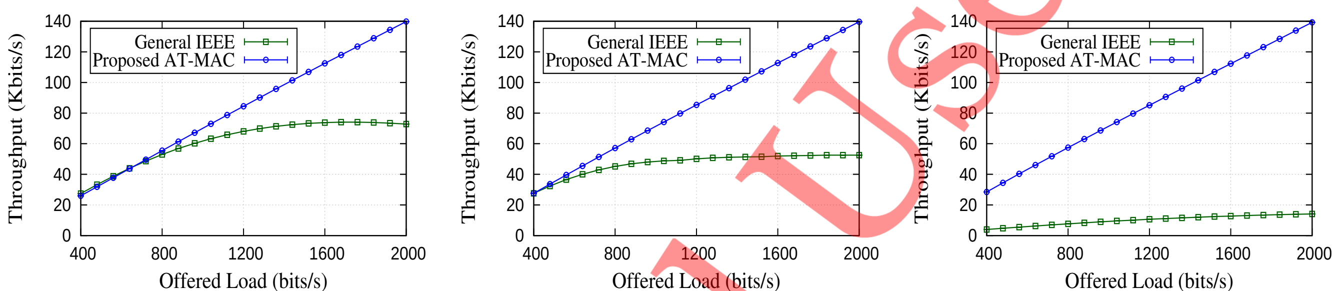


(a) Simulated with 20 nodes (b) Simulated with 30 nodes (c) Simulated with 40 nodes

Fig. 8: Variation of Average Delay versus Offered Load



(a) Simulated with 20 nodes (b) Simulated with 30 nodes (c) Simulated with 40 nodes

Fig. 9: Variation of Throughput versus Offered Load

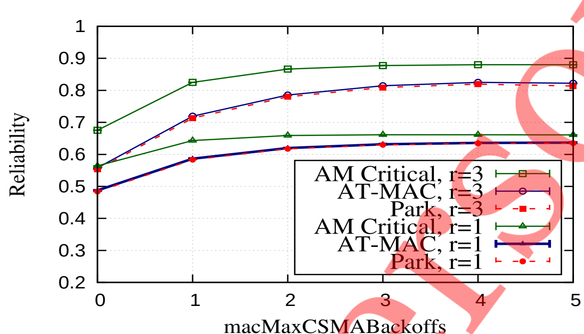


Fig. 10: Reliability Comparison

maximize reliability with satisfying the minimum reliability requirement of the selected mode, as discussed earlier. It takes care of the number of sensors within the optimization, and achieves maximum reliability. Thus, we observe that there is not much effect of the number of sensors on the related attributes such as – the reliability, collision probability, failure probability of the critical node, and as well as on the average throughput of the AT-MAC system, in which the critical node with its optimized payload becomes an important contributor.

VI. Performance Comparison

In this Section, we compare the performance of the proposed AT-MAC algorithm with one of the most recent works of Park et al. [20], as both of these works deal with a common goal to increase the reliability of communication. The proposed AT-MAC algorithm yields much better reliability for the critical node, with respect to the model proposed by Park et al. Even the average reliability of the proposed AT-MAC system is slightly higher than the average reliability of the Park's model. Figure 10 illustrates the effects of different $macMaxCSMABackoffs$ and $macMaxFrameRetries$ on reliability of packet delivery for the critical node of the AT-MAC model, average reliability of the AT-MAC model, and the Park's model. According to the slotted CSMA/CA algorithm, for high value of $macMaxCSMABackoffs$ or m, the source gets more opportunity to sense the channel as idle, and thus the probability of discarding a packet due to busy channel decreases. Similarly, higher the value of $macMaxFrameRetries$ or r, the source get more chance to retry packet transmission, which failed in previous transmission attempts. Either of these circumstances increase the reliability of packet delivery at the destination node. However, it is evident from Figure 10, that the prposed AT-MAC model is more reliable than the Park's model, especially when the critical node uses its optimized payload range.

Apart from the better reliability achievement, the proposed AT-MAC model also yields slightly less delay, and less power consumption than the Park's model, as illustrated in Figure 11. On the other hand, the average throughput of the Park's system is trivially higher than the proposed AT-MAC system.

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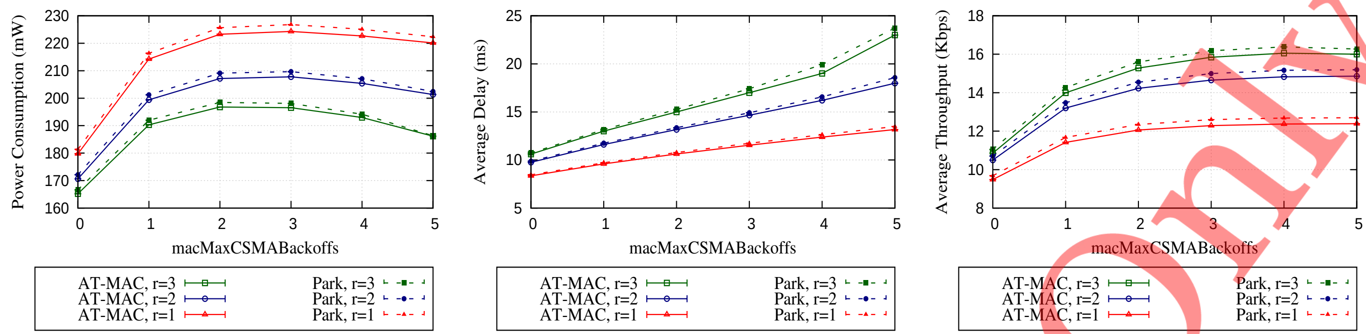

(a) Power Consumption VS. m

(b) Average Delay VS. m

(c) Average Throughput VS. m

Fig. 11: Comparison with Park's Model with 20 sensor nodes

However, the minor less throughput of AT-MAC system is considerable as the benefits we get from this proposed system are manyfold, and most importantly it efficiently identifies the critical node and maximizes it's reliability significantly, at a particular instant of time.

