Priority-Based Dedicated Slot Allocation With Dynamic Superframe Structure in IEEE 802.15.6-Based Wireless Body Area Networks

Kamal Das, Soumen Moulik, *Member, IEEE*, and Chih-Yung Chang, *Member, IEEE*

***Abstract*—Wireless body area networks (WBANs) support various types of medical applications with heterogeneous requirements. Therefore, we need to use an efficient medium access control (MAC) protocol to ensure reliable data transmission. In this article, we propose a dynamic superframe structure-based MAC protocol extending the principles of the IEEE 802.15.6 standard. In this work, to allocate dedicated slots for each sensor device, a prioritized dedicated slot allocation mechanism using the criteria importance through intercriteria correlation (CRITIC) is proposed. With the help of this method, the priority value of sensor devices is calculated based on different sensors' parameters. We compared the performance of our proposed work with standard IEEE 802.15.6 MAC and a few other MAC protocols. The simulation result shows that our proposed MAC protocol performed better in terms of energy efficiency and reliability, as well as reducing the packet drop probability. Results show that the reliability of data transmission increases over the IEEE 802.15.6 MAC protocol by more than 50%.**

***Index Terms*—Criteria importance through intercriteria correlation (CRITIC), IEEE 802.15.6 MAC, priority-based slot allocation, wireless body area network (WBAN).**

I. INTRODUCTION

MOBILE healthcare through wireless body area networks (WBANs) is the future of healthcare. In general, a WBAN consists of numerous independent on-body physiology monitoring sensor devices connected to a central coordinator (or hub) via a wireless communication medium. The primary benefit of WBAN is early detection of health complications by continuous or periodic monitoring of physiological functions, such as blood pressure, body temperature, ECG, heart rate, breathing, etc. [1]–[3]. Data gathered by WBANs during periodic health monitoring assist in making the diagnosis more accurate and quick. Recently, we are also witnessing a dramatic increase of WBANs in many heterogeneous applications for a wide range of areas, such as ubiquitous health monitoring, sports, military, gaming, etc., and even in association with different cutting-edge enabling technologies, such as Internet of Things (IoT), big data, and software-defined networks (SDNs) [4]–[8].

Physiology monitoring sensors in a WBAN are divergent in the context of different parameters, such as user priority (UP), packet generation rate, data transmission rate, packet size, buffer size, etc. All these sensor parameters play an important role in the overall performance of a WBAN. The existing works based on IEEE 802.15.6 standard did not take such divergent nature of sensor devices into consideration. In this proposed work we consider all these parameters in the process of prioritization of sensor devices. The main objective of the proposed work is to enhance the reliability and energy efficiency of a whole WBAN by priority-based dedicated slot (fixed time slots) allocation for individual sensor devices.

A. Brief Overview of IEEE 802.15.6 MAC Protocol

In order to standardize the communication among sensor devices connected with a WBAN, the IEEE task group had come up with a standard—IEEE 802.15.6—in the year 2012 [9]. According to this standard, the hub shall operate in one of the following three access modes, such as—1) beacon mode with beacon periods; 2) nonbeacon mode with beacon periods; and 3) nonbeacon mode without beacon periods. Beacon mode with beacon periods is the most useful access mode, because of its efforts to synchronize the communication between heterogeneous sensor devices. In this mode, the hub divides the time axis into beacon periods of equal length, which are known as superframes (SFs). Except for the inactive SFs, hub broadcasts beacon frames, that carry information about the network and SF structure, at the beginning of each SF. The SF structure of IEEE 802.15.6 medium access control (MAC) consists of different access phases, such as two EAPs, two RAPs, one CAP, and two MAPs, as illustrated in Fig. 1. The details of these Access Phases are summarized in Table I. UP mapping with data traffic type is mentioned in Table II. Except for RAP1, the length of all other access phases can have zero in a beacon phase, as stated in the standard. The hub sets the duration of all the access phases depending on the application requirements. The hub transmits a preceding B2 beacon frame to provide a nonzero length CAP; otherwise, it will not transmit the B2 frame. To receive a B2 frame or to transmit in a CAP, a node shall be active in the time interval wherein a B2 frame may be sent.

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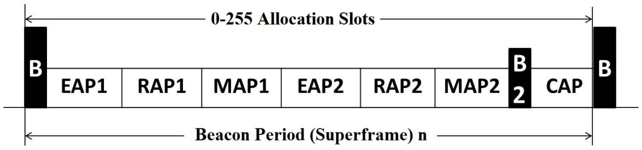


Fig. 1. Superframe structure of IEEE 802.15.6 MAC in Beacon mode with beacon periods.

TABLE I
ACCESS PHASES AND RELATED ACCESS METHODS

Access Phase	Full Name	Description	Access Method
EAP 1	Exclusive Access Phase 1	Transmit data with highest UP, or emergency data, i.e. UP7	Nodes contend for resource allocation using either CSMA/CA or Slotted ALOHA
EAP 2	Exclusive Access Phase 2		
RAP 1	Random Access Phase 1	Transmit all kinds of traffic	
RAP 2	Random Access Phase 2		
CAP	Contention Access Phase		
MAP 1	Managed Access Phase 1	Used for uplink, downlink, bilink, and delay bilink allocation intervals	Type I/II polling mechanism is used
MAP 2	Managed Access Phase 2		

TABLE II
USER PRIORITY MAPPING [9]

User priority	Traffic designation	Frame type
0	Background (BK)	Data
1	Best effort (BE)	Data
2	Excellent effort (EE)	Data
3	Video (VI)	Data
4	Voice (VO)	Data
5	Medical data or network control	Data or management
6	High-priority medical data or network control	Data or management
7	Emergency or medical implant event report	Data

In IEEE 802.15.6 standard, the length of the EAP phases is fixed, and it is used for emergency data transmission only. Due to the fixed length of EAPs, if there is no emergency data in the network at a particular time, then the whole EAP phases will be wasted. Moreover, in the presence of a large number of emergency data, the fixed-sized EAPs cannot transmit all the emergency data, which will degrade the emergency data transmission. To solve this problem, we proposed the concept of dynamic length EAP. Another problem in the IEEE 802.15.6 standard is that the emergency data has to contend for channel allocation, which is not a good idea in EAP phases. Therefore, in our proposed work, we allocated dedicated slots for emergency data in EAP using time division multiple access (TDMA).

B. Contributions

The contributions of the proposed MAC are as follows.

1) A hybrid SF structure with dynamic EAP and MAP is considered in the proposed MAC.
2) Prioritization of sensor devices is achieved using the values of various parameters and the criteria importance through the intercriteria correlation (CRITIC) method.
3) Special windows are inserted dynamically in MAP to allocate dedicated slots for all the sensor devices according to their priority values.
4) The proposed MAC ensures reliable data transmission while higher throughput and lesser average energy consumption, in comparison with the IEEE 802.15.6 MAC and its different benchmark variants.

II. RELATED WORKS

Researchers across the globe are proposing innovative MAC mechanisms that are developed centering the original framework of IEEE 802.15.6 MAC. Naturally, these works have certain pros and cons that are discussed briefly in this section.

