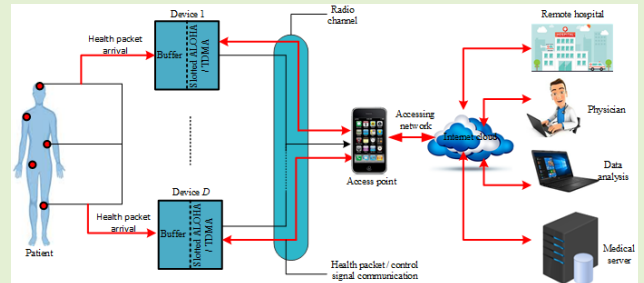


# A Hybrid Multi-Class MAC Protocol for IoT-Enabled WBAN Systems

Damilola D. Olatinwo, Adnan M. Abu-Mahfouz<sup>IP</sup>, *Senior Member, IEEE*,  
and Gerhard P. Hancke, *Senior Member, IEEE*

**Abstract**—This study proposes a hybrid MAC protocol that can efficiently and effectively optimize the communication channel access of a WBAN multi-class system. The proposed protocol consists of two major processes that include the contention phase (CP) and the transmission phase (TP). In the CP, only the biomedical devices that have health packets to transmit randomly contend with equal probabilities using a slotted ALOHA scheme for transmission opportunities and the successful biomedical devices are allocated a transmission time-slot by employing a reservation-based time division multiple access (TDMA) scheme in the transmission phase. A multi-objective optimization problem was formulated to maximize the system sum-throughput, packet success-access-ratio, as well as the reservation ratio, and solved by the controller (i.e., access point) to determine the optimal length of the CP and the number of biomedical devices that can transmit in the TP. Monte Carlo simulation was performed and the optimization solution improved the proposed protocol's performances. For validation purposes, the simulated results in MATLAB revealed that the proposed protocol performs better than the contemporary system in the context of the system sum-throughput, reservation ratio, and the average health packet delay with performance gains of about 9.2%, 9.5%, and 9.6% respectively.

**Index Terms**—WBAN, MAC protocols, M2M, PSO, slotted ALOHA, TDMA, Internet of Things, multi-objective optimization.



## I. INTRODUCTION

OWING to the recent advancement in the modern health-care sphere, different technologies, including the machine-to-machine (M2M) networks, internet of things (IoT) technology, and wireless body area networks (WBANs), can be used in health-care monitoring (HCM) for seamless healthcare services [1], [2].

Manuscript received October 19, 2020; accepted November 8, 2020. This work was supported in part by the Council for Scientific and Industrial Research, Pretoria, South Africa, through the Smart Networks collaboration initiative and IoT-Factory Program (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 Dr. Prosanta Gope. (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.2020.3037788

For instance, the M2M concept in HCM involves the usage of suitable sensor devices which are placed on, in, and around patient's body for early detection and prevention of critical health conditions, and to also enable the monitoring of patients vital signs remotely [2], [3]. This means that the sensor devices in an M2M network could be deployed in a body area and connected via a short range communication technology to form a WBAN system [2]. As in WBAN systems, when an M2M network is deployed in HCM, the sensory data are collected by an access point for onward processing and transmission to remote health-care facilities. Some examples of studies that have employed M2M for HCM are [2]–[7].

In the modern health-care domain, the usage of IoT technologies play vital roles in patient's monitoring since it could be applied to different medical spheres like real-time HCM as well as patient health-care and information management. Similarly, the usage of IoT in HCM systems could offer cost-effective services and may also help to reduce patient's hospitalization. In HCM settings, one of the essential technologies of the IoT advancement is the WBAN technology [9], which is used to monitor patient's health condition(s). Therefore, combining the IoT and WBAN technologies together are essential in a HCM system for an improved productivity [8]. This has led to several research studies in

literature integrating WBAN and IoT, technologies, examples include [10]–[13].

As promising as WBAN and/or M2M systems are in HCM, the ability to effectively access the communication channel by the biomedical devices presently pose a great challenge, in terms of collisions, when efficient channel access protocols are not considered, and this may have devastating impacts on the WBAN systems' performance in the context of the system throughput, channel utilization efficiency, and delay [14], [15]. To address this concern, the design of robust and efficient medium access control (MAC) protocols are promising solutions which could help to coordinate and manage how the devices gain access to the communication channel.

Typically, WBAN systems mostly operates on a single MAC protocol channel and the communication between the device-to-device or device-to-coordinator in the case of a WBAN deployment with a large number of devices may result to high traffic load which could cause collisions, leading to degradation of the system's performance. To address this concern, a hybrid multi-class MAC protocol that is frame based is considered in this paper to improve the WBAN system performance.

The proposed multi-class concept is composed of four phases that include the notification phase (NP), contention phase (CP), announcement phase (AP), and the transmission phase (TP). At the beginning of a frame, all the devices in the network, which are subset of the network, receive a notification message from the access point notifying them about the beginning of the CP. In the CP, only the devices that are active, i.e., devices that have health packets (i.e., the packet generated by the biomedical devices used for monitoring patient's health conditions for example, the packets generated by an electrocardiogram (ECG) sensor device, electroencephalogram (EEG) sensor device, and electromyography (EMG) sensor device) to transmit, contends for transmission opportunities with equal probabilities by using a slotted ALOHA scheme and the successfully contended devices will send their health packets by employing a time division multiple access (TDMA) scheme in the TP.

It is important to mention that in a given frame duration, the number of successfully contended devices increases if the CP duration is increased, but then, at the expense of a reduced TP duration, resulting to a decrease in the transmission slot opportunities. So, to obtain an optimal trade-off between the CP and the TP duration, an optimization problem is solved by the access point to maximize the system performances. Similarly, to enhance the system performance gains, the network was grouped into two classes, including classes 1 and 2. Class 1 is assumed to contain critical health packets, which requires a high reliability and a low delay, while class 2 is assumed to contain health packets that are less critical. The principal contributions of this work are highlighted as:

- The design of a multi-class hybrid MAC protocol for a WBAN system is proposed to enhance the system performance gains.
- The formulation of optimization solution models that optimizes the trade-off between the contention phase and the transmission phase to maximize the system

sum-throughput, packet success-access-ratio, and the reservation ratio.

- Based on the optimization problem that was formulated, we propose a particle swarm optimization (PSO) based algorithm that can efficiently determine the optimal value for the contention phase duration for the network so as to improve the system performance.
- Based on the criticality of the WBAN health packets for decision making by the concerned healthcare providers, we investigate how delay could be minimized and the results of the analysis were presented.
- We applied a hybrid MAC protocol, including the slotted ALOHA scheme and the TDMA scheme in the proposed WBAN system for the purpose of contention and reservation of transmission slot opportunities respectively.

To authors' best knowledge, there is no existing work on a hybrid multi-class MAC protocol that include the slotted ALOHA and TDMA schemes for WBAN systems in literature.

This work is structured as follows: Section II presents the related works. Section III explains the system model. Section IV investigates the proposed MAC protocol performance parameters. Section V presents the formulation of the optimization problem. Section VI discusses the proposed optimized hybrid multi-class MAC protocol and optimization algorithm. Section VII presents the simulation results and Section VIII concludes the work.

## II. RELATED WORKS

This section reviews some existing works on MAC protocols that have been proposed in literature to improve the efficiency of the WBAN systems. For example, an adaptive MAC protocol that can adjust the IEEE 802.15.6 superframe structure, prioritize the type of service, and assign a dynamic time-slot based on traffic changes was proposed in [16], to reduce the network delay, improve the energy consumption level, and enhance the adaptability of the network. Also, authors of [17] introduced a priority based adaptive MAC protocol for allocating time-slots according to the priority of the traffic in the network in a dynamic manner so as to improve the throughput of the system, reduce energy consumption, and collision ratio.

While in literature, there are only a few works on hybrid MAC protocol for WBANs and some of them are reviewed in this paper, for example [18]. In [18], authors proposed a hybrid MAC protocol that includes the carrier sense multiple access with collision avoidance (CSMA/CA) and the TDMA schemes. The proposed system was designed to address interference issue in an inter-WBAN application which allows multiple data transmission on different channels resulting to an improved throughput performance and a collision reduction. A context-aware MAC mechanism was introduced in [19] where slotted CSMA/CA and TDMA mechanisms were employed to address fading channel concern. Another example is [20], authors designed an emergency-aware MAC protocol which adopts a dynamic TDMA mechanism and a direct sequence code division multiple access (DS-CDMA) mechanism to address periodic and emergency traffic requirements.

Also, in [21], authors proposed a hybrid energy-harvesting MAC protocol that employs a dynamic scheduling method to provide different nodes priority levels, flexibility, and energy efficiency. To enhance periodic and emergency traffic in WBANs, authors of [22] proposed a SmartBAN hybrid MAC protocol that uses a TDMA protocol and a slotted ALOHA protocol to improve energy consumption and the delay of the system. Similarly, the investigation of a hybrid MAC protocol based on the SmartBAN and the IEEE 802.15.6 standards in the context of energy efficiency and delay were considered in [23]. Furthermore, the authors of [15] designed a hybrid MAC protocol that is based on a CSMA/CA protocol and a TDMA protocol to extend the network's lifespan and enhance the energy utilization performance of the system. In contrast to [15], [18]–[23], we introduced a hybrid multi-class MAC protocol which adopts a slotted ALOHA mechanism and a TDMA mechanism to improve the WBAN systems performance gains, such as the sum-throughput, packet-success-access ratio, reservation ratio, and average delay.

