Energy Efficient Priority-Based Hybrid MAC Protocol for IoT Enabled WBAN Systems

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Abstract**—Among the WBAN scarce resources, energy resource is an essential resource on which most of the WBAN biomedical devices activities depend upon. These devices are usually battery-powered and if they fail to operate as required because of battery power drain, the WBAN system would become unreliable and this could lead to life-threatening situations. As a consequence, it would be of advantage and logical to minimize energy consumption and energy wastage issues to achieve an energy efficient WBAN system. Following this, we proposed a coordinated superframe duty cycle hybrid MAC (SDC-HYMAC) protocol to enhance energy efficiency and to prolong the biomedical devices lifetime. To improve the energy efficiency of the WBAN system, we introduced different energy resource management strategies including the design of a priority-based slot-allocation scheme to minimize time-slot and energy wastage. Also, we proposed a coordinated superframe duty cycle (SDC) scheme to accurately select an appropriate superframe order (SO) based on the traffic information and the priority level of the biomedical devices to save energy and prolong the devices lifetime. We compared the SDC-HYMAC protocol with other related protocols like MG-HYMAC, HyMAC, and CPMAC for the sake of validation and is simulated in MATLAB. The outcome of the simulation results revealed that the SDC-HYMAC protocol performed better than the existing protocols using performance metrics like convergence speed, energy efficiency, delay, packet drop ratio, and devices lifetime.**

Index Terms**— IoT enabled WBAN, MAC protocols, transition probability, Markov model, low-power wake-up radio, guaranteed time slot, contention access phase, contention free phase**

I. Introduction

In recent years, internet of things (IoT) technology has been tagged as a technological revolution because of its positive impacts in various sectors [1] – [3].

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Some prominent application areas of the IoT technology include the healthcare monitoring system, industrial system, surveillance system, water monitoring, and agricultural systems [4] – [8]. An IoT enabled WBAN system is composed of low power, intelligent, wearable, light-weight, and miniature-size biomedical devices. The IoT biomedical devices are used to sense the patients' physiological information and the sensed information are wirelessly transmitted to an access point (AP) which could be an internet enabled mobile phone.

Generally, WBAN biomedical devices are usually powered by their in-built batteries which could get drained during an operation. The rate at which the battery power is depleted is directly proportional to the system load and operation. Also, it is worth mentioning that among other WBAN scarce resources, energy resource is an essential resource on which almost all the other WBAN biomedical devices activities depend on [9]. For instance, a biomedical device needs energy to perform its sensing or monitoring task, health data processing task, health data storage task as well as health data communication task.

As a consequence, if the biomedical devices fail to operate as required due to the complete depletion of their battery power, then the WBAN network becomes unreliable and this could lead to life threatening cases [10], [11]. Following this, it would be advantageous and reasonable to prevent energy wastage issue and minimize the energy consumption by designing an energy efficient WBAN network. One of the ways to achieve this is by designing and developing efficient medium access control (MAC) protocols combined with novel resource management strategies.

MAC protocols play a crucial role in achieving a real time, reliable, and an efficient WBAN system [12] – [14]. Therefore, designing and developing efficient MAC protocols and resource management strategies for IoT enabled WBAN systems is a promising adventure that would be highly helpful to optimally control how the WBAN biomedical devices access the communication channel as well as to improve the allocation of the limited WBAN channel resources (e.g., timeslot) and device resources (e.g., energy) [15] – [17].

Presently, there are a few solutions designed for tackling energy consumption and energy wastage issues in WBAN using MAC protocols [18] – [21]. However, the existing solutions are yet to fully address these issues and these research concerns have consequently resulted in the current low acceptance and productivity of the IoT enabled WBANs for healthcare monitoring applications. Thus, in this paper we proposed an energy efficient MAC protocol and new energy resource management strategies that can be incorporated into the IoT enabled WBAN system for healthcare monitoring purposes.

Based on the application requirements of a WBAN system, in our proposed system, the health packet generated by the biomedical devices through the sensing or monitoring of patients' vital signs are classified into two types, namely the critical and the less-critical health packets. The critical health packets are life-threatening data which denotes abnormalities in patients' vital signs that exceeds the boundary of normal readings. While, the less-critical health packets represent the normal patients' physiological signal readings [22] – [24].

The generated health packets are transmitted to the AP through two phases that include the contention access phase (CAP) and the contention free phase (CFP). During the CAP, the biomedical devices with less-critical health packets contends for transmission opportunities using a CSMA/CA scheme and only successful contended devices are allocated a guaranteed time slot in the CFP using a TDMA scheme. However, because of the time-sensitive nature of the critical health packets, the AP assigns dedicated guaranteed time slots to the critical health packets without contention since they require little or no delay. To reduce energy wastage issues due to collisions, control overhead, idle listening, and overhearing, we attach a low-power wake-up radio chip to each of the biomedical devices to switch on the main radio during active periods and switch them off during inactive periods (IP) [25] – [27]. We introduced a transmission queue state as a special type of idle state during the CFP to conserve energy. Also, we move the main communication overheads to the AP to save energy.

In addition, we introduced different energy resource management strategies by designing a priority-based slot-allocation scheme to prevent time-slot and energy wastage. Similarly, a coordinated superframe duty cycle (SDC) scheme was designed to accurately select appropriate superframe orders (SO) based on the traffic information and the priority level of the biomedical devices to save energy. The biomedical devices states are modelled as a continuous-time Markov model.

We outlined the main contributions of this paper as follows:

- The design and development of a SDC hybrid MAC (SDC-HYMAC) protocol based on the traffic information and priority of the biomedical devices to improve energy consumption and energy wastage issues during health packet transmission in an IoT enabled WBAN system.
- Based on the heterogeneity of the WBAN systems, we introduced a multi-variate concept to classify the biomedical devices into two types based on their traffic information and priority into critical and less-critical health packets.
- The design of a priority-based slot-allocation scheme to prioritize patients' health packet for appropriate allocation of slots to prolong the lifetime as well as improve the energy efficiency of the WBAN system.
- Also, a coordinated superframe duty cycle (SDC) scheme was designed to accurately select appropriate superframe order (SO) based on the traffic information and the priority level of the biomedical devices to save energy.
- We introduced a transmission queue state whereby only the synchronous clock of the biomedical devices is allowed to operate, while all other operations of the devices were disabled. Also, the transmission queue state helps to prevent the conflict that may want to arise when two devices transmit to the AP simultaneously.
- We proposed a continuous finite state Markov model to analyze and provide the transition probability of the devices states so as to accurately determine the probability of the final state in order to estimate the time spent by the devices in relation to energy consumption.
- Furthermore, our proposed SDC-HYMAC scheme outperforms other protocols such as MG-HYMAC, HyMAC, and CPMAC protocols using similar methods.

The structuring of the rest of the sections are as follows: In Section II, we review related works on MAC protocols in literature that are designed to enhance WBAN energy efficiency. We discuss the system and the mathematical models of the proposed system in Section III. In Section IV, Markov model and the transition probability of each state are presented. Section V presents time and energy consumption analysis. The description of the proposed SDC-HYMAC scheme is discussed in Section VI. Section VII presents the simulation results. The conclusion of the work is drawn in Section VIII.

II. Related Works

This section presents the review of some related articles on MAC protocols designed to improve WBAN energy efficiency. These works are discussed based on the scheme proposed by the researchers to improve the energy efficiency of the WBAN systems and they are compared with our work. An example is [27], authors proposed an energy-aware hybrid MAC protocol which adopts the CSMA/CA and the TDMA schemes was proposed. In the paper, authors categorize the health data generated by the biomedical devices into two groups. The devices in the first group were all assumed to have critical health packets to send and would all contend for transmission opportunities. Whereas, not all the devices in the second group with less critical packets have data to send, so only those that have data to send would contend for transmission opportunities. A transmission scheduling mechanism was proposed to duty cycle the operations of the devices to improve the energy efficiency of the network. The paper also employs a sleep-wake-up approach to save energy. However, this paper did not consider the appropriate selection of superframe order which plays an important role in energy savings. Also, the system experienced a lot of time-slot wastage. Additionally, since critical data are emergency-based data which requires little or no delay, hence, the real-time delivery of this type of data is very important especially in life threatening situations but this was not catered for in this paper. Different from [27], we proposed an SDC-HYMAC protocol that adopts the CSMA/CA and the TDMA schemes to enhance energy efficiency in a WBAN system. Based on the traffic information and priority of the biomedical devices in the network, a multi-variate concept was employed to efficiently classify the devices in the network into two types, namely type *A* and type *B*. The type *A* devices generates critical health packets and the type *B* devices generates less critical health packets. Because the critical health packets are emergency-based and requires little or no delay, in contrast to [27] the AP assigned a guaranteed time slots to them without having to contend for transmission opportunities before they could send their packets to the AP. Only the type *B* devices contend for transmission opportunities during the contention access phase. To prolong the lifetime and increase the energy efficiency of the system, we design a priority-based slot-allocation scheme to prioritize patients' health packets for accurate allocation of time slots to prevent time slot and energy wastage. Additionally, we introduced a superframe duty cycle scheme for appropriate selection of a superframe order to enhance the energy efficiency of the system. Also, we used a Markov model to model the time spent in each transition states. As a consequence, the algorithm approaches, protocol design, the mathematical formulation, the concept, and the idea proposed in this paper are different from [27].

