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RESEARCH ARTICLE

Adaptive Medium Access Control Protocol for Dynamic Medical Traffic With Quality of Service Provisioning in Wireless Body Area Network

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ABSTRACT The performance of a Wireless Body Area Network (WBAN) depends on the Quality of Service (QoS) and energy efficiency. The traffic generated by WBAN is heterogeneous in nature, and consists of both periodic and emergency events. One crucial challenge in designing a WBAN Medium Access Control (MAC) protocol is guaranteeing high-reliability transmission while satisfying diverse QoS requirements. Therefore, this paper proposes a QoS-aware MAC protocol named the Adaptive MAC (ADT-MAC) that accommodates dynamic medical traffic by addressing emergency and periodic traffic requirements. ADT-MAC utilizes a hybrid and adaptive superframe structure based on the IEEE 802.15.6 standard. Additionally, an M/M/1 queuing algorithm with a non-preemptive priority is modeled using SimEvents in MATLAB to validate the packet delay of the priority queues. The proposed ADT-MAC protocol is simulated using Castalia and OMNeT++ to evaluate its performance against state-of-the-art MAC protocols. Simulation findings reveal that ADT-MAC achieves lower packet delay, higher PDR, and increased network throughput while reducing energy consumption compared to its benchmarks. Furthermore, the result of packet delay from priority queues validates the accuracy of the proposed ADT-MAC and queueing algorithm. The two-fold simulation approach using Castalia and SimEvents demonstrated that the packet delay for each priority level remains below the 125 ms threshold set by the IEEE 802.15.6 specifications.

INDEX TERMS Quality of service, