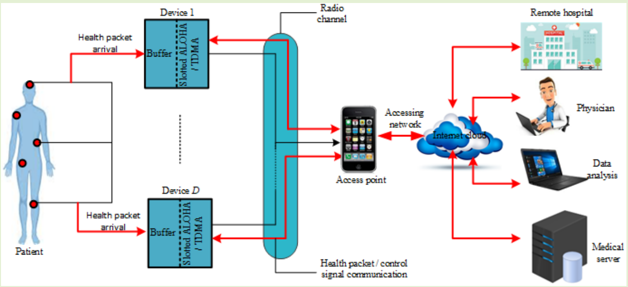
A Hybrid Multi-Class MAC Protocol for IoT-Enabled WBAN Systems

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

***Abstract*—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].

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, combing 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

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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@city.edu.hk).

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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. PROSPOSED 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 devices that are categorized based on their packet priority. It is assumed that the class 1 contain devices that are denoted as $\{l_1, l_2, \ldots, L\}$ 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 $\{q_1,q_2, ...,Q\}$. Additionally, it is assumed that only some of the devices in both class 1 and class 2 are active. Thus, let $\{m_1,m_2, ...,M\}$ and $\{n_1, n_2, ..., N\}$ represents the active devices for class 1 and class 2 respectively in each frame. This implies that in class 1 we have $M[[space]] \leq [[space]]L$ 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.

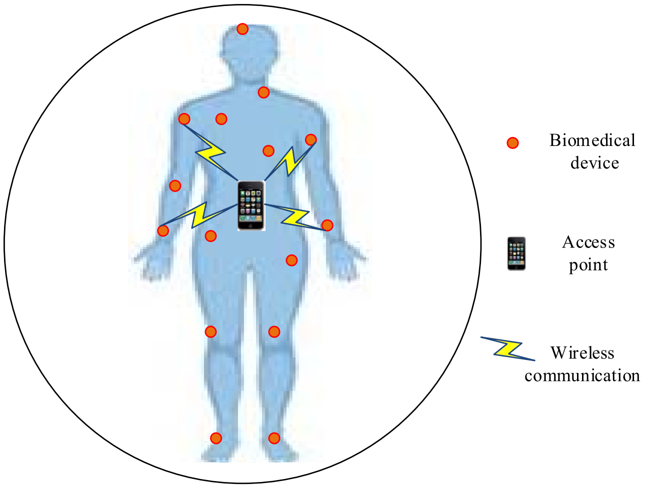

Fig. 1. WBAN system architecture.

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:

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

where t is the time interval and λ 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 to address 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 carter 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:

$$P_r = \frac{P_{type}}{\lambda \times P_{length}} \tag{2}$$

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 λ. Therefore, the expected value for the traffic generation time

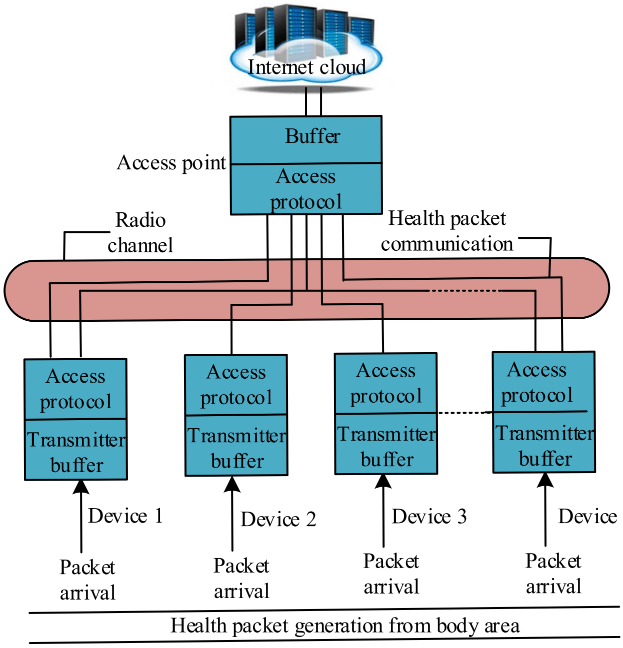

Fig. 2. WBAN packet generation process.