In [28], authors proposed a multi-class hybrid MAC protocol that employs slotted ALOHA and TDMA schemes to improve the efficiency of WBANs. The proposed system is composed of two major phases that include the contention and the transmission phases. The proposed protocol was designed to improve the system sum throughput, success access ratio, and the reservation ratio of WBANs. To achieve this, a maximization optimization problem was formulated to balance the trade-off between the contention and transmission phases. But then, the proposed MAC protocol does not focus on enhancing the energy efficiency of WBAN systems. Unlike [28], we designed a new hybrid MAC scheme that employs the CSMA/CA and the TDMA schemes to enhance WBAN energy efficiency. We design a SDC hybrid MAC (SDC-HYMAC) protocol based on the traffic information and priority of the biomedical devices to improve energy consumption and energy wastage issues during health packet transmission in an IoT enabled WBAN system. Different from [28], this paper focus on improving energy efficiency and extending the lifetime of the WBAN biomedical devices.

Another hybrid MAC protocol was proposed in [29] but was focused on a homogenous-based WBAN system. The advantages of the CSMA/CA and TDMA schemes were harnessed to improve WBAN energy efficiency. Also, the proposed protocol introduced an awaiting order state to minimize energy wastage issue as well move the control overhead to the PS. Contrary to [29], we designed a new MAC protocol for a heterogenous-based WBAN system. Based on the heterogeneity of the proposed system, we introduced a multi-variate concept to classify the devices in the network into two types according to their traffic information and priority into critical and less-critical health packet. Following this, we design a priority-based slot-allocation scheme to prioritize patients' health packets for appropriate slot allocation to minimize time slot wastage as well as prolong the lifetime of the devices in the network. In addition, since the critical health packets are emergency based, therefore, the AP allocates a guaranteed time slot for their transmission. Additionally, to minimize energy wastage issues due to collisions, idle listening, control overhead, and overhearing, we attach a low-power-wake-up radio chip to the biomedical devices to switch on the main radio during active periods and turn them off during inactive periods.

In [30], a polling-based MAC protocol was proposed to improve energy efficiency by utilizing a wake-up mechanism to enable the devices in the network to access the channel only when it is strong for a reliable data transmission. However, the proposed system experienced a high delay and there was a decrease in the lifetime of the biomedical devices and energy wasted issues were encountered. In contrast to [30], an SDC-HYMAC protocol that harnesses the benefits of the CSMA/CA and the TDMA schemes to improve WBAN energy efficiency is introduced. Energy consumption and energy wastage issues were addressed by designing a priority-based slot-allocation scheme and a coordinated SDC scheme. In addition, energy wastage due to collisions, overhearing, idles listening, and control overhead were addressed by attaching a low-power-wake-up radio chip to the biomedical devices to switch on the main radio during active periods and turn them off during inactive periods. Also, the major control overhead was moved to the AP.

Authors in [31] proposed an asymmetric MAC (aSymMAC) protocol to improve energy efficiency in WBANs by designing an energy balancing model to balance energy between WBAN nodes and the coordinator. However, the aSymMAC slot utilization rate needs to be improved upon. Also, the proposed system has a relatively high delay which have a bad influence on the nodes lifetime. Contrary to [31], we designed a SDC hybrid MAC scheme that harness the benefits of the CSMA/CA and the TDMA schemes to enhance WBAN energy efficiency. We design a priority-based slot-allocation scheme to prioritize patients' health packets for accurate allocation of time slots to prevent time slot and energy wastage issues. Additionally, we introduced a superframe duty cycle scheme for appropriate selection of superframe order to enhance the energy efficiency of the system. To address energy consumption problem and extend the devices lifetime, we proposed a Markov model to estimate the time spent by the devices in each transition states.

A scheduled access MAC protocol based on the IEEE 802.15.6 protocol was introduced in [32] to improve sensor nodes lifetime. But then, the energy efficiency of the system needs more improvement. Also, packet prioritization for critical health packets was not considered. Different from [32], we introduced a multi-variate concept based on the traffic information and priority of the WBAN biomedical devices to categorize their health packets into critical and less-critical health packets. Since the critical health packets are emergency based, we designed a priority-based slot-allocation scheme to prioritize patients' health packets for accurate slot allocation to minimize time slot and energy wastage issues.

Based on this scheme, the AP then allocates a guaranteed time slot to the devices with critical health packets. Furthermore, to tackle energy wastage issues a low-power-wake-up scheme was adopted and this helps to turn on the main radio of the devices during active periods and turned them off during inactive periods. Also, a transmission queue state was introduced to reduce collision and the major transmission control overhead was moved to the AP.

Authors of [33] proposed a MAC protocol that is traffic adaptive focused. A duty cycle technique was used to adjust the operations of the sensor nodes based on the traffic information they generated to improve the energy efficiency of the system. But then the latency of the proposed system needs more improvement. In contrast to [33], we consider an heterogenous WBAN system where the devices in a network have different properties such as the consideration of emergency health packets and normal health packets transmission to the AP. We introduced a superframe order selection algorithm and a priority-based slot-allocation scheme to improve the latency, energy efficiency, and prolong the lifetime of the system.

III. System and Mathematical Modelling

This section presents a detail discussion on the system architecture, the SDC-HYMAC system model, and the SDC-HYMAC mathematical model as follows in the subsection below.

A. System Architecture

Our proposed system presents a new WBAN system architecture that consists of one AP which acts as the coordinator and is surrounded by Q successive IoT biomedical devices as shown in Fig. 1. The IoT biomedical devices include temperature sensor, electrocardiography (ECG) sensor, electromyography (EMG) sensor, electroencephalogram (EEG) sensor, glucose monitoring sensor and so on. The biomedical devices are used to monitor patients' health condition(s) and they generate unstructured health data. The health data is forwarded by the IoT biomedical devices through an IoT communication technology to a local base station such as an internet-enabled smart phone. The smart phone then uploads the health data to a medical database for analysis and decision-making purposes.

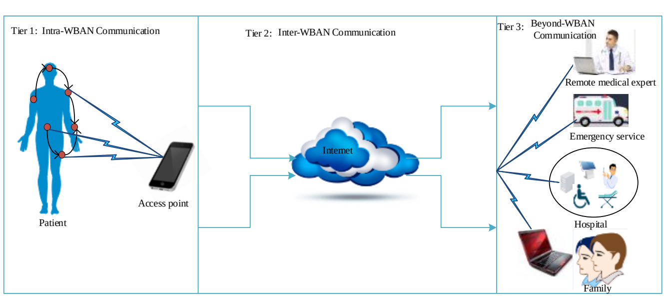

Fig. 1. A typical IoT enabled WBAN system architecture

B. SDC-HYMAC System Model

The biomedical devices in the network are categorized into two priority types such as type A and type B using a multi-variate concept based on their traffic information and priority level. We assumed that the type A biomedical devices contain d active devices with h^A critical health data packets which are life-threatening data and are regarded as abnormalities in patients' physiological information that exceeds the boundary of normal readings such as high blood pressure and low respiratory rate. Whereas, we assume that the type B devices contain k active devices with h^B less-critical health packets which are the normal patients' physiological signal readings such as the normal body temperature measurement, glucose level, and so on. In addition, the type A critical health packets are delay intolerant that requires a high reliability, while the type B less-critical health packets are delay tolerant that requires a low reliability. As a consequence, the AP allocated a guaranteed time slot (GTS) to each of the type A devices that has health packets to transmit during the CFP without having to contend for transmission opportunity and the type B devices are allocated a CAP to contend for transmission opportunities and only the successful contended devices are allocated a GTS.

To enhance the energy efficiency of the proposed SDC-HYMAC protocol, we designed a priority-based slot-allocation scheme to prioritize the patients' health packets for appropriate slot allocation to minimize time slot wastage as well as prolong the lifetime of the devices in the network. Also, we introduced a SDC scheme to efficiently select appropriate superframe orders (SO) based on the traffic information and the priority level of the devices to enhance energy efficiency. Technically, selecting an appropriate SO duration in WBANs play a significant role in energy savings. For instance, assigning a high value of SO when traffic is low would be unnecessary as this would increase the rate at which energy is consumed and cause a delay. Also, assigning a small value of SO in high traffic will lead to packet loss as some of the health packets would be dropped since the network will not be able to process all of them due to the small value of the SO. However, energy would be saved but the rate of packet loss will be high. So, appropriate selection of the SO is very important for the purpose of energy conservation and successful health packet delivery.

In general, the biomedical devices in the network performs two major functions, such as the transmission of health packets to the AP and the reception of control packets from the AP, but this work focus more on the transmission of health packets from the devices to the AP.

C. SDC-HYMAC Mathematical Model

We represent the total number of devices in the network as Q. The type A devices are represented by a set $\{d_1, d_2, \ldots, D\}$ and $\forall\, d \in Q$. Based on the criticality of the type A devices health packets, the AP allocates GTSs during the CFP for them to transmit their health packet without contention using the TDMA scheme. The type B devices are represented by a set $\{k_1, k_2, \ldots, K\}$ $\forall\, k \in Q$. Each k is allocated a CAP to contend for transmission opportunity using the CSMA/CA scheme. In the proposed system, we assumed that the active devices in the network follows five different transition states that include the sleep state $(S_0^{A,B})$, the idle state $(S_1^{A,B})$, the active state $(S_2^{A,B})$, the receiving state $(S_3^{A,B})$, and the transmission state $(S_4^{A,B})$. While, the set of all the devices states are represented as $S_n^{A,B} = \{S_0^{A,B}, S_1^{A,B}, S_2^{A,B}, S_3^{A,B}, S_4^{A,B}\}$ and are assumed as a stochastic process.

IV. MARKOV MODEL

To estimate the time the devices spent in each state, we propose a continuous-time finite Markov chain and based on this model:

- The arrival of the health packets follows a Poisson process.
- The proposed system supports a retransmission process and are regarded as a truncated Poisson distribution process.
- The devices in the network have different transmission probabilities based on their priority types.
- The biomedical devices cannot transmit health packets to the AP as well as receive control packets/signals from the AP simultaneous.
- All the devices have a fixed power level for a specific state, however, they use different power level across the different states.

The proposed Markov model has a finite state space (i.e., countable states) and each biomedical device can change its status at any time with a continuous interval. Fig. 2 presents the proposed Markov model for the different states with their transition probability.

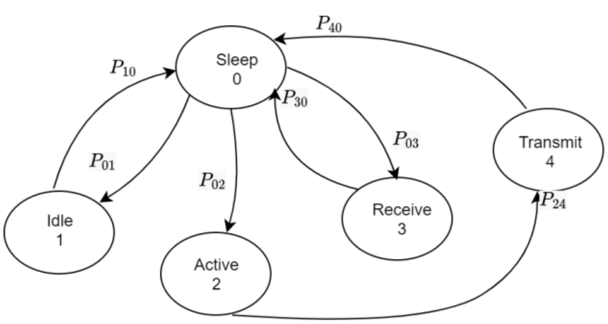

Fig. 2. SDC-HYMAC state transition diagram

A. Markov Model Assumption

In the proposed Markov model, we model the devices states to find the possible transitions and identify their probabilities. Consequently, based on the Markov property, the future states depend only upon the present state and not on the past, that is, the past state does not have anything to do with how a state gets to its present state or future predictions [34]. As said earlier, we use the continuous-time Markov chain $(X_t)_{t \geq 0}$ which is defined by a finite state space S. The arrival requests are modelled using a Poisson distribution process, while the service time follows an exponential distribution.

Let us assume X_0 is the start time of the system and the time parameter (t) runs continuously for $t \geq 0$. Also, we assume that the random variable $X(t)$ represent the system state at time t. So, $X(t)$ takes on one of its $(N+1)$ possible values over an interval of $0 \leq t < t_1$. Thereafter, $X(t)$ will jump from the previous value of $(N+1)$ to another value over the next interval of $t_1 \leq t < t_2$, $t_2 \leq t < t_3$, and so on, where the non-negative $(t_1, t_2, t_3, \dots)$ are the random transit points in time. So, we consider and interprets the points in time as follows:

- $t = u$ represent the past time, where $u \geq 0$,
- $t = r$ is the present time, where $r > u$,
- $t = r + t'$ and t'denotes the future time, where $t' > 0$.

We observe the system state at $t = r$ and at $t = u$ and we denote these states in (1) as:

$$X(r) = i \text{ and } X(u) = x(u) \tag{1}$$

Consequently, a continuous-time stochastic process $\{X(t); t \geq 0\}$ on state space S satisfy the Markov property in (2) if:

$$\begin{aligned} P &= \{X(t'+r) = j \,|X(r) = i \text{ and } X(u) = x(u)\} = \\ &= P\{X(t'+r) = j | X(r) = i\} \quad \forall i, j = 0, 1, \dots, N \\ &\text{and } \forall\, u > 0, r > u, \text{ and } t' > 0 \end{aligned} \tag{2}$$

Therefore, the probability that a device would transit from a state to another, e. g., from $S_0^{A,B}$ to $S_1^{A,B}$ is expressed as:

$$p_{ij}(t') = P\,\{X(t'+r) = j \,|X(r) = i\} \;\; \forall \;\; S_n^{A,B} \in i, j \tag{3}$$

$$p_{ij}(t') = P\,\{X(t') = j|\, X(0) = i\} \qquad \forall \;\; S_n^{A,B} \in i, j \tag{4}$$

where (4) shows the stationary transition probabilities and the continuous-time transition probability function is denoted as p_{ij}. Also, $X(t')$ is the final state after t' number of transitions and $X(0)$ represents the initial state. Moreover, there could be different states transition between i and j, therefore, to find the final state j, the state before the final state must be identified first, so it is assumed that:

$$\lim_{t' \to 0} p_{ij}\, t' = \begin{cases} 1 & if \;\; i = j \\ 0 & otherwise \end{cases} \tag{5}$$

As a consequence, it is important to mention that each time the device enters state i, the time the device would spend in state i before it moves to another state is assumed to be a random variable denoted as $T_i \;\forall\; i = 0, 1, \dots, N$. Assuming a device at time $t = r$ enters state i. Then, for a fixed number of times $t' > 0$, it is important to note that $T_i > t'$ iff $X(t) = i, \;\forall\, t$ over an interval of $r \leq t \leq r + t'$.

Also, the probability of the remaining time a device spends in a particular state before transition to another state is the same and can be expressed in (6) as:

$$P\{T_i > t' + r \,|T_i > r\} = P\{T_i > t'\} \tag{6}$$

Following this, the probability that there will be an event occurrence (i.e., the continuous probability distribution) can be determined using (7), where λ represents the exponential distribution parameter and $1/\lambda$ represents the mean (μ).

$$P\{T_i\} = 1 - exp^{-\lambda T_i} \quad (7)$$

While, the expected time a device spends per visit in a state i is expressed in (8) and the expected total time a device would transits from a state i to j can be determined in (9) as:

$$\lambda_i = \frac{1}{E[T_i]} \quad (8)$$

$$\lambda_i = \sum_{j \neq i} \lambda_{ij} \quad (9)$$

where λ_i denote the transition rate out of a state i and λ_{ij} is the transition rate from i to j. Also, the probability that when a transition occurs, it is going to state j is given in (10) as:

$$p_{ij} = \frac{\lambda_{ij}}{\lambda_i} \quad (10)$$

Therefore, the total number of the transition states can be determined in (11) as:

$$p_{ij}(t') = \sum_{f=1}^{N} p_{if}(r) p_{fj}(t' - r), \quad \forall\ S_n^{A,B} \in i, j \quad (11)$$

The steady state probabilities can be determined using (12).

$$\lim_{t' \to \infty} p_{ij}(t') = \pi_j \quad (12)$$

$$\pi_j = \sum_{i=0}^{N} \pi_j\, p_{ij}(t'), \quad \forall\, j = 0, 1, \dots N \text{ and } t' \geq 0 \quad (13)$$

In (13), π denotes the transition rate from all the possible states to state j.

V. Time and Energy Consumption Analysis

In this section, we analyse the average time used and the energy consumed by the devices based on [22] and [27] respectively.

A. Time Analysis

We define the time spent by a device in the different states, i.e., $S_n^{A,B} = \{S_0^{A,B},\ S_1^{A,B},\ S_2^{A,B},\ S_3^{A,B},\ S_4^{A,B}\}$, as a set of $T_{S_n}^{A,B} = \{T_{S_0}^{A,B},\ T_{S_1}^{A,B},\ T_{S_2}^{A,B},\ T_{S_3}^{A,B},\ T_{S_4}^{A,B}\}$ where $T_{S_4}^{A,B}$ include the setup time i.e., the time the devices leave the idle state to the transmission state, the end-beacon transmission time, the health packet transmission time, and the time it takes to send all acknowledgments (ack). Based on the proposed Markov model, the probability that there would be at least a transmission event in the CFP and a sensing event occurrence in the CAP is denoted as P_{tran} and P_{sen} respectively and they are modelled in (14) and (15) as:

$$P_{tran} = 1 - exp^{-\lambda p T_{idle}} \quad (14)$$

$$P_{sen} = 1 - exp^{-\lambda p T_{idle}} \quad (15)$$

where T_{idle} is the maximum time spent in the idle state before moving to the next state and λp denotes the health packet average arrival time for the Poisson process in the CAP and CFP. Since the devices with critical health packets are allocated a GTS without having to participate in contention before transmitting their data packets, then, the total time a device with critical health packets spent on the transition states is modelled in (16) and the overall time spent by all the devices on the transition states is modelled in (17) as:

$$T_{Total}^{A} = T_{S_0}^{A} + T_{S_1}^{A}[1 - P_{tran}]|None + [P_{tran}]T_{S_1}^{A}|\text{Event} + T_{S_3}^{A}[P_{tran}] + T_{S_4}^{A}[P_{tran}] \quad (16)$$

$$T_{Sum}^{A} = \sum_{d=1}^{D} T_{Total}^{A} \quad (17)$$

While, the time spent by a device with less-critical packets and the overall time spent by all the devices on the transition states are modelled in (18) and (19) as:

$$T_{Total}^{B} = T_{S_0}^{B} + T_{S_1}^{B}[1 - P_{tran} - P_{sen} + (P_{tran}P_{sen})]|None + T_{S_1}^{A}[P_{tran} + P_{sen} - (P_{tran}P_{sen})]|\text{Event} + P_{sen}\left[T_{S_2}^{B} + T_p\right] + P_{tran}\left[T_{S_3}^{B}\right] + T_{S_4}^{B}[P_{sen} + P_{tran} - (P_{tran}P_{sen})] \quad (18)$$

$$T_{Sum}^{B} = \sum_{k=1}^{K} T_{Total}^{B} \quad (19)$$

In (18), T_p is used to represent the processing time and we compute the mean values of (16) and (18) respectively as:

$$E[T_{Total}^{A}] = T_{S_0}^{A} + T_{idle} - \left[\frac{T_{idle}}{2}\right][1 - P_{tran}] + P_{tran}\left[\mu_{S_3}^{A}\right] + [P_{tran}]\mu_{S_4}^{A} \quad (20)$$

$$E[T_{Total}^{B}] = T_{S_0}^{B} + T_{idle} - \left[\frac{T_{idle}}{2}\right][P_{tran} + P_{sen} - (P_{tran}P_{sen})] + P_{sen}\left[\mu_{S_4}^{B} + {}^{1}/_{k}\right] + P_{tran}\left[\mu_{S_3}^{B}\right] + [P_{tran} + P_{sen} - (P_{tran}P_{sen})]\mu_{S_4}^{B} \quad (21)$$

While, the overall mean value of the time spent by the type A and type B devices in the network are computed in (22) as:

$$\zeta = \sum_{d=1}^{D} E[T_{Total}^{A}] + \sum_{k=1}^{K} E[T_{Total}^{B}] \tag{22}$$

B. Energy Consumption Analysis

We define the energy consumed by a device in the different states as a set of $\mathrm{P}_{S_n}^{A,B} = \{\mathrm{P}_{S_0}^{A,B},\ \mathrm{P}_{S_1}^{A,B},\ \mathrm{P}_{S_2}^{A,B},\ \mathrm{P}_{S_3}^{A,B},\ \mathrm{P}_{S_4}^{A,B}\}$. As said earlier, the operation power of the devices in each state is fixed, i.e., the devices will all use the same amount of power in a particular state. Consequently, the total energy consumed, E_{Total}, by the devices with critical health packets and the devices with less-critical packets are calculated in (23) and (24) respectively as:

$$\mathrm{E}_{Total}^{A} = [\mathrm{P}_{S_0}^{A}(T_{S_0}^{A})] + [\mathrm{P}_{S_1}^{A}(T_{S_1}^{A})] + \epsilon_{01}^{A} [\mathrm{P}_{S_3}^{A}\ \sigma_r^{A}\ (T_{S_3}^{A})] + \epsilon_{13}^{A} + [\mathrm{P}_{S_4}^{A}\ \sigma_r^{A}\ (\ T_{S_4}^{A})] \tag{23}$$

$$\mathrm{E}_{Total}^{B} = [\mathrm{P}_{S_0}^{B}(T_{S_0}^{B})] + [\mathrm{P}_{S_1}^{B}(T_{S_1}^{B})] + \epsilon_{01}^{B} + \sigma_s^{B}[\mathrm{P}_{S_2}^{B}(\ T_{S_2}^{B}) + \mathrm{P}_{S_4}^{B}(\ T_{S_4}^{B})] + \epsilon_{13}^{B} + [\mathrm{P}_{S_3}^{B}\ \sigma_r^{B}\ (T_{S_3}^{B})] \tag{24}$$

In (23) and (24), σ_r^{A} and σ_s^{B} are the parameters used to indicate whether there is a receiving and a sensing transmission event respectively. Consequently, based on the proposed Markov model, if there is at least a transmission event occurrence, then, it becomes 1, if otherwise it becomes 0. Also, we denote the energy consumed for switching from the sleep to the idle state as $\epsilon_{01}^{A,B}$ and from sleep to receiving state as $\epsilon_{13}^{A,B}$. Therefore, we compute their mean value in (25) and (26) as:

$$E[\mathrm{E}_{Total}^{A}] = [\mathrm{P}_{S_0}^{A}(T_{S_0}^{A})] + [\mathrm{P}_{S_1}^{A}(T_{idle})] - \left[\frac{T_{idle}}{2}\mathrm{P}_{S_1}^{A}\right][P_{tran}] + \epsilon_{01}^{A} + \left[\mathrm{P}_{S_3}^{A}\ P_{tran}\ \mu_{S_3}^{A}\right] + \epsilon_{13}^{A} + \left[\mathrm{P}_{S_4}^{A}\ \mu_{S_4}^{A}\right][P_{tran}] \tag{25}$$

$$E[\mathrm{E}_{Total}^{B}] = [\mathrm{P}_{S_0}^{B}(T_{S_0}^{B})] + [\mathrm{P}_{S_1}^{B}(T_{idle})] - \left[\frac{T_{idle}}{2}\mathrm{P}_{S_1}^{B}\right][P_{tran} + P_{sen} - (P_{tran}P_{sen})] + \epsilon_{01}^{B} + P_{sen}\left[\mathrm{P}_{S_2}^{B}\mu_{S_2}^{B} + \frac{1}{k}\ \mathrm{P}_{pro}\right] + \left[\mathrm{P}_{S_3}^{B}\ P_{tran}\ \mu_{S_3}^{B}\right] + \epsilon_{13}^{B} + \left[\mathrm{P}_{S_4}^{B}\ \mu_{S_4}^{B}\right][P_{tran} + P_{sen} - (P_{tran}P_{sen})] \tag{26}$$

We determine the overall mean value (ℓ) of the energy consumed by the type *A* and type *B* devices in the network in (27) as:

$$\ell = \sum_{d=1}^{D} E[\mathrm{E}_{Total}^{A}] + \sum_{k=1}^{K} E[\mathrm{E}_{Total}^{B}] \tag{27}$$

VI. Design of the Proposed SDC-HYMAC Protocol

In this section, we present the detailed design of the proposed SDC-HYMAC protocol which focus mainly on the biomedical device traffic priority, IoT enabled WBAN slot allocation, and the proposed SDC scheme as follows:

A. Traffic Priority-Based Slots Allocation

In the SDC-HYMAC protocol, the biomedical devices health packets are classified into two types, namely critical and less-critical health packets based on their traffic information and priority level. The critical health packets are the data packets generated from the monitoring of patients' vita sign with abnormal readings, i.e., they exceed the boundary of normal readings. As an example, a patient's vital sign readings with a very high or low respiratory rate and a very high or low heartbeat rate would require an urgent medical attention because of its criticality. These type of health packets are delay intolerant and they require a high reliability with a minimum packet loss rate. While, the less-critical health packet are the data packets generated from patients' vital signs monitoring with normal readings, for example, a normal glucose level measurement or a normal body temperature measurement. These type of health data packets are delay tolerant, require a low reliability, and they could accommodate some amount of packet loss.

As a consequence, the AP allocates a GTS to each of the devices with critical health packets that have data to send without participating in the contention process and allocate a CAP to the less-critical health packets. For this to be achieved, the AP computes the threshold values of the measured vital signal for each of the biomedical devices that have packets to send and allocate slots based on their priority level. The biomedical devices priority level is modelled in (28) as:

$$\Psi_{thres\_val} = \frac{M_{thres\_val}}{\lambda p\ \times\ Packet_{len}} \tag{28}$$

In (28), $Packet_{len}$ represents the packet length of the devices and Ψ_{thres_val} is used to represent the priority of the devices based on their threshold values and M_{thres_val} represents the measured vital sign threshold value which could be either high or low. In the proposed system the biomedical devices are aware of the high and low threshold values of the measured vital signals, for example, a low pulse rate is around $\leq 50\ bpm$ and a high pulse rate is around $\geq 120\ bpm$, while, a respiratory rate is around ≥ 20 breath per minutes and a low respiratory rate is about ≤ 11 breath per minutes [35]. Following this, the AP use the priority-based slot-allocation scheme in Algorithm 1 to allocate slots to the devices so as to prevent time slot wastage and also prolong their lifetime. For instance, if the priority threshold value of a device is high, the AP allocates a GTS and if low a CAP would be allocated.

Algorithm 1. Priority-Based Slot-Allocation Scheme

1: Initialization of type *A* and type *B* biomedical devices
2: **for** each $\{d_1,\ d_2,\ \ldots,\ D\}\ \forall\ d\ \in Q$ && $\{k_1,\ k_2,\ \ldots,\ K\}\ \forall\ k\ \in Q$
3: AP use (26) to compute priority threshold value
4: **if** priority is low **then**

5: it is a less-critical health packet
6: assign a priority of 0
7: use algorithm 2 to compute the required SO duration
8: configure SO in the CAP
10: allocate the CAP slot in the SO field and
11: apply a CSMA/CA scheme
12: **end if**
13: **if** priority is high **then**
14: it is a critical health packet
15: assign a priority of 1
16: use algorithm 2 to compute the required SO duration
17: configure SO in the CFP
18: allocate the needed GTS in the GTS field
19: apply a TDMA scheme
20: **end if**
21: **if** GTS $<= BO$ **then**
22: assign the remaining slots for CAP
23: **repeat** the process in step 6
24: **end if**
25: compute $\boldsymbol{SO_{num}} = \sum \boldsymbol{N_{CAP}} + \sum \boldsymbol{N_{GTS}}$
26: **end for**

B. Slot Allocation Computation for the Proposed SDC-HYMAC

Typically, a WBAN system is an heterogenous system in which the biomedical devices in the network have different properties such as data rate. The data rate of the biomedical sensor devices varies from device to device, for example, a temperature sensor has a data rate of 1 kbps, blood pressure sensor has 1.92 kbps, pulse rate has 2.4 kbps, EEG 86.4 kbps, and ECG has 192 kbps [2] and so on. In the proposed system initial slots are allocated to the biomedical devices by the AP based on their data rate. Therefore, the AP calculates the number of slots to be allocated to each device using (29) – (31).

$$Sym_{Num} = \frac{Data_{rate}}{Sym_{len}} \tag{29}$$

$$Sym_{Num}/fr = \frac{Sym_{Num}}{50\ fr/sec} \tag{30}$$

$$Slot_{Num} = \left\lceil \frac{Sym_{Num}}{60\ symbols} \right\rceil \tag{31}$$

In (29) – (31), Sym_{Num} represent the number of symbols, Sym_{len} is the length of the symbol which is equal to 16 bits, the number of symbols per frame is denoted as Sym_{Num}/fr, and $Slot_{Num}$ is the slot number. Based on (29) – (31), the AP assigns an initial slot to each of the biomedical devices. For instance, 1 slot would be assigned to a pulse rate sensor, while 2 slots would be assigned to an EEG sensor device. Then, the AP stores the initial slot values for each of the biomedical devices in form of an array. Furthermore, for the critical health packet in type *A* devices which has a high priority assumed to be 1, the AP would allocate the slots as a GTS and for the less-critical health packet in the type *B* devices which has a low priority assumed to be 0, the AP would allocate the slots as a CAP. It is important to mention that based on the patients' health condition(s) the medical expert could also determine the health packet priority.

C. Superframe order Duty Cycle Scheme (SDC)

In our proposed scheme, the AP has an array that contains all the biomedical devices information which include their ID number, data rates, and transmission queue state. So, based on the data rate, the AP computes, stores and update the SO value for each biomedical device in the array and this denote their initial value. Additionally, the configuration of the superframe order is used to represent the beginning of the proposed scheme and serves as a default setting.

Therefore, for the appropriate selection of the SO, the AP use algorithm 1 and because the biomedical devices in type *A* have a high priority level which requires a specific amount of time for their transmission process, hence, the AP first allocate the GTS during the CFP to them based on the proposed SDC scheme in Algorithm 2 to save energy and as well to ensure a successful packet delivery. Thereafter, the remaining slots are then allocated to the type *B* devices as a CAP. During this process, the AP checks to confirm the current number of the GTS slots against the maximum number of the beacon order (BO) in the proposed system. Then, the AP computes the total number of the CAP (N_{CAP}) slots and the total number of the GTS (N_{GTS}) slots.

In addition, the proposed SDC scheme helps to compute the slots number for each biomedical devices based on the ratio of the number of pending packets (NPP) remaining at the biomedical devices transmission queue to the number of the health packets received (NPR) by the AP. Following this, the AP compares the NPP remaining at the biomedical devices' transmission queue against the NPR at the AP to determine the next value of the SO for the biomedical devices. As presented in Algorithm 2, the next SO value of the devices is determined under the following conditions:

- If NPP > NPR, then, the traffic is high, i.e., the active phase is not sufficient for transmitting the high traffic. As a result of this, the AP increases the SO value to make room for more data transmission time for the successful delivery of the health packets. Technically, the increased SO value will increase the CAP or the GTS slots based on the devices' priority. Moreover, it is important to note that the total value of the SO must not exceed the BO's maximum value. Therefore, the SO and BO parameters must satisfy the condition in (32) and we compute the next SO (SO_N) value using (33).

$$0 \le SO \le BO \le Slot_{Num} \tag{32}$$

$$SO_N = SO_{curr} + \left\lceil \log_2 \left\lceil \frac{NPP}{NPR} \right\rceil \right\rceil \tag{33}$$

- If the NPR < NPP, this means the traffic is low, then the AP would reduce the active phase by decreasing the SO value to conserve energy. So, the AP determines the next SO value by decreasing the current SO value (SO_{curr}) by 1.

With this approach, a reasonable amount of energy is saved and this also result to the successful delivery of the health packets. Therefore, we compute the next SO value in this case in (34) as:

$$SO_N = SO_{curr} - 1 \quad (34)$$

- And lastly, if NPP = NPR, then the AP maintains the current SO value as expressed in (35) as:

$$SO_N = SO_{curr} \quad (35)$$

Consequently, the SDC scheme calculates the SO value and the AP would adjust the SO duration according to the biomedical devices traffic information. It is worthy to mention that the time duration of the superframe structure is determined by the BO, while the active phase duration of the superframe structure is determined by the SO.

Algorithm 2. Superframe Order Duty Cycle Scheme

Require: AP, SO, BO, SO_{curr}, SO_N, NPP, NRP
1: Initialize**:** type *A* and type *B* biomedical devices
3: AP check the biomedical device in the array
4: **if** NPP > = NPR **then**
5: **if** $SO_{curr} < BO$ **then**
6: $SO_N = SO_{curr} + \left\lceil \log_2 \left\lceil \frac{NPP}{NPR} \right\rceil \right\rceil$
7: **if** $SO_N > BO$ **then**
8: $SO_N = BO$
9: **else**
10: use SO_N for data transmission
11: **end if**
12: **end if**
13: **end if**
14**:** **if** NPP < = NPR **then**
15: **if** $SO_{curr} > 0$ **then**
16: $SO_N = SO_{curr} - 1$
17: **if** $SO_N > 0$
18: repeat step 9
19: **else**
20: $SO_{curr} = -1$
21: **end if**
22: **end if**
23: **end if**

VII. Operations of the Proposed SDC-HYMAC Protocol

This section presents the implementation of the low-power wake-up radio and the description of the proposed SDC-HYMAC protocol. In our proposed system, the basic operation of the biomedical devices is to transmit their health packets to the AP and to receive command signals from the AP. Therefore, based on the superframe structure of the IEEE 802.15.4 standard for WBANs, our proposed system technically consists of two major phases, namely the active phase (i.e., CAP and CFP) and the IP. The proposed system operates in a beacon enabled mode and the superframe structure begins with a beacon message from the AP which has all the information about slot allocation, address of the AP and the biomedical devices, the beginning and the end of the phase. Moreover, we assume that the major operation of the biomedical devices is to transmit their health packets to the AP, thus, the AP allocates most of the slots for their health packet transmission. Fig. 3 presents the proposed SDC-HYMAC protocol, where BI = aBaseSuperframDuration $\times$ 2^{BO} and SD = BaseSuperframDuration $\times$ 2^{SO}. Following this, the detailed discussion on the implementation of the low-power wake-up radio and the major active phases of the proposed SDC-HYMAC superframe structure are discussed in the following subsections.

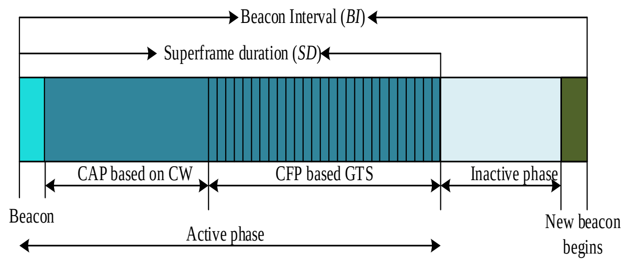

Fig. 3. The proposed SDC-HYMAC protocol superframe structure.

A. *Low-power Wake-up Radio Scheme*

In the proposed system, we assume that each of the biomedical devices are attached with a low-power wake-up radio chip to enhance energy efficiency. The low-power wake-up radio is used to switch on the main radio of the devices whenever it is needed [36], [37] and [38]. As mentioned in [38], the low-power wake-up radio only consumes a power of about 50 μW and this makes their implementation helpful in WBANs. It is important to mention that the energy consumption of a device attached with the wake-up radio is lower compared to the conventional duty cycling techniques. Also, the low-power radio does not come with an extra energy cost because it does not use the main energy of the device. Thus, we neglect the power of the low-power wake-up radio.

So, at the beginning of the cycle, we assume that all the devices are in the sleep state waiting for a ready to receive beacon message from the AP. When the wake-up radio sense an incoming signal from the AP, it generates an interrupt signal to switch on the main radio of the devices. As a consequence, the type *A* devices switches to the active state of the CFP to transmit their critical health packets while the type *B* devices switches to the active state of the CAP for contention process.

B. *Contention Access Phase (CAP)*

This phase is majorly allocated to the type *B* biomedical devices with less-critical health packets. In this phase, the biomedical devices that have data to send would contend for transmission opportunities during their own contention window (CW) using a CSM/CA scheme and only successful devices would be allocated a transmission slot in the CFP phase. While, the devices that have no data to send switches to the sleep mode to conserve energy. The biomedical devices that are ready to contend for transmission slot would send a transmission request message to the AP.

