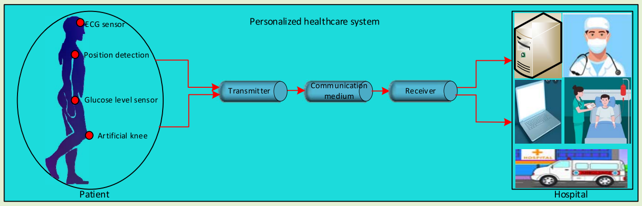
Energy-Aware Hybrid MAC Protocol for IoT Enabled WBAN Systems

Damilola D. Olatinwo, Adnan M. Abu-Mahfouz, *Senior Member, IEEE*,
and Gerhard P. Hancke, *Senior Member, IEEE*

***Abstract*—Energy efficiency is an important quality-of-service requirement that needs to be considered when designing an efficient MAC protocol for a WBAN system due to the limited power resources of biomedical sensor devices. To address this, an energy-aware multi-group hybrid MAC (MG-HYMAC) protocol is proposed in this work to improve energy efficiency as well as the lifetime of the biomedical sensor devices in a personalized healthcare system. The proposed protocol combines both the advantages of the CSMA/CA and the TDMA schemes to enable the biomedical sensors to efficiently contend for transmission opportunities and to allow them to efficiently transmit health data. The MG-HYMAC protocol is combined with a transmission scheduling technique to duty cycle the operations of the biomedical devices with less critical data to determine when and how the biomedical sensor devices will transmit their health data packets in order to reduce collisions to save energy and prolong the battery lifetime of the biomedical sensor devices so as to improve the overall network lifetime. Also, a stochastic probability model and a heuristic-based power control scheme are developed to solve time allocation and power control problems to improve energy efficiency and the biomedical sensor devices lifetime. To validate the MG-HYMAC protocol, it was compared with other related protocols (including HyMAC and CPMAC) and simulated in MATLAB. The simulation results proved that the proposed MG-HYMAC protocol outperformed the existing MAC protocols using standard metrics like energy efficiency, biomedical sensor devices lifetime, and convergence speed.**



***Index Terms*—WBAN, MAC protocols, personalization, stochastic probability, CSMA/CA, TDMA, Internet of Things, transmission scheduling scheme.**

I. INTRODUCTION

WITH the increasing advances of the internet of things (IoT) technologies and smart devices, wireless body area network (WBAN) technology design has received significant attention from both the academia and industry [1]–[3]. The IoT technology is a communication paradigm that can be integrated into many wireless systems [4] such as the WBAN systems to seamlessly connect different types of devices, over the internet to accomplish the critical tasks of such systems ubiquitously [5]–[8].

In the health domain, IoT technologies can be incorporated into WBANs to enable real-time monitoring of patients' health conditions, patients' information management, process control, and to also enable decision making with or without the intervention of humans remotely [9] and [10]. Additionally, combining an IoT technology with a WBAN system could help to provide a cost-effective service as well as help to minimize patients' frequent hospital visits. Therefore, integrating IoT technologies into WBANs are advantageous for healthcare monitoring purposes to achieve a better productivity [11] and [12].

An IoT enabled WBAN system is a body-focused type of wireless network that is composed of various IoT biomedical sensors which are characterized as smart, tiny, light-weight, wearable, and low powered devices. These IoT biomedical sensors are usually positioned in the body, on the body or placed around the human body, they include the gyroscope sensor, electromyography (EMG) sensor,

AQ:1 Manuscript received September 16, 2021; revised November 2, 2021; accepted November 30, 2021. This work was supported by the Council for Scientific and Industrial Research, Pretoria, South Africa, throu the Smart Networks Collaboration Initiative and IoT-Factory Progra (Funded by the Department of Science and Innovation (DSI), South Africa). The associate editor coordinating the review of this article and approving it for publication was Prof. Giancarlo Fortino. *(Corresponding author: Damilola D. Olatinwo.)*

Damilola D. Olatinwo is with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa (e-mail: damibaola@gmail.com).

Adnan M. Abu-Mahfouz is with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa, and also with the Council for Scientific and Industrial Research (CSIR), Pretoria 0184, South Africa (e-mail: a.abumahfouz@ieee.org).

Gerhard P. Hancke is with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa, and also with the Department of Computer Science, City University of Hong Kong, Hong Kong (e-mail: gp.hancke@cityu.edu.hk).

Digital Object Identifier 10.1109/JSEN.2021.3133461

electroencephalogram (EEG) electrocardiography (ECG) sensor, pulse oximeter sensor, heart-rate monitoring sensor, blood pressure sensor, temperature sensor, mental health sensor and so on. The IoT biomedical sensors are used for diagnosing, monitoring, and treating patients with health challenges such as obesity, cancer, diabetes, strokes, myocardial infraction, and tropical diseases [13] seamlessly. They also gather and communicate sensed health data through an access point (AP) such as a smart phone [14] in the body area to designated healthcare centers [15], [16].

However, despite the unique properties of the WBAN systems, they are still confronted with an energy scarcity issue [17] and [18] because the WBAN biomedical sensors are usually configured to use batteries which have limited power capacities and they are sometime impractical to replace or recharge especially when they are implanted in a patient's body. Also, it is well established that the energy consumed by the biomedical devices during data communication to the AP is typically significant. Because of the limited battery power concern and the long lifetime requirement of the biomedical sensors, hence, the need to minimize energy consumption during health data communications is very important, but then, this poses a great challenge in designing robust MAC protocols for a WBAN system [19]–[21]. Therefore, to address this power consumption issue, we propose a new MAC protocol that is energy-aware for an effective patient's health condition sensing and data communication.

The proposed energy-aware MAC protocol is composed of two major phases that include the transmission phase (TP) and the receiving phase (RP). During health data communication phase, i.e., the transmission and the receiving phases, the biomedical sensors waste energy through unnecessary idle listening, collisions, overhearing, and control overhead. To address this and save energy, we employ a sleep-wake-up scheduling mechanism, and we also assign the major transmission overhead to the AP since it can be charged easily unlike the biomedical sensors. Also, we allocate a specific time slot to each of the biomedical sensors for their health data transmission to prevent collisions. A waiting order (WO) state was introduced as a specific type of idle state that only occur during the TP of the TDMA period to save energy. Furthermore, based on the WBAN application requirements, we classify the health data of the biomedical sensors into two groups, namely the critical health data and the less critical health data. To save energy, we as well employ a transmission scheduling technique to duty cycle the operations of the biomedical sensor devices with less critical data packets to determine when and how the biomedical sensor devices will transmit their health data packets to reduce collisions. The major contributions of this paper are outlined below:

- The design of an energy-aware hybrid MAC protocol to reduce the power consumption of WBAN biomedical sensors during data communication was proposed.
- We introduced the idea of a multi-variate concept based on the WBAN application requirements to classify the health data of the biomedical sensors into critical and less critical data according to their priority level.
- To address the longstanding energy efficiency design concern related to the WBAN systems, a transmission scheduling technique is applied to duty cycle the operations of the WBAN biomedical devices with less critical data packets to determine when and how the devices will transmit their health data packets to reduce collisions in order to save energy and prolong the battery lifetime of the biomedical sensor devices to improve the overall network lifetime.
- Since the major sources of energy wastage issues during health data communications are idle listening, control overhead, and collisions, therefore, to save energy and extend the lifetime of the biomedical sensors, we assign the major transmission overhead to the AP side. To conserve energy during idle listening state, we introduced a waiting order state to enable only the synchronous clock of the biomedical sensors to work, while all other operations are disabled. Also, we adopted a sleep-wake-up scheduling mechanism to reduce energy wastage issue to prolong the network lifetime.
- In addition, the biomedical sensors that have health data to transmit are assigned a specific time slot to prevent collisions and thereby reducing energy wastage due to frequent re-transmissions.
- We harnessed the advantages of the CSMA/CA and TDMA schemes as well as the state division of the biomedical sensors to achieve energy efficiency during health data sensing and communication.
- We developed a stochastic probability model and a heuristic-based power control scheme to solve time allocation and power control problems to enhance energy efficiency and prolong the lifetime of the devices.

There is no existing work that has considered a multi-group hybrid MAC (MG-HYMAC) in WBANs that studied this issue in literature to the best of authors' knowledge.

This work is organized in the following manner: The related works is presented in Section II. Section III presents the system model. Section IV presents the analysis of time spent in different states of the proposed MG-HYMAC protocol. The proposed power control scheme and power consumption model for the MG-HYMAC protocol is discussed in Section V. Section VI presents the operations of the proposed MG-HYMAC protocol. Simulation results are discussed in Section VII, while we conclude the work in Section VIII.

II. RELATED WORKS

In this section, we discuss some existing articles in literature that considered MAC protocols to improve the energy efficiency of the WBAN systems. Examples are [2], [22]–[32]. They are discussed and compared with this work in Table I.

III. SYSTEM MODELLING

The proposed system model presents the details on the system architecture and mathematical modelling. In the modelling of the proposed hybrid MAC protocol, the following assumptions are made:

- We assume that not all the biomedical sensors in the network have data to transmit.