Zia *et al.* [10] introduced a novel group-based traffic classification to avoid contention and inefficient use of SF duration in IEEE 802.15.6 standard. Chen and Chiu [11] proposed an MAC protocol for cross-layered energy-aware resource allocation. Li *et al.* [12] proposed a joint power allocation scheme on the maximum ratio combining protocol. In order to maximize the overall network throughput, the authors formulated an optimization problem and then solved it. Wang *et al.* [13] addressed the problem of throughput heterogeneity, and attempted to minimize energy consumption for both battery-free and battery-assisted scenarios. The authors used gradient descent, bisection search algorithms, the Lagrange dual subgradient method, etc., to confront these problems. Liang *et al.* [14] proposed an energy-efficient and energy-aware MAC (EEEA-MAC) protocol to ensure low power and low delay for emergency data reporting. He *et al.* [15] proposed a joint weights optimizing time slot allocation protocol (JWTA) where the weight is calculated using an analytical hierarchy process; throughput is maximized for each sensor by assigning joint weights and times. Rasheed *et al.* [16] proposed a modified SF structure of IEEE 802.15.4-based MAC protocol to improves the delay and the energy consumption efficiency. Hao *et al.* [17] proposed an approach to estimate the Pareto-optimal powercap configurations to obtain fine-grained powercap allocation and energy optimization for power-constrained systems by combining the powercap with uncore frequency scaling. Cicioğlu and Çalhan [18] developed an IEEE 802.15.6-based event-driven wireless body sensor networks (WBSNs) method to provide a more energy-efficient structure. They also designed a WBSN architecture for energy harvesting. In one of their other works, the same authors considered battery levels, specific absorption rates, and priorities of the sensor devices for the dynamic HUB selection procedure, in order to decrease the negative impacts of electromagnetic signals on human tissue due to fixed HUB placement [19].

Apart from the above-mentioned works we also survey the following studies that are more relevant to the proposed work. We also considered them as benchmarks during performance comparison. Enkoji *et al.* [20] proposed a protocol, where the authors adjust the length of EAPs and RAPs depending on the traffic sensed by the hub in beacon phases. The authors allocate dedicated slots in EAPs for emergency data. In RAPs, all nonemergency sensors must contend for channel allocation. The polling mechanism is used for data transmission in MAPs. Huq *et al.* [21] proposed an MAC protocol called medical emergency body MAC (MEB MAC), to balance the power consumption and channel access delay. This protocol dynamically inserts multiple listening windows (LWs) to achieve quick channel access for emergency traffic within the MAPs. The authors used TDMA in MAPs to transmit emergency traffic quickly and reliably. The EAPs are not included in the SF structure of MEB MAC. Sadra and Abolhasan [22] proposed two IEEE 802.15.6-based MAC protocols, saturation aware for the user priorities (SAUPs) and saturation Aware for the highest UP (SAH). Along with other access phases, the SF structure of SAUP and SAH additionally include a phase for allocating guaranteed time slots (GTSs). In SAUP, during the MAP phase, the polling method is used to grant a GTS to a node for data transmission in the GTS phase. SAH allocates GTSs to emergency data in EAP using the TDMA mechanism rather than using the CSMA/CA mechanism. Saboor *et al.* [23] proposed a dynamic slot allocation (DSA) scheme using nonoverlapping contention windows (CWs) to improve the SF utilization of IEEE 802.15.6 MAC protocol. In this work, the authors proposed a nonoverlapping backoff algorithm (NOBA) to avoid interpriority collisions. They also introduced a DSA scheme to prevent wastage due to fixed slot size. Deepak and Babu [24] proposed an adaptive SF structure-based channel access mechanism to improve the reliability of emergency data transmission. Misra *et al.* [25] introduced an energy-efficient MAC protocol for IEEE 802.15.6-based WBAN. In this, the authors proposed an SF structure where the first half is used for emergency data transmission, and the latter half is designed for regular data transmission.

Synthesis: Apart from proposing the concepts of dynamic length EAP and dedicated slots for emergency data in EAP using TDMA, we also introduced a sensor prioritization mechanism to decide the order of dedicated slot allocation to sensor nodes according to their urgency. The urgency of sensor nodes is decided by calculating priority value using the CRITC model based on various sensor-associated parameters. It is noted that none of these existing works considered any approaches like these. Importance of various sensor parameters, such as packet generation rate, buffer occupancy status, data transmission rate, and packet size are not realized in the existing works. For example, sensor devices with a high-packet generation rate and highly occupied buffer require fast channel access; otherwise, it can lead to packets loss due to buffer overflow. Thus, in the proposed work, we consider all such relevant parameters while prioritizing the sensor devices using the CRITIC method, and also compare the performance of the proposed MAC with several benchmarks [20]–[25].

III. PROPOSED WORK

The main goal of the proposed work is to allocate dedicated slots based on sensor prioritization with better network performance. In this regard, the main challenges that we face are—designing a dynamic SF structure and prioritizing sensor devices based on important parameters. For readers' convenience, the proposed solution is described using the following sections: A) superframe structure of the proposed MAC; B) sensor prioritization using CRITIC; C) mathematical model of CRITIC; and D) description of aspects used for comparison.

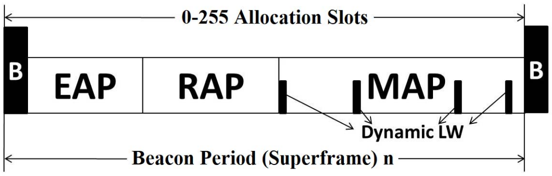


Fig. 2. Superframe structure of the proposed MAC protocol.

A. Superframe Structure of the Proposed MAC

The proposed MAC protocol is developed for a star topology WBAN, where a hub controls the entire operation of the network. The proposed MAC contains both the contention access phase and contention-free phases. The hub will always stay awake. In the proposed MAC, we consider one dynamic length EAP, one fixed length RAP, and one dynamic length MAP. We keep the length of the RAP fixed as stated out in the IEEE 802.15.6 standard. Fig. 2 depicts the SF structure of the proposed MAC protocol. In EAP, we assign dedicated slots for all the emergency sensor devices (having data packets of UP 7) using TDMA according to the descending order of their priority value. Allocation of dedicated slots in EAP using TDMA can provide fast and reliable channel access to the emergency sensor devices. In RAP, sensors with all types of traffic will transmit their data using the CSMA/CA mechanism. In the MAP, multiple LWs are inserted dynamically to allocate slots for all types of sensor devices. In both the EAP and MAP, the hub allocates slots according to the priority value of sensor devices, which is calculated using CRITIC based on the value of different parameters received from sensor devices.