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:

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

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

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:

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

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

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:

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

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:

$$S_{reservation} = \frac{k_{res}}{k_{acc}} \tag{12}$$

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.

$$L_{CP1} + L_{CP2} + L_{TP1} + L_{TP2} \leq T_{fr} \tag{13}$$

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:

$$L^*_{CP1} + L^*_{CP2}$$
$$= \begin{cases} \arg\max S_{sum} = S_1 + S_2 + \ldots + S_\Omega \\ \arg\max S_{access} = S_{acc1} + S_{acc2} + \ldots + S_{acc\beta} \\ \arg\max S_{reservation} = S_{res1} + S_{res2} + \ldots + S_{resg} \end{cases} \tag{14}$$

s. t. (13),

$$P_{s1} + P_{s2} = (k_{s1} + k_{s2})\, P_{length} \tag{15}$$
$$k_{s1} + k_{s2} = \sum\nolimits_{l=1}^{k_{res1}} k_l + \sum\nolimits_{q=1}^{k_{res2}} k_q \tag{16}$$
$$T_t = k_{T_t} T_{fr} \tag{17}$$
$$L_{CP1} + L_{CP2} = (V_{s1} + V_{s2})\, T_s \tag{18}$$
$$L_{TP1} + L_{TP2} = (V_{r1} + V_{r2})\, T_r \tag{19}$$

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 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:

$$L^*_{CP1} + L^*_{CP2} = \max \begin{pmatrix} \omega_1 S_{sum} + \omega_2 S_{access} \\ +\omega_3 S_{reservation} \end{pmatrix} \tag{20}$$

where ω_1, ω_2, and ω_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:

$$T_{fr} - L^*_{CP1} + L^*_{CP2} - L_{NP} - L_{AP} \tag{21}$$

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

A. Proposed MAC Scheme Architecture Framework

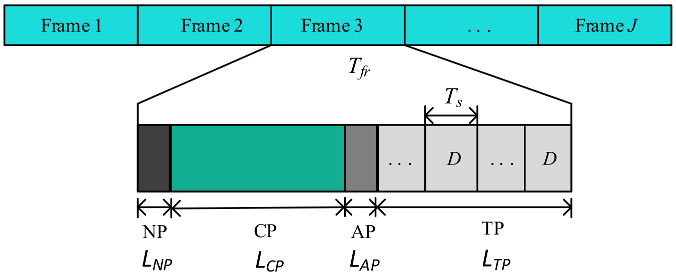

Fig. 3. Proposed MAC protocol time frame structure.

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

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

4) Transmission Phase: Here, the successfully contented devices transmit their health packets using the TDMA mechanism by switching on their transmitter module during their own specific assigned time-slots and switch it off during others time-slots.

B. Proposed Hybrid Multi-Class MAC Protocol Optimization Algorithms

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

Note that, in Algorithm 1 φ stands for the available TDMA slot.

It is important to mention that the agenda of (20) is to determine the optimal time to be allocated to L_{CP1} and L_{CP2}. To get the optimal values for L^*_{CP1} and L^*_{CP2}, the optimal solutions that optimizes S_{sum}, S_{access}, and the $S_{reservation}$ are determined. Note, there are several optimization methods that could be used to solve (20), examples include the nature-inspired optimization methods, such as the PSO method, ant colony optimization (ACO) method, GA method, and so on. 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 [33]. Even though, methods like a penalty function could be combined with a GA method to deal with constraint optimization problems, this method is still limited because of the difficulty in choosing a suitable penalty parameter value [30].

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

As said earlier, a PSO algorithm is applied to (20) and the optimization problem is denoted by $L^*_{CP1} + L^*_{CP2}$ (ψ, σ), where ψ and σ depends on the design variables (L_{CP1}, L_{TP1}) and (L_{CP2}, L_{TP2}) for classes 1 and 2 respectively. Each device l and q is denoted by a particle in classes 1 and 2 respectively and they serve as possible solutions to (20). Also, each particle l position is defined using vector ψ_l and each particle q position has a vector form of σ_q. Hence, the vector form of $\forall l \in (l_1, l_2, \ldots, L)$ and $\forall q \in (q_1, q_2, \ldots, Q)$ is defined by $\psi_l = \left[x_{l1}, x_{l2}, \ldots, x_{l\xi}\right]^T$ and $\sigma_q = \left[x_{q1}, x_{q2}, \ldots, x_{qF}\right]^T$ where $\xi \in (l_1, l_2, \ldots, L)$ and $F \in (q_1, q_2, \ldots, Q)$.