TABLE I

COMPARISON OF THE EXISTING MAC PROTOCOLS AND THE PROPOSED MAC PROTOCOL

Reference	Contribution of the existing MAC protocol	Contribution of the newly proposed MAC protocol
[2]	A hybrid multi-class MAC protocol that adopts slotted ALOHA and TDMA mechanisms was proposed. The proposed protocol consists of two main processes, namely contention phase and transmission phase. An optimization problem was formulated to maximize the system sum-throughput, packet success-access-ratio, and the reservation ratio to determine the trade-off between the two processes. The paper employed a concept that efficiently divided the devices in the network into two classes. In each class, not all the devices have data to transmit. This helped to improve the network performance. However, the energy efficiency of the system was not considered in this work.	Different from [2], an energy-aware MAC protocol that adopts a CSMA/CA scheme and a TDMA scheme was proposed. The proposed protocol consists of two main processes, namely the reception phase and the transmission phase. We developed a stochastic probability model and a heuristic-based power control scheme to solve time allocation and power control problems. Unlike [2], the focus of this work is to improve energy efficiency and to prolong the lifetime of the biomedical devices by addressing energy wastage and energy consumption problems during data communication. Here, we employ a multi-variate concept to classify the devices in the network into two groups. The devices in the first group were all assumed to have data to transmit, while a few out of the second group have data to transmit.
[22]	An energy harvesting hybrid MAC protocol that adopts a dynamic scheduling method to improve energy efficiency was proposed. But then, the latency of the proposed system is relatively high and could still be improved on.	In contrast to [22], we proposed a new hybrid MAC protocol that exploit the CSMA/CA scheme and the TDMA scheme to improve energy efficiency. Also, we tackle energy wastage problems that are generally common during data communication by introducing some power saving mechanisms such as low power listening, contention, and transmission scheduling mechanisms.
[23]	An out-of-band wake-up radio was introduced to save energy during idle listening and the transmission of control overhead. However, more efficient mechanisms could still be investigated to reduce energy consumption and energy wastage issues so as to increase the lifetime of the system.	Contrary to [23], we assign the major transmission overhead to the AP side since it has sufficient power resource and can be charged. Also, to cater for energy wastage during idle listening we employ a sleep-wake-up scheduling mechanism as well as introduce a waiting order state which works by only allowing the synchronous clock of the biomedical sensors to function while other operations are disabled.
[24]	An investigation on a hybrid MAC protocol in the context of energy efficiency and delay was carried out in [24]. However, more investigations that focus on the development of new mechanisms are required to address energy wastage and energy consumption issues.	Different from [24], a multi-variant hybrid MAC protocol which combines the benefits of the CSMA/CA and the TDMA schemes was introduced to enhance energy efficiency. The operations of the WBAN biomedical sensors were divided into different states to tackle energy wastage issues such as collisions, idle listening, and control overhead during data communication. Furthermore, we apply a transmission scheduling and a sleep-wake-up scheduling mechanism to conserve energy.
[25]	A SmartBAN. hybrid MAC protocol was introduced to mix the slotted ALOHA and the TDMA scheme to improve energy efficiency and minimize delay in the network in an attempt to enhance periodic and emergency traffic. However, the proposed system is not scalable and this calls for further improvements.	In contrast to [25], we exploited both the CSMA/CA and the TDMA schemes. For instance, the CSMA/CA scheme was employed to handle collision problem during data communication to reduce the energy wastage associated with frequent retransmissions of health data. In addition, to reduce energy wastage issues we allocate specific time slots to the biomedical sensors to prevent collisions. Also, a transmission scheduling technique was employed to duty cycle the operations of the biomedical sensors to save energy.
[26]	A MAC protocol that is based on the IEEE 802.15.6 protocol was proposed to handle normal and emergency traffic. A slot reallocation technique was employed to conserve energy. However, this has a negative influence on the latency of the system. Therefore, the latency of the system needs to be improved on.	Contrary to [26], we introduced a multi-variant technique based on the WBAN application requirements to classify the health data of the biomedical sensors into critical and less critical data according to their priorities. We introduce some power saving mechanisms such as a low power listening, contention and transmission scheduling mechanisms to minimize energy consumption.
[27]	An energy efficient MAC protocol that exploits the advantages of the body area network static nature was introduced to implement a TDMA scheme that saved a reasonable amount of energy with a little idle listening and overhead. But then, the data transfer reliability and the flexibility of the system are still considered low and could still be improved on.	Unlike [27], the advantages of the CSMA/CA and the TDMA schemes were combined to improve energy efficiency and extend the lifetime of the network. To achieve an energy efficient WBAN system, the major transmission overhead was observed at the AP side, a waiting order state which only allow the synchronous clock of the biomedical sensors to work was introduced while other operations are turned off.
[28]	Authors proposed a RFID-enabled MAC protocol to adjust the wakeup and the sleep state of the body nodes dynamically based on their traffic pattern to address energy consumption problem. However, the proposed system is yet to fully address energy wastage and energy consumption concerns. Hence, the work is still limited in terms of the lifetime of the system.	In contrast to [28], we introduced the idea of a multi-variant technique which harness the CSMA/CA and the TDMA benefits to address energy consumption problems. Furthermore, a transmission scheduling technique was employed to duty cycle the operations of the biomedical sensors such that only the biomedical sensors that have data to transmit are assigned specific time slots, while others go into a sleep mode to conserve energy.
[29]	A traffic adaptive MAC protocol that is based on the traffic information of the sensor nodes was designed. To conserve energy, the duty cycles of the nodes were adjusted based on their traffic pattern. Unfortunately, the proposed system has a relatively high latency that resulted to energy wastage issues. Therefore, the energy efficiency of the proposed system could still be improved on.	Contrary to [29], we addressed the energy consumption issues during data communication by dividing the operations of the biomedical sensors into different states and minimizing the energy consumed in each state, for example, we employ a transmission scheduling mechanism to duty cycle the operations of the biomedical sensors based on their data type.
[30]	Here, authors designed a MAC protocol based on a TDMA scheme where nodes are allocated time slots to transmit packets and goes into a Q-sleep mode at others time slot to	Different from [30], we designed a new MAC protocol that is based on the CSMA/CA and the TDMA mechanisms which adopts a sleep-wake-up

TABLE I
(Continued.) COMPARISON OF THE EXISTING MAC PROTOCOLS AND THE PROPOSED MAC PROTOCOL

	save energy. But then, the throughput and lifetime of the system decreased due to time slot wastage. As a consequence, the utilization of time slot could still be improved on.	scheduling method. We introduced some power saving mechanisms such as low power listening, contention and transmission scheduling mechanisms.
[31]	Authors proposed a polling-based MAC protocol where sensors can efficiently utilize the channel in such a way that the sensors are waked up to transmit their packets only when the channel is strong to enable a fast and reliable transmission to enhance energy efficiency, transmission reliability as well as data rate performance. But then, this resulted to a high latency which technically led to energy wastage and a decrease in the lifetime of the system.	Unlike [31], we proposed the idea of a multi-variant technique which harness the advantages of the CSMA/CA and the TDMA mechanisms to address energy consumption problem due to collisions, idle listening, overhearing, and control overhead. In addition, we employ a transmission scheduling technique to duty cycle the operations of the biomedical sensors such that a particular time slot is assigned to a biomedical sensor device that have data to transmit, while others go into a sleep mode to save energy.
[32]	A homogenous hybrid MAC protocol involving the CSMA/CA protocol and the TDMA protocol was proposed to improve energy efficiency. An awaiting order state was considered to save energy. Also, energy wastage due to packet overload was addressed by setting the major overhead transmission at the PS side. However, the mechanisms proposed are yet to fully tackle the longstanding energy consumption and energy wastage issues. Hence, there are still needs for improvements.	In contrast to [32] that only considered a homogenous WBAN system, i.e., they do not provide any scheme to cater for a heterogeneous network, where the biomedical sensors in a network may have different properties like the consideration of critical health data and less critical health data. For this reason, we extend the work done in [32] by introducing the idea of a multi-variant concept to cater for network heterogeneity. To further improve energy efficiency and extend the battery lifetime of the biomedical sensors, we apply a transmission scheduling technique to duty cycle the operations of the WBAN biomedical sensors with less critical data packets to determine when and how the biomedical sensor devices will transmit their health data packets to reduce collisions in order to save energy and prolong the battery lifetime of the biomedical sensor devices so as to improve the overall network lifetime. Also, we developed a stochastic probability model and a heuristic-based power control scheme to solve time allocation and power control problems to enhance energy efficiency and prolong the lifetime of the devices. Furthermore, we employed a sleep-wake-up scheduling mechanism which helped in saving a reasonable amount of power and increasing the network lifetime. Thus, the protocol design, proposed algorithmic methods, and the mathematical formulation proposed in this work are different compared to [32].

- We assume that the system uses a sense-and-send approach.
- The data packet arrival is based on a Poisson process, while the retransmission of the data packets is considered as a truncated Poisson distribution process.
- We assume two types of events for the biomedical sensor devices (i.e., the transmission of data packets to the AP and the reception of control signals from the AP) data in the TP and the amount of energy consumed in these events are different in a fixed TP.
- We also assume that a biomedical sensor device consumes different amount of power across the states, but then, all the biomedical sensors in the network operates using a fixed power in a particular state.

A. System Architecture

Here, we introduce a new personalized WBAN system architecture that is made up of a low power AP device (i.e., a mobile cell phone) that can be charged easily as well as various biomedical devices that are uniformly distributed all over a patient's body for health condition(s) monitoring as shown in Fig 1. Each of the biomedical devices perform health condition(s) sensing and send their sensed health data to the AP. The AP acts as the coordinator as well as an intermediary between the biomedical devices and other components of the system, including the medical experts, health centers, and the health data analysis platforms.

B. Mathematical Modelling

Let K denote the total number of the biomedical sensor devices in the network. The biomedical sensor devices within this network are classified into a multi-group (for example, group P, group Q, and so on) using a multi-variate concept according to their health data priority-level using (1). Note, we assume that each device will have to assign a priority-level (η) to its health data to provide a high priority and a low priority to the critical health data and less critical health data respectively based on (1) [33].

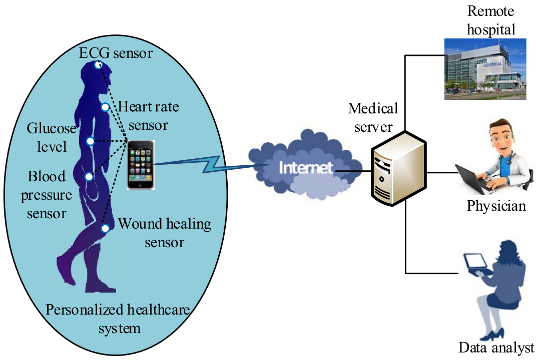


Fig. 1. A typical personalized WBAN system architecture.

$$\eta = \frac{D_T}{\lambda_{rate} x P_{len}} \tag{1}$$

where D_T is the health data type, λ_{rate} is the traffic arrival rate, and P_{len} is the packet length. Based on the priority-level, the devices and the AP takes decision during the allocation of resources and transmission.

As a consequence, the biomedical devices with critical health data packets are categorized into group P and are

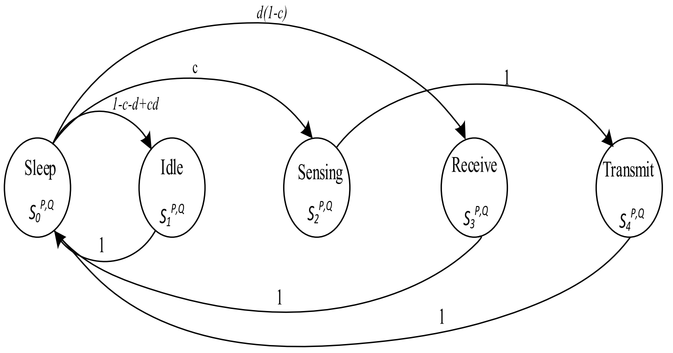


Fig. 2. Proposed state transition probability of the biomedical sensor devices.

denoted as A in a set of $A = \{m_1, m_2, m_3, \ldots m_A\}$, while the biomedical devices with less critical health data packets are categorized into group Q and are denoted as B in a set of $B = \{n_1, n_2, n_3, \ldots n_B\}$.

In each TP, we assume that not all the biomedical devices with less critical health data packets in group Q have data packets to send based on the applied transmission scheduling method. Meanwhile, only the ones that have data packets to send are enabled to contend for channel utilization opportunities for transmission purposes. While we assume that all the biomedical devices in group P all have health data packets to send to the AP, hence, all of them are allowed to contend for channel utilization opportunities.

It was assumed that each of the biomedical devices in the network follows a stochastic process with five states. Consequently, $S_n^{P,Q} = \left\{S_0^{P,Q}, S_1^{P,Q}, S_2^{P,Q}, S_3^{P,Q}, S_4^{P,Q}\right\}$ was used to represent the five states of a biomedical sensor device, where we denote the set of all the device states as $S_n^{P,Q}$ while $S_0^{P,Q}$, $S_1^{P,Q}$, $S_2^{P,Q}$, $S_3^{P,Q}$, and $S_4^{P,Q}$ represents the sleep, idle, sensing, receiving, and transmitting states respectively in groups P and Q as shown in Fig. 2.

IV. ANALYSIS OF TIME SPENT IN DIFFERENT STATES

In this section, we present the analysis of the average time spent in each state of the proposed MG-HYMAC protocol. For this to be achieved, we use a continuous-time Markov chain to estimate the time a device spent in each state [34].