1) Dynamic EAP and MAP: Dynamic EAP and dynamic MAP can be obtained by adjusting the length of them based on the information collected from all the sensors by the hub in the beacon phase. Based on the number of packets in emergency sensors (UP 7), the hub measures the length of the EAP (L_{EAP}), and the length of the MAP (L_{MAP}). The variable L_{EAP} is determined by calculating the total time required to transmit all the packets from emergency sensors sensed by the hub in the beacon phase (T_{EAP}). Mathematically, it can be represented as

$$T_{\mathrm{EAP}} = \sum_{i=1}^{N_{\mathrm{emg}}} \frac{N_i' \times \mathrm{PS}_i}{\mathrm{DTR}_i} + \left(\sum_{i=1}^{N_{\mathrm{emg}}} N_i'\right) \times (T_{\mathrm{ACK}} + 2T_{\mathrm{SIFS}}) \quad (1)$$

where N_{emg} denotes the number of emergency sensors, N_i' denotes the number of packets in ith emergency sensor, and PS_i and DTR_i are the packet size and data transmission rate of ith emergency sensor, respectively. Variable T_{ACK} denotes the time required to send an acknowledgement (ACK) and T_{SIFS} denotes the amount of time a sensor device takes to process a received frame and to respond with a response frame, which

Algorithm 1 Dedicated Slot Allocation in EAP Using TDMA

```
Input: Number of emergency sensors $N_{\text{emg}}$, various sensor parameters.
Output: Dedicated slot allocation for emergency sensors using TDMA.
1: Sort all the emergency sensors according to their priority value calculated using CRITIC based on various sensor parameters
2: $required\_slot = \text{ceil}\left(\frac{T_{EAP}}{L_{slot}}\right)$
3: $available\_slot = (L_{BEACON} - L_{RAP})$
4: $remaining\_slot = available\_slot$
5: if $required\_slot \le available\_slot$ then
6:     for $i = 1$ to $N_{\text{emg}}$ do
7:         $time\_req = N'_i \times \left(\frac{PS_i}{DTR_i} + T_{ACK} + 2T_{SIFS}\right)$
8:         $slot\_req = \text{ceil}\left(\frac{time\_req}{L_{slot}}\right)$
9:         Allocate "$slot\_req$" time slots for the $i^{th}$ emergency sensor
10:    end for
11: else
12:    for $i = 1$ to $N_{\text{emg}}$ do
13:        $N''_i = \text{ceil}\left(N'_i \times \frac{available\_slot}{required\_slot}\right)$
14:        $time\_req = N''_i \times \left(\frac{PS_i}{DTR_i} + T_{ACK} + 2T_{SIFS}\right)$
15:        $slot\_req = \text{ceil}\left(\frac{time\_req}{L_{slot}}\right)$
16:        if $slot\_req \le remaining\_slot$ then
17:            Allocate "$slot\_req$" time slots for the $i^{th}$ emergency sensor
18:            $remaining\_slot = remaining\_slot - slot\_req$
19:        else
20:            Allocate "$remaining\_slot$" time slots for the $i^{th}$ emergency sensor
21:            $remaining\_slot = 0$
22:        end if
23:    end for
24: end if
```

Algorithm 2 Dynamic Listening Window Insertion and Dedicated Slot Allocation in MAP

```
Input: Number of sensors $N$, various sensor parameters
Output: Dedicated slot allocation for all the sensor devices using TDMA.
$LWI_{min}$ //Minimum listening window interval
$used\_slot = 0$ //Number of slots already used in the MAP
while $used\_slot < L_{MAP}$ do
    Insert LW in the current time slot
    Sort all the sensors according to their priority value calculated using the CRITIC based on various sensor parameters
    $used\_slot = used\_slot + L_{\text{LW}}$
    $required\_slot = \frac{\sum_{i=1}^{N} N'_i \times \left(\frac{PS_i}{DTR_i} + T_{ACK} + 2T_{SIFS}\right)}{L_{slot}}$
    $available\_slot = L_{MAP} - used\_slot$
    $remaining\_slot = available\_slot$
    if $required\_slot \le available\_slot$ then
        for $i = 1$ to $N$ do
            $time\_req = N'_i \times \left(\frac{PS_i}{DTR_i} + T_{ACK} + 2T_{SIFS}\right)$
            $slot\_req = \text{ceil}\left(\frac{time\_req}{L_{slot}}\right)$
            Allocate "$slot\_req$" time slots for the $i^{th}$ sensor
        end for
        if $required\_slot < LWI_{min}$ then
            Wait ($LWI_{min} - required\_slot$) slots before inserting next LW
            $used\_slot = used\_slot + LWI_{min}$
        else
            $used\_slot = required\_slot$
        end if
    else
        for $i = 1$ to $N$ do
            $N''_i = \text{ceil}\left(N'_i \times \frac{available\_slot}{required\_slot}\right)$
            $time\_req = N''_i \times \left(\frac{PS_i}{DTR_i} + T_{ACK} + 2T_{SIFS}\right)$
            $slot\_req = \text{ceil}\left(\frac{time\_req}{L_{slot}}\right)$
            if $slot\_req \le remaining\_slot$ then
                Allocate "$slot\_req$" time slots for the $i^{th}$ sensor
                $remaining\_slot = remaining\_slot - slot\_req$
            else
                Allocate "$remaining\_slot$" time slots for the $i^{th}$ sensor
                $remaining\_slot = 0$
            end if
        end for
        $used\_slot = L_{MAP}$
    end if
end while
```

is also known as short interframe space (SIFS) time. Each packet transmission consists of two components—1) actual packet transmission time and 2) as well as T_{ACK} and $2T_{\text{SIFS}}$, for each packet. Finally, the length of the EAP (L_{EAP}) is calculated by choosing the minimum number of time slots between the required time slots for T_{EAP} and available time slots for both EAP and MAP phases in the SF as

$$L_{\text{EAP}} = \textbf{Min}\left\{\textbf{ceil}\left(\frac{T_{\text{EAP}}}{L_{\text{slot}}}\right), (L_{\text{BEACON}} - L_{\text{RAP}})\right\} \tag{2}$$

where, L_{slot}, L_{BEACON}, and L_{RAP} are the length of a time slot, length of SF, and length of RAP, respectively. Here, the unit of L_{slot} is the amount of time duration (in second) and the unit of L_{EAP}, L_{RAP}, L_{MAP}, and L_{BEACON} is the number of time slots. The length of the MAP (L_{MAP}) is calculated as the remaining slots in the SF

$$L_{\text{MAP}} = L_{\text{BEACON}} - (L_{\text{EAP}} + L_{\text{RAP}}). \tag{3}$$

2) Dedicated Slot Allocation in EAP and MAP: The TDMA-based dedicated slot allocation mechanism for emergency sensors in EAP is demonstrated in Algorithm 1. At first, the hub will sort all emergency sensor devices according to their priority value, which is calculated using CRITIC, based on various sensor parameters. Then the hub calculates the number of time slots required (*required_slot*) to transmit all the packets from emergency sensor devices sensed in the beacon phase. The variable *available_slot* in line 3 indicates the maximum number of slots that can be allocated to EAP, which is the total combined slots for both EAP and MAP. If the *required_slot* is less than or equal to the *available_slot*, the hub will allocate dedicated slots to all emergency sensors for transmission of all packets stored in their buffer; otherwise, the *available_slot* will be distributed among all the emergency sensors according to the number of packets stored in their buffer. The variable *time_req* denotes the amount of time required to transmit N'_i or N''_i packets. The number of packets of the *i*th emergency sensors for which the hub will allocate dedicated time slots is denoted by N''_i. Variable *slot_req* indicates the number of time slots required to transmit N'_i packets, if *required_slot* is less than or equal to *available_slot*, otherwise to transmit N''_i packets.