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
```

The modeling of the positions is done using a coordinate system (x, y). Note, the position expression for particle l and particle q are defined using $(1 \leq l \leq E)$ and $(1 \leq q \leq H)$ respectively where variables E and H are the maximum values of the particles. In the objective function (20), each particle l and q position contain the variables for the contention phase and the transmission phase, and the constraint functions (13) and (15)-(19). ψ_l and σ_q include time indexes represented as $\psi_l\,(t)$ and $\sigma_q\,(t)$. Also, the position of each of the particle l and q include velocities represented as $\upsilon_l\,(t)$ and $\upsilon_q\,(t)$ respectively. The $\upsilon_l\,(t)$ and $\upsilon_q\,(t)$ shows how each particle moves in the context of distance as well as direction. In every iteration, the devices l and q fitness value for $L^*_{CP1} + L^*_{CP2}\,(\psi_l\,(t))$ and $L^*_{CP1} + L^*_{CP2}\left(\sigma_q\,(t)\right)$ are calculated. Moreover, for every particle l and q, positions and velocities are updated based on the proposed hybrid multi-class MAC protocol PSO algorithm model as expressed in Algorithm 2.

In Algorithm 2, represents the acceleration coefficients are defined by c_1 as well as c_2 and are both assigned 2 being a standard value, while ω denotes the inertial weight and is allocated a value of 1, also, being a s standard value [34], [35],

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
for $l = 1$ to $E$ &&$q = 1$ to $H$ do
    initialize t:= 0, then start the process
    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
    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
    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 $q$
    repeat
end for loop
for every particle $l$ do
    let t← t + 1
    compute the velocity of particle $l$ as: $v_l(t+1) = \omega v_l(t) + c_1(\bar{\psi}_{lPBest}(t) - \psi_l(t)) + c_2(\bar{\psi}_{lGBest}(t) - \psi_l(t))$
    update each particle $l$'s position by using:
    $\psi_l(t+1) = \psi_l(t) + v_l(t+1)$
end for loop
for every particle $q$ do
    let t← t + 1
    compute the velocity of particle $q$ as: $v_q(t+1) = \omega v_q(t) +$
    $c_1(\bar{\sigma}_{qPBest}(t) - \sigma_q(t)) + c_2(\bar{\sigma}_{qGBest}(t) - \sigma_q(t))$
    update each particle $q$'s position by using:
    $\sigma_q(t+1) = \sigma_q(t) + v_q(t+1)$
end for loop
for every particle $l$ do
    if $L^*_{CP1} + L^*_{CP2}(\psi_l(t)) \gg (\bar{\psi}_{lPBest}(t))$ then
        update $\bar{\psi}_{lPBest}(t) = \psi_l(t)$
    end if
    if $L^*_{CP1} + L^*_{CP2}(\psi_l(t)) \gg (\bar{\psi}_{lGBest}(t))$ then
        update $\bar{\psi}_{lGBest}(t) = \psi_l(t)$
    end if
end for loop
repeat until $t \gg R$
return $\bar{\psi}_{lGBest}(t)$
until convergence
for every particle $q$ do
    if $L^*_{CP1} + L^*_{CP2}\left(\sigma_q(t)\right) \gg (\bar{\sigma}_{qPBest}(t))$ then
        update $\bar{\sigma}_{qPBest}(t) = \sigma_q(t)$
    end if
    if $L^*_{CP1} + L^*_{CP2}\left(\sigma_q(t)\right) \gg (\bar{\sigma}_{qGBest}(t))$ then
        update $\bar{\sigma}_{qGBest}(t) = \sigma_q(t)$
    end if
end for loop
repeat until $t \gg R$
return $\bar{\sigma}_{qGBest}(t)$
until convergence
return $\boldsymbol{L^*_{CP1} + L^*_{CP2}}$
```