In [24], the authors designed a hybrid MAC protocol where a slotted ALOHA protocol was used as a contention mechanism and a TDMA protocol was used as a transmission mechanism. The lengths of the contention as well as the transmission durations were optimized and estimated to enhance the total system throughput, the packet success-access-ratio, and the reservation ratio. However, this work, i.e., [24], is only applicable to a system with a homogeneous network requirement. Also, the system throughput, packet success-access-ratio, and the reservation ratio could still be improved further than the presented solutions in [24]. To cater for these deficiencies, we consider a practical setting where network devices may have varying properties, such as the consideration of critical health packets and less critical health packets. As a consequence, this work expands on [24] by introducing a multi-class concept to cater for the heterogeneity requirement of the proposed network unlike [24] as well as maximize the total system throughput, packet success-access-ratio, and the reservation ratio. In addition, based on the critical nature of the WBAN health packets, the average packet delay of the proposed protocol was also improved upon. For the purpose of clarity, Table I presents a summary of the related works.

### III. PROPOSED SYSTEM MODEL

Our proposed network model explains the WBAN system model, health packet generation process, and the classification of the health packets. All these are discussed in the following subsections.

#### A. WBAN System Model

The WBAN system consists of a single access point surrounded by a number of biomedical devices, which are used for monitoring patients' health conditions as illustrated in Fig. 1.

Each of the devices gather its health packets and send it to the access point. Let  $D$  denotes the total number of devices in the network. Within this network, there exists two classes of

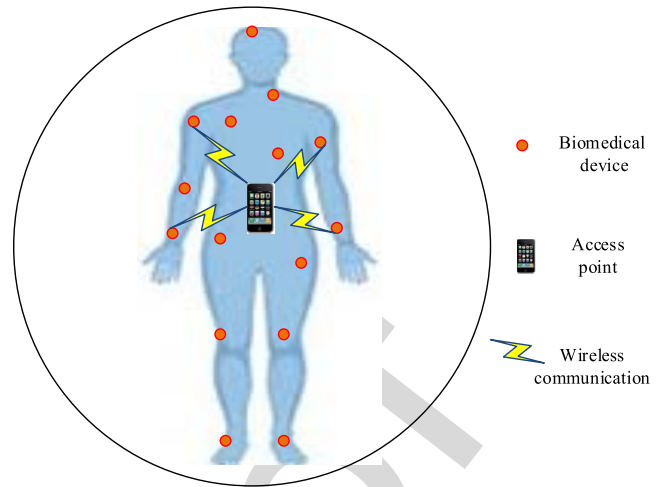


Fig. 1. WBAN system architecture.

devices that are categorized based on their packet priority. It is assumed that the class 1 contain devices that are denoted as  $\{l_1, l_2, \dots, L\}$  and require a higher transmission performance that include higher channel utilization, higher throughput, and a low delay-rate than the class 2 devices which are denoted as  $\{q_1, q_2, \dots, Q\}$ . Additionally, it is assumed that only some of the devices in both class 1 and class 2 are active. Thus, let  $\{m_1, m_2, \dots, M\}$  and  $\{n_1, n_2, \dots, N\}$  represents the active devices for class 1 and class 2 respectively in each frame. This implies that in class 1 we have  $M \leq L$  and in class 2 we have  $N \leq Q$  active devices that have to contend for the transmission slot opportunities in order to transmit their health packets.

#### B. Packet Generation Process

In the proposed protocol, each device that has health packets to transmit has its offered traffic generated based on a Poisson distribution and is stored in a transmitter buffer until the beginning of a frame when there is an opportunity to contend for a transmission. The probability that the Poisson arrival of a device generates  $k$  health packets is expressed in (1) according to [25] and [26] as:

$$P_k(t) = \frac{(\lambda \times t)^k \times e^{-\lambda \times t}}{k!}, \quad k = 0, 1, 2, \dots \quad (1)$$

where  $t$  is the time interval and  $\lambda$  is the arrival rate. For the sake of simplicity, an illustration of the health packet arrival process for each device is shown in Fig. 2. While, Poisson model process is considered in the work because it is an efficient method that could be employed to model the total traffic generated by a large plethora of related and independent users.

#### C. Classification of Health Packet Priority

In this work, we assume that the devices have to assign their health packets with two different priorities, such as the critical health packets and the less critical health packets, such that the critical health packets are classified into class1, while the less

TABLE I  
SUMMARY OF RELATED WORKS

Reference	Contribution of related works	Contribution of the proposed MAC protocol
[16]	An adaptive MAC protocol for adjusting the IEEE 802.15.6 superframe structure that can prioritize service type and allocate time-slot so as to reduce delay and improve energy efficiency	Contrary to [16], we introduced an optimized hybrid MAC protocol to determine the optimal value of the contention and transmission phase in order to improve the system sum-throughput, packet success-access-ratio, reservation ratio, and delay.
[17]	A priority based adaptive MAC protocol was introduced for allocating time-slots to improve the system throughput, reduce energy consumption, and collision ratio.	Unlike [17], an optimized hybrid MAC protocol was introduced to determine the optimal length of the contention and transmission phase so as to improve the system sum-throughput, packet success-access-ratio, reservation ratio, and delay.
[18]	A hybrid MAC protocol that is based on the CSMA/CA and the TDMA protocol was proposed to address interference issue using multiple channels to improve the throughput performance of the system and reduce collision ratio	Different from [18], a multi-class hybrid MAC protocol with a single channel that is based on slotted ALOHA and TDMA mechanisms was introduced. The proposed protocol was optimized to determine the optimal value of the contention and transmission phase to enhance the system sum-throughput, packet success-access-ratio, reservation ratio, and improve delay rate.
[19]	A context-aware MAC mechanism that is based on slotted CSMA/CA and TDMA mechanisms was introduced to tackle channel fading concern.	In contrast to [19], we introduced a multi-channel hybrid MAC protocol that is based on slotted ALOHA and TDMA mechanisms to improve the trade-off between the contention and the transmission phases in order to enhance the system sum-throughput, packet success-access-ratio, reservation ratio, and minimize delay.
[20]	Authors designed an emergency-aware MAC protocol that adopts dynamic TDMA and DS-CDMA mechanisms to handle periodic and emergency traffic requirements.	Different from [20], we designed a hybrid MAC protocol that adopts the slotted ALOHA and TDMA mechanisms and determines the appropriate optimal length of the contention and transmission phase in order to improve the system sum-throughput, packet success-access-ratio, reservation ratio, and delay rate.
[21]	An energy-harvesting MAC protocol that employs a dynamic scheduling method to assign different priority to nodes and improve energy efficiency was proposed.	Contrary to [21], an optimized hybrid MAC protocol was introduced to determine the optimal length of the contention and transmission phase so as to improve the system sum-throughput, packet success-access-ratio, reservation ratio, and delay.
[22]	Authors proposed a SmartBAN hybrid MAC protocol that adopts the slotted ALOHA and TDMA mechanisms to improve energy consumption and delay.	Unlike [22], we proposed a multi-class hybrid MAC protocol that adopts the slotted ALOHA and TDMA mechanisms and optimize the lengths of the contention and transmission phases and also to enhance the system sum-throughput, packet success-access-ratio, reservation ratio, and minimize delay.
[23]	An investigation on hybrid MAC protocol based on SmartBAN and IEEE 802.15.6 standards in the context of energy efficiency and delay was carried out.	In contrast to [23], we proposed an optimized hybrid MAC protocol to determine the optimal value of the contention and transmission phase in order to improve the system sum-throughput, packet success-access-ratio, reservation ratio, and delay.
[24]	Authors designed a hybrid MAC protocol that is based on slotted ALOHA and TDMA mechanisms that is applicable to a system with homogenous network. The lengths of the contention as well as the transmission durations were optimized by employing a genetic-based algorithm, and estimated to enhance the total system throughput, the packet success-access-ratio, and the reservation ratio.	Different from [24], we design a new hybrid MAC protocol that is based on the slotted ALOHA and TDMA mechanisms to cater for a system with a heterogeneous network, where the network devices may have varying properties. Therefore, we introduced a multi-class concept to cater for the heterogeneity requirement of the proposed network. We further introduced a new optimization method which is based on a PSO algorithm for maximizing the sum-throughput, packet-success-access ratio unlike the existing work that employed a genetic algorithm (GA). A PSO based algorithm is adapted for solving the optimization problem in this work because of its benefits over methods like the GA, which is not really efficient for handling optimization problems with constraints. In addition, with the help of the newly introduced PSO algorithm we are able to minimize the average packet delay.

critical health packets are classified into class 2. Consequently, decisions are taken by the devices and the coordinator (i.e., access point) based on these priorities during transmission and allocation of resources. Priorities are modelled in (2) based on [27] as:

$$P_r = \frac{P_{type}}{\lambda \times P_{length}} \quad (2)$$

where priority is denoted as  $P_r$ ,  $P_{length}$  is the length of packet generated in bits, and  $P_{type}$  is the packet type. Note, the critical health packets are assumed to have higher priority as compared to the less critical health packets, and they are required to be transmitted in a timely and reliable manner.

#### IV. PERFORMANCE MODELING OF THE PROPOSED MAC PROTOCOL

In this section, we consider the performance modeling of the proposed MAC protocol. Since we assume that there are  $M$  and  $N$  active devices in the system that will have to contend for transmission slots during the contention phase, then, their transmission period is divided into different slots based on the TDMA reservation protocol. Each transmission period has a time-slot duration denoted as  $T_S$ .