Algorithm 2 shows the insertion of dynamic LWs and the dedicated slot allocation mechanism for all sensor devices in the MAP. The process of allocating dedicated slots in MAP is similar to the slot allocation mechanism in EAP. The only difference is that in MAP, the hub allocates dedicated slots to all sensor devices, whereas in EAP, the hub allocates dedicated slots for emergency sensor devices only. We insert multiple LW in MAP to collect information about various parameters from sensor devices and allocate dedicated slots for them according to the descending order of their priority value. Algorithm 2 also describes the process of inserting LWs dynamically in MAP. The hub inserts an LW at the beginning of the MAP. The next LW will be inserted after *required_slot* slots if the *required_slot* is greater than or equal to the LWI_{min}. If *required_slot* is less than LWI_{min}, after transmitting all the packets by the sensor nodes in the current LW, the hub will wait for another ($\text{LWI}_{\text{min}} - required\_slot$) slots before inserting the next LW. The process of inserting LW will continue until there is no slot left in the MAP. The variable LWI_{min} shown in line 1 denotes the minimum LW interval, which is initialized by the hub. Inserting LWs frequently leads to high-energy consumption for sensor devices in the low-traffic network. Therefore, we set a minimum LW interval between two LWs to prevent the unnecessary energy consumption of sensor devices in the low traffic network. Lines 16–18 show the process of inserting LW with the minimum LW interval (LWI_{min}) between two LWs if *required_slot* is less than LWI_{min}.

B. Sensor Prioritization Using CRITIC

In both the algorithms for dedicated slot allocation, various sensor parameters are mentioned as *Input*. It is also mentioned that priority values are calculated using the CRITIC method and the sensors are sorted in descending order of their priority values before slot allocation. The basic structure of the multicriteria weight measurement method CRITIC comprises three components: 1) goal; 2) criteria; and 3) alternatives [26]. The goal is to calculate the priority value of sensor devices. The criteria set represents the sensor-specific parameters depending on which priority value will be calculated. Finally, the alternatives are the sensor devices whose priority value is calculated by this model to allocate dedicated slots for them. We consider five parameters as criteria to calculate the priority value of each sensor devices. They are formally defined below.

Definition 1: UP of a sensor node indicates the criticality measure of its sensed data.

The highest UP data is the emergency data whose priority value is 7. UP mapping with data traffic type is already mentioned in Table II.

Definition 2: Buffer occupancy status (BOS) of a sensor node is the ratio of present buffer occupancy (BO) and buffer size (BS) of the node. The BOS of *i*th sensor node is

$$\text{BOS}_i = \frac{\text{BO}_i}{\text{BS}_i} \tag{4}$$

where BO_i and BS_i represent the present buffer occupancy (in kB) and the buffer size (in kB) of the *i*th sensor node, respectively. The BOS is an important factor in priority measurement because data can loss due to buffer overflow. Sensor nodes with high BOS are given high preference in sensor prioritization.

Definition 3: Packet size (PS) is the length of the data or message in the transmitted frame by a sensor node.

Definition 4: Data transmission rate (DTR) is the data rate at which a sensor node transmits data.

In this work, the DTR is considered as kilobits per second (kbps). Sensors with small PS and high DTR required less time to transmit. Hence, the sensor with small PS and high DTR will be given high preference in sensor prioritization.

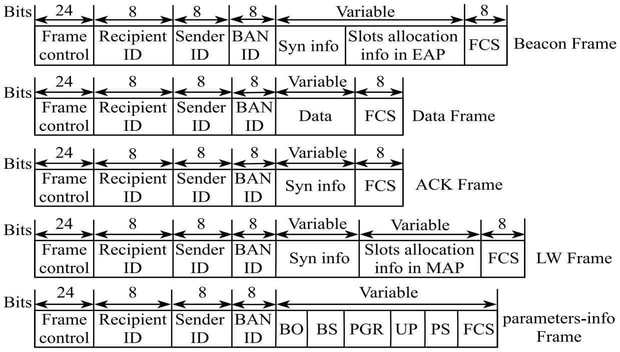


Fig. 3. Frame formats of the proposed MAC.

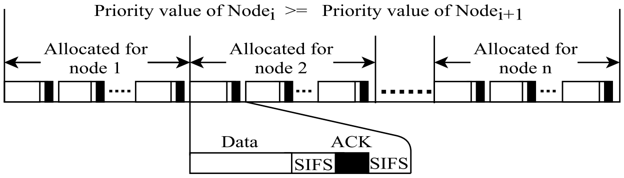


Fig. 4. Dedicated slot allocation using TDMA.

Definition 5: Packet generation rate (PGR) is the number at which rate the sensors will generate packets in a second.

Sensor with high PGR will be given high priority; otherwise, it can lead to loss of packets due to buffer overflow.

In the beacon phase and LW phases, the hub will poll all the sensor devices one by one to collect the values of UP, BO, BS, PS, and PGR. The sensor devices will then send a *parameters-info frame* to the hub, which contains the value of parameters, as illustrated in Fig. 3. The hub then calculates BOS based on BO and BS and calculates the DTR of sensor devices based on the received symbol rate. Whenever a sensor device is unable to transmit this information frame, the hub will consider its past value of parameters for calculating priority value. The hub calculates the priority value of each sensor device based on the received parameters information and uses TDMA to assign dedicated time slots to each sensor device according to the descending order of their priority value. The structure of dedicated slot allocation for sensor devices in EAP and MAP using TDMA is shown in Fig. 4. The hub will broadcast a beacon frame or an LW frame to all the sensor devices after dedicated slots allocation. The beacon frame contains information about the length of various access phases and dedicated slot allocation information in EAP for emergency sensor devices. LW frames contain dedicated slot allocation information of sensor devices in MAP. The operations of the hub in the beacon phase and LW phases are shown in Fig. 5.

C. Mathematical Model of CRITIC

CRITIC is an efficient multicriteria decision-making approach that emphasizes the objective weight of criteria, which indicates how much information each one contains. This approach calculates the objective weight based on the information given by criteria in two dimensions. The first

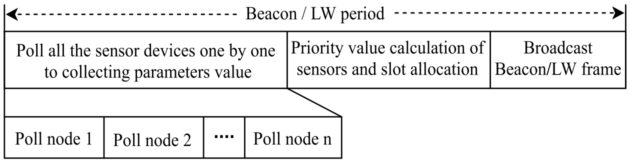


Fig. 5. Functional operation of hub in Beacon/LW phases.

one is the degree of contrast, which represents each criterion individually. The standard deviation is calculated for quantifying the degree of contrast. The second one is the contradiction between criteria determined by the linear correlation coefficient between criteria. In this work, objective weights determined by the CRITIC method are coupled with subjective weights denoted by the decision matrix to obtain more realistic weights for decision making. The details of the internal computation of CRITIC, which the hub take cares, are described below.

The hub generates an $N \times M$ decision matrix (DM) based on the sensor devices who want to send data and criteria parameters of those sensor devices as input of the model, where N denotes the number of sensor devices and M denotes the number of criteria. The DM matrix is represented as

$$\mathrm{DM} = \begin{array}{c} \\ S_1 \\ S_2 \\ \vdots \\ S_N \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_M \end{array} \\ \begin{pmatrix} \beta_{1,1} & \beta_{1,2} & \ldots & \beta_{,1M} \\ \beta_{2,1} & \beta_{2,2} & \ldots & \beta_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{N,1} & \beta_{N,2} & \ldots & \beta_{N,M} \end{pmatrix} \end{array} \tag{5}$$

where each element $\beta_{i,j}$ represents the jth parameter value of the ith sensor. After receiving *parameters-info frames* from individual sensor devices in the beacon phase and LW phases, the hub assigns $\beta_{i,j}$ values and forms this matrix DM.