Therefore, the probability that there is at least a sensing event occurrence is expressed in (2) and the probability that there is at least one transmission event occurrence is expressed in (3) respectively as:

$$c = 1 - e^{-\lambda_{sen} T_t} \tag{2}$$

$$d = 1 - e^{-\lambda_{tran} T_t} \tag{3}$$

where T_t represent the maximum time spent by a device in the idle state during the CSMA/CA period of the TP, while λ_{sens} and λ_{tran} denotes the average arrival rate of the health data packets for the Poisson process in the sensing as well as the transmission phases, respectively.

Recall that the biomedical devices in the network are classified into multi-groups including group P that contains the critical health data packets and group Q that contains the less critical health data packets. Hence, the time spent by a device in group P on the S_n^P state is denoted as $T_{S_n}^P$, while $E\left[T_{S_n}^P\right] = \mu_{S_n}^P$ represents the $T_{S_n}^P$ mean value.

For example, the time a biomedical sensor spends in the sleep state is represented as $T_{S_0}^P$. The expected value of $T_{S_0}^P$ is assumed to be equal to its mean value as expressed in (4):

$$E\left[T_{S_0}^P\right] = \mu_{S_0}^P \tag{4}$$

If a device switches from S_0^P to S_1^P, then, the time spent in S_1^P, is denoted as $T_{S_1}^P$. For each transmission event occurrence, the $T_{S_1}^P$ mean value is expressed in (5) as:

$$E\left[T_{S_1}^P|event\right] = \mu_{S_1}^P|event = \int_{\aleph_t}^{\aleph_t + \mathrm{T}_t} \left(\varphi - \aleph_t\right)/\mathrm{T}_t \partial_\varphi = \left(\frac{1}{2}\mathrm{T}_t\right) \tag{5}$$

In (6), $\aleph_t$ denotes the period that the biomedical sensor device switches from S_1^P to an active state, i.e., either the transmitting or the receiving state.

We denote the maximum time and the minimum time a biomedical sensor device spends in S_2^P as ς_{max}^P and ς_{min}^P, respectively. Thus, the mean value of $T_{S_2}^P$ is computed in (6) as:

$$E\left[T_{S_2}^P\right] = \mu_{S_2}^P = \frac{1}{2}\left(\varsigma_{max}^P + \varsigma_{min}^P\right) \tag{6}$$

While, for the receiving and transmitting states, we denote the time spent in each state as $T_{S_3}^P$ and $T_{S_4}^P$, respectively and their mean values are expressed in (7) and (8) as:

$$E\left[T_{S_3}^P\right] = \mu_{S_3}^P \tag{7}$$

$$E\left[T_{S_4}^P\right] = E\left[\mathrm{T}_{prep}^P\right] + E[\mathrm{T}_{data}^P + \mathrm{T}_{beacon}^P + \mathrm{T}_{ACK}^P] \tag{8}$$

In (8), T_{prep}^P, T_{data}^P, T_{beacon}^P, and T_{ACK}^P denotes the time a biomedical sensor device prepares to transmit, the time spent on health data packet transmission, the time spent on sending all end-beacons, and the time spent on sending all ACKs, respectively. Note, we assume that the T_{prep}^P begins from when a biomedical sensor device enters the transmitting state till when it successfully delivers its health data packets. Thus, the T_{prep}^P, T_{data}^P, T_{beacon}^P, and T_{ACK}^P can all be determined using ${P_{len}}/{\mathfrak{R}}$, where $\mathfrak{R}$ is the transmission rate.

From (4) – (8), the total time spent by a biomedical sensor device in group P on the transition states is modelled in (9) as:

$$\begin{aligned}\mathrm{T}_{Total}^P = T_{S_0}^P + (c + d - cd)\, T_{S_1}^P|\text{event} + c\left(T_{S_2}^P + \mathrm{T}_{proc}^P\right) \\ + d\left(T_{S_3}^P\right) + (c + d - cd)\, T_{S_4}^P\end{aligned} \tag{9}$$

where T_{proc} is the processing time.

And the mean value of T_{Total}^P is determined in (10) as:

$$\begin{aligned}E\left[\mathrm{T}_{Total}^P\right] = T_{S_0}^P - (c + d - cd)\left(\frac{1}{2}\mathrm{T}_t\right) + c\left(\mu_{S_1}^P + \frac{1}{a}\right) \\ + d\mu_{S_3}^P + (c + d - cd)\, \mu_{S_4}^P\end{aligned} \tag{10}$$

For group Q, the time spent by a biomedical sensor device on the S_n^Q state is denoted as $T_{S_n}^Q$ and its mean value is $\left[T_{S_n}^Q\right] = \mu_{S_n}^Q$. Consequently, $T_{S_0}^Q$ is the time spent in S_0^Q and the expected value of $T_{S_0}^Q$ is assumed to be equal to its mean value as given in (11):

$$E\left[T_{S_0}^Q\right] = \mu_{S_0}^Q \tag{11}$$

The time spent in S_1^Q is denoted as $T_{S_1}^Q$. If ∃ a transmission event occurrence, then, the $T_{S_1}^Q$ mean value is determined in (12) as:

$$\begin{aligned} E\left[T_{S_1}^Q|\text{event}\right] &= \mu_{S_1}^Q|\text{event} = \int_{\aleph_t}^{\aleph_t+\mathrm{T}_t} \left(\varphi - \aleph_t\right)/\mathrm{T}_t \partial_\varphi \\ &= \left(\frac{1}{2}\mathrm{T}_t\right) \end{aligned} \tag{12}$$

Recall that not all the biomedical devices in group Q have data packets to send and/or will not participate in data transmission in each TP cycle, hence, for no transmission occurrence, we model the mean value of $T_{S_1}^Q$ in (13) as:

$$E\left[T_{S_1}^Q|\text{none}\right] = \mu_{S_1}^Q|\text{none} = \mathrm{T}_t \tag{13}$$

The time a biomedical sensor device spend in the sensing state is $T_{S_2}^Q$ and the mean value is expressed in (14) as:

$$E\left[T_{S_2}^Q\right] = \mu_{S_2}^Q = \frac{1}{2}\left(\varsigma_{max}^Q + \varsigma_{min}^Q\right) \tag{14}$$

While the time spent by a biomedical sensor device in either the receiving and transmitting states are represented as $T_{S_3}^Q$ and $T_{S_4}^Q$, respectively and their mean values are modelled in (15) and (16) as:

$$E\left[T_{S_3}^Q\right] = \mu_{S_3}^Q \tag{15}$$

$$E\left[T_{S_4}^Q\right] = E\left[\mathrm{T}_{prep}^Q\right] + E\left[\mathrm{T}_{data}^Q + \mathrm{T}_{beacon}^Q + \mathrm{T}_{ACK}^Q\right] \tag{16}$$

To determine the total time spent by a biomedical sensor device in group Q, we combine (11) – (14) to model (17) as:

$$\begin{aligned} &\mathrm{T}_{Total}^Q \\ &\quad = T_{S_0}^Q + (1-(\mathrm{c}+\mathrm{d}-\mathrm{cd}))\, T_{S_1}^Q|\text{none} + (\mathrm{c}+\mathrm{d}-\mathrm{cd}) T_{S_1}^Q|\text{event} \\ &\qquad + c\left(T_{S_2}^Q + \mathrm{T}_{proc}^Q\right) + d\left(T_{S_3}^Q\right) + (c+d-cd)\, T_{S_4}^Q 5 \end{aligned} \tag{17}$$

While the mean value of T_{Total}^Q is computed in (18) as:

$$\begin{aligned} E\left[\mathrm{T}_{Total}^Q\right] = T_{S_0}^Q + \mathrm{T}_t - (c+d-cd)\left(\frac{1}{2}\mathrm{T}_t\right) + c\left(\mu_{S_1}^Q + \frac{1}{\mathrm{b}}\right) \\ + d\mu_{S_3}^Q + (c+d-cd)\,\mu_{S_4}^Q \end{aligned} \tag{18}$$

The total time spent by all the biomedical devices A and B is computed from (9) and (17) in (19) and (20), respectively as:

$$\sum\nolimits_{a=1}^{A} \mathrm{T}_{Total}^p \quad \forall_a,\ a = 1, 2, \ldots, A \tag{19}$$

$$\sum\nolimits_{b=1}^{\mathrm{B}} \mathrm{T}_{Total}^Q \quad \forall_b,\ b = 1, 2, \ldots, B \tag{20}$$

The total mean value of the time spent by all the biomedical devices A and B is computed from (10) and (18) in (21) and (22) respectively as:

$$\sum\nolimits_{a=1}^{\mathrm{A}} \left(E\left[\mathrm{T}_{Total}^P\right]\right) \quad \forall_a,\ a = 1, 2, \ldots, A \tag{21}$$

$$\sum\nolimits_{b=1}^{\mathrm{B}} \left(E\left[\mathrm{T}_{Total}^Q\right]\right) \quad \forall_b,\ b = 1, 2, \ldots, B \tag{22}$$

Furthermore, to calculate the overall time spent by group P and group Q, we add (19) and (20). The overall time spent by all the biomedical devices in both groups P and Q is defined by Θ_{sum} and expressed in (23) as:

$$\Theta_{sum} = \sum\nolimits_{a=1}^{A} \mathrm{T}_{Total}^P + \sum\nolimits_{b=1}^{\mathrm{B}} \mathrm{T}_{Total}^Q \tag{23}$$

Also, their overall mean value (i.e., groups P and Q) is defined by $\mathfrak{H}_{sum}$ and computed in (24) by adding (21) and (22).

$$\mathfrak{H}_{sum} = \sum\nolimits_{a=1}^{\mathrm{A}} \left(E\left[\mathrm{T}_{Total}^P\right]\right) + \sum\nolimits_{b=1}^{\mathrm{B}} \left(E\left[\mathrm{T}_{Total}^Q\right]\right) \tag{24}$$

To solve the problem of the overall time spent by all the biomedical devices in the system, we employed the proposed stochastic probability scheme presented in Algorithm 1.

V. PROPOSED POWER CONTROL SCHEME AND POWER CONSUMPTION MODEL FOR THE MG-HYMAC PROTOCOL

In this section, we propose a power control scheme for the MG-HYMAC protocol and model the power consumption of the biomedical sensor devices in the network. The amount of power allocated to each biomedical sensor device in the five states by the AP is controlled by the power control scheme. The schemes apply a set of $\varrho_n^{P,Q} = \left\{\varrho_0^{P,Q}, \varrho_1^{P,Q}, \varrho_2^{P,Q}, \varrho_3^{P,Q}, \varrho_4^{P,Q}\right\}$ and a set of $S_n^{P,Q} = \left\{S_0^{P,Q}, S_1^{P,Q}, S_2^{P,Q}, S_3^{P,Q}, S_4^{P,Q}\right\}$to process the optimal control and the allocation of power during each TP cycle.