Each successful health packets have its own information which include the ID number of the device which is useful during transmission to the AP. Upon the reception of the biomedical device health packets, the AP sends an overall acknowledgment (ack) message after the contention phase to conserve energy by reducing the waiting time delay and the transmission congestion delay mostly experienced by the devices instead of sending the ack message after each received health packets. The overall ack message contains the transmission in which each of the biomedical devices is allocated a guaranteed time slot during the CFP.

C. Contention Free Phase (CFP)

In this phase, the AP allocates the GTS to the type *A* biomedical devices with critical health packets for their transmission without any delay. Also, the successfully contended devices with less-critical health packets are GTS. The biomedical devices transmit their health packets using a TDMA scheme. For efficient transmission and energy conservation, we introduce a transmission queue state which is a kind of idle state where only the synchronous clock of the devices is enabled and other operations are disabled. During the transmission period, the biomedical devices are modelled using the transmission queue state base on their priority. The devices with higher priority are allowed to transmit their health packets first while the remaining transmission slots are allocated to the devices with a low priority. The AP use the transmission queue state to estimate the traffic in the network. A device in the transmission queue is activated to any other active state using active beacon messages including the device ID. A device switches to an active state upon receiving an active beacon message from the AP or whenever it wants to transmit.

As a consequence, each device transmits an end beacon to the AP after transmitting their health packets then, the AP transmit back an ack order message to them. In case of failed health packet transmission, no ack order message would be sent. Moreover, the device would send a retransmission beacon message to the AP to get prepared for the retransmission process. Immediately the device receives an ack message from the AP, then the next biomedical device in the queue starts it packet transmission and this continues until the operation ends.

D. Delay Analysis of the Active Phase

The time spent in the CAP (T_{CAP}) and the time spent in the CFP T_{CFP} are expressed in (33) and (34) as:

$$T_{CAP} = CW + T_{data} \qquad (33)$$

$$T_{CFP} = \frac{1}{2}(BI - T_{CAP}) + CW + T_{data} \qquad (34)$$

Therefore, the less-critical health packet delivery delay is expressed in (35) as:

$$Delay_B = T_{CAF} \qquad (35)$$

While, the critical health packet delivery delay is expressed in (36) and (37) as:

$$A_{health\ packet} = \frac{T_{Bmessage} + ack_{Beacon}}{BI} \qquad (36)$$

$$Delay_A = A_{health\ packet} \qquad (37)$$

In (33) – (36), T_{data} is the data transmission time, $A_{health\ packet}$ is the detection of abnormal health data packet which could be either a high or a low threshold value, $T_{Bmessage}$ denote the time used to send a beacon message to the AP for the abnormal detection, and ack_{Beacon} is the time it takes the AP to send an ack order message the devices.

VIII. Simulation Results

In this section, we present the simulation results of the proposed SDC-HYMAC protocol.

A. Simulation Model

In the proposed system, we consider a system with 15 biomedical devices that are deployed and connected with an AP in a star topology to monitor a patient's physiological vital signs. The devices sense and communicate their health packets to the AP using a single-hop network. The biomedical devices are static and are deployed randomly in the AP's coverage area of a 500 m radius using a coordinate system as shown in Fig. 4. We simulate the proposed SDC-HYMAC protocol in MATLAB and we compare it with other existing protocols such as MG-HYMAC, HyMAC, and CPMAC. We employ the same simulation parameters as [27] and are presented in Table I.

Table I
Simulation Parameters [12], [27]

Parameter	Value
AP radius	500m
Devices	(3-15)
ACK packet size	64 bits
Beacon size	64 bits
BO	1-20
SD	7860 symbols
BI	15,360 symbols
CW_{Max}	32
CW_{Min}	256
Noise	-100dBm
Battery power	1200 J
Transmission rate ($\Re$)	5 Mbps
$\epsilon_{01}^{A,B}$	0.02 mJ
$\epsilon_{13}^{A,B}$	0.03 mJ
$P_{S_0}^{A,B}$	0.5 mW
$P_{S_1}^{A,B}$	10.5 mW
$P_{S_2}^{A,B}$	28 mW
$P_{S_3}^{A,B}$	30 mW
$P_{S_4}^{A,B}$	50 mW

In addition, the proposed SDC-HYMAC protocol is composed of two types of biomedical devices, namely type *A* and type *B*. The type *A* devices are assumed to have h_D critical health packets and the less-critical health packets of the type *B* devices are assumed to be denoted as h_K. Since there are usually a few biomedical devices positioned in, on or near a patient's body, then, we select different number of biomedical devices that includes 3, 5, 7, and 9 in the simulation experiments.

For the sake of evaluation and validation, we compare the proposed SDC-HYMAC protocol with the existing protocols like MG-HYMAC, HyMAC, and CPMAC using standard metrics such as convergence speed, energy efficiency, delay, packet-drop probability (reliability), and the devices lifetime.

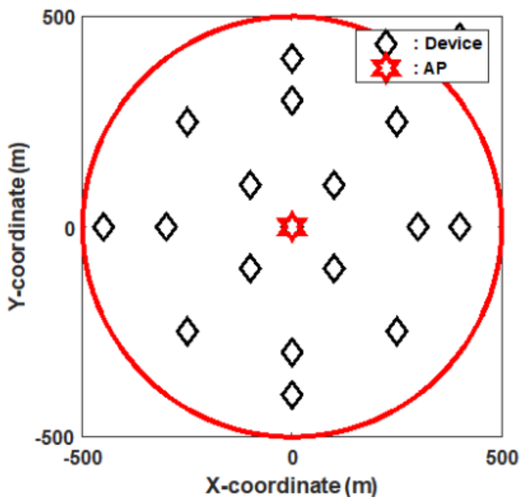

Fig. 4. SDC-HYMAC network topology of devices and AP

B. Convergence Comparison

This section presents the performance comparison of the proposed SDC-HYMAC protocol with other existing protocols based on their convergence speed. The convergence speed evaluation was performed on the four protocols, i.e., SDC-HYMAC, MG-HYMAC, HyMAC, and CPMAC by comparing their energy efficiency against some number of iterations. For this to be achieved, the proposed system was configured with $Q = 9$ devices while, $D = 5$ devices and $K = 4$ devices for type *A* and type *B* devices respectively. Also, we configure the existing protocols in parallel with 9 devices. Based on this configuration, we carried out some simulation experiments using different iterations and some results were generated. The generated results are shown in Fig. 5 and we noticed that the SDC-HYMAC algorithm converged after around 90 iterations and performs better than the existing algorithms such as MG-HYMAC, HyMAC, and CPMAC algorithms which converged after around 100, 110, and 120 respectively. So, the SDC-HYMAC algorithm convergence speed has a better performance improvement of about 10%, 15%, and 18% over MG-HYMAC, HyMAC, and CPMAC respectively. As a consequence, the efficiency of the SDC-HYMAC protocol is emphasized in the context of a fast convergence.

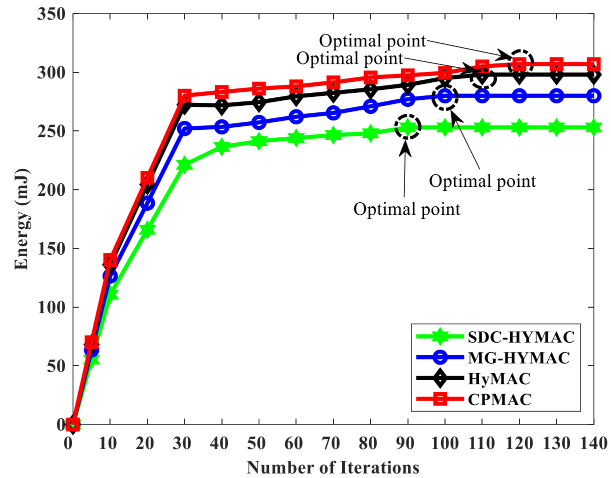

Fig. 5. Convergence of the SDC-HYMAC, MG-HYMAC, HyMAC, and CPMAC algorithms

C. Impact of Energy Consumption on the Number of Biomedical Devices

The impact of energy consumption on the biomedical devices was investigated on the proposed SDC-HYMAC and some existing protocols such as MG-HYMAC, HyMAC, and CPMAC protocols for performance evaluation in a whole transmission cycle. To achieve this, we configure the proposed SDC-HYMAC as well as the considered existing protocols with a few numbers of devices such as Q = 3, 5, 7and 9 devices. Therefore, for the SDC-HYMAC protocol, we set the type *A* and type *B* devices to 5 and 4 respectively. However, we assume that not all the devices in the network have data to send. Following this, the proposed SDC-HYMAC algorithms were enabled and disabled for the considered existing protocols for simulations, while we set their transmission probabilities to 0.8 for both P_{tan} and P_{sen}. The outcome of the simulation experiments is shown in Fig. 6 and from there we could deduce that as the number of the devices were increased from 3, 5, 7, to 9 devices the more energy was consumed. However, as a result of the proposed SDC-HYMAC algorithms as well as the different energy resource management approaches considered, a reasonable amount of energy was saved which led to the devices spending less energy for their operations. As a consequence, the SDC-HYMAC protocol outperforms the existing protocols, for example, when we set the number of the devices to 9 about 265 mJ energy was consumed, whereas using the MG-HYMAC, HyMAC, and CPMAC protocols about 278 mJ, 295 mJ, and 310 mJ energy respectively were consumed. It is obvious that the SDC-HYMAC protocol consumes less energy compared to the MG-HYMAC, HyMAC, and CPMAC with an energy reduction of about 5%, 10%, and 14% respectively. These energy improvements were attributed to the designed priority-based slot-allocation scheme which helps to prioritize patients' health packet for appropriate allocation of slots to prevent slot wastage and thereby prolong the lifetime as well as improve energy efficiency. Also, the designed coordinated SDC scheme was able to enable the AP to accurately select appropriate SO based on the traffic information and the priority level of the devices and this helps to minimize energy consumption and enhance a successful health packet delivery. Additionally, the proposed system was able to reduce energy wastage issues due to collisions, control overhead, idle listening, and overhearing, by attaching a low-power wake-up radio chip to each of the biomedical devices to switch on their main radio during active periods and switch them off during the IP.