The steps of calculating the priority value of sensor devices are described as follows.

1) Normalize the decision matrix as

$$\beta_{i,j} = \frac{\beta_{i,j}}{\sum_{i=1}^{N} \beta_{i,j}}. \tag{6}$$

2) Calculate standard deviation (σ_j) for each criteria as in (7), where $\bar{\beta}_j$ is the mean value of jth column of $\beta_{i,j}$

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{N} \left(\beta_{i,j} - \bar{\beta}_j\right)^2}{N-1}}. \tag{7}$$

3) Construct a symmetric matrix of $M \times M$ with generic elements of $\beta_{j,k}$, which is the linear correlation coefficient between the criteria vectors X_j and X_k using the (8), where $j, k = 1, \ldots, M$

$$\mathrm{corr}\left(X_j, X_k\right) = \frac{M\left(\sum X_j X_k\right) - \left(\sum X_j\right)\left(\sum X_k\right)}{\sqrt{\left[M \sum {X_j}^2 - \left(\sum X_j\right)^2\right]\left[M \sum {X_k}^2 - \left(\sum X_k\right)^2\right]}}. \tag{8}$$

The criteria vectors X_j and X_k can be expressed as $X_j = C_1, C_2, \ldots, C_M$ and $X_k = C_1, C_2, \ldots, C_M$. The symmetric matrix can be represented as

$$\begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_M \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_M \end{array} \\ \begin{pmatrix} X_{1,1} & X_{1,2} & \ldots & X_{1,M} \\ X_{2,1} & X_{2,2} & \ldots & X_{2,M} \\ \vdots & \vdots & \ddots & \vdots \\ X_{M,1} & X_{M,2} & \ldots & X_{M,M} \end{pmatrix} \end{array} \tag{9}$$

where $X_{j,k} = \mathrm{corr}(X_j, X_k)$ and $j, k = 1, \ldots, M$.

4) Calculate measure of the conflict created by the criterion j with respect to the decision situation defined by the rest of criteria as

$$\sum_{k=1}^{M} \left(1 - X_{j,k}\right). \tag{10}$$

5) Determine the quality of the information in relation to each criterion as

$$C_j = \sigma_j \times \sum_{k=1}^{M} \left(1 - X_{j,k}\right). \tag{11}$$

6) Determine the criterion weight as

$$W_j = \frac{C_j}{\sum_{k=1}^{M} C_j}. \tag{12}$$

In the above equation, higher the value of C_j, the greater amount of information emitted by the corresponding criterion that gives relatively higher importance for the calculation of the priority value.

7) Calculate priority values of sensor devices as

$$S_i = \sum_{j=1}^{M} \beta_{i,j} \times W_j \tag{13}$$

where $i = 1, \ldots, N$. For criteria PS, $\beta_{i,j}$ will be replaced by $[(\sum_{i=1}^{N} \beta_{i,j})/\beta_{i,j}]$, because sensors with small PS will be given high preference.

8) Normalize the priority value of sensor devices within the range 0 to 1 as in (14), where $S_{\min}$ and $S_{\max}$ are the minimum and maximum priority value among the sensors, and $i = 1, \ldots, N$

$$S_i = \frac{S_i - S_{\min}}{S_{\max} - S_{\min}}. \tag{14}$$

While allocating dedicated slots, the proposed algorithm considers the sensor devices one by one, following decreasing order of their priority values. The proposed MAC might be extended for 2-hop transmission, where dedicated slots can be allocated for a relayed node by scheduling a bi-link allocation between the relaying node and the relayed node, and allocating an uplink for the relaying node to transmit data.

D. Description of Aspects Used for Comparison

The various network performance metrics used in this work to evaluate its performance, are defined below.

Definition 6: Reliability (R) of a sensor node is the probability of successful packet delivery by that node [27].

Mathematically, reliability of a sensor device is expressed as

$$R = \frac{P_{\text{succ}}}{P_{\text{gen}}} \tag{15}$$

where P_{succ} is the number of packets successfully delivered by a sensor and P_{gen} is the number of packets generated by that sensor.

Definition 7: Packet delivery delay (D) of a sensor device is the amount of time between the generation of a packet at the sensor device and its reception at the hub.

The average packet delivery delay of sensor devices is depicted as

$$D = \frac{\sum_{i=1}^{N} \sum_{j=1}^{P_{\text{succ}_i}} \text{delay}_j}{\sum_{i=1}^{N} P_{\text{succ}_i}} \tag{16}$$

where N denotes the number of sensor devices, P_{succ_i} represents the number of packets that successfully delivered by the ith sensor, and delay_j is the packet delivery delay of the jth packet of the ith sensor.

Definition 8: Energy consumption (E) of a sensor device is the total power consumed by the transceiver during its communication period.

The total energy consumption of a sensor device is determined by summing up the energy consumption in different modes of that sensor, such as wake-up mode, transmitting mode, receiving mode, and sleeping mode [28]. In our simulation, we compute the average energy consumption (E) to transmit one-kilobit data successfully. Energy consumption per kilobit data transmission is calculated as

$$E = \frac{\sum_{i=1}^{N} V \times \left\{ (T_{t_i} \times TC) + (T_{r_i} \times \text{RC}) + (T_{w_i} \times \text{WC}) + (T_{s_i} \times \text{SC}) \right\}}{\delta} \tag{17}$$

where N, TC, RC, WC, and SC denote the number sensor nodes, transmission current, receive current, wake-up current, and sleep current, respectively. T_{t_i}, T_{r_i}, T_{w_i}, and T_{s_i} represent the time spent by the ith sensor in transmission mode, receive mode, wake-up mode, and sleep mode, respectively. δ denotes the total data transmission by all the sensor devices in kilobits.

Definition 9: Throughput (T) of the network is defined as the average data transmitted per second, which is measured in bits per second (bps).

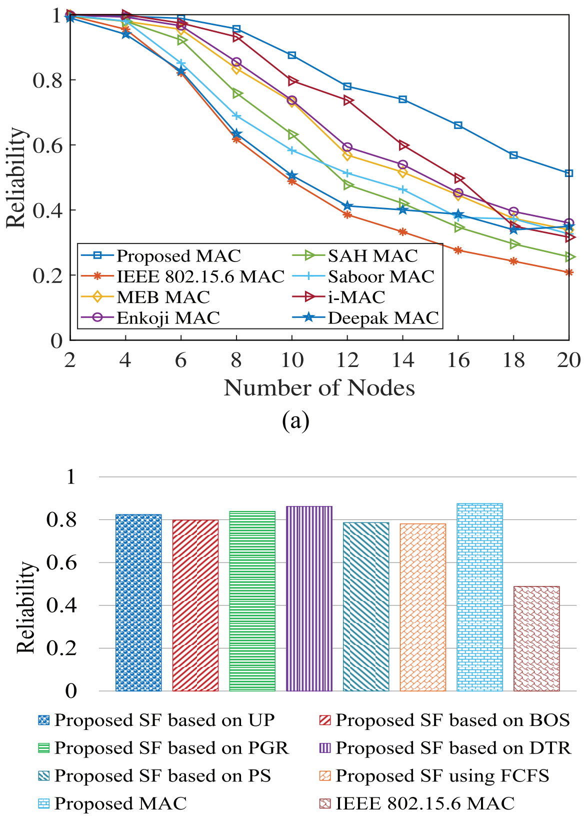
Our simulation calculates the throughput by averaging the data transmission of all the sensor devices in kbps. The throughput is calculated as

$$T = \frac{\delta}{N \times Sim\_time} \tag{18}$$

where, N and Sim_time denote the number of sensor devices and simulation time, respectively. δ denotes the total data transmission by all the sensor devices in kilobits.