The biomedical devices in the network have their operational power fixed for each state and we denote the power consumed by each biomedical sensor device when switching from $S_0^{P,Q}$ to $S_1^{P,Q} as \varepsilon_{01}^{P,Q}$ and as $\varepsilon_{13}^{P,Q}$ when switching from $S_1^{P,Q}$ to $S_3^{P,Q}$. Following this, the total power consumed is represented as Φ_{Total} and modelled in (25) and (26) for both groups P and Q, respectively as:

$$\begin{aligned} \Phi_{Total}^P = T_{S_0}^P \varrho_0^P + T_{S_1}^P \varrho_1^P + \varepsilon_{01}^P + \tau_s\left(T_{S_2}^P \varrho_2^P + T_{S_4}^P \varrho_4^P\right) \\ + \varepsilon_{13}^P + \tau_r T_{S_3}^P \varrho_3^P \end{aligned} \tag{25}$$

$$\begin{aligned} \Phi_{Total}^Q = T_{S_0}^Q \varrho_0^Q + T_{S_1}^Q \varrho_1^Q + \varepsilon_{01}^Q + \tau_s\left(T_{S_2}^Q \varrho_2 + T_{S_4}^Q \varrho_4\right) \\ + \varepsilon_{13}^Q + \tau_r T_{S_3}^Q \varrho_3^Q \end{aligned} \tag{26}$$

In (25) and (26), τ_s and τ_r are used to show the occurrence of transmission event in the sensing and receiving states, respectively. So, if ∃ a transmission occurrence it turns to 1 otherwise it turns to 0. The mean value of the total power consumption for both groups P and Q is modelled in (27) and (28) respectively as:

$$E\left[\Phi_{Total}^P\right] = T_{S_0}^P \varrho_0^P (c+d-cd)\left(\frac{1}{2}\mathrm{T}_t \varrho_1^P\right) + \varepsilon_{01}^P$$

Algorithm 1 MG-HYMAC Stochastic Probability Scheme

```
Require: $A, B \triangleright$ biomedical sensors in group $P$ and group $Q$, $S_n^{P,Q} = \left\{S_0^{P,Q}, S_1^{P,Q}, S_2^{P,Q}, S_3^{P,Q}, S_4^{P,Q}\right\} \triangleright$ transition states, AP, $\Theta_{sum}$ && $\mathfrak{H}_{sum}$
Initialize: biomedical devices with data packets to transmit
Assign $\eta$ to each group based on their data type using (1)
for a = 1, …, $A$ do
  let $T_{S_n}^{P}$ denote time spent by each $a$ in $S_n^P$ states
  for $S_0^P$ do
    calculate mean value of $T_{S_0}^{P}$ as (4)
  end for
  if $a$ switches from $S_0^P$ to $S_1^P$ then
    time spent in $S_1^P == T_{S_1}^{P}$
    for each transmission event do
      calculate mean value of $T_{S_1}^{P}$ as (5)
    end for
  end if
  for $S_2^P$ do
    assign the $\varsigma_{max}^{P}, \varsigma_{min}^{P}$ in $S_2^P$
    compute mean value of $T_{S_2}^{P}$ using (6)
  end for
  for $S_3^P$ && $S_4^P$ do
    calculate mean value of $T_{S_3}^{P}$ && $T_{S_4}^{P}$ using (7) && (8)
  end for
  for each $a$ in $\mathcal{A} = \{m_1, m_2, m_3, \ldots m_A\}$ do
    compute total time spent in the transition states as (9)
    compute total mean as (10)
  end for
end for loop
for $b$= 1, …, $B$ do
  let $T_{S_n}^{Q}$ denote time spent by each $b$ in $S_n^Q$ states
  for $S_0^Q$ do
    compute mean value of $T_{S_0}^{Q}$ using (11)
  end for
  if $b$ switches from $S_0^Q$ to $S_1^Q$ then
    time spent in $S_1^Q == T_{S_1}^{Q}$
    if ∃ a transmission event then
      compute mean value of $T_{S_1}^{Q}$ as (12)
    else
      compute mean value of $T_{S_1}^{Q}$ as (13)
    end if
  end if
  for $\boldsymbol{S_2^Q}$ do
    assign the $\boldsymbol{\varsigma_{max}^{Q}, \varsigma_{min}^{Q}}$ in $\boldsymbol{S_2^Q}$
    calculate mean value of $\boldsymbol{T_{S_2}^{Q}}$ using (14)
  end for
  for $\boldsymbol{T_{S_3}^{Q}}$ && $\boldsymbol{T_{S_4}^{Q}}$ do
    compute mean value of $\boldsymbol{T_{S_3}^{Q}}$ && $\boldsymbol{T_{S_4}^{Q}}$ using (15) && (16)
  end for
  for each b in $\mathcal{B} = \{\boldsymbol{n_1, n_2, n_3, \ldots n_B}\}$ do
    compute total time spent on the transition states as (17)
    compute total mean value as (18)
  end for
  for all biomedical sensor devices in A && B do
    compute total time spent on the transition states sing (19) && (20)
    compute total mean using (21) && (22)
  end for
  for all the biomedical devices in the two groups do
    calculate $\boldsymbol{\Theta_{sum}}$ using (23)
    calculate $\boldsymbol{\mathfrak{H}_{sum}}$ using (24)
  end for
end for
end
return $\boldsymbol{\Theta_{sum}}$
return $\boldsymbol{\mathfrak{H}_{sum}}$
```

$$+c\left(\mu_{S_2}^{P}\varrho_2^{P} + \frac{1}{A}\varrho_{Proc}\right) + d\mu_{S_3}^{P}\varrho_3^{P}$$

$$+\varepsilon_{13}^{P} + (c+d-cd)\mu_{S_4}^{P}\varrho_4^{P} \tag{27}$$

$$E\left[\Phi_{Total}^{Q}\right] = T_{S_0}^{Q}\varrho_0^{Q} + \mathrm{T}_t\varrho_1^{Q} - (c+d-cd)\left(\frac{1}{2}\mathrm{T}_t\varrho_1^{Q}\right)$$
$$+\varepsilon_{01}^{Q} + c\left(\mu_{S_2}^{Q}\varrho_2^{Q} + \frac{1}{B}\varrho_{Proc}\right) + \mu_{S_3}^{Q}\varrho_3^{Q}$$
$$+\varepsilon_{13}^{Q} + (c+d-cd)\mu_{S_4}^{Q}\varrho_4^{Q} \tag{28}$$

Therefore, the total power consumed by all the biomedical devices A and B is computed from (25) and (26) in (29) and (30) as:

$$\sum\nolimits_{a=1}^{A} \Phi_{Total}^{P} \quad \forall_a,\ a = 1, 2, \ldots, A \tag{29}$$
$$\sum\nolimits_{b=1}^{\mathrm{B}} \Phi_{Total}^{Q} \quad \forall_b,\ b = 1, 2, \ldots, B \tag{30}$$

Then, the total mean value of the power consumed by all the biomedical devices A and B is computed from (27) and (28) in (31) and (32) as:

$$\sum\nolimits_{a=1}^{A} E\left[\Phi_{Total}^{P}\right] \quad \forall_a,\ a = 1, 2, \ldots, A \tag{31}$$
$$\sum\nolimits_{b=1}^{\mathrm{B}} E\left[\Phi_{Total}^{Q}\right] \quad \forall_b,\ b = 1, 2, \ldots, B \tag{32}$$

To calculate the overall power ($\mathfrak{I}_{sum}$) consumed by all the biomedical devices in both groups P and Q, we combine (29) and (30) to derive (33).

$$\mathfrak{I}_{sum} = \sum\nolimits_{a=1}^{A} \Phi_{Total}^{P} + \sum\nolimits_{b=1}^{\mathrm{B}} \Phi_{Total}^{Q} \tag{33}$$

And the overall mean value (Υ_{sum}) of both group P and group Q is calculated in (34) as:

$$\Upsilon_{sum} = \sum\nolimits_{a=1}^{A} E\left[\Phi_{Total}^{P}\right] + \sum\nolimits_{b=1}^{B} E\left[\Phi_{Total}^{Q}\right] \tag{34}$$

To optimize the time spent by each biomedical sensor device in states $S_n^{P,Q} = \left\{S_0^{P,Q}, S_1^{P,Q}, S_2^{P,Q}, S_3^{P,Q}, S_4^{P,Q}\right\}$, we set a time constraint in (35) to allocate different time (t) to a biomedical device in the different state of $S_n^{P,Q}$ as:

$$t = t_0 + t_1 + t_2 + t_3 + t_4 = 1 \tag{35}$$

Also, to reduce the power spent by the devices in each state of $S_n^{P,Q} = \left\{S_0^{P,Q}, S_1^{P,Q}, S_2^{P,Q}, S_3^{P,Q}, S_4^{P,Q}\right\}$, we compute a power resource allocation solution to allocate an optimal power to a device in the different $S_n^{P,Q}$ states based on Algorithm 2.

Also, the power consumption computation scheme for the MG-HYMAC is present in Algorithm 3.

A. Complexity Analysis

To improve the proposed scheme (MG-HYMAC stochastic probability scheme), we optimize the time spent by each device in the different states of the system to reduce power consumption and increase the lifetime of the devices using Algorithm 2.

To investigate the implementation of the proposed scheme (i.e., MG-HYMAC) in real health devices, we analyze the time complexity of Algorithm 2. Basically, the time complexity of an algorithm is used to determine the execution time (i.e., speed) of an algorithm of an input size n [35].

Algorithm 2 A Heuristic-Based Power Control Scheme

```
Require: States $S_n^{P,Q} = \left\{S_0^{P,Q},\ S_1^{P,Q},\ S_2^{P,Q},\ S_3^{P,Q}, S_4^{P,Q}\right\}$ power allocation solution $\varrho_n^{P,Q} = \left\{\varrho_0^{P,Q},\ \varrho_1^{P,Q},\ \varrho_2^{P,Q},\ \varrho_3^{P,Q}, \varrho_4^{P,Q}\right\}$
Initialize biomedical sensors in the five states
for $a = 1, \ldots, A$ in $S_n^P = \left\{S_0^P,\ S_1^P,\ S_2^P,\ S_3^P, S_4^P\right\}$ do
    set $t = t_0 + t_1 + t_2 + t_3 + t_4 = 1$
    compute $\varrho_0^P \exists\, t_0 = [0, 1]$ && $P_{min} \le \varrho_0^P \le P_{max}, \forall a \in S_0^P$
    compute $\varrho_1^P \exists\, t_1 = [0, 1]$ && $P_{min} \le \varrho_1^P \le P_{max}, \forall a \in S_1^P$
    compute $\varrho_2^P \exists\, t_2 = [0, 1]$ && $P_{min} \le \varrho_2^P \le P_{max}, \forall a \in S_2^P$
    compute $\varrho_3^P \exists\, t_3 = [0, 1]$ && $P_{min} \le \varrho_3^P \le P_{max}, \forall a \in S_3^P$
    compute $\varrho_4^P \exists\, t_4 = [0, 1]$ && $P_{min} \le \varrho_4^P \le P_{max}, \forall a \in S_4^P$
end for
for $b = 1, \ldots, B$ in $S_n^Q = \left\{S_0^Q,\ S_1^Q,\ S_2^Q,\ S_3^Q, S_4^Q\right\}$ do
    set $t = t_0 + t_1 + t_2 + t_3 + t_4 = 1$
    compute $\varrho_0^Q \exists\, t_0 = [0, 1]$ && $P_{min} \le \varrho_0^Q \le P_{max}, \forall b \in S_0^Q$
    compute $\varrho_1^Q \exists\, t_1 = [0, 1]$ && $P_{min} \le \varrho_1^Q \le P_{max}, \forall b \in S_1^Q$
    compute $\varrho_2^Q \exists\, t_2 = [0, 1]$ && $P_{min} \le \varrho_2^Q \le P_{max}, \forall b \in S_2^Q$
    compute $\varrho_3^Q \exists\, t_3 = [0, 1]$ && $P_{min} \le \varrho_3^Q \le P_{max}, \forall b \in S_3^Q$
    compute $\varrho_4^Q \exists\, t_4 = [0, 1]$ && $P_{min} \le \varrho_4^Q \le P_{max}, \forall b \in S_4^Q$
end for
end
```

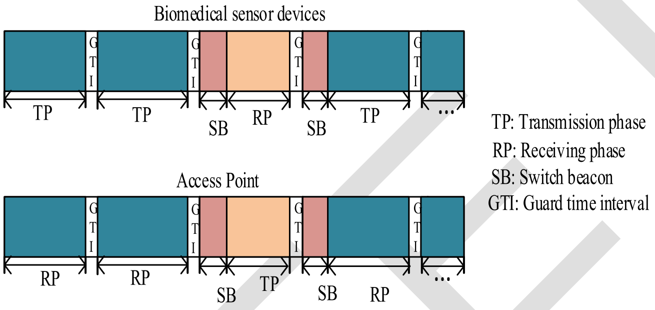


Fig. 3. The proposed MG-HYMAC protocol slot allocation.