TABLE II
SIMULATION SETTINGS

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

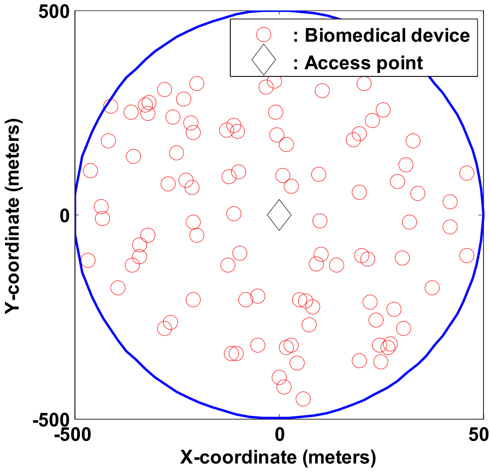

Fig. 4. Network deployment structure.

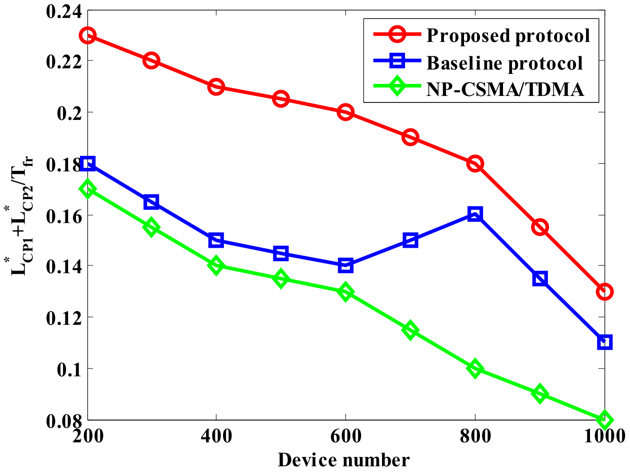

Fig. 5. Optimized $L^*_{CP1} + L^*_{CP2}/T_{fr}$ ratio against the number of devices.

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 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.

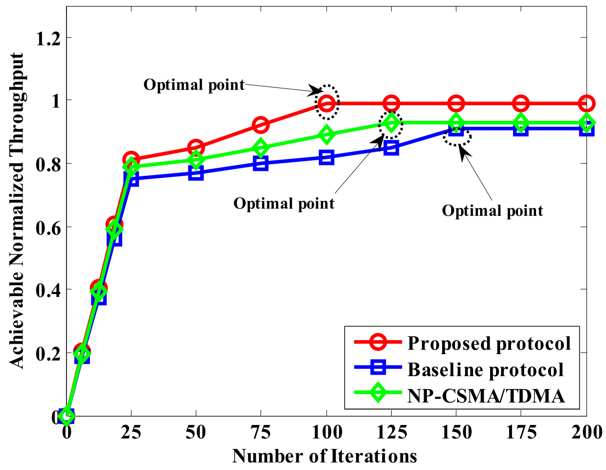

Fig. 6. Achievable system sum-throughput versus number of iterations.

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

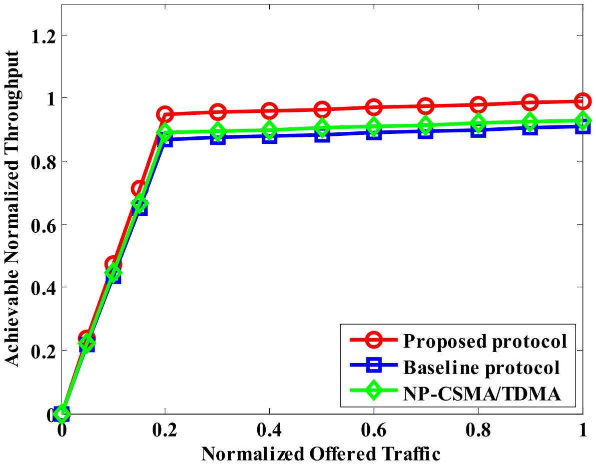

Fig. 7. Achievable throughput versus offered traffic.