Recall that the health traffic generation for each device is based on a Poisson distribution and has an arrival rate  $\lambda$ . Therefore, the expected value for the traffic generation time

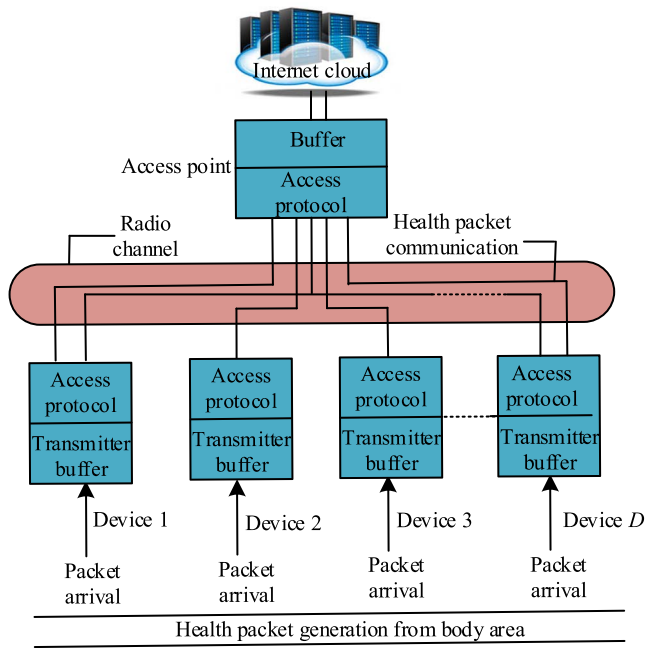


Fig. 2. WBAN packet generation process.

interval ( $T_{interval}$ ) is modelled as (3):

$$T_{interval} = \left( \frac{-T_{R1}}{\log\left(1 - \frac{G}{L}\right)} \right) + \left( \frac{-T_{R2}}{\log\left(1 - \frac{G}{Q}\right)} \right) \quad (3)$$

where  $\lambda = \frac{1}{T_{interval}}$ ,  $T_{interval} = \left(\frac{1}{\lambda}\right)$ , the duration of T-REQ message is denoted as  $T_R$ , while  $L$  and  $Q$  are the number of the devices in class 1 and 2 respectively. Also, the offered traffic is denoted as  $G$ . Thus, the health traffic arrival time for each individual device  $l$  and  $q$  in classes 1 and 2 respectively is expressed in (4) and (5) as:

$$t_l = -T_{interval} \log(1 - (rad(l))), \quad \forall l = 1, 2, \dots, L \quad (4)$$

$$t_q = -T_{interval} \log(1 - (rad(q))), \quad \forall q = 1, 2, \dots, Q \quad (5)$$

where  $rad$  is a random number that follows a uniform distribution.

Additionally, the data traffic (or message) of each device in class 1 and 2, i.e.,  $l$  and  $q$ , are divided into  $k$  random health packets. Therefore, the  $k$  random generated health packets for each class is calculated in (6) and (7) as:

$$k_l = -T_s \log(1 - (rad(l))), \quad \forall l = 1, 2, \dots, L \quad (6)$$

$$k_q = -T_s \log(1 - (rad(q))), \quad \forall q = 1, 2, \dots, Q \quad (7)$$

### A. System Performance Parameters

The performance parameters we put into consideration to measure the performance of our proposed MAC protocol are the system sum-throughput, packet success-access-ratio, reservation ratio, and delay.

1) **System Sum-Throughput:** This performance metric was employed to evaluate the number of health packets that are transmitted successfully over the proposed protocol communication channel. The system sum-throughput was applied to

determine the total data rates that are successfully delivered at a time interval from all the devices that are active to the access point in the proposed network. It can be measured in bps (or bits per second). Since the achievable throughput value at the access point depends on the number of health packets successfully transmitted over the communication channel, we employed an optimization method to develop a throughput efficient MAC protocol that is suitable for a WBAN system. To this end, we formulated an optimization problem for throughput maximization to improve the throughput performance of the proposed WBAN system.

Let  $S_{sum}$  be the system sum-throughput,  $P_s$  be the total health packets that are successful and is calculated as  $k_s P_{length}$ ,  $k_s$  be the number of the successfully transmitted health packets,  $S_r$  be the symbol rate of the biomedical devices, and  $T_t$  be the transmission time. Then, the value of the normalized throughput is modelled in (8) as:

$$S_{sum} = \frac{P_s S_r}{T_t} = \frac{k_s P_{length}}{S_r T_t} \quad (8)$$

2) **Average Health Packet Delay:** The average health packet delay was used to determine the time it will take from when a health packet is being generated until when it is successfully received at the access point during a frame. In this study, we calculate the average health packet delay to investigate the reliability of the proposed MAC protocol. For this to be achieved, we represent  $Avg_{Del}$  to be the average health packet delay,  $T_{Del}$  as the total number of delay for all  $S_k$  health packets that are transmitted successfully over the communication channel and  $T_t$  as the transmission time. Therefore, we model the normalized value of the health packet delay in (9) as:

$$Avg_{Del} = \left( \frac{T_{Del}}{S_k} \right) / T_t \quad (9)$$

Moreover,  $T_{Del}$  is expressed in (10) as:

$$T_{Del} = T_{delay} + L_{CP1} + L_{CP2} + L_{NP} + L_{AP} + L_{TP1} + L_{TP2} \quad (10)$$

In (10),  $T_{delay}$  represents the previous frame delay time,  $L_{CP1}$ ,  $L_{CP2}$ ,  $L_{TP1}$ , and  $L_{TP2}$  are the lengths of the contention phase and transmission phase for both classes 1 and 2 respectively.  $L_{NP}$  and  $L_{AP}$  are the lengths of the notification phase and the announcement phase respectively.

3) **Packet Success-Access-Ratio:** This performance measure was used to evaluate the ratio of the successfully contended requests to that of the total number of the access requests. Note, we assume that all the biomedical devices that are active will contend for transmission opportunities, which determines the total number of the access requests, and only the successfully contended biomedical devices will request for transmission opportunities. To enhance the packet success-access ratio of the proposed MAC protocol, we optimize the ratio of the successfully contended request which is denoted as  $k_{req}$  and the total number of access request which is denoted as  $k_{acc}$ . Therefore, the packet success-access-ratio (i.e.,  $S_{access}$ ) is modelled in (11) as:

$$S_{access} = \frac{k_{req}}{k_{acc}} \quad (11)$$

In addition, the  $S_{access}$  is useful for evaluating how efficient the CP scheme is in terms of robustness, which in turn determines the value of  $S_{access}$ .

4) **Reservation Ratio:** The reservation ratio of the proposed protocol was estimated by finding the ratio of requests that are successfully reserved to that of the total access requests. Technically, it is not all the biomedical devices that access the communication channel will have a reserved transmission slot due to the fact that the access point will only reserve transmission slots for the successfully contended biomedical devices, hence, to increase the number of transmission slots of the proposed MAC protocol, we optimize the ratio of the successfully reserved request which is represented as  $k_{res}$  and the total access requests which is denoted as  $k_{acc}$ . Therefore, the reservation ratio (i.e.,  $S_{reservation}$ ) of the proposed protocol is calculated in (12) as:

$$S_{reservation} = \frac{k_{res}}{k_{acc}} \quad (12)$$

## V. FORMULATION OF OPTIMIZATION PROBLEM

Here, an optimization problem is formulated to obtain an optimal value for either  $L_{CP}$  or  $L_{TP}$ . This is vital to the performance of the system as the increase in the  $L_{CP}$  will technically increase the probability of successful contention of the devices, while causing a reduction to the  $L_{TP}$  subject to the constraint in (13), also, the reservation ratio will decrease, and this could lead to a significant packet delay.

$$L_{CP1} + L_{CP2} + L_{TP1} + L_{TP2} \leq T_{fr} \quad (13)$$

Moreover, the trade-off between the  $L_{CP}$  and the  $L_{TP}$  in each class was solved by formulating an optimization problem aimed at improving the system sum-throughput, the packet success-access-ratio, and the reservation ratio. The optimization problem for the two classes in the network is modelled in (14) as:

$$L_{CP1}^* + L_{CP2}^* = \begin{cases} \arg \max S_{sum} = S_1 + S_2 + \dots + S_\Omega \\ \arg \max S_{access} = S_{acc1} + S_{acc2} + \dots + S_{acc\beta} \\ \arg \max S_{reservation} = S_{res1} + S_{res2} + \dots + S_{res\gamma} \end{cases} \quad (14)$$

s. t. (13),

$$P_{s1} + P_{s2} = (k_{s1} + k_{s2}) P_{length} \quad (15)$$

$$k_{s1} + k_{s2} = \sum_{l=1}^{k_{res1}} k_l + \sum_{q=1}^{k_{res2}} k_q \quad (16)$$

$$T_t = k_{T_t} T_{fr} \quad (17)$$

$$L_{CP1} + L_{CP2} = (V_{s1} + V_{s2}) T_s \quad (18)$$

$$L_{TP1} + L_{TP2} = (V_{r1} + V_{r2}) T_r \quad (19)$$

where  $V_s$ ,  $V_r$ ,  $k_s$ ,  $k$ , and  $k_{res}$  are integers,  $S_1 + S_2 = \frac{P_{s1} + P_{s2}}{S_r T_t}$ ,  $S_{acc1} + S_{acc2} = \frac{k_{req1} + k_{req2}}{k_{acc1} + k_{acc2}}$ ,  $S_{res1} + S_{res2} = \frac{k_{res1} + k_{res2}}{k_{acc1} + k_{acc2}}$ . Also,  $k_{T_t}$  represents the total simulated frames,  $V_s$  is the number of the TDMA slots,  $V_r$  is the total request, and  $k_l$  and  $k_q$  are the health packets for devices  $l$  and  $q$  as expressed in (6) and (7) respectively.

The optimization problem formulated in (14) is referred to as a multi-objective optimization problem. A multi-objective

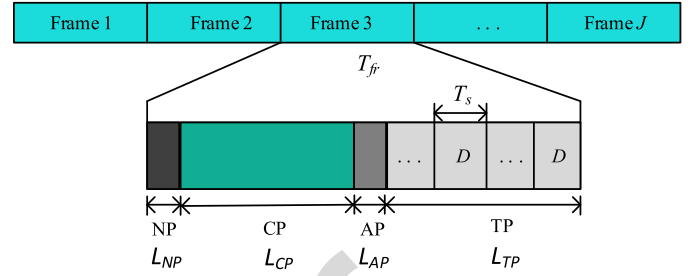


Fig. 3. Proposed MAC protocol time frame structure.

optimization is considered when balancing the trade-off among two or more objectives [28]. To solve the optimization problem, we combine and reformulate the three objective functions in (14) together to form a maximization single-objective optimization problem or fitness function in (20) according to [28] and [29] using a weighting function method. Consequently, a weighting factor is assigned to each objective function in (20) [30]–[32] as:

$$L_{CP1}^* + L_{CP2}^* = \max \left( \begin{matrix} \omega_1 S_{sum} + \omega_2 S_{access} \\ + \omega_3 S_{reservation} \end{matrix} \right) \quad (20)$$

where  $\omega_1$ ,  $\omega_2$ , and  $\omega_3$  are the weighting factors associated with the objective functions in (20), and satisfies a normalization condition of 1.