For this to be achieved, we applied the Big-O (O) notation and the time complexity of Algorithm 2 is $O\,(A + B)$. Thus, Algorithm 2 has a linear time complexity. Now, we further validate our contribution with respect to HyMAC and CPMAC and we discovered that our proposed scheme has a similar linear time complexity with both HyMAC and CPMAC. But then, the proposed scheme requires a smaller computational time compared to both HyMAC and CPMAC. This contribution makes the proposed scheme more efficient for implementation in real health devices.

VI. DESCRIPTION OF THE PROPOSED MG-HYMAC PROTOCOL OPERATIONS

In this section, we describe the operations of the proposed MG-HYMAC protocol and the wake-up scheme that we employed to reduce energy consumption. The biomedical sensor in the network performs two major operations such as the transmission of health data to the AP as well as the reception of control signals from the AP. Consequently, the AP acts as a gateway to the internet and can also send data, including health data, query requests/health alert or configuration changes from the healthcare service providers to the biomedical sensors [36]. In this work, we assume that the major function of the biomedical devices is to transmit sensed health data to the AP, and so we assign most of the time slots to the biomedical devices for health data communication. However, to guard against overlapping in time slots when the AP tries to send control signals to the biomedical sensors, a GTI is applied, and a SB message is sent first at the end of AP's receiving phase before transmission can take place as described in Fig. 3.

Algorithm 3 MG-HYMAC Power Consumption Computation Scheme

```
Require: $\varrho_n^{P,Q} = \left\{\varrho_0^{P,Q},\ \varrho_1^{P,Q},\ \varrho_2^{P,Q},\ \varrho_3^{P,Q}, \varrho_4^{P,Q}\right\}$ power consumed by the devices, $\varepsilon_{01}^{P,Q}, \varepsilon_{13}^{P}, \ \tau_s, \ \tau_r \Phi_{Total}^P$ && $\Phi_{Total}^Q \triangleright$ total power consumed by a device in group $P$ and group $Q$
Initialize biomedical sensors in the five states ($S_n^{P,Q}$)
for $a = 1, \ldots, A$, b $= 1, \ldots, B$ do
    compute the total power consumption using (22) && (26)
    compute the mean value of $\Phi_{Total}^P$ && $\Phi_{Total}^Q$ using (27) && (28)
    if $\exists$ a transmission event then
        assign 1
    else
        assign 0
    end if
    for $A$ && $B$ do
        compute the total power consumed using (29) && (30)
        compute the mean of the total power consumed using (31) && (32)
    end for
    for the overall power consumption of group $P$ && group $Q$ do
        compute $\Im_{sum}$ using (33)
        compute $\Upsilon_{sum}$ (34)
    end for
end for
end
return $\Im_{sum}$
return $\Upsilon_{sum}$
```

The two major operations of the biomedical sensor devices are discussed in detail in the following subsection.

A. Wake-Up Scheme

A wake-up radio is a special type of radio attachable with the main radio circuit of the biomedical device to trigger off its main radio when it is not transmitting data to circumvent unnecessary power wastage, such as idle listening. A wake-up radio can be used to monitor the environment as well as sense any incoming control signals from the AP and generate an interrupt signal to switch on/off the main radio [37] and [38].

There are two types of wake-up radios, namely active and passive wake-up radios. The active wake-up radio consumes more energy compared to the passive wake-up radio. The passive wake-up radio can harvest energy from the incoming wake-up signals and does not use the energy of the biomedical sensors [3] and [39]. A passive wake-up radio only consumes about 50 μW energy [3] and [40] which makes it reasonable for a WBAN system.

In our proposed system, we equipped the biomedical devices with a passive wake-up radio to improve the efficiency of the biomedical devices and we assume the power of the wake-up radio to be negligible since it relies on power harvesting. Note, at the beginning of a cycle we assume that all the biomedical devices are in the sleep state and when the AP sends the request to receive (RTR) beacon, the wake-up radio immediately generate an interrupt signal to switch on the main radio of the biomedical devices, then the devices that have health data packet to transmit contend for transmission slots, while others with no health data packets goes into the sleep state.

B. Transmission Phase of the Biomedical Sensors

In this phase, we discuss the operations of the hybrid CSMA/CA+TDMA scheme as follows.

1) CSMA/CA Period: At the beginning of the CSMA/CA period which can also be called the contention period, RTR beacon is sent by the AP to all the biomedical sensor devices in the network informing them of its availability to receive health data. Thereafter, only the biomedical devices that have health data to transmit will contend for transmission opportunities based on their own CW length. Other biomedical devices that have no packets to transmit goes into the sleep state to save energy.

The contending biomedical devices will send a request to transmit (REQ-T) message randomly to the AP. If more than one device sends the REQ-T messages simultaneously to the AP without a GTI, there is a likelihood of collision occurrence. However, if only one device sends the REQ-T message to the AP at a given time, contention is successful.

Each successful contended device's health data contains its own information, such as the device ID number. This unique number is useful during communication with the AP. To conserve energy, the AP broadcast an overall acknowledgment (O_{ACK}) message to all the biomedical devices at the end of the contention period or CSMA/CA period informing them about the reception of their health data packets rather than sending the message each time it received their data packets. In addition, the O_{ACK} message contains the biomedical sensor devices order of transmission such that each device is given a specific time slot by the AP for its health data transmission during the TDMA phase. Furthermore, the O_{ACK} sent by the AP helps to reduce the delay often experienced at the biomedical sensor's side, such as the transmission congestions and waiting time, resulting to a shorter delay compared to the conventional ACK used in most literature.

2) TDMA Period: As said earlier, we introduce a WO state in this phase. The WO state is regarded as a kind of idle state in which only the synchronous clock of a biomedical sensor device in this state is enabled while all other operations are disabled to save energy. A device is activated from the WO state to any other active states only through active beacons with the device ID. A biomedical sensor device switches to an active state promptly immediately it receives an active message from the AP or when it wants to transmit health data packets to the AP.

During health data packet transmission, the biomedical sensor devices are modelled using a transmission queue and they transmit their health data after a successful contention. The AP knows all the biomedical sensor devices in the network within its coverage zone, just like a Wi-Fi router having knowledge of all the biomedical devices connected to it, and therefore serves as a global controller.

Consequently, each biomedical sensor device sends an end beacon to the AP at the end of its health data packet transmission and the AP sends them an ACK-order message upon a successfully received health data packet, while no ACK-order message will be sent in the case of a failed health data packet transmission.

In the case of a failed health data packet transmission, a biomedical sensor device will transmit a retransmission beacon to prepare the AP for the retransmission process and the AP sends an ACK-order message after receiving an end beacon from a device. Once the transmitting biomedical sensor device receives an ACK-order message, the next device in the transmission queue starts its data packet transmission and the process continues until the end of operations of the CSMA+TDMA scheme when all the biomedical devices having health data packets to transmit have successfully send their health data packets to the AP.

C. Reception Phase of the Biomedical Sensor Devices

In this phase, the AP is the one transmitting command messages/signals to the devices. The phase can be described as the TP of the AP and the receiving phase of the devices. The TDMA scheme with WO slots is employed for transmissions in this phase. The AP starts its operation in this phase by broadcasting a wake to receive (WTR) beacon to all the biomedical devices to ensure they are in the active state as well as to prepare them for data reception.

To save energy in this phase, only the first biomedical device in the WO slots will be active to receive the WTR beacon and is set ready to receive data from the AP, while others remain in the WO state. Note, each device ID is included in the WRT. Following the reception of this signal, the biomedical device transmits an ACK message to the AP and thereafter enters the sleep state to conserve energy.

An interval guard time is introduced to prevent overlapping of any two adjacent transmission slots, i.e., overlapping between two data transmissions. For the next biomedical device in the WO slot to receive data from and/or communicate with the AP, the AP will first have to send a switching WO (SWO) beacon containing the device's ID and an active beacon to the biomedical device. Thereafter, the device will switch from the WO state to the receiving state.

In the case of a failed data reception, the biomedical device enters the WO state and no ACK message will be sent to the AP and thus, the AP knows that the transmission has failed. Afterward, the AP sends the SWO to the next biomedical device in the WO slot before transmitting another data. After the completion of all data transmissions, the AP then starts the retransmission process. The retransmission process is done at the end of all transmissions to reduce the WO time and to also minimize the overall wake-up time to save energy.

For further insights into the operation of the proposed multigroup hybrid MAC protocol, Algorithm 4 details the process of the protocol.

Algorithm 4 Operation of the Proposed MG-HYMAC

```
1:  Initialize biomedical devices that have data to send in groups P and Q
2:  Ensure an optimal CW length: $CW_{min} \leq CW \leq CW_{max}$
3:  for the beginning of a cycle do
4:      apply a CSMA/CA protocol
5:      assign a WO to successfully contended devices
6:  end for
7:  Go to TP
8:  for successfully contended biomedical devices in $A$ and $B$ do
9:      allocate a TDMA slot based on the WO/transmission queue
10:     transmit health data packets to the AP
11:     for each successfully received health data packets do
12:         send an ACK-order message to the device
13:     end for
14:     for each failed transmission do
15:         set a back-off time
16:         let the device stay in the WO state
17:     end for
18: end for
19: if this is the end of the TP then
20:     enable retransmission process
21: repeat step 7 to 15 for all failed transmissions
22:     until an ACK-order message is received
22: end if
23: end
```

TABLE II
SIMULATION PARAMETER VALUES [32]

Parameter	Value
AP radius	500m [3]
Number of biomedical sensors	(3-15)
Battery power	1200 J
Transmission rate ($\Re$)	5 Mbps
ACK packet size	64 bits
Guard time interval	0.00003 sec
Beacon size	64 bits
Minimum CW	32
Maximum CW	256
Maximum power consumed in $S_0^{P,Q}$ ($\varrho_0^{P,Q}$)	0.5 mW
Maximum power consumed in $S_1^{P,Q}$($\varrho_1^{P,Q}$)	10.5 mW
Maximum power consumed in $S_2^{P,Q}$($\varrho_2^{P,Q}$)	28 mW
Maximum power consumed in $S_3^{P,Q}$ ($\varrho_3^{P,Q}$)	30 mW
Maximum power consumed in $S_4^{P,Q}$($\varrho_4^{P,Q}$)	50 mW
$\varepsilon_{01}^{P,Q}$	0.02 mJ
$\varepsilon_{13}^{P,Q}$	0.03 mJ
Noise	-100dBm

VII. SIMULATION RESULTS

We present and discuss the simulation results of the proposed MG-HYMAC protocol in this section.