IV. PERFORMANCE EVALUATION

We have simulated the proposed MAC protocol in C++ and considered the average of 100 runs of the simulation to generate results. The performance of the proposed MAC protocol is compared with IEEE 802.15.6 MAC [9], and existing benchmark works, such as Enkoji MAC [20], MEB MAC [21], SAH MAC [22], Saboor MAC [23], Deepak MAC [24], and i-MAC [25]. We considered a star topology where the hub is connected to multiple sensor devices. The values of the simulation parameters are summarized in Table III. The specifications of the criteria used for simulation are shown in Table IV. The specifications of the SF structure of the proposed MAC and other benchmark MAC protocols [9], [20]–[24] are described in Table V, where L_{EAP}, L_{RAP}, L_{MAP}, L_{CAP}, and L_{LW} are the length of EAP, RAP, MAP, CAP, and LW, respectively, and LW_{int} represents the LW interval. The unit of all these parameters is "number of time slots." The length of all the access phases of i-MAC is dynamic.



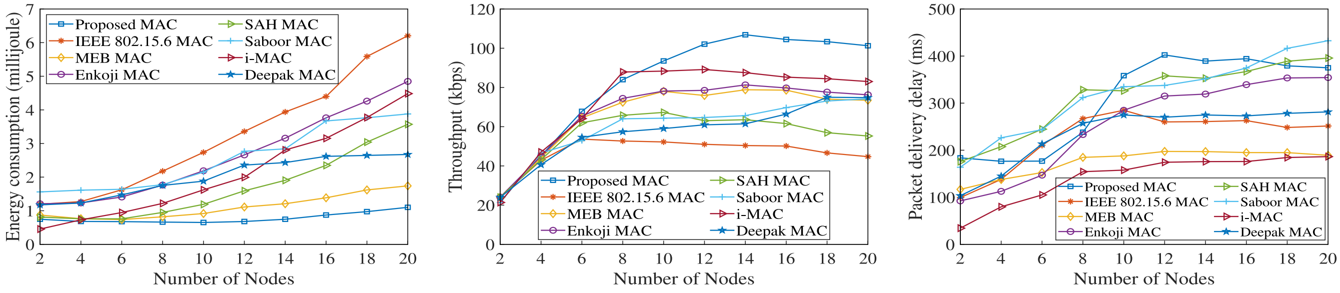
(a)

(b)

Fig. 6. Comparison of overall data transmission reliability. (a) Reliability comparison of proposed MAC with various benchmarks. (b) Reliability comparison of the proposed MAC with its different variants.

A. Reliability Comparison

In the proposed protocol, the reliability of data transmission is enhanced as we proposed a dynamic SF structure and priority-based dedicated slot allocation for each sensor device using TDMA. Fig. 6(a) depicts the overall data transmission reliability of our proposed MAC protocol compared with IEEE 802.15.6 MAC and other benchmark MAC protocols. The result is evident that the proposed MAC protocol improves the overall data transmission reliability over IEEE 802.15.6 MAC and other MAC protocols. In comparison, the reliability of data transmission improves over the IEEE 802.15.6 MAC protocol by more than 50%. Fig. 6(a) also shows that the overall reliability decreases continuously as the number of nodes



(a) (b) (c)

Fig. 7. Performance comparison of the proposed MAC with various benchmarks. (a) Average energy consumption for per kilobit data transmission. (b) Average network throughput. (c) Average packet delivery delay.

TABLE III
VALUES OF SIMULATION PARAMETERS

Parameter Name	Value	Parameter Name	Value
Superframe Length	64 slots	Voltage Supply	3V
Slot Length	5 ms	Transmission Current	10 mA
MAC Header Size	7 Bytes	Receive Current	10 mA
FCS	2 Bytes	Wake-up Current	5 mA
Beacon size	17 Bytes	Sleep Current	1 mA
ACK size	7 Bytes	Simulation Time	50 s

TABLE IV
CRITERIA VALUES CONSIDERED IN SIMULATION

Criteria Name	Value Range
Used priority (UP)	(0 - 7)
Packet size (PS)	(30 - 200) Bytes
Packet generation rate (PGR)	(10 - 40) packets/s
Data transmission rate (DTR)	(50 - 300) kbps
Buffer size (BS)	(1 - 4) KBytes

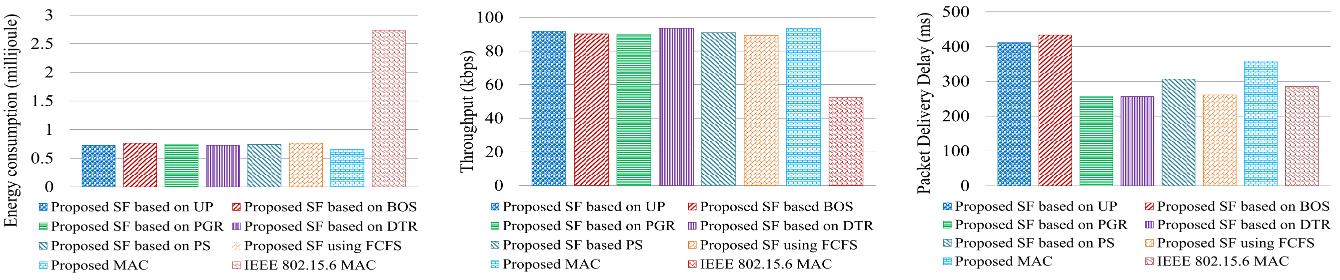
TABLE V
SUPERFRAME STRUCTURE OF DIFFERENT MAC PROTOCOL

MAC	Enkoji	MEB	SAH	Deepak	Saboor	IEEE	Proposed
L_{EAP1}	Dyn.	-	12	-	6	6	Dyn.
L_{RAP1}	Dyn.	10	20	-	10	10	20
L_{MAP1}	16	22	32	Dyn.	16	16	Dyn.
L_{EAP2}	Dyn.	-	-	1	6	6	-
L_{RAP2}	Dyn.	10	-	20	10	10	-
L_{MAP2}	16	22	-	Dyn.	16	16	-
L_{CAP}	-	-	-	Dyn.	-	-	-
LW_{int}	-	12	-	-	-	-	Dyn.
L_{LW}	-	Dyn.	-	-	-	-	Dyn.

increases due to the channel access failure and the buffer overflow. Simulating with the nodes, Fig. 6(b) depicts the reliability comparison of the proposed MAC with its different variants. We can clearly observe that the reliability is highest in the case of the proposed MAC which includes the proposed SF structure and considers a combined effect of all the criteria. Even the reliability measures of individual criteria (with proposed SF) is better than the same of IEEE 802.15.6 MAC. If we do not consider any criteria, then also the proposed SF, with the first come first serve (FCFS) scheme, yields better reliability than IEEE 802.15.6 MAC.

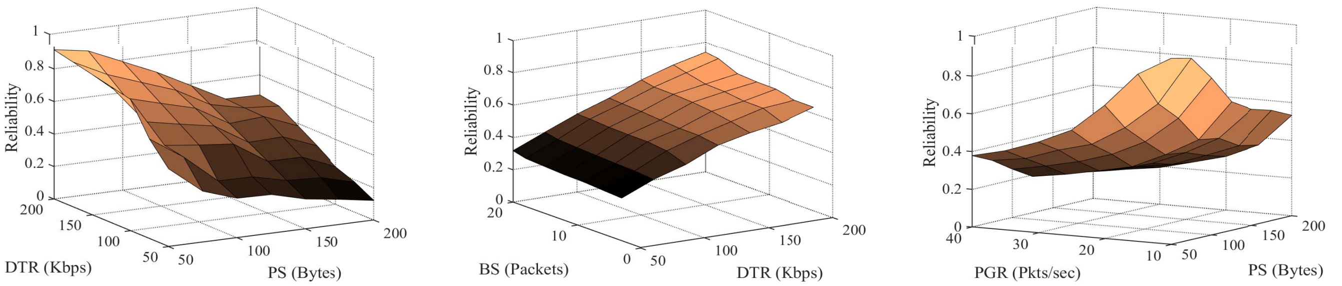
B. Performance Comparison

Fig. 7 illustrates the performance comparison of the proposed MAC with IEEE 802.15.6 MAC and other existing benchmark MAC protocols. Fig. 7(a) shows that the proposed MAC protocol consumes less energy per kilo-bit data transmission as compared to the IEEE 802.15.6 MAC protocol and existing MAC protocols. The energy consumption of the proposed MAC significantly decreases due to dedicated slot allocations in the EAP and MAP. In the dedicated slot allocation scheme, a sensor node will only wake up in the time slot assigned to it; otherwise, it will remain in sleep mode. Dedicated slot allocation for sensor devices exhibits low collision and packet drop probability and maximizes data transmission probability, thus reduce the energy consumption for per kilo-bit data transmission. Moreover, when the number of sensor devices increases, the probability of obtaining the idle channel for data transmission decreases. As a result, the energy consumption per kilo-bit data transmission increases, as reducing the total data transmission probability. Fig. 7(b) depicts that the average throughput of the proposed MAC protocol is better than the IEEE 802.15.6 MAC protocols and other MAC protocols. The throughput of the network increases as we increase the number of sensor nodes for a certain limit. After a certain limit, the network throughput gets affected for more number of sensor nodes. The involvement of more number of sensor nodes increases the collision probability and the probabilities of finding channel busy in contention-based periods. Thus, it affects the overall network throughput. The network throughput of the proposed MAC is improved over IEEE 802.15.6 MAC by 50% and the energy consumption per kbps data transmission is reduced by 70%, respectively. Fig. 7(c) reveals that although the average packet delivery delay of the proposed MAC is a little bit higher than the IEEE 802.15.6 MAC and other MAC protocols, it provides significant improvements in terms of reliability, energy consumption, and throughput. Therefore, the high-packet delivery delay of the proposed MAC is acceptable as it provides better improvements in other aspects. Fig. 8 shows the performance comparison of the proposed MAC with the different sensor prioritization method in the proposed SF structure for ten sensor nodes. The overall performance is much better (low-energy consumption, high throughput) in the proposed MAC in comparison with IEEE 802.15.6 MAC. Even in case of the



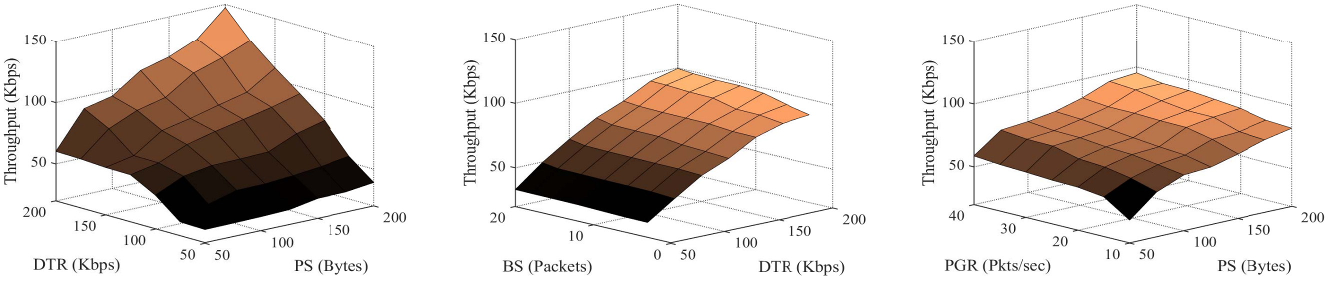
(a) (b) (c)

Fig. 8. Performance comparison of the proposed MAC with different prioritization in the proposed SF structure. (a) Average energy consumption. (b) Average network throughput. (c) Average packet delivery delay.



(a) (b) (c)

Fig. 9. Effect of different criteria on Reliability. Simulated with ten nodes. (a) Effect of PS and DTR. (b) Effect of BS and DTR. (c) Effect of PGR and PS.



(a) (b) (c)

Fig. 10. Effect of different criteria on Throughput. Simulated with ten nodes. (a) Effect of PS and DTR. (b) Effect of BS and DTR. (c) Effect of PGR and PS.

proposed SF using single criteria and using FCFS (no-criteria), energy consumption and throughput better in comparison with IEEE 802.15.6 MAC. The proposed MAC performs better than the FCFS-based slot allocation because the later does not take care of the criteria that reduce the packet drop due to buffer overflow.

Figs. 9 and 10 illustrate the combined effect of various sensor parameters on reliability and throughput, respectively. We only displayed the cases where the effects are significant. Reliability is proportional to both BS and DTR, however inversely proportional to PS and PGR. Throughput is proportional to all the parameters BS, PS, DTR, and PGR. Increasing the buffer size of sensor nodes reduces the packet drop rate caused by the buffer overflow. As a result, the reliability and throughput of the network also slightly increase with the increment of buffer size. In WBAN, SF structure is divided into equal-length time slots. Packets with small size required fewer slots to transmit; thus, more data can be transmitted in a short time. On the other way, if the time required to transmit a packet is less than the time slot allocated for that packet, then some time will be unutilized within that allocated time slot. That means, in a particular time period, for packets with a small size, the number of packet transmission will be more; however, the amount of data transmission will be less. Therefore, the reliability of data transmission increases with the decreasing packet size. However, the network throughput decreases with the decrease of packet size. WBAN has a limit on data transmission capability. Although we increase the PGR of sensor nodes, the number of successful packet transmission will be constant after a certain limit. Therefore, the reliability of data transmission decreases with the increasing PGR and gets saturated after sometime. The throughput of a network increases with the PGR in low traffic conditions, after a certain level of traffic, the throughput will be constant.