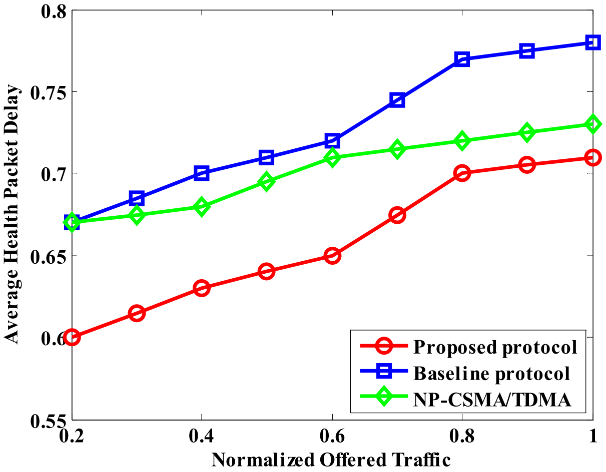

Fig. 8. Average health packet delay versus offered traffic.

protocol was also compared with the NP-CSMA/TDMA protocol in [24]. It was observed that the proposed protocol performs better than the NP-CSMA/TDMA protocol as it saturates to an optimal solution at about 100 iterations unlike the NP-CSMA/TDMA protocol which attain its optimal solution at about 125 iterations. The proposed algorithm was able to realize a performance improvement of about 12.1% and 6.7% when compared with the baseline protocol and the NP-CSMA/TDMA protocol, respectively in the convergence iterations and is indicative of efficiency in terms of fast convergence.

D. Comparison of the Achievable System Sum-Throughput

Simulation investigations were carried out on the proposed hybrid multi-class MAC protocol and the existing hybrid MAC protocol for different configuration scenarios to investigate its impact on the normalized sum-throughput. Fig. 7. presents the system sum-throughput versus offered traffic for $D = 1000$ devices with a configuration of $L = 750$ and $Q = 250$ devices for class 1 and class 2 respectively. Also, the baseline protocol was equally configured with a total number of 1000 devices. During the experiments, the proposed algorithms were enabled for the proposed protocol and disabled for the baseline protocol. Based on the generated results, it is very clear that as the offered traffic is increasingly varied, the throughput of the system also has a slight increase. To further show how efficient our proposed protocol is compared to the baseline protocol, the performance of the system was further analyzed, for instance, when the offered traffic is at 0.2, the proposed protocol has a normalized throughput of 0.95, while the result of baseline protocol has a normalized throughput of 0.87. This indicates that the proposed protocol has an improvement of about 9.2% in the system throughput rate over the baseline protocol. This improvement was as a result of the proposed multi-class concept that was introduced and also the proposed PSO based algorithm which was able to accommodate more devices.

In addition, the proposed protocol was compared with the NP-CSMA/TDMA protocol in [24], and at 0.2 offered traffic, the NP-CSMA/TDMA protocol has a normalized throughput of 0.89, while the proposed protocol has a normalized throughput of 0.95. Therefore, a performance improvement of about 6.7% was achieved.

E. Average Health Packet Delay

In this section, we investigate the average health packet transmission delay against the offered traffic. For this purpose, we configure the proposed hybrid multi-class MAC protocol and the baseline protocol with $D = 200, 400, 600, 800$, and 1000 devices. For the proposed protocol, when $D = 1000$ devices, L was set to 750, while Q was set to 250 for class 1 and class 2 respectively. Based on the simulation results that were generated and presented in Fig. 8, the newly proposed protocol was able to minimize the average health packet delay by optimizing the contention duration and the transmission duration. Also, from Fig. 8, we observe that the average health packet transmission delay increases as the offered traffic is increased. However, the proposed protocol was able to obtain a reduced average health packet delay compared to the baseline protocol. As an example, at offered traffic of 0.2, 0.4, 0.6, 0.8, and 1.0, we have average delays of 0.60, 0.63, 0.65, 0.70, and 0.71 respectively as against the baseline protocol with average delays of 0.67, 0.70, 0.72, 0.77, and 0.78 respectively. This means that there is an overall improvement of about 9.6% in the health packet delay time over the baseline protocol.

Also, we compared the proposed protocol with the NP-CSMA/TDMA protocol in [24], and at offered traffic of 0.2, 0.4, 0.6, 0.8, and 1.0, the proposed protocol has average delays of 0.60, 0.63, 0.65, 0.70, and 0.71 respectively, while the NP-CSMA/TDMA protocol has average delays of 0.67, 0.68, 0.71, 0.72, and 0.73 respectively. An overall performance improvement of about 6.2% was achieved.