A. Simulation Configuration

The proposed system follows a typical WBAN system with several biomedical devices implanted or deployed around a patient's body. In the simulation experiments, we considered different number of biomedical devices in a star topology to connect them directly to an AP. The proposed MG-HYMAC protocol was simulated in MATLAB and compared with the HyMAC and the CPMAC protocols.

The same simulation configuration values employed in the baseline HyMAC protocol (i.e., [32]) as shown in Table II are also assumed in this work to configure and evaluate the performance of proposed MG-HYMAC protocol.

We considered different number of devices such as 3, 5, 7, 9 in proposed MG-HYMAC protocol. Fig. 4 shows the star topology and the location of the biomedical sensor devices deployed in a random manner in the coverage area of an AP with a radius of 500 m using a coordinate system.

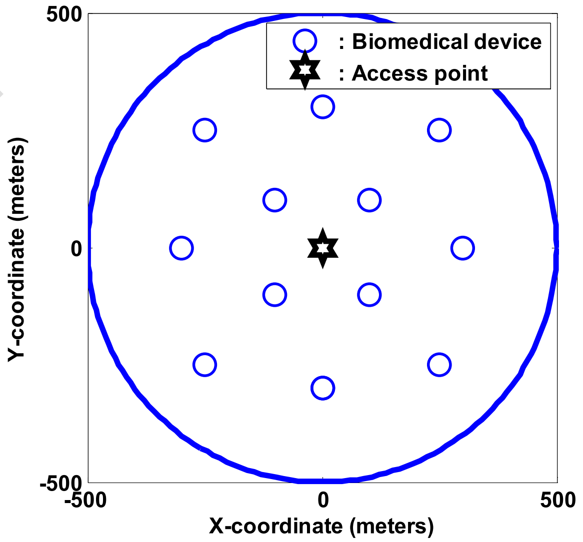


Fig. 4. Proposed network topology of biomedical devices and an access point.

Furthermore, the proposed system comprises of a multi-group, including groups P and Q. We assume that group P contains A biomedical sensors with h_A critical health data packets while, group Q contains B biomedical sensors with h_B less-critical health data packets.

For evaluation and validation, we compare the proposed MG-HYMAC protocol with the existing HyMAC and CPMAC protocols and standard metrics like the convergence speed, energy efficiency, and the lifetime of the devices are applied.

B. Convergence Comparison

In this section, the performance of the proposed MG-HYMAC protocol and the existing protocols are investigated based on convergence speed. The convergence performance evaluation of the three protocols were carried out by investigating the energy consumption of the three protocols versus the number of iterations. To achieve this, we configure the proposed MG-HYMAC protocol with $K = 9$ devices, and we set $A = 5$ devices and $B = 4$ devices for groups P and Q respectively, while the existing protocols were configured with 9 devices in parallel. In addition, we consider different number of iterations, and based on the configurations we performed some simulation experiments and the results generated are presented in Fig. 5. From Fig. 5, we observed that the proposed MG-HYMAC algorithm outperformed the existing algorithms as it converges after about 60 iterations unlike the HyMAC and the CPMAC algorithms that converged

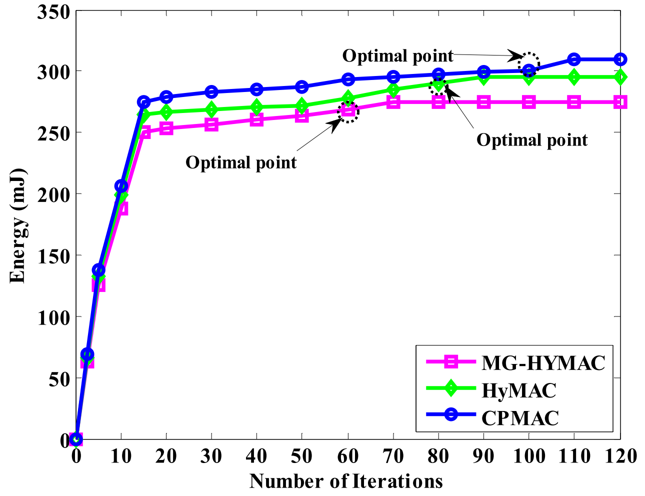


Fig. 5. Convergence of the MG-HYMAC, HyMAC, and CPMAC algorithms.

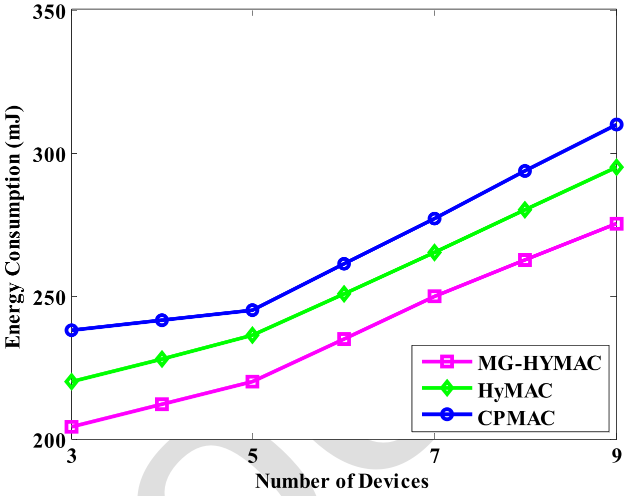


Fig. 6. Energy consumption versus number of devices.

after about 80 and 100 iterations, respectively. Therefore, it is evident that the MG-HYMAC algorithm has a better convergence speed compared to the existing protocols and has performance improvements of about 12% over the HyMAC and 3% over the CPMAC and this emphasize the efficiency of the proposed protocol in terms of fast convergence.

C. Investigation of Energy Efficiency Performance Based on the Number of Devices

In this section, we carried out some simulation investigations on the proposed MG-HYMAC protocol and the existing protocols, i.e., HyMAC and CPMAC to study their performance in terms of energy efficiency. For this reason, we studied and compared the energy consumption of the devices in a complete transmission cycle, including both the TP and the RP. For this to be achieved, we configure the proposed MG-HYMAC and the existing protocols with different number of biomedical devices, including $K = 3$, 5, 7, and 9 devices. For the proposed MG-HYMAC protocol, when $S = 9$ devices, A was set to 5 devices for group P and B was set to 4 devices for group Q and we assume that not all the devices in group Q have data packets to send. In addition, the transmission probability for the three protocols were set to $c = 0.8$ and $d = 0.8$. Based on these configurations, we enabled the proposed algorithms for the MG-HYMAC protocol and disabled them for the HyMAC and CPMAC protocols and simulated the three protocols. The obtained simulation results are presented for the three protocols in Fig. 6. From Fig. 6, it was noticed that the more we increase the number of devices in the network from 3, 5, 7 to 9 devices, the more the energy consumption. But then, the proposed MG-HYMAC protocol was able to achieve a reasonable reduction in the amount of energy consumed by the biomedical devices compared to the HyMAC and the CPMAC protocols. For instance, when the number of devices in the network was set to 3, about 204 mJ energy was consumed using the proposed MG-HYMAC protocol, while using the HyMAC and the CPMAC protocols about 220 mJ and 238 mJ energy were consumed, respectively. This is an indication that the proposed MG-HYMAC protocol is more energy efficient by achieving an energy reduction of about 7% when compared to the HyMAC protocol and about 14% energy reduction when compared to the CPMAC protocol. The performance improvement of the MG-HYMAC protocol over the HyMAC and CPMAC protocol was due to the introduced transmission scheduling policy used to duty cycle the operations of the biomedical devices with less critical data packets. It helped to reduce energy wastage due to collisions and idle listening and consequently assisted in saving energy and prolonging the battery lifetime of the biomedical sensor devices as well as improving the overall network lifetime. Also, the introduced sleep-wake-up scheduling mechanism helped to address energy wastage due to overhearing by only switching on the biomedical devices for data transmission and reception and goes into sleep mode afterward.

D. Investigation of Energy Efficiency Performance Based on Transmission Probability

This section presents the simulation investigations of the MG-HYMAC protocol and the baseline protocols on energy consumption against the transmission probability of the devices. To achieve this, we configure the MG-HYMAC and the baseline protocols with $K = 7$ devices. For the MG-HYMAC protocol, when $K = 7$ devices, A was set to 4 devices for group P and B was set to 3 devices for group Q, but we assume that not all the devices in group Q have data packets to send. The outcomes of the simulations are presented in Fig. 7. From Fig. 7, it can be inferred that the higher the transmission probability the more the energy consumed. However, the proposed MG-HYMAC protocol outperforms the existing protocols as it achieves a significant reduction in the amount of energy consumed by the devices. For example, when the transmission probability of the devices was set to 0.1 and 0.2, about 190 mJ and 205 mJ energy were consumed respectively using the proposed MG-HYMAC protocol, when the HyMAC protocol was applied, about 205 mJ and 220 mJ energy were consumed respectively, while about 206 mJ and 222 mJ energy were consumed respectively using the CPMAC protocol. Also, we noticed that at the transmission probability

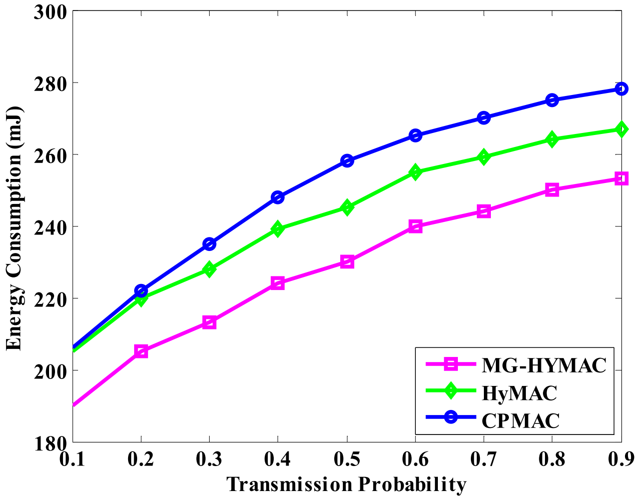


Fig. 7. Energy consumption versus transmission probability.