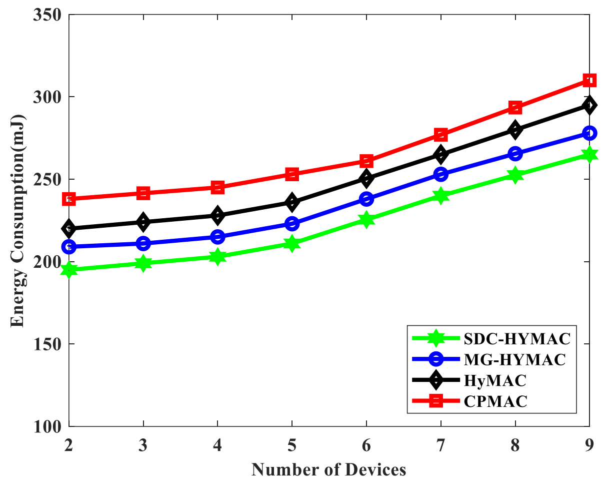

Fig. 6. Energy consumption versus no. of devices

D. Impact of Energy Consumption on Transmission Probability

To evaluate the performance of the proposed SDC-HYMAC protocol with the existing protocols, we investigated the impact of energy consumption on the devices' transmission probability. Therefore, we configure the proposed SDC-HYMAC protocol and the existing protocols, i.e., MG-HYMAC, HyMAC, and CPMAC protocols with $Q = 9$ devices. For the SDC-HYMAC protocol, when $Q = 9$ devices we set the type A and the type B devices to 5 and 4 devices respectively. But then we assume that not all the devices in the network have data to transmit. The simulation experiments results are presented in Fig. 7, and from there we could deduce that a high transmission probability leads to a high energy consumption. But then, the SDC-HYMAC protocol is advantaged compared to the existing protocols due to the algorithms proposed and the different resource management strategies we put in place that helps the devices reduce energy wastage while spending less energy for their operations. As a consequence, the SDC-HYMAC protocol performs better than the existing protocols in terms of energy efficiency. For instance, when we set the transmission probability of the proposed protocol and the existing protocols to 0.9, the proposed SDC-HYMAC protocol achieve an energy reduction improvement of about 5%, 9%, and 13 % over the existing MG-HYMAC, HyMAC, and CPMAC protocols. These significant improvements are attributable to the proposed SDC scheme which enables the AP to adjust the superframe order duration accurately based on the traffic information and the priority level of the devices. To minimize time-slot wastage which technically increases energy wastage, we designed a priority-based slot-allocation scheme to prioritize the patients' health packet for appropriate slot allocation. Also, energy wastage issues due to collisions, control overhead and idle listening were addressed by introducing a transmission queue state in the idle state, by moving the major control overhead to the AP, and by attaching a low-power wake-up radio chip to each device to switch on or off their main radio to save energy.

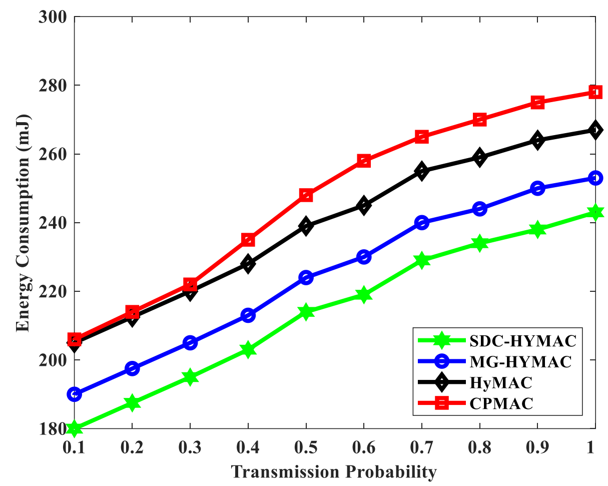

Fig. 7. Energy consumption of devices versus transmission probability

E. Investigation of Health Packet Delivery Delay Based on Number of Devices

Here, we investigated the average health packets delivery delay based on the number of the devices in the network. To achieve this, we configure the proposed SDC-HYMAC protocol and the existing MG-HYMAC, HyMAC, and CPMAC protocols with $Q = 15$ devices. For the SDC-HYMAC protocol, when $Q = 15$ devices we set the type $A = 9$ devices and the type $B = 7$ devices. As a consequence, different simulation experiments were carried out and the results of the simulation experiments are presented in Fig. 8. From Fig. 8, we could infer that the more the number of devices participating in data transmission process the higher the delay due to collisions. Collisions occur mostly in the CAP when the devices would have to contend for transmission opportunities. Therefore, most devices create more delay during the CAP when the probability that the channel would be found free is low. As a consequence, in our proposed system, the type A devices with critical health packets which are delay intolerant are allocated a GTS to transmit their health packets without having to contending for transmission opportunities to enable the successful delivery of the health packets and also minimize delay. Similarly, the proposed system was able to reduce delay by allocating contention slots to the type B devices with less-critical health packets to minimize collisions as presented in algorithm 1. Following this, the proposed SDC-HYMAC protocol outperforms the MG-HYMAC, HyMAC, and CPMAC protocols in terms of delay reduction with an overall improvement of about 55%, 78%, and 79% respectively.

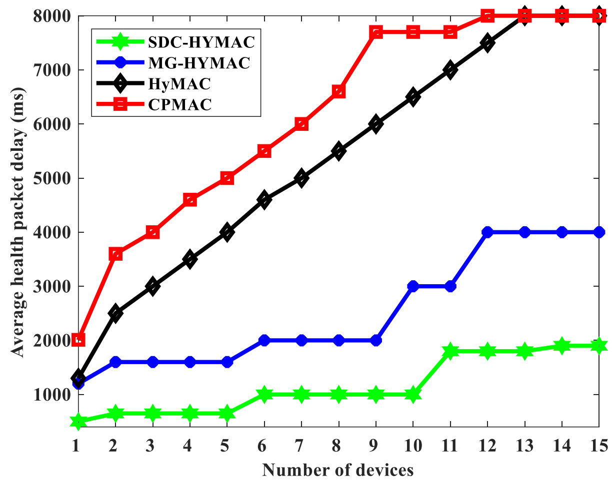

Fig. 8. Average health packet delay versus number of devices

F. Investigation of Packet Drop Probability on Number of Cycles

In this section, we carried out some simulation investigations on the health packet drop probability against different number of cycles. In practice, there is a possibility that the total number of health packets transmitted by the biomedical devices is not the same as the total number of health packets received by the AP due to packet drop issue. As a consequence, we analyze the total number of health packets that are dropped during transmission for the proposed SDC-HYMAC and the existing protocols using a uniform random model where the probability of good link is 70%, while the bad link's probability is 30%. So, we perform some simulation experiments to investigate the number of health packets transmitted by the devices, the number of health packets received by the AP, and the number of dropped health packets against different number of cycles. The outcome of the simulation experiments is presented in Fig. 9, 10, 11, and 12 for SDC-HYMAC, MG-HYMAC, HyMAC, and CPMAC protocols respectively. From Fig. 13, we noticed that for the SDC-HYMAC protocol about 85% health packets were received at the AP and about 15% were dropped. In the case of the MG-HYMAC protocol, about 76% health packets were received at the AP and about 25.5% were dropped. The HyMAC protocol has about 70% health packet received at the AP and about 30.5% were dropped. For the CPMAC protocol, the AP received about 63% health packets and about 35.4% were dropped. Therefore, the SDC-HYMAC outperforms the existing protocols in terms of a high successful health packet delivery and a low packet drop probability compared to the MG-HYMAC, HyMAC, and the CPMAC protocols. The significant improvements could be attributed to the proposed SDC scheme which enables the AP to select appropriate SO durations to save energy. For example, allocating a high value of SO when traffic is low would be unnecessary as this would increase the rate at which energy is consumed. Also, allocating a small value of SO in high traffic will lead to packet loss as some of the health packets would be dropped since the network will not be able to process all of them due to the small value of the SO. However, energy would be saved but the probability of packet drop will be high. So, appropriate selection of the SO is very important for the purpose of energy conservation and successful health packet delivery.