Based on (20), the optimized value for  $L_{CP1}^* + L_{CP2}^*$  was obtained. While, the  $L_{TP1}^* + L_{TP2}^*$  is determined in (21) as:

$$T_{fr} - L_{CP1}^* + L_{CP2}^* - L_{NP} - L_{AP} \quad (21)$$

## VI. PROPOSED OPTIMIZED HYBRID MULTI-CLASS MAC PROTOCOL AND OPTIMIZATION ALGORITHM

### A. Proposed MAC Scheme Architecture Framework

As said earlier, the considered WBAN system operation is based on a frame by frame approach and each of the frame consists of four major phases that include the NP, CP, AP, as well as the TP. It is noteworthy to mention that each frame has a time frame length of  $T_{fr}$  and could be classified into four length phases, i.e.,  $L_{NP}$ ,  $L_{CP}$ ,  $L_{AP}$ , and  $L_{TP}$  as illustrated in Fig. 3.

For the purpose of simplicity, each of the phase is discussed as follows in the context of operation:

1) **Notification Phase:** In this phase, a notification message is sent by the access point to all the devices notifying them about the beginning of a time frame. Once the message is received by all the devices, then, only the devices which have health packets to transmit will enter the CP in order to contend for transmission slots opportunity, while the rest will go into a sleep mode to save energy.

2) **Contention Phase:** In the contention phase, the devices that are active contend for the reservation of transmission slots based on the slotted ALOHA scheme with equal probabilities. The contending devices will have to send a transmission request (T-REQ) message in a random manner to the access point. If more than a device sends the T-REQ message to the access point concurrently without a time interval, there is a possibility of a collision occurrence. But, if only one

448 device sends the T-REQ message to the access point at a time,  
 449 contention is said to be successful and the access point reserve  
 450 a transmission slot during the transmission phase to transmit its  
 451 health packet. In the case of a collision occurrence, the device  
 452 waits for a period of time before retransmitting the health  
 453 packets. Furthermore, when a T-REQ message is received  
 454 successfully by the access point from a device, the access point  
 455 sends an acknowledgment (ACK) message along with the  
 456 reserved number of time-slots during the AP to the successful  
 457 devices. Thereafter, the device will no longer send a T-REQ  
 458 message once an ACK message is received from the access  
 459 point.

460 **3) AnnouncementPhase:** This is the phase where the access  
 461 point announces the successful contended devices through  
 462 an announcement message. After the announcement message,  
 463 the successful devices switch to the transmission mode and  
 464 are ready to transmit their health packets, while the devices  
 465 that are unsuccessful during the CP goes into a sleep mode.

466 **4) Transmission Phase:** Here, the successfully contended  
 467 devices transmit their health packets using the TDMA mech-  
 468 anism by switching on their transmitter module during their  
 469 own specific assigned time-slots and switch it off during others  
 470 time-slots.

## 471 *B. Proposed Hybrid Multi-Class MAC Protocol* 472 *Optimization Algorithms*

473 The operation of the proposed hybrid multi-class MAC  
 474 protocol is presented in Algorithm 1 to describe process of the  
 475 protocol. In Algorithm 1, the active devices are initialized and  
 476 an optimization model presented in Algorithm 2 is employed  
 477 to obtain optimal values of  $L_{CP1}^* + L_{CP2}^*$ .

478 Note that, in Algorithm 1  $\varphi$  stands for the available TDMA  
 479 slot.

480 It is important to mention that the agenda of (20) is to  
 481 determine the optimal time to be allocated to  $L_{CP1}$  and  $L_{CP2}$ .  
 482 To get the optimal values for  $L_{CP1}^*$  and  $L_{CP2}^*$ , the optimal  
 483 solutions that optimizes  $S_{sum}$ ,  $S_{access}$ , and the  $S_{reservation}$   
 484 are determined. Note, there are several optimization methods  
 485 that could be used to solve (20), examples include the  
 486 nature-inspired optimization methods, such as the PSO  
 487 method, ant colony optimization (ACO) method, GA method,  
 488 and so on. A PSO based algorithm is adapted for solving  
 489 the optimization problem in this work because of its benefits  
 490 over methods like the GA, which is not really efficient for  
 491 handling optimization problems with constraints [33]. Even  
 492 though, methods like a penalty function could be combined  
 493 with a GA method to deal with constraint optimization  
 494 problems, this method is still limited because of the difficulty  
 495 in choosing a suitable penalty parameter value [30].

496 Based on the adopted PSO method in this work, we determine  
 497 the optimal values, i.e.,  $L_{CP1}^*$ ,  $L_{CP2}^*$ ,  $L_{TP1}^*$ , and  $L_{TP2}^*$ ,  
 498 for both the contention as well as the transmission phases for  
 499 each class to be used in the proposed hybrid multi-class MAC  
 500 protocol process.

501 As said earlier, a PSO algorithm is applied to (20)  
 502 and the optimization problem is denoted by  $L_{CP1}^* + L_{CP2}^*$   
 503  $(\psi, \sigma)$ , where  $\psi$  and  $\sigma$  depends on the design variables

---

### Algorithm 1 Proposed Hybrid Multi-Class MAC Protocol

---

```

1: Initialization of active devices
2: Ensure the optimal values of:  $L_{CP1}^*$ ,  $L_{CP2}^*$ ,  $L_{TP1}^*$ ,  $L_{TP2}^*$ 
   using
   Algorithm 2 and (21)
3: for a new time frame do
4:   apply a slotted ALOHA protocol
5: end for
6: if there is an available TDMA slot then
7:   reserve a TDMA slot
8:    $\varphi = \varphi - 1$ 
9: else
10:  set a back-off period
11: end if
12: if this is the end of  $L_{CP1}^* + L_{CP2}^*$  then
13:  apply a TDMA protocol
14: else
15:  go back to step 4
16: end if
17: if this is the end of  $L_{TP1}^* + L_{TP2}^*$  then
18:  go back to step 2
19: else
20:  go back to step 13
21: end if
22: end
    
```

---

( $L_{CP1}$ ,  $L_{TP1}$ ) and ( $L_{CP2}$ ,  $L_{TP2}$ ) for classes 1 and 2 respec- 504  
 tively. Each device  $l$  and  $q$  is denoted by a particle in 505  
 classes 1 and 2 respectively and they serve as possible solu- 506  
 tions to (20). Also, each particle  $l$  position is defined using 507  
 vector  $\psi_l$  and each particle  $q$  position has a vector form 508  
 of  $\sigma_q$ . Hence, the vector form of  $\forall l \in (l_1, l_2, \dots, L)$  and 509  
 $\forall q \in (q_1, q_2, \dots, Q)$  is defined by  $\psi_l = [x_{l1}, x_{l2}, \dots, x_{l\xi}]^T$  510  
 and  $\sigma_q = [x_{q1}, x_{q2}, \dots, x_{qF}]^T$  where  $\xi \in (l_1, l_2, \dots, L)$  and 511  
 $F \in (q_1, q_2, \dots, Q)$ . 512

The modeling of the positions is done using a coordinate 513  
 system (x, y). Note, the position expression for particle  $l$  and 514  
 particle  $q$  are defined using  $(1 \leq l \leq E)$  and  $(1 \leq q \leq H)$  515  
 respectively where variables  $E$  and  $H$  are the maximum values 516  
 of the particles. In the objective function (20), each particle 517  
 $l$  and  $q$  position contain the variables for the contention 518  
 phase and the transmission phase, and the constraint functions 519  
 (13) and (15)-(19).  $\psi_l$  and  $\sigma_q$  include time indexes represented 520  
 as  $\psi_l(t)$  and  $\sigma_q(t)$ . Also, the position of each of the particle  $l$  521  
 and  $q$  include velocities represented as  $v_l(t)$  and  $v_q(t)$  respec- 522  
 tively. The  $v_l(t)$  and  $v_q(t)$  shows how each particle moves in 523  
 the context of distance as well as direction. In every iteration, 524  
 the devices  $l$  and  $q$  fitness value for  $L_{CP1}^* + L_{CP2}^*(\psi_l(t))$  525  
 and  $L_{CP1}^* + L_{CP2}^*(\sigma_q(t))$  are calculated. Moreover, for every 526  
 particle  $l$  and  $q$ , positions and velocities are updated based on 527  
 the proposed hybrid multi-class MAC protocol PSO algorithm 528  
 model as expressed in Algorithm 2. 529

In Algorithm 2, represents the acceleration coefficients are 530  
 defined by  $c_1$  as well as  $c_2$  and are both assigned 2 being 531  
 a standard value, while  $\omega$  denotes the inertial weight and is 532  
 allocated a value of 1, also, being a standard value [34], [35], 533  
 534  
 535