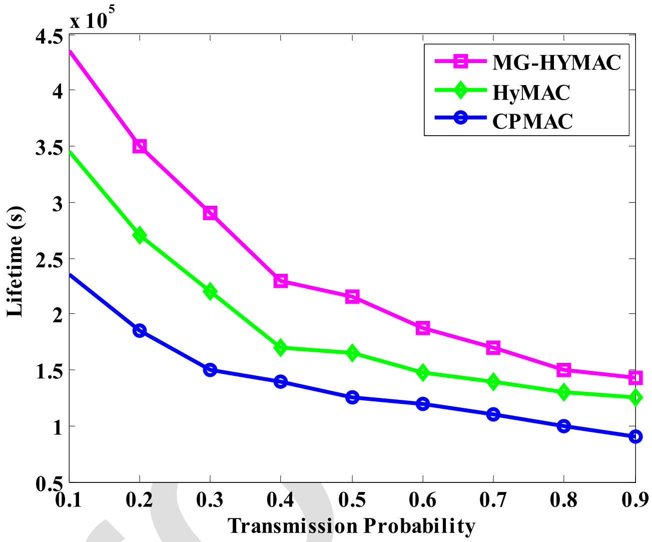


Fig. 8. Devices lifetime versus transmission probability.

of 0.1 and 0.2, the existing protocols have almost the same amount of energy consumption. Following this, we could infer that the proposed protocol is advantageous in terms of saving energy as it is able to achieve an energy reduction of about 7% compared to the HyMAC protocol and about 8% compared to the CPMAC protocol. These energy efficiency performance improvements are attributed to the proposed algorithms which were able to minimize energy wastage issues, such as collision, idle listening, and overhearing during data communication. Furthermore, the obtained improvements by the proposed MG-HYMAC protocol could be attributed to its efficiency in harnessing the advantages of both the CSMA/CA protocol and the TDMA protocol to efficiently make use of each time slot to reduce collisions during data communications for small scale network. In addition, energy wastage is reduced, and energy efficiency is improved by assigning most transmission overhead to the AP side since it can be charged easily.

E. Comparison of Devices Lifetime Based on Transmission Probability

In this section, we studied the lifetime performance of the biomedical devices against the transmission probability. Simulation investigations were performed on the proposed MG-HYMAC and the existing protocols (i.e., HyMAC [32] and CPMAC [31]) using different values of transmission probability to study its impact on the lifetime of the biomedical sensor devices. We set $K = 7$ devices and the battery power to be 1200 J for the three protocols. While we configure the proposed protocol with $A = 4$ devices for group P and $B = 3$ devices for group Q. Based on these configurations, the three protocols were simulated, and the obtained results are presented in Fig. 8. According to Fig. 8, we noticed that high transmission probability resulted into a decrease in the lifetime of the devices for the three protocols. But then, the proposed protocol improved the lifetime performance of the biomedical devices. For example, when the transmission probability was set to 0.4, our proposed protocol was able to achieve a prolonged lifetime of about 230,000 seconds, when the HyMAC protocol was applied, a lifetime of about 170,000 seconds was achieved, also, when the CPMAC protocol was applied, a lifetime of about 140,000 was achieved. This implies that significant improvements of about 35% and 64% were achieved by the MG-HYMAC over the HyMAC and the CPMAC protocols, respectively. The achieved improvements are attributable to the developed stochastic probability model and the heuristic-based power control scheme that were employed to solve time allocation and power control problems to enhance energy efficiency and prolong the lifetime of the devices. In addition, the introduced transmission scheduling technique for duty cycling the operations of the biomedical sensor devices with less critical data packets helped to reduce collisions in order to save energy and prolong the battery lifetime of the biomedical sensor devices so as to improve the overall network lifetime.

F. Impact of High Number of Devices on Energy Efficiency

In this section, we perform different experiments on the MG-HYMAC protocol and the existing protocols to investigate the performance of the MG-HYMAC protocol in terms of energy efficiency based on the impact of high number of biomedical sensor devices. To achieve this, we configure the proposed MG-HYMAC and the existing protocols with $K =$ 9, 11, 13, and 15 devices. For the proposed MG-HYMAC protocol, when $K =$ 9, 11, 13, and 15 devices, we set $A =$ 5, 6, 7, and 8 devices, respectively for group P and we set $B =$ 4, 5, 6, and 7 devices, respectively for group Q. Also, the transmission probability for the three protocols was set to $c = 1$ and $d = 1$. Following this, we enabled the proposed algorithms for the MG-HYMAC protocol and disabled them for the HyMAC and CPMAC protocols during the experiments. The obtained results are presented in Fig. 9 and we observed from the figure that the number of devices in the network directly influences the amount of energy consumed. For a large-scale network, the energy consumption of the devices tends to increase more due to the possibility of an increase in the number of collisions. However, the proposed MG-HYMAC

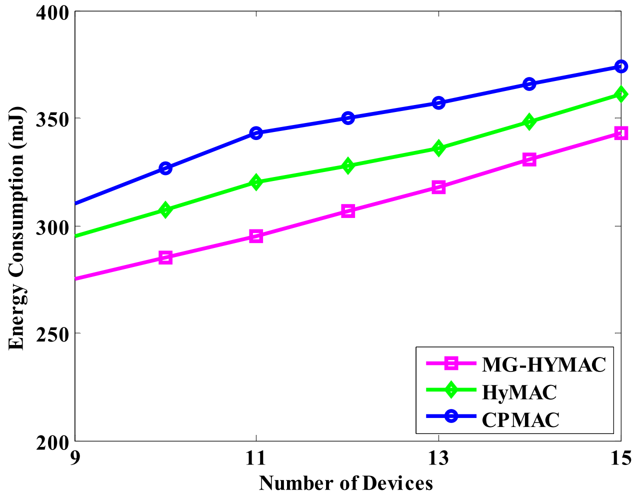


Fig. 9. Energy consumption versus number of devices for $K = 15$ devices.

protocol outperformed the existing protocols based on the proposed algorithms which were able to allocate efficiently specific time slots to the devices to reduce collisions and save energy. For instance, when the number of devices in the network was increased from 9 to 11, about 295 mJ energy was consumed using the proposed MG-HYMAC protocol, when the HyMAC and the CPMAC protocols were used about 320 mJ and 343 mJ amount of energy were consumed, respectively. This indicates that the proposed MG-HYMAC protocol achieved improvements of about 8% over the HyMAC protocol and about 14% over the CPMAC protocol. These improvements emphasize the efficiency of the proposed MG-HYMAC protocol.

G. Impact of Low Transmission Probability on Energy Efficiency

In this section, we investigate the impact of low transmission probability on energy efficiency for the proposed protocol and the existing protocols. During the experiments, we set $K = 9$ devices for the three protocols, and for the MG-HYMAC protocol we set $A = 5$ devices for group P and $B = 4$ devices for group Q. Based on the simulation performed, the obtained results are described in Fig. 10. We tried to compare the results in Fig. 10 involving a low transmission probability to when the transmission probability is high in Fig. 8 and we noticed that the energy consumed by the devices for a low transmission probability is reduced. Also, from Fig. 10, it is noticed that the proposed MG-HYMAC protocol performs better than the existing protocols in the context of energy efficiency. For example, at a transmission probability of 0.05, about 107 mJ energy was consumed when the proposed protocol was applied, while about 119 mJ and 120 mJ energy were consumed when the HyMAC and CPMAC protocols were applied, respectively. This shows that the proposed protocol is energy efficient with improvements of about 10% and 11% over the HyMAC protocol and the CPMAC protocol, respectively. These improvements are contributed by the algorithms we proposed as well as the introduced WO state for saving energy without incurring any transmission delay.

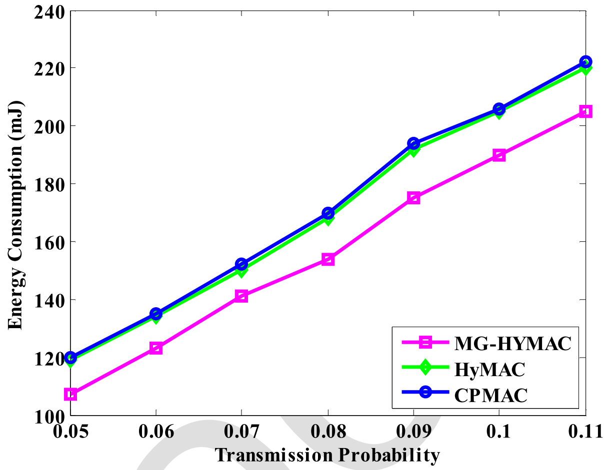


Fig. 10. Energy consumption versus low transmission probability.

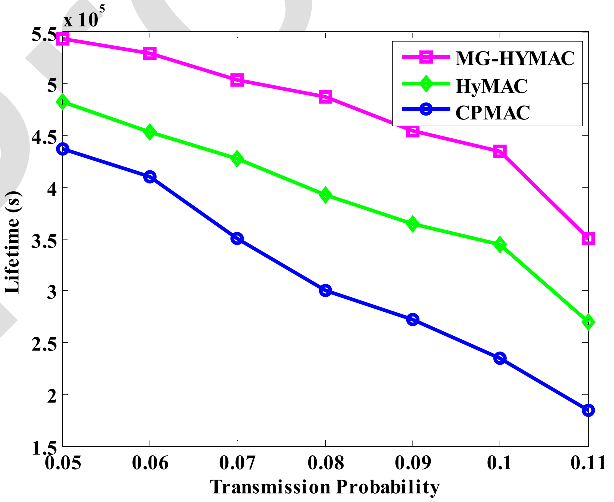


Fig. 11. Device Lifetime versus low transmission probability.

H. Impact of Low Transmission Probability on the Lifetime of the Devices.

The impact of low transmission probability on the lifetime of the proposed protocol and the existing protocols are studied in this section. We consider a configuration of $K = 9$ devices and a battery power of 1200 J for the three protocols. The proposed protocol was configured with $A = 5$ devices for group P and $B = 4$ devices for group Q when $K = 9$. Based on these, the three protocols were simulated, and the obtained results are reported in Fig. 11. Comparing the results in Fig. 11 to the results of when the traffic in the network was high as in Fig. 9, we noticed a rapid increase in the lifetime of the biomedical sensor devices for the three protocols. Note, for low traffic, the energy efficiency of the network is enhanced and this in turn prolongs the lifetime of the biomedical sensor devices. We also observe from Fig. 11 that the proposed protocol outperforms the existing protocols. As an example, when the transmission probability was set to 0.05, the proposed protocol had a lifetime of about 544,000 seconds compared to the HyMAC protocol with a lifetime of about 483,000 seconds and the CPMAC protocol with a lifetime of about 437,000 seconds. This means that the proposed MG-HYMAC is more efficient with performance gains of about 13% and 24% over the HyMAC protocol and CPMAC protocol, respectively. These performance gains are engineered by the stochastic probability model and the heuristic-based power control scheme we employed to solve time allocation and power control problems to enhance energy efficiency and prolong the lifetime of the devices. Also, the introduction of a transmission scheduling technique to duty cycle the operations of the biomedical sensor devices with less critical data packets to determine when and how the biomedical sensor devices will transmit their health data packets to reduce collisions in order to save energy and prolong the battery lifetime of the biomedical sensor devices so as to improve the overall network lifetime.

VIII. CONCLUSION

An energy-aware multi-group hybrid MAC protocol for health data communications has been proposed for a personalized WBAN system in this paper. To achieve an energy efficient data communication, we combined the benefits of the CSMA/CA protocol and the TDMA protocol, set the major transmission overhead to the AP side, and introduced a WO state. Also, we employed a sleep-wake-up scheduling mechanism which helped in saving a significant amount of energy and increasing the devices lifetime. A transmission scheduling technique was introduced to duty cycle the operations of the devices that have less critical data packets to determine when and how the biomedical sensor devices will transmit their health data packets to optimize their power consumption and prolong their battery lifetime in an attempt to improve the overall network lifetime. Furthermore, we developed a stochastic probability model and a power control model to solve time allocation and power control problems to enhance energy efficiency and prolong the lifetime of the devices. We validated the proposed MG-HYMAC protocol based on energy efficiency, lifetime of the biomedical sensor devices, and speed of convergence. Going by the simulation results, the proposed MG-HYMAC protocol proved to be more efficient when compared to the HyMAC and CPMAC protocols using the above-mentioned metrics.