We also compare the proposed solution with the solution provided by Rodrigues et al. [21]. The latter work primarily focuses on mobile application development in order to setup completely functional health-monitoring platforms that can be accessed via different smart-phones. On the contrary, the proposed algorithm, AT-MAC, primarily emphasizes on the theoretical modeling of IEEE 802.15.4 with the help of the three-dimensional Markov chain in order to optimize QoS parameters. However, still we compare the different analytical attributes that are common between the above mentioned works and the proposed AT-MAC algorithm. Rodrigues et al. [21] considered the LDPU as a mobile device, whereas, in the present work, we have used a DELL Inspiron N4050 laptop with Intel Core i5 2nd gen processor with 4GB DDR3 RAM as the LDPU. In our simulations, the connection time or the delay time is obtained in the range of $30 - 50$ ms. The processing time lies in the range of $7 - 10$ ms. The connection time indicates the time required to fetch and transfer information from body sensors to the LDPU. The processing time is an indicator of the time required for conversion of the packet data into useful health information within the LDPU. The amount of corrupted data in our simulation is observed to be 4.31%, on an average. Corrupted data indicates the amount of data corrupted due to inherent channel errors, and is calculated as the difference between the probability of failure and the probability of collision. Hence, comparing the proposed work with the work of Rodirigues et al. [21], we observe that the amount of corrupted data is nearly equal, whereas the connection and processing times are much less in case of the proposed system.

VII. Conclusion

In this paper, we present an adaptively-tuned MAC algorithm for enhancing the reliability of a critical sensor node, by optimizing the MAC-frame payload of the critical node. Based on the AT-MAC algorithm, we propose a Markov chain-based analytical model for slotted CSMA/CA of IEEE 802.15.4 with retry limits and backoffs. Numerical results show that the proposed scheme is efficient and ensures maximum reliability of the critical sensor node. In case of medical emergency, the critical sensor node in a WBAN-assisted health monitoring system, exploits the benefits of the proposed AT-MAC system with less failure probability and delay.

In the future, we wish to extend this work with a multi-objective optimization approach, where we plan to maximize reliability and minimize energy consumption of a critical node simultaneously. On the other hand, we performed the Markov chain formulation and analysis for a saturated network. However, in case of an unsaturated network, which may occur in a WBAN in real-life, the analysis is different. Therefore, in the future, we also wish to extend this work for unsaturated networks.

Appendix

Proof of Proposition 2:

From the proposed Markov chain model, by the normalization condition, we have

$$\frac{1}{P_x\tau}\Bigg(\sum_{i=1}^{p}\sum_{j=L_{min}}^{L_{max}}\sum_{k=1}^{r} S_{i,j,k} + S_{p_s,0,r} + \sum_{i=1}^{p} S_{i,0,0} + S_{0,0,r} + \sum_{i=1}^{p} S_{i,L_{max},0}\Bigg) = 1 \quad (43)$$

Using Eqs. 12-22 and owing to chain regularities, we obtain

$$\sum_{i=1}^{p}\sum_{j=L_{min}}^{L_{max}}\sum_{k=1}^{r} S_{i,j,k}$$

$$= P_x\tau(1-\alpha)(1-\beta)\sum_{x=0}^{r-1} P_{coll}\sum_{u=0}^{p-1}(\alpha+(1-\alpha)\beta)^u S_{0,0,0}$$

$$= P_x\tau\frac{1-P_{coll}^r}{1-P_{coll}}(1-(\alpha+(1-\alpha)\beta)^p)S_{0,0,0} \quad (44)$$

$$S_{p_s,0,r} = P_x\tau(1-P_{coll})(1-\alpha)(1-\beta)\sum_{u=0}^{r-1} P_{coll}^u\sum_{x=0}^{p-1}(\alpha+(1-\alpha)\beta)^x S_{0,0,0}$$

$$= P_x\tau(1-P_{coll}^r)(1-(\alpha+(1-\alpha)\beta)^p)S_{0,0,0} \quad (45)$$

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$$\sum_{i=1}^{p} S_{i,0,0} = P_x \tau \sum_{x=0}^{p-1} (\alpha + (1-\alpha)\beta)^x S_{0,0,0}$$
$$= P_x \tau \left(\frac{1 - (\alpha + (1-\alpha)\beta)^p}{(1-\alpha)(1-\beta)} \right) S_{0,0,0} \quad (46)$$

$$S_{0,0,r} = P_x \tau ((1-\alpha)(1-\beta) P_{coll}^r \sum_{x=0}^{p-1} (\alpha + (1-\alpha)\beta)^x$$
$$+ (\alpha + (1-\alpha)\beta)^p) S_{0,0,0} \quad (47)$$

$$\sum_{i=1}^{p} S_{i,L_{max},0} = P_x \tau (1-\alpha) \sum_{x=0}^{p-1} (\alpha + (1-\alpha)\beta)^x$$
$$= P_x \tau \frac{1 - (\alpha + (1-\alpha)\beta)^p}{1-\beta} \quad (48)$$

By adding Eqs. 44-48, and equating them to 1 using Eq. 43, we get the desired expression for $S_{0,0,0}$.

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