---

**Algorithm 2** Proposed Hybrid Multi-Class MAC Protocol PSO Optimization Algorithm
 

---

Input:  $\omega$ ,  $E$ ,  $R$ ,  $H$ ,  $c_1$ ,  $c_2$ ,  $V_{max}$ Output:  $L_{CP1}^* + L_{CP2}^*$ Solve for class 1 and 2 active devices  $l$  and  $q$   $L_{CP1}^* + L_{CP2}^*$  in a frame

```

1: for  $l = 1$  to  $E$  &&  $q = 1$  to  $H$  do
2:   initialize  $t := 0$ , then start the process
3:   generate new particles  $\psi_l(t)$  &&  $\sigma_q(t)$  with velocities
      $v_l(t)$ 
     &&  $v_q(t)$  randomly,  $\ni v_l(t)$  &&  $v_q(t)$  has a lower and
     upper
     bounds of  $V_{max}$  &&  $-V_{max}$  respectively
4:   compute the fitness values for particles  $l$  and  $q$ ,  $L_{CP1}^* + L_{CP2}^*$ 
     ( $\psi_l(t)$ ,  $\sigma_q(t)$ ), based on the fitness function in (20), and
     (13), (15) -
     (19) and set the best solutions for the particles  $l$  and  $q$ 
     as  $\bar{\psi}_{lPBest}(t)$  until the  $l$ -th iteration &&  $\bar{\sigma}_{qPBest}(t)$ 
     until the  $q$ -th iteration
5:   select the particles with best fitness values amongst
     particles  $l$ 's
     and  $q$ 's, then, let the best solution denote  $\bar{\psi}_{lGBest}(t)$  until
     the  $l$ -th iteration for particle  $l$  and set  $\bar{\sigma}_{qGBest}(t)$  as the
     best
     solution until the  $q$ -th iteration for particle  $q$ 
6:   repeat
7: end for loop
8: for every particle  $l$  do
9:   let  $t \leftarrow t + 1$ 
10:  compute the velocity of particle  $l$  as:  $v_l(t+1) = \omega v_l(t) +$ 
      $c_1(\bar{\psi}_{lPBest}(t) - \psi_l(t)) + c_2(\bar{\psi}_{lGBest}(t) - \psi_l(t))$ 
11:  update each particle  $l$ 's position by using:
      $\psi_l(t+1) = \psi_l(t) + v_l(t+1)$ 
12: end for loop
13: for every particle  $q$  do
14:  let  $t \leftarrow t + 1$ 
15:  compute the velocity of particle  $q$  as:  $v_q(t+1) =$ 
      $\omega v_q(t) +$ 
      $c_1(\bar{\sigma}_{qPBest}(t) - \sigma_q(t)) + c_2(\bar{\sigma}_{qGBest}(t) - \sigma_q(t))$ 
16:  update each particle  $q$ 's position by using:
      $\sigma_q(t+1) = \sigma_q(t) + v_q(t+1)$ 
17: end for loop
18: for every particle  $l$  do
19:  if  $L_{CP1}^* + L_{CP2}^*(\psi_l(t)) \gg (\bar{\psi}_{lPBest}(t))$  then
20:    update  $\bar{\psi}_{lPBest}(t) = \psi_l(t)$ 
21:  end if
22:  if  $L_{CP1}^* + L_{CP2}^*(\psi_l(t)) \gg (\bar{\psi}_{lGBest}(t))$  then
23:    update  $\bar{\psi}_{lGBest}(t) = \psi_l(t)$ 
24:  end if
25: end for loop
26: repeat until  $t \gg R$ 
27: return  $\bar{\psi}_{lGBest}(t)$ 
28: until convergence

```

---



---

**Algorithm 2 (Continued.)** Proposed Hybrid Multi-Class MAC Protocol PSO Optimization Algorithm
 

---

29: **for** every particle  $q$  **do**30: **if**  $L_{CP1}^* + L_{CP2}^*(\sigma_q(t)) \gg (\bar{\sigma}_{qPBest}(t))$  **then**31: update  $\bar{\sigma}_{qPBest}(t) = \sigma_q(t)$ 32: **end if**33: **if**  $L_{CP1}^* + L_{CP2}^*(\sigma_q(t)) \gg (\bar{\sigma}_{qGBest}(t))$  **then**34: update  $\bar{\sigma}_{qGBest}(t) = \sigma_q(t)$ 35: **end if**36: **end for** loop37: repeat until  $t \gg R$ 38: return  $\bar{\sigma}_{qGBest}(t)$ 

39: until convergence

40: return  $L_{CP1}^* + L_{CP2}^*$ 


---

TABLE II  
SIMULATION SETTINGS

Parameter	Value
Access point radius	500 m [24]
Time frame ( $T_{fr}$ )	100 ms [24] [18]
Number of devices	{20, 50, 100} [4], [19], [36]
Symbol rate ( $S_r$ )	256 kbps [4], [24]
Transmission time	0.5 ms [24]
Run times	(0–200 times)
Length of the packet ( $P_{length}$ )	128 bits [4]
Length of the AP ( $L_{AP}$ )	10 $\mu$ s [24]
Length of the NP ( $L_{NP}$ )	10 $\mu$ s [24]
Length of the acknowledgment message	7 $\mu$ s [24]
Duration of T-REQ ( $T_R$ )	25 $\mu$ s [24]

and  $\omega \in [\omega_1, \omega_2, \omega_3] = 1$ . Moreover,  $V_{max}$  was used to define the maximum movement that can be made by each particle during iterations and  $R$  denotes the maximum number of iterations.

## VII. SIMULATION RESULTS

### A. Simulation Configuration

The proposed hybrid multi-class MAC protocol was configured using the settings in Table II. In this work, we assume the same simulation settings used in the baseline protocol, i.e., [24], for the newly proposed protocol, which would serve as a baseline for evaluating the obtained results.

The proposed protocol is composed of a total number of  $D = 1000$  devices. The position of the devices and the access point is modelled using a coordinate system with an access point of 500 m radius at the center as shown in Fig. 4.

Additionally, the proposed protocol includes two classes, i.e., class 1 and class 2, and is assumed that the class 1 contains  $l$  devices with  $k_l$  critical health packets, while class 2 contains  $q$  devices that have  $k_q$  less critical health packets. The traffic generated by the devices in each class of the system follows a Poisson distribution as discussed earlier in Section III. Also, the proposed protocol was compared with a

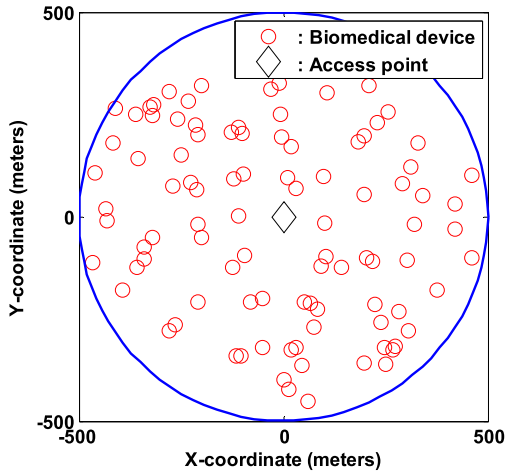


Fig. 4. Network deployment structure.

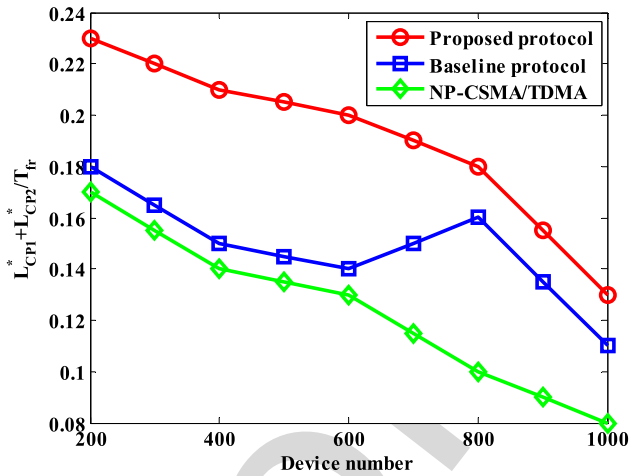


Fig. 5. Optimized  $L_{CP1}^* + L_{CP2}^*/T_{fr}$  ratio against the number of devices.

contemporary optimized hybrid MAC protocol for validation and performance gain evaluation purposes.

### B. Comparison of the Optimization Results

For the purpose of comparison and validation, this section presents the optimization results of the  $L_{CP1}^* + L_{CP2}^*/T_{fr}$  ratio for different configurations of  $D = 200, 400, 600, 800,$  and  $1000$  devices. For  $D = 1000$  devices,  $L$  was set to 750 devices for class 1 and  $Q$  was set to 250 devices for class 2. This help to investigate the optimal value of the  $L_{CP1}^* + L_{CP2}^*/T_{fr}$  ratio to optimize the system performance related to the sum-throughput, packet success-access-ratio, and the reservation ratio. The outcome of the Monte Carlo's simulation experiments for the configurations is presented in Fig. 5. From Fig. 5, it is apparent that the optimal value achieved by the proposed protocol for  $L_{CP1}^* + L_{CP2}^*$  outperforms that of the baseline protocol in [24], for example, for  $D = 200, 400,$  and  $600$  devices we obtain optimized values of 0.23, 0.21, and 0.20 respectively, while the baseline protocol has optimized values of 0.18, 0.15, and 0.14 respectively. This implies that a performance improvement of 36.1% was achieved in the optimized value over the baseline protocol. The improvement could be attributed to the proposed multi-class concept that was introduced and the proposed PSO-based optimization algorithm that efficiently determines the optimal values of the  $L_{CP1}$  and  $L_{CP2}$  which optimizes the system sum-throughput, packet-success-access ratio, and the reservation ratio based on the total number of devices in both class 1 and class 2. We observed that both the proposed and the baseline protocols experienced a slight decrease in the value of the  $L_{CP1}^* + L_{CP2}^*$  achieved for different number of  $D$  devices. The slight decrease experienced by the systems were as a result of the increase in the number of  $D$  devices participating in the  $L_{CP1}$  and  $L_{CP2}$  phase. Furthermore, the proposed protocol was compared with another protocol in [24], such as the non-persistent carrier sense multiple access (NP-CSMA) /TDMA. We noticed that the NP-CSMA-CA/TDMA protocol requires more value of the contention length due to high occurrence of collisions as compared to the proposed protocol. Also, the proposed protocol outperforms

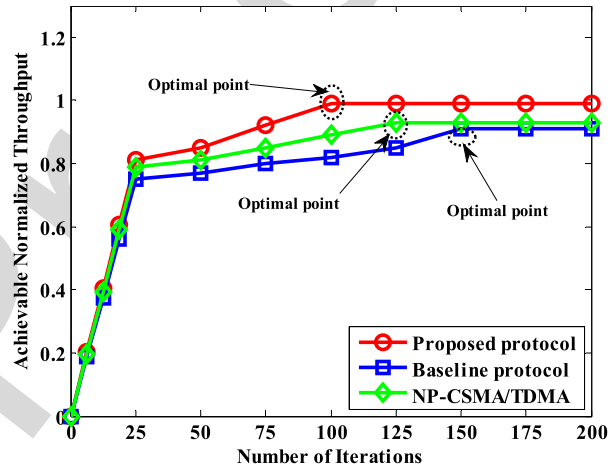


Fig. 6. Achievable system sum-throughput versus number of iterations.

the NP-CSMA/TDMA protocol, for instance, for  $D = 200, 400,$  and  $600,$  the proposed protocol has optimized values of 0.23, 0.21, and 0.20, while the NP-CSMA/TDMA protocol has optimized values of 0.17, 0.14, and 0.13 respectively. This shows that a significant gain of about 45.4% was achieved over the NP-CSMA/TDMA protocol.