REFERENCES

[1] D. D. Olatinwo, A. Abu-Mahfouz, and G. P. Hancke, "A survey on LPWAN technologies in WBAN for remote health-care monitoring," *Sensors*, vol. 19, pp. 1–26, Nov. 2019.

[2] D. D. Olatinwo, A. Abu-Mahfouz, and G. P. Hancke, "A hybrid multi-class MAC protocol for IoT-enabled WBAN systems," *IEEE Sensors J.*, vol. 21, no. 5, pp. 6761–6774, Nov. 2020.

[3] D. D. Olatinwo, A. M. Abu-Mahfouz, and G. P. Hancke, "Towards achieving efficient MAC protocols for WBAN-enabled IoT technology: A review," *EURASIP J. Wireless Commun. Netw.*, vol. 2021, no. 1, pp. 1–47, Mar. 2021.

[4] S. O. Olatinwo and T.-H. Joubert, "Energy efficient solutions in wireless sensor systems for water quality monitoring: A review," *IEEE Sensors J.*, vol. 19, no. 5, pp. 1596–1625, Mar. 2019.

[5] M. M. Alam, H. Malik, M. I. Khan, T. Pardy, A. Kuusik, and Y. Le Moullec, "A survey on the roles of communication technologies in IoT-based personalized healthcare applications," *IEEE Access*, vol. 6, pp. 36611–36631, 2018.

[6] T. Wu, F. Wu, J.-M. Redouté, and M. R. Yuce, "An autonomous wireless body area network implementation towards IoT connected healthcare applications," *IEEE Access*, vol. 5, pp. 11413–11422, 2017.

[7] S. Chatterjee *et al.*, "Internet of Things and body area networks-an integrated future," in *Proc. IEEE 8th Int. Conf. Ubiquitous Comput. Electron. Mobile Commun. (UEMCON)*, New York, NY, USA, Oct. 2017, pp. 396–400.

[8] M. Cicioğlu and A. Çalhan, "IoT-based wireless body area networks for disaster cases," *Int. J. Commun. Syst.*, vol. 33, pp. 1–12, Nov. 2018.

[9] P. Pace *et al.*, "INTER-health: An interoperable IoT solution for active and assisted living healthcare services," in *Proc. IEEE 5th World Forum Internet Things (WF-IoT)*, Apr. 2019, pp. 81–86.

[10] G. Aloi, G. Fortino, R. Gravina, P. Pace, and C. Savaglio, "Simulation-driven platform for edge-based AAL systems," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 2, pp. 446–462, Feb. 2021.

[11] I. Nasr, L. N. Atallah, S. Cherif, and B. Geller, "Time synchronization in IoT networks case of wireless body area network," in *Proc. IEEE Int. Symp. Signal Image, Video Commun. (ISIVC)*, Tunis, Tunisia, Nov. 2016, pp. 297–301.

[12] M. Ali, H. Moungla, M. Younis, and A. Mehaoua, "IoT-enabled channel selection approach for WBANs," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Valencia, Spain, Jun. 2017, pp. 1784–1790.

[13] S. Olatinwo, J. Emuoyibofarhe, F. Alamu, O. Omitola, and D. Olatinwo, "An ontology-based system for chronic tropical diseases using the Protégé-OWL tool," *Songklanakarin J. Sci. Technol.*, vol. 40, no. 6, pp. 1–15, Nov. 2018.

[14] P. Pace, G. Aloi, R. Gravina, G. Caliciuri, G. Fortino, and A. Liotta, "An edge-based architecture to support efficient applications for healthcare industry 4.0," *IEEE Trans. Ind. Informat.*, vol. 15, no. 1, pp. 481–489, Jan. 2019.

[15] B. Liu, Z. Yan, and C. W. Chen, "MAC protocol in wireless body area networks for E-health: Challenges and a context-aware design," *IEEE Wireless Commun.*, vol. 20, no. 4, pp. 64–72, Aug. 2013.

[16] J. Liu, M. Li, B. Yuan, and W. Liu, "A novel energy efficient MAC protocol for wireless body area network," *China Commun.*, vol. 12, no. 2, pp. 11–20, Feb. 2015.

[17] S. Olatinwo and T.-H. Joubert, "Optimizing the energy and throughput of a water-quality monitoring system," *Sensors*, vol. 18, no. 4, p. 1198, Apr. 2018.

[18] S. O. Olatinwo and T. H. Joubert, "Energy efficiency maximization in a wireless powered IoT sensor network for water quality monitoring," *Comput. Netw.*, vol. 176, no. 1, pp. 1–10, Jul. 2020.

[19] A. Rajandekar and B. Sikdar, "A survey of MAC layer issues and protocols for machine-to-machine communications," *IEEE Internet Things J.*, vol. 2, no. 2, pp. 175–186, Apr. 2015.

[20] S. Bhandari and S. Moh, "A priority-based adaptive MAC protocol for wireless body area networks," *Sensors*, vol. 16, no. 3, p. 401, Mar. 2016.

[21] T. T. T. Le and S. Moh, "Hybrid multi-channel MAC protocol for WBANS with inter-WBAN interference mitigation," *Sensors*, vol. 18, no. 5, p. 1373, Apr. 2018.

[22] E. Ibara, A. Antonopoulos, E. Kartsakli, and C. Verikoukis, "Energy harvesting aware hybrid MAC protocol for WBANs," in *Proc. IEEE 15th Int. Conf. E-Health Netw. Appl. Services*, Lisbon, Portugal, Oct. 2013, pp. 120–124.

[23] L. Ruan, M. P. I. Dias, and E. Wong, "Towards low-delay body area networks: An investigation on the hybrid MAC of SmartBAN and IEEE 802.15.6 wireless body area network," in *Proc. IEEE 20th Int. Conf. High Perform. Switching Routing (HPSR)*, May 2019, pp. 1–6.

[24] L. Ruan, M. P. I. Dias, and E. Wong, "Towards ubiquitous E-health: Modeling of SmartBAN hybrid MAC under periodic and emergency traffic," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2017, pp. 1–6.

[25] R. Jaramillo, A. Quintero, and S. Chamberland, "Energy-efficient MAC protocol for wireless body area networks," in *Proc. Int. Conf. Workshop Comput. Commun. (IEMCON)*, Oct. 2015, pp. 1–5.

[26] S. J. Marinkovic, E. M. Popovici, C. Spagnol, S. Faul, and W. P. Marnane, "Energy-efficient low duty cycle MAC protocol for wireless body area networks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 13, no. 6, pp. 915–925, Nov. 2009.

[27] S. Ullah, "RFID-enabled MAC protocol for WBAN," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2013, pp. 6030–6034.

[28] S. Ullah and K. S. Kwak, "An ultra low-power and traffic-adaptive medium access control protocol for wireless body area network," *J. Med. Syst.*, vol. 36, no. 3, pp. 1021–1030, Jun. 2012.

[29] J. Liu, M. Li, B. Yuan, and W. Liu, "A novel energy efficient MAC protocol for wireless body area network," *China Commun.*, vol. 12, no. 2, pp. 11–20, Feb. 2015.

[30] C.-H. Lin, K. C.-J. Lin, and W.-T. Chen, "Channel-aware polling-based MAC protocol for body area networks: Design and analysis," *IEEE Sensors J.*, vol. 17, no. 9, pp. 2936–2948, May 2017.

[31] X. Yang, L. Wang, and Z. Zhang, "Wireless body area networks MAC protocol for energy efficiency and extending lifetime," *IEEE Sensors Lett.*, vol. 2, no. 1, Mar. 2018, Art. no. 7500404.

[32] M. B. Rasheed, N. Javaid, M. Imran, Z. A. 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, pp. 1–16, Feb. 2016.

[33] K. Sigman, "IEOR 6711: Continuous-time Markov chains," Tech. Rep., 2009.

[34] S. O. Olatinwo and T. H. Joubert, "Efficient energy resource utilization in a wireless sensor system for monitoring water quality," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, pp. 1–22, Dec. 2019.

[35] J. C. Kwan and A. O. Fapojuwo, "Sum-throughput maximization in wireless sensor networks with radio frequency energy harvesting and backscatter communication," *IEEE Sensors J.*, vol. 18, no. 17, pp. 7325–7339, Sep. 2018.

[36] C. C. Enz, A. El-Hoiydi, J.-D. Decotignie, and V. Peiris, "WiseNET: An ultralow-power wireless sensor network solution," *Computer*, vol. 37, no. 8, pp. 62–70, Aug. 2004.

[37] P. Le-Huy and S. Roy, "Low-power 2.4 GHz wake-up radio for wireless sensor networks," in *Proc. IEEE Int. Conf. Wireless Mobile Comput., Netw. Commun.*, Avigon, France, Oct. 2008, pp. 13–18.

[38] R. Piyare, A. L. Murphy, C. Kiraly, P. Tosato, and D. Brunelli, "Ultra low power wake-up radios: A hardware and networking survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2117–2157, 4th Quart., 2017.

[39] H. Ba, I. Demirkol, and W. Heinzelman, "Feasibility and benefits of passive RFID wake-up radios for wireless sensor networks," in *Proc. IEEE Int. Conf. Global Telecommun.*, Dec. 2010, pp. 1–5.

Damilola D. Olatinwo is a Researcher and an Academic who has research expertise in the mathematical modeling of problems in research areas, like the Internet of Things, wireless body area networks, healthcare monitoring, machine-to-machine communications, and low power and long-range communication systems. Her research expertise also includes the design of resource management strategies, design and development of efficient communication protocols, application of artificial intelligence techniques, application of optimization theory, and development of stochastic probability models.

Adnan M. Abu-Mahfouz (Senior Member, IEEE) received the M.Eng. and Ph.D. degrees in computer engineering from the University of Pretoria. He is currently the Centre Manager of the Emerging Digital Technologies for 4IR (EDT4IR) Research Centre, Council for Scientific and Industrial Research (CSIR), a Professor Extraordinaire at the Tshwane University of Technology, a Visiting Professor at the University of Johannesburg, and an Extraordinary Faculty Member at the University of Pretoria. He is the founder of the smart networks collaboration initiative that aims to develop efficient and secure networks for the future smart systems, such as smart cities, smart grid, and smart water grid. His research interests are wireless sensor and actuator networks, low power wide area networks, software defined wireless sensor networks, cognitive radio, network security, network management, and sensor/actuator node development. He is a member of many IEEE technical communities. He has participated in the formulation of many large and multidisciplinary research and development successful proposals (as a principal investigator or a main author/contributor). He is an Associate Editor of IEEE ACCESS, IEEE INTERNET OF THINGS JOURNAL, and IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS.

Gerhard P. Hancke (Senior Member, IEEE) received the B.Eng. and M.Eng. degrees in computer engineering from the University of Pretoria, South Africa, in 2002 and 2003, respectively, and the Ph.D. degree in computer science for the security group from the Computer Laboratory, University of Cambridge, in 2008. He was with the Smart Card Centre and Information Security Group, Royal Holloway, University of London. He is currently an Assistant Professor with the Department of Computer Science, City University of Hong Kong.