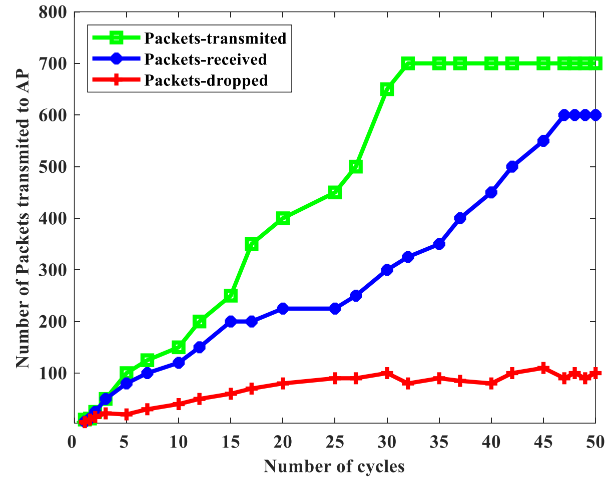

Fig. 9. Analysis of packet drop for SDC-HYMAC protocol

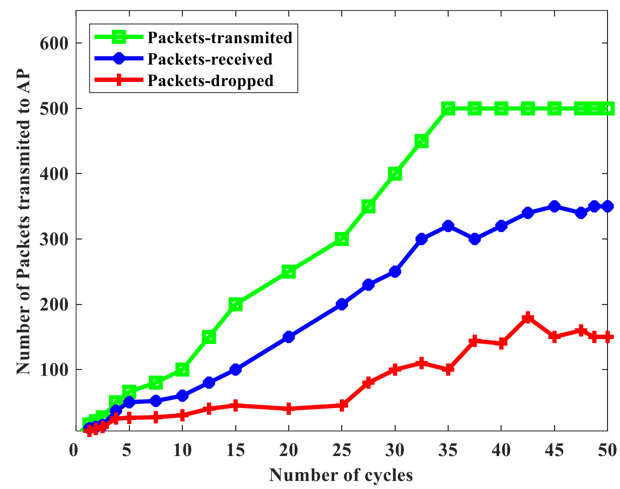

Fig. 10. Analysis of packet drop for MG-HYMAC protocol

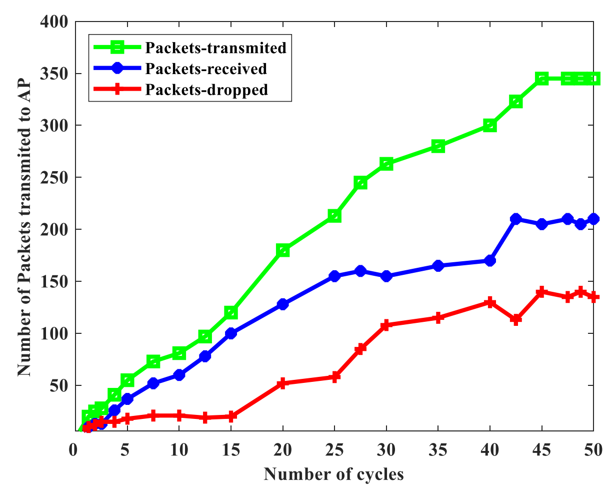

Fig. 11. Analysis of packet drop for HyMAC protocol

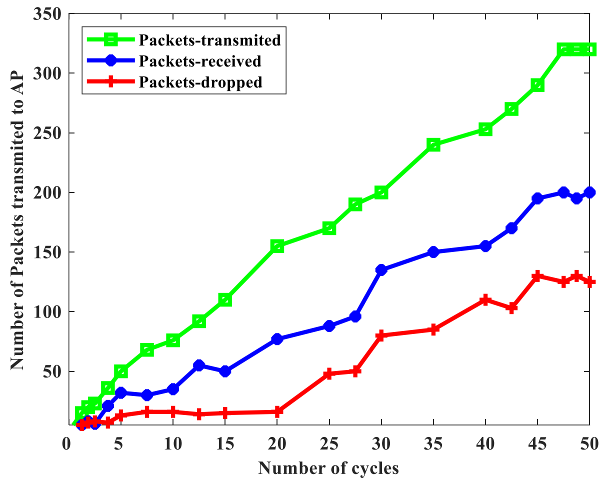

Fig. 12. Analysis of packet drop for CPMAC protocol

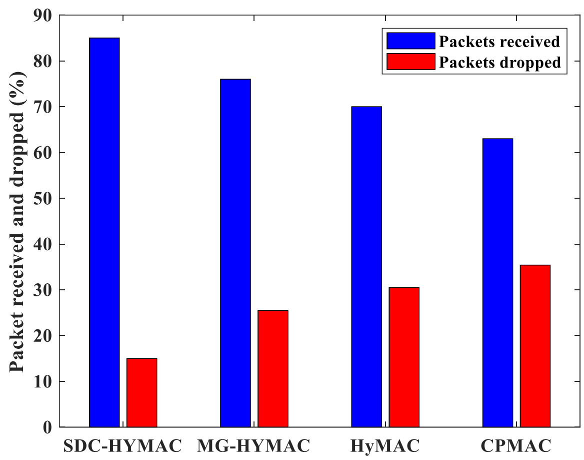

Fig. 13. Total number of health packets received and dropped for the SDC-HYMAC, MG-HYMAC, HYMAC, and CPMAC protocols

G. Impact of Transmission Probability on the Lifetime of the Devices

Here, we present a discussion on the impact of transmission probability against the lifetime of the devices. To achieve this, simulation experiments were carried out on the proposed SDC-HYMAC protocol and the MG-HYMAC, HyMAC, and CPMAC protocols with different transmission probability values. The four protocols are then set to $Q = 9$ devices as well as the battery power to 1200 J. For the SDC-HYMAC protocol, we set the type A devices to 5 devices and the type B devices to 4 devices. The outcome of the simulation experiments as presented in Fig. 14 indicates that the higher the transmission probability the lower the lifetime of the devices for the four protocols. However, the proposed SDC-HYMAC protocol outperforms the existing protocols with a significant improvement of about 60% over the MG-HYMAC, about 40% over the HyMAC, and about 50% over the CPMAC when the transmission probability was set to 0.5. The significant improvement achieved by the SDC-HYMAC protocol could be attributed to the designed priority-based slot-allocation scheme which helps to prioritize patients' health packet for appropriate allocation of slots to prevent time slot wastage and thereby prolong the lifetime of the devices. Also, the proposed SDC scheme enables the AP to adjust the superframe order duration accurately based on the traffic information and the priority level of the devices. Thus, minimizing energy consumption as well as prolong the lifetime of the devices. Furthermore, different resource management strategies such as introducing a transmission queue state in the idle state to address energy wastage due to collisions, by moving the major control overhead to the AP, and by attaching a low-power wake-up radio chip to each device to switch on or off their main radio to save energy.

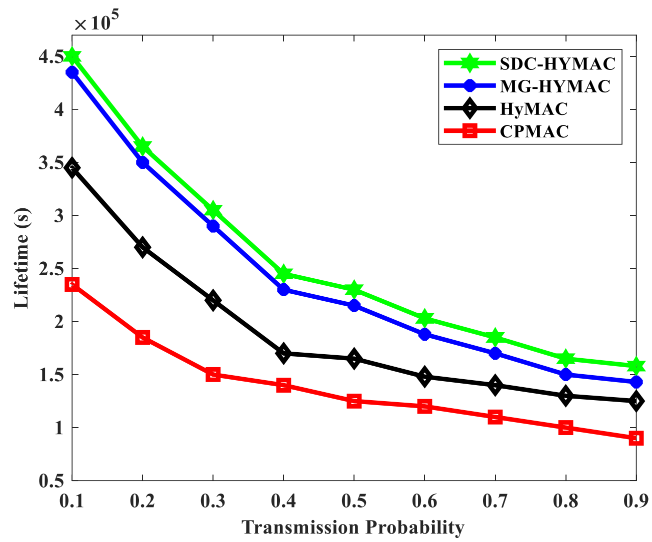

Fig. 14. Devices lifetime versus transmission probability

IX. Conclusion

In this paper, we addressed energy wastage, energy consumption, time-slot wastage, and health packet loss issues by designing a priority-based slot-allocation scheme to prioritize patients' health data packets for appropriate allocation of slots to prevent time slot wastage and thereby prolong the lifetime of the devices. Also, we proposed a coordinated superframe duty cycle scheme based on the traffic information and the priority of the biomedical devices for appropriate selection of the SO duration as this plays a significant role in energy savings. In addition, we proposed a continuous finite state Markov model to analyze the biomedical devices states. The model was able to provide the transition probabilities of the devices in the different states and this helps to know the state before the next state so that we can accurately determine the probability of the final state. The effectiveness of the proposed mechanism was evident in our simulation results in the context of energy consumption, packet drop ratio, delay, and the lifetime of the devices. Furthermore, different energy resource management strategies such as introducing a transmission queue state in the idle state to address energy wastage due to collisions, moving the major control overhead to the AP, and attaching a low-power wake-up radio chip to each device to switch on or off their main radio to save energy was considered. The proposed SDC-HYMAC protocol was validated and compared with some existing MAC protocols including the MG-HYMAC, HyMAC, and CPMAC protocols based on their convergence speed, energy efficiency, delay, packet drop ratio, and devices lifetime. As a consequence, the SDC-HYMAC protocol performed better than the HYMAC, HyMAC, and CPMAC protocols.

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