### C. Convergence Performance Comparison

This section studied the performance of the proposed protocol in terms of convergence speed. This performance evaluation experiment was carried out by studying the achievable sum-throughput of the proposed protocol against the number of iterations. For this to be achieved, the proposed protocol was configured with  $D = 1000$  devices, involving  $L = 750$  and  $Q = 250$  devices for class 1 and class 2 respectively, while the baseline protocol was also configured with 1000 devices in parallel. Also, different number of iterations were considered. Based on these configurations, simulation experiments were carried out and the results obtained are presented in Fig. 6. From Fig. 6, the proposed algorithm performed better than the existing algorithm as it saturates to an optimal solution at about 100 iterations compared to the existing genetic algorithm-based solution in [24]. Additionally, the proposed

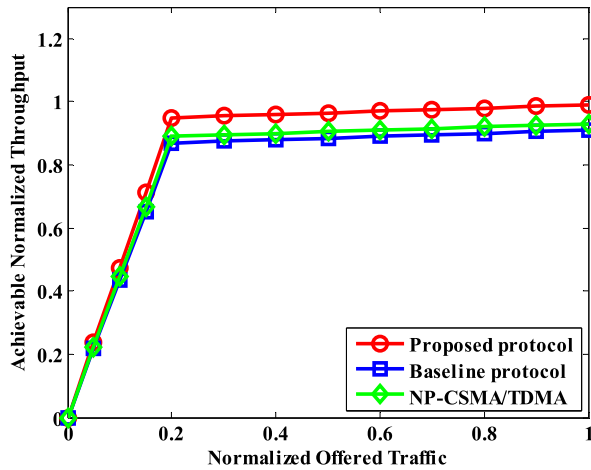


Fig. 7. Achievable throughput versus offered traffic.

617 protocol was also compared with the NP-CSMA/TDMA pro- 618  
 619 tocol in [24]. It was observed that the proposed protocol 620  
 621 performs better than the NP-CSMA/TDMA protocol as it 622  
 623 saturates to an optimal solution at about 100 iterations unlike 624  
 625 the NP-CSMA/TDMA protocol which attain its optimal solu- 626  
 627 tion at about 125 iterations. The proposed algorithm was 628  
 629 able to realize a performance improvement of about 12.1% 630  
 631 and 6.7% when compared with the baseline protocol and the 632  
 633 NP-CSMA/TDMA protocol, respectively in the convergence 634  
 635 iterations and is indicative of efficiency in terms of fast 636  
 637 convergence. 638

#### 628 D. Comparison of the Achievable System 629 Sum-Throughput

630 Simulation investigations were carried out on the proposed 631  
 632 hybrid multi-class MAC protocol and the existing hybrid MAC 633  
 634 protocol for different configuration scenarios to investigate its 635  
 636 impact on the normalized sum-throughput. Fig. 7. presents the 637  
 638 system sum-throughput versus offered traffic for  $D = 1000$  639  
 640 devices with a configuration of  $L = 750$  and  $Q = 250$  devices 641  
 642 for class 1 and class 2 respectively. Also, the baseline protocol 643  
 644 was equally configured with a total number of 1000 devices. 645  
 646 During the experiments, the proposed algorithms were enabled 647  
 648 for the proposed protocol and disabled for the baseline proto- 649  
 650 col. Based on the generated results, it is very clear that as 651  
 652 the offered traffic is increasingly varied, the throughput of 653  
 654 the system also has a slight increase. To further show how 655  
 656 efficient our proposed protocol is compared to the baseline 657  
 658 protocol, the performance of the system was further analyzed, 659  
 660 for instance, when the offered traffic is at 0.2, the proposed 661  
 662 protocol has a normalized throughput of 0.95, while the result 663  
 664 of baseline protocol has a normalized throughput of 0.87. This 665  
 666 indicates that the proposed protocol has an improvement of 667  
 668 about 9.2% in the system throughput rate over the baseline 669  
 670 protocol. This improvement was as a result of the proposed 671  
 672 multi-class concept that was introduced and also the proposed 673  
 674 PSO based algorithm which was able to accommodate more 675  
 676 devices. 677

654 In addition, the proposed protocol was compared with the 655  
 656 NP-CSMA/TDMA protocol in [24], and at 0.2 offered traffic, 657

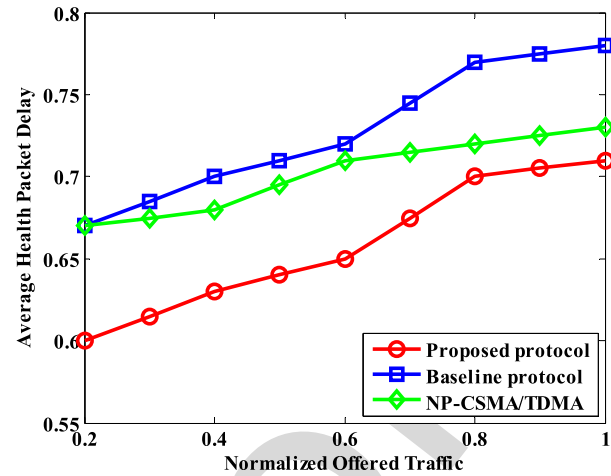


Fig. 8. Average health packet delay versus offered traffic.

656 the NP-CSMA/TDMA protocol has a normalized throughput 657  
 658 of 0.89, while the proposed protocol has a normalized through- 659  
 660 put of 0.95. Therefore, a performance improvement of about 661  
 662 6.7% was achieved. 663

#### 660 E. Average Health Packet Delay 661

662 In this section, we investigate the average health packet 663  
 664 transmission delay against the offered traffic. For this purpose, 665  
 666 we configure the proposed hybrid multi-class MAC protocol 667  
 668 and the baseline protocol with  $D = 200, 400, 600, 800,$  and 669  
 670 1000 devices. For the proposed protocol, when  $D = 1000$  671  
 672 devices,  $L$  was set to 750, while  $Q$  was set to 250 for 673  
 674 class 1 and class 2 respectively. Based on the simulation 675  
 676 results that were generated and presented in Fig. 8, the newly 677  
 678 proposed protocol was able to minimize the average health 679  
 680 packet delay by optimizing the contention duration and the 681  
 682 transmission duration. Also, from Fig. 8, we observe that 683  
 684 the average health packet transmission delay increases as the 685  
 686 offered traffic is increased. However, the proposed protocol 687  
 688 was able to obtain a reduced average health packet delay 689  
 690 compared to the baseline protocol. As an example, at offered 691  
 692 traffic of 0.2, 0.4, 0.6, 0.8, and 1.0, we have average delays 693  
 694 of 0.60, 0.63, 0.65, 0.70, and 0.71 respectively as against 695  
 696 the baseline protocol with average delays of 0.67, 0.70, 0.72, 697  
 698 0.77, and 0.78 respectively. This means that there is an overall 699  
 700 improvement of about 9.6% in the health packet delay time 701  
 702 over the baseline protocol. 703

682 Also, we compared the proposed protocol with the 683  
 684 NP-CSMA/TDMA protocol in [24], and at offered traffic 685  
 686 of 0.2, 0.4, 0.6, 0.8, and 1.0, the proposed protocol has average 687  
 688 delays of 0.60, 0.63, 0.65, 0.70, and 0.71 respectively, while 689  
 690 the NP-CSMA/TDMA protocol has average delays of 0.67, 691  
 692 0.68, 0.71, 0.72, and 0.73 respectively. An overall performance 693  
 694 improvement of about 6.2% was achieved. 695

#### 689 F. Reservation Ratio 690

691 In this section, we consider the comparison of the newly 692  
 693 proposed protocol with the baseline protocol in terms of the 694  
 695 reservation ratio. To achieve this, we consider a configura- 696  
 697 tion of  $D = 1000$  devices and we set  $L$  and  $Q$  to be 698  
 699 699

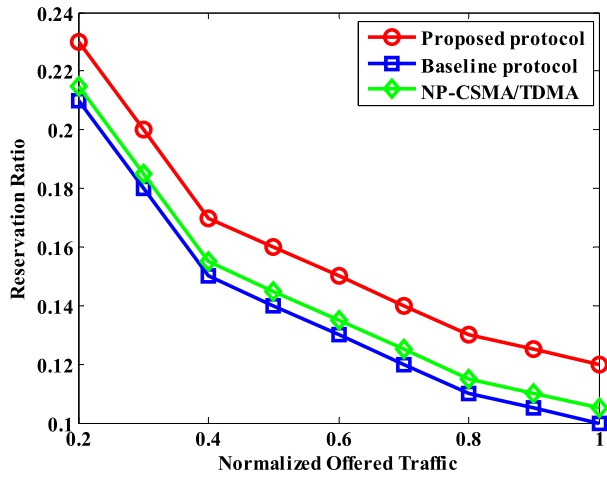


Fig. 9. Reservation ratio versus offered traffic.

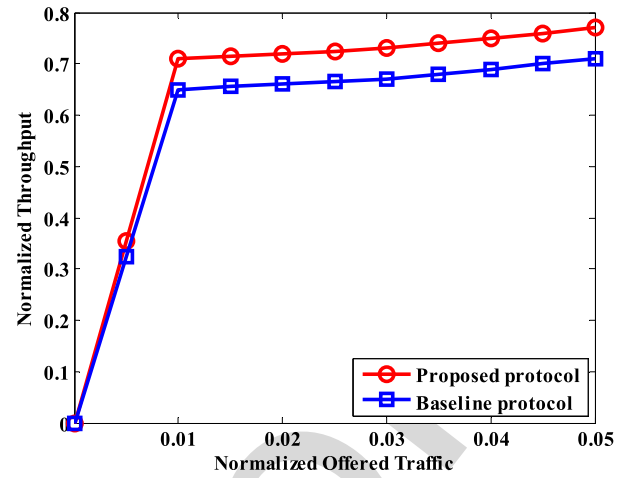


Fig. 10. Throughput versus offered traffic for  $D = 100$  devices.

694 750 and 250 devices for class 1 and class 2 respectively. Also,  
 695 the baseline protocol was configured with 1000 devices. Based  
 696 on these configurations, simulation results were obtained and  
 697 presented in Fig. 9. It can be deduced from Fig. 9 that the  
 698 higher the offered traffic in the network the lower the reser-  
 699 vation ratio, which means that there will be limited available  
 700 TDMA slot for transmission opportunity. For instance, when  
 701 the offered traffic is at 0.2, the proposed protocol has a  
 702 reservation ratio of 0.23, while the baseline protocol has a  
 703 reservation ratio of 0.21. We can infer from this that the  
 704 proposed protocol outperforms the baseline protocol with a  
 705 performance gain of about 9.5% which was as a result of  
 706 the efficiency of the proposed multi-class concept and the  
 707 PSO algorithm we introduced that was able to increase the  
 708 number of transmission slots of the proposed MAC protocol  
 709 and therefore increases the reservation ratio. Fig. 9 presents  
 710 the reservation ratio of the TDMA slot against the devices  
 711 offered traffic.

712 Moreover, we further investigate the performance of the  
 713 proposed protocol with the NP-CSMA/TDMA protocol in [24],  
 714 and we noticed that at an offered traffic of 0.2,  
 715 the proposed protocol has a reservation ratio of 0.23, while  
 716 the NP-CSMA/TDMA protocol has a reservation ratio of 0.215.  
 717 This means that an improvement of about 6.9% was achieved.

718 We also observed that the reservation ratio and the packet  
 719 success-access-ratio with normalized offered traffic have a  
 720 similar performance.

721 **G. Impact of Less Number of Devices on**  
 722 **Sum-Throughput**

723 In this section, an experiment was performed on the pro-  
 724 posed and the baseline protocols in terms of sum-throughput  
 725 versus offered traffic with less number of devices. This experi-  
 726 ment was considered to further investigate the performance of  
 727 the newly proposed protocol. For this to be achieved, we con-  
 728 figure  $D$  to be 100, 50, and 20 devices, and we set  $L = 80, 40,$   
 729 and 15 devices for class 1 respectively and  $Q = 20, 10,$  and  
 730 5 devices for class 2 respectively. The proposed protocol and  
 731 the baseline protocol were both simulated based on the config-  
 732 urations of 100, 50, and 20 devices. From Fig. 10, 11, and 12,

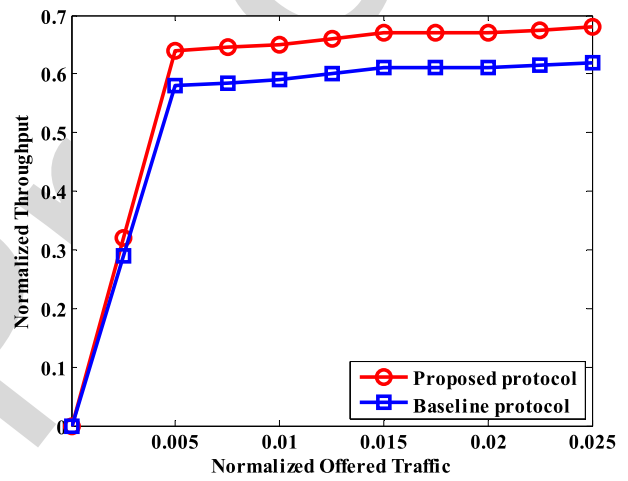


Fig. 11. Throughput versus offered traffic for  $D = 50$  devices.

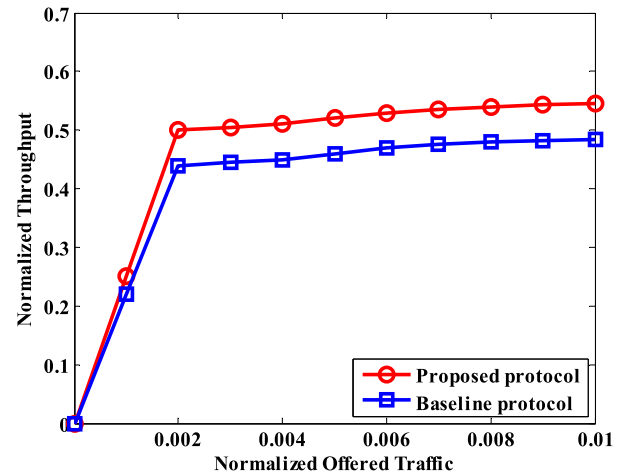


Fig. 12. Throughput versus offered traffic for  $D = 20$  devices.

733 it is obvious that the normalized sum-throughput reduced  
 734 drastically compared to when considering a larger number  
 735 of devices. It is also clear that the proposed protocol has a  
 736 better performance than the baseline protocol. For example, in  
 737 Fig 10, when the offered traffic is at 0.01 for  $D = 100$  devices,

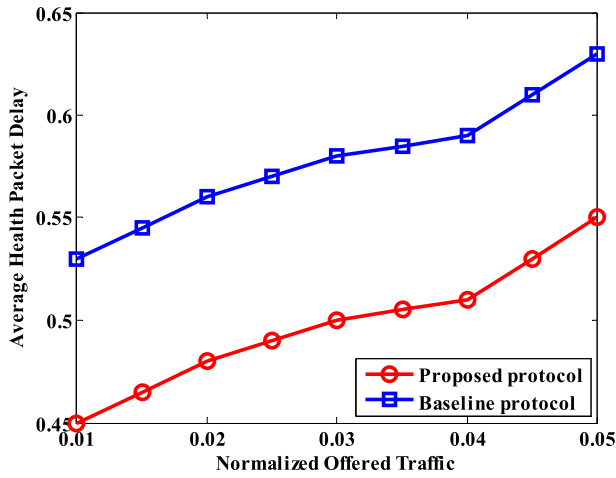


Fig. 13. Average health packet delay versus offered traffic with  $D = 100$  devices.

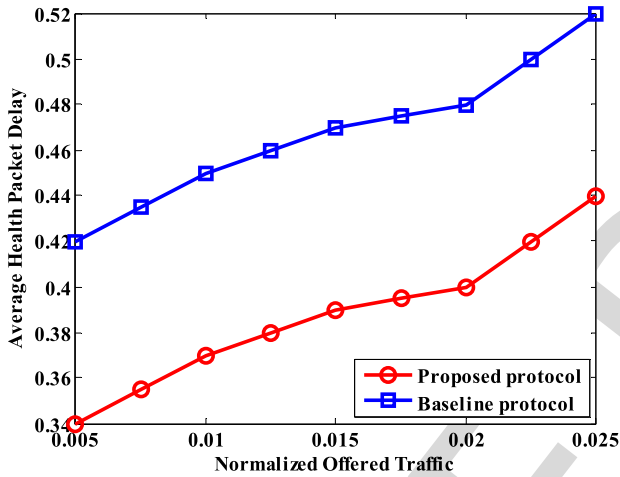


Fig. 14. Average health packet delay versus offered traffic with  $D = 50$  devices.

the proposed protocol has a throughput of 0.71, while the baseline protocol has a throughput of 0.65. This means a significant gain of about 9.2% of the sum-throughput rate was achieved by the proposed protocol over the baseline protocol. Also, from Fig. 11, when  $D$  is configured to be 50 devices, the proposed protocol has a throughput of 0.64, while the baseline protocol has a throughput of 0.58 when the offered traffic is at 0.005 which implies a performance gain of about 10.3%. Additionally, from Fig. 12, when  $D$  is configured to be 20 devices, the proposed protocol has a throughput of 0.50, while the baseline protocol has a throughput of 0.44 when the offered traffic is at 0.002, we noticed a performance gain of 13.6%.

#### H. Impact of Less Number of Devices on Average Delay

The impact of less number of devices on health packet delay for the proposed protocol and baseline protocol are investigated in this section. This experiment was based on a configuration of  $D = 100, 50,$  and  $20$  devices, where we set  $L = 80, 40,$  and  $15$  devices for class 1 respectively, and  $Q = 20, 10,$  and  $5$  devices for class 2 respectively. Based on

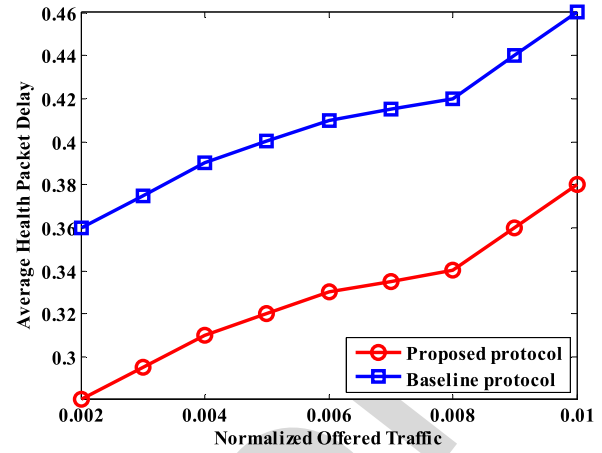


Fig. 15. Average health packet delay versus offered traffic with  $D = 20$  devices.

the results generated, compared to when there was a larger number of devices in the system, we observed that there is a reduction in the health packet delay. Also, we noticed that as the offered traffic of the system increases, the average delay time also increases. This experience is due to the fact that the offered traffic has a direct relationship with the health packet delay because of the likelihood of the increase in the number of collisions. But then, our proposed protocol was able to efficiently optimize the contention duration so as to reduce collisions and therefore minimizes delay as evident in Fig. 13, 14, and 15. From Fig. 13, we also noticed that the proposed protocol outperforms the baseline protocol, for instance, at an offered traffic of 0.01 when  $D = 100$  devices, there is an average delay of 0.45 as against the baseline protocol with average delay of 0.53. This means that the proposed protocol has a performance gain of about 15.1% in the health packet delay over the baseline protocol. Also, from Fig. 14, at an offered traffic of 0.005 when  $D = 50$  devices, the proposed protocol has an average delay of 0.34 and the baseline protocol has an average delay of 0.42 which implies a significant gain of about 19%. In addition, when we configure  $D$  to be 20 devices and at an offered traffic of 0.002 in Fig. 15, the proposed protocol has an average delay of 0.28 and the baseline protocol has an average delay of 0.36 and this implies a significant gain of about 22%.

## VIII. CONCLUSION

A hybrid multi-class MAC protocol for WBAN systems has been introduced in this paper. The proposed protocol's operation has two major processes in a single frame, namely the contention phase and the transmission phase. The contention phase employs the slotted ALOHA protocol as a contention mechanism for the reservation of transmission slots, while the transmission phase employs the TDMA protocol for transmission purposes. The trade-off between these two phases was optimized through multi-objective optimization techniques and a particle swarm optimization algorithm to improve the system performance gains in terms of the system fast convergence, sum-throughput, reservation ratio, success-access-ratio, and the average delay. The proposed algorithms

were validated based on the considered performance comparison criteria, including the convergence speed of the system against different number of iterations, impact of less number of devices on the achievable throughput and on the average health packet delay. From the simulation results, the proposed protocol performs better than the baseline protocol in terms of the system sum-throughput with a performance gain of about 9.2%, reservation ratio with a performance gain of about 9.5%, and average health packet delay with an overall performance gain of about 9.6%. Considering the power-constrained nature of the biomedical devices, it will be interesting to investigate solutions to improve the energy efficiency performance in future.

## 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] E. Kartsakli *et al.*, "A survey on M2M systems for mHealth: A wireless communications perspective," *Sensors*, vol. 14, no. 10, pp. 18009–18052, Sep. 2014.
- [3] *Machine to Machine Communications (M2M): Use Cases of M2M Applications for Ehealth*, document TR 102732 v0.4.1, ETSI, Mar. 2011.
- [4] A. Ali and M. Shoaib, "Energy efficient uplink MAC protocol for M2M devices," *IEEE Access*, vol. 7, pp. 35952–35962, 2019.
- [5] S.-J. Jung, R. Myllyla, and W.-Y. Chung, "Wireless machine-to-machine healthcare solution using Android mobile devices in global networks," *IEEE Sensors J.*, vol. 13, no. 5, pp. 1419–1424, May 2013.
- [6] K. Saleem, A. Derhab, J. Al-Muhtadi, and B. Shahzad, "Human-oriented design of secure machine-to-machine communication system for e-Healthcare society," *Comput. Hum. Behav.*, vol. 51, pp. 977–985, Oct. 2015.
- [7] K.-C. Chen, "Machine-to-machine communications for healthcare," *J. Comput. Sci. Eng.*, vol. 6, no. 2, pp. 119–126, 2012.
- [8] M. Cicioglu and A. Calhan, "IoT-based wireless body area networks for disaster cases," *Int. J. Commun. Syst.*, vol. 5, pp. 1–12, Nov. 2018.
- [9] P. Gope and T. Hwang, "BSN-care: A secure IoT-based modern healthcare system using body sensor network," *IEEE Sensors J.*, vol. 16, no. 5, pp. 1368–1376, Mar. 2016.
- [10] T. Wu, F. Wu, J.-M. Redoute, and M. R. Yuce, "An autonomous wireless body area network implementation towards IoT connected healthcare applications," *IEEE Access*, vol. 5, pp. 11413–11422, 2017.
- [11] M. Ali, H. Mounqila, 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.
- [12] I. Nasr, L. N. Atallah, S. Cherif, and B. Geller, "Time synchronization in IoT networks: Case of a wireless body area network," in *Proc. Int. Symp. Signal, Image, Video Commun. (ISIVC)*, Tunis, Tunisia, Nov. 2016, pp. 297–301.
- [13] S. Chatterjee *et al.*, "Internet of Things and body area networks—an integrated future," in *Proc. IEEE 8th 2017 Int. Conf. Ubiquitous Comput. Electron. Mobile Commun. (UEMCON)*, New York, NY, USA, Oct. 2017, pp. 396–400.
- [14] 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, Jan. 2015.
- [15] 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.
- [16] D. Yuan, G. Zheng, H. Ma, J. Shang, and J. Li, "An adaptive MAC protocol based on IEEE 802.15.6 for wireless body area networks," *Wireless Commun. Mobile Comput.*, vol. 5, pp. 1–9, Feb. 2019.
- [17] 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.
- [18] 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.
- [19] M. S. Akbar, H. Yu, and S. Cang, "Delay, reliability, and throughput based QoS profile: A MAC layer performance optimization mechanism for biomedical applications in wireless body area sensor networks," *J. Sensors*, vol. 2016, pp. 1–17, 2016.
- [20] N. B. Dargham, A. Makhoul, J. B. Abdo, J. Demerjian, and C. Guyeux, "Efficient Hybrid emergency aware MAC protocol for wireless body sensor networks," *Sensors*, vol. 7, pp. 1–18, Oct. 2018.
- [21] E. Ibarra, 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 (Healthcom)*, Lisbon, Portugal, Oct. 2013, pp. 120–124.
- [22] 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.
- [23] L. Ruan, M. P. Imali 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] W. Saad, S. A. El-Feshawy, M. Shokair, and M. I. Dessouky, "Optimised approach based on hybrid MAC protocol for M2M networks," *IET Netw.*, vol. 7, no. 6, pp. 393–397, Nov. 2018.
- [25] O. N. C. Yilmaz, J. Hämäläinen, and S. Hämäläinen, "Self-optimization of random access channel in 3rd generation partnership project long term evolution," *Wireless Commun. Mobile Comput.*, vol. 11, no. 12, pp. 1507–1517, Dec. 2011.
- [26] H. Harada and R. Prasad, "Simulation and software radio for mobile communications," *Artech House, Universal Pers. Commun.*, vol. 1, p. 311, Dec. 2002.
- [27] 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. 5, pp. 1–16, Feb. 2016.
- [28] S. S. Rao, *Engineering Optimization Theory and Practice*. Hoboken, NJ, USA: Wiley, 2009, pp. 761–764.
- [29] X. S. Yang and J. P. Papa, *Bio-Inspired Computation and its Applications in Image Processing: An Overview*. New York, NY, USA: Academic, 2016, pp. 3–5.
- [30] E. M. Malatji, J. Zhang, and X. Xia, "A multiple objective optimisation model for building energy efficiency investment decision," *Energy Buildings*, vol. 61, pp. 81–87, Jun. 2013.
- [31] N. I. Nwulu and X. Xia, "Multi-objective dynamic economic emission dispatch of electric power generation integrated with game theory based demand response programs," *Energy Convers. Manage.*, vol. 89, pp. 963–976, Nov. 2014.
- [32] M. Mahfouf, M. Y. Chen, and D. A. Linkens, "Adaptive weighted particle swarm optimization for multi-objective optimal design of alloy steels," in *Proc. Springer Int. Conf. Parallel Problem Solving from Nature*, Berlin, Germany, 2004, pp. 762–771.
- [33] Ö. Yeniay, "Penalty function methods for constrained optimization with genetic algorithms," *Math. Comput. Appl.*, vol. 10, no. 1, pp. 45–56, Apr. 2005.
- [34] E. Elbeltagi, T. Hegazy, and D. Grierson, "Comparison among five evolutionary-based optimization algorithms," *Adv. Eng. Informat.*, vol. 19, no. 1, pp. 43–53, Jan. 2005.
- [35] K. Huang and E. Larsson, "Simultaneous information and power transfer for broadband wireless systems," *IEEE Trans. Signal Process.*, vol. 61, no. 23, pp. 5972–5986, Dec. 2013.
- [36] S. Ullah, "RFID-enabled MAC protocol for WBAN," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Budapest, Hungary, Jun. 2013, pp. 6030–6034.

**Damilola D. Olatinwo** received the B.Sc. (Hons.) and M.Sc. degrees in computer science. She is a Postgraduate Research Fellow with the Department of Electrical, Electronic and Computer Engineering. Her research interests include low-power wide area networks, low-power MAC protocols for fifth generation networks, energy resource management, fog, cloud, and edge computing technologies for wireless body area networks, and the Internet of Things in e-health/health-care monitoring.

933  
934  
935  
936  
937  
938  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
950  
951  
952  
953  
954  
955



**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 at the Council for Scientific and Industrial Research (CSIR); Professor Extraordinaire at the Tshwaane University of Technology; a Visiting Professor at the University of Johannesburg; and an Extraordinary Faculty Member at the University of Pretoria. His research interests are wireless sensor and actuator network, low power wide area networks, software-defined wireless sensor network, cognitive radio, network security, network management, and sensor/actuator node development. He has participated in the formulation of many large and multidisciplinary Research and Development successful proposals (as Principal Investigator or main author/contributor). 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. He is currently an Associate Editor at the IEEE ACCESS, the IEEE INTERNET OF THINGS, and the IEEE TRANSACTION ON INDUSTRIAL INFORMATICS, and a member of many IEEE Technical Communities.



**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.

956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966  
967

IEEE Proof