V. CONCLUSION

In this article, we proposed an MAC protocol based on dynamic SF structure and priority-based dedicated slots allocation for each sensor device. Here, the allocation of slots in EAP and MAP for each sensor device is done on the basis of their priority value. Using a mathematical model called CRITIC, the priority value for each sensor device is determined based on different sensor parameters, such as UP, packet generation rate, buffer occupancy status, data transmission rate, and packet size. The simulation results show substantial improvement in network QoS and energy efficiency over standard IEEE 802.15.6 and other MAC protocols.

REFERENCES

[1] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, and V. C. Leung, "Body area networks: A survey," *Mobile Netw. Appl.*, vol. 16, no. 2, pp. 171–193, 2011.

[2] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1658–1686, 3rd Quart., 2014.

[3] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, and R. Verdone, "A survey on wireless body area networks: Technologies and design challenges," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1635–1657, 3rd Quart., 2014.

[4] Y. A. Qadri, A. Nauman, Y. B. Zikria, A. V. Vasilakos, and S. W. Kim, "The future of healthcare Internet of Things: A survey of emerging technologies," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 1121–1167, 2nd Quart., 2020.

[5] R. Atat, L. Liu, J. Wu, G. Li, C. Ye, and Y. Yang, "Big data meet cyber-physical systems: A panoramic survey," *IEEE Access*, vol. 6, pp. 73603–73636, 2018.

[6] M. Cicioğlu and A. Çalhan, "SDN-based wireless body area network routing algorithm for healthcare architecture," *ETRI J.*, vol. 41, no. 4, pp. 452–464, 2019.

[7] M. Cicioğlu and A. Çalhan, "HUBsFLOW: A novel interface protocol for SDN-enabled WBANs," *Comput. Netw.*, vol. 160, pp. 105–117, Sep. 2019.

[8] M. Cicioğlu and A. Çalhan, "Energy-efficient and SDN-enabled routing algorithm for wireless body area networks," *Comput. Commun.*, vol. 160, pp. 228–239, Jul. 2020.

[9] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.6: Wireless Body Area Networks*, IEEE Standard 802.15.6-2012, 2012.

[10] Y. Zia, F. Bashir, and K. N. Qureshi, "Dynamic superframe adaptation using group-based media access control for handling traffic heterogeneity in wireless body area networks," *Int. J. Distrib. Sens. Netw.*, vol. 16, no. 8, 2020, Art. no. 1550147720949140.

[11] D.-R. Chen and W.-M. Chiu, "Collaborative link-aware protocols for energy-efficient and QoS wireless body area networks using integrated sensors," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 132–149, Feb. 2018.

[12] S. Li, F. Hu, Z. Xu, Z. Mao, Z. Ling, and H. Liu, "Joint power allocation in classified WBANs with wireless information and power transfer," *IEEE Internet Things J.*, vol. 8, no. 2, pp. 989–1000, Jan. 2021.

[13] T. Wang, Y. Shen, L. Gao, Y. Jiang, T. Ma, and X. Zhu, "Energy consumption minimization with throughput heterogeneity in wireless-powered body area networks," *IEEE Internet Things J.*, vol. 8, no. 5, pp. 3369–3383, Mar. 2021.

[14] B. Liang, X. Liu, H. Zhou, V. C. M. Leung, A. Liu, and K. Chi, "Channel resource scheduling for stringent demand of emergency data transmission in WBANs," *IEEE Trans. Wireless Commun.*, vol. 20, no. 4, pp. 2341–2352, Apr. 2021.

[15] M. He, F. Hu, Z. Ling, Z. Mao, and Z. Huang, "A dynamic weights algorithm on information and energy transmission protocol based on WBAN," *IEEE Trans. Veh. Technol.*, vol. 70, no. 2, pp. 1528–1537, Feb. 2021.

[16] M. Rasheed, N. Javaid, M. Imran, Z. Khan, U. Qasim, and A. Vasilakos, "Delay and energy consumption analysis of priority guaranteed MAC protocol for wireless body area networks" *Wireless Netw.*, vol. 23, no. 4, pp. 1249–1266, 2017.

[17] M. Hao, W. Zhang, Y. Wang, G. Lu, F. Wang, and A. V. Vasilakos, "Fine-grained powercap allocation for power-constrained systems based on multi-objective machine learning," *IEEE Trans. Parallel Distrib. Syst.*, vol. 32, no. 7, pp. 1789–1801, Jul. 2021.

[18] M. Cicioğlu and A. Çalhan, "Energy efficiency solutions for IEEE 802.15.6 based wireless body sensor networks," *Wireless Pers. Commun.*, vol. 119, pp. 1499–1513, Feb. 2021.

[19] M. Cicioğlu and A. Çalhan, "Dynamic HUB selection process based on specific absorption rate for WBANs," *IEEE Sensors J.*, vol. 19, no. 14, pp. 5718–5722, Jul. 2019.

[20] A. Enkoji, M. Li, J. D. Brisky, and R. Melvin, "Dynamic EAP based MAC protocol for wireless body area networks," in *Proc. Int. Conf. Comput. Netw. Commun. (ICNC)*, 2019, pp. 531–536.

[21] M. A. Huq, E. Dutkiewicz, G. Fang, R. P. Liu, and R. Vesilo, "MEB MAC: Improved channel access scheme for medical emergency traffic in WBAN," in *Proc. Int. Symp. Commun. Inf. Technol. (ISCIT)*, 2012, pp. 371–376.

[22] S. Sadra and M. Abolhasan, "On improving the saturation performance of IEEE 802.15.6-based MAC protocols in wireless body area networks," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, 2017, pp. 1233–1238.

[23] A. Saboor *et al.*, "Dynamic slot allocation using non overlapping backoff algorithm in IEEE 802.15.6 WBAN," *IEEE Sensors J.*, vol. 20, no. 18, pp. 10862–10875, Sep. 2020.

[24] K. S. Deepak and A. V. Babu, "Improving reliability of emergency data frame transmission in IEEE 802.15.6 wireless body area networks," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2082–2093, Sep. 2018.

[25] S. Misra, P. K. Bishoyi, and S. Sarkar, "i-MAC: In-body sensor MAC in wireless body area networks for healthcare IoT," *IEEE Syst. J.*, early access, Sep. 14, 2020.

[26] D. Diakoulaki, G. Mavrotas, and L. Papayannakis, "Determining objective weights in multiple criteria problems: The critic method," *Comput. Oper. Res.*, vol. 22, no. 7, pp. 763–770, 1995.

[27] K. Das and S. Moulik, "PBCR: Parameter-based backoff counter regulation in IEEE 802.15.6 CSMA/CA," in *Proc. Int. Conf. Commun. Syst. Networks (COMSNETS)*, 2021, pp. 565–571.

[28] S. Moulik, S. Misra, and C. Chakraborty, "Performance evaluation and delay-power trade-off analysis of ZigBee protocol," *IEEE Trans. Mobile Comput.*, vol. 18, no. 2, pp. 404–416, Feb. 2019.