F. Reservation Ratio

In this section, we consider the comparison of the newly proposed protocol with the baseline protocol in terms of the reservation ratio. To achieve this, we consider a configuration of $D = 1000$ devices and we set L and Q to be

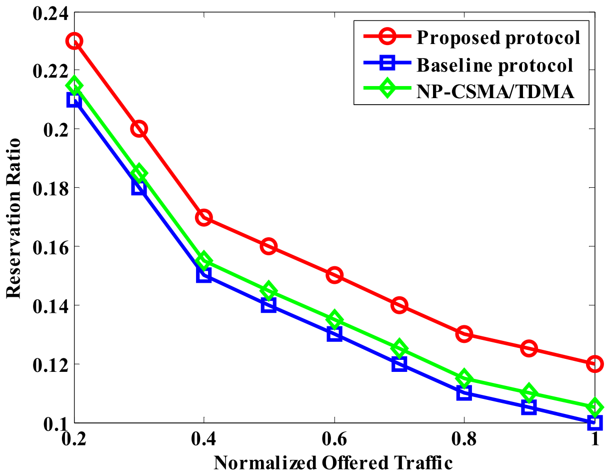

Fig. 9. Reservation ratio versus offered traffic.

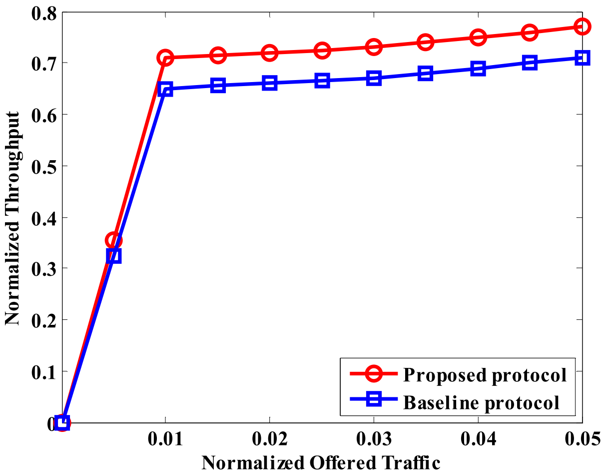

Fig. 10. Throughput versus offered traffic for $D = 100$ devices.

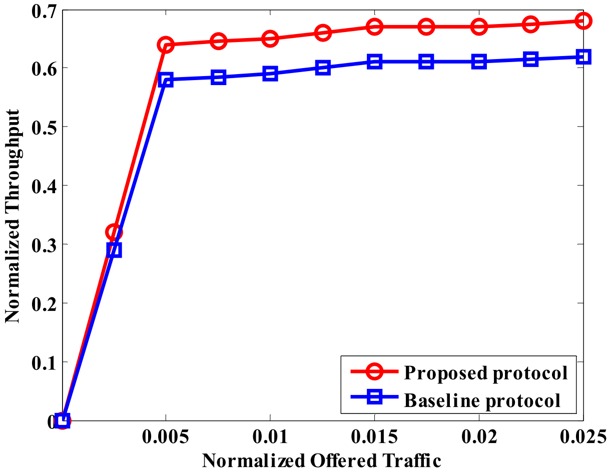

Fig. 11. Throughput versus offered traffic for $D = 50$ devices.

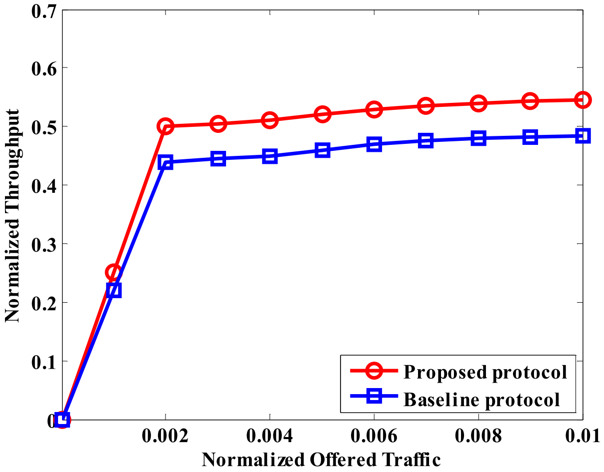

Fig. 12. Throughput versus offered traffic for $D = 20$ devices.

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

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

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

G. Impact of Less Number of Devices on Sum-Throughput

In this section, an experiment was performed on the proposed and the baseline protocols in terms of sum-throughput versus offered traffic with less number of devices. This experiment was considered to further investigate the performance of the newly proposed protocol. For this to be achieved, we configure D to be 100, 50, and 20 devices, and we set $L = 80$, 40, and 15 devices for class 1 respectively and $Q = 20$, 10, and 5 devices for class 2 respectively. The proposed protocol and the baseline protocol were both simulated based on the configurations of 100, 50, and 20 devices. From Fig. 10, 11, and 12, it is obvious that the normalized sum-throughput reduced drastically compared to when considering a larger number of devices. It is also clear that the proposed protocol has a better performance than the baseline protocol. For example, in Fig 10, when the offered traffic is at 0.01 for $D = 100$ devices,

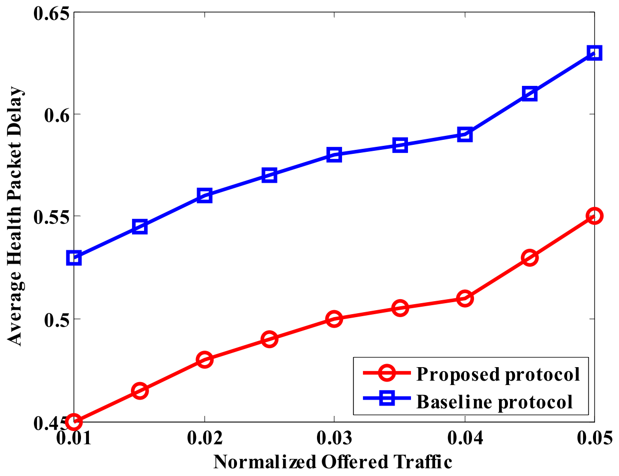

Fig. 13. Average health packet delay versus offered traffic with $D = 100$ devices.

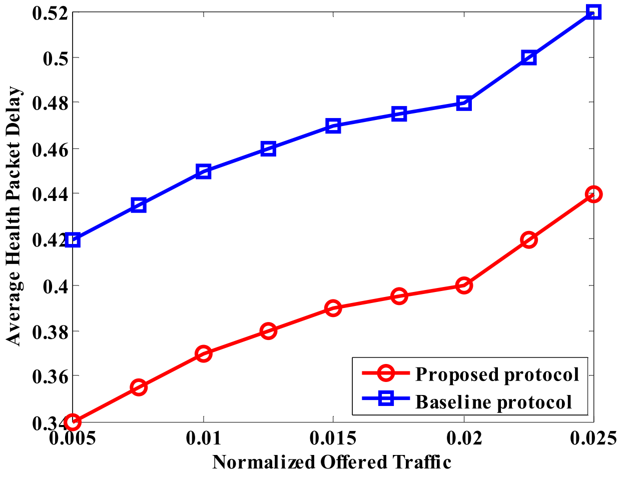

Fig. 14. Average health packet delay versus offered traffic with $D = 50$ devices.

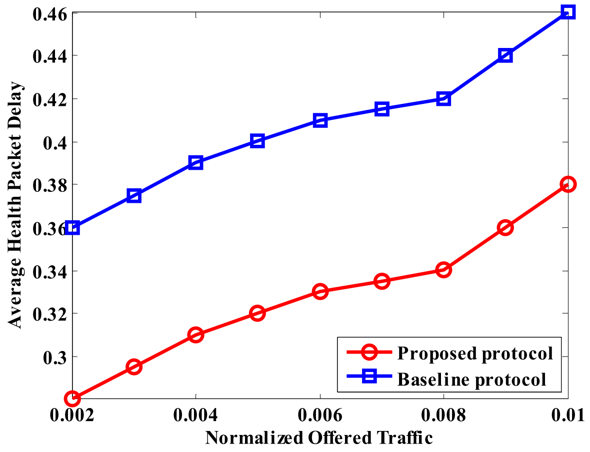

Fig. 15. Average health packet delay versus offered traffic with $D = 20$ devices.

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 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.

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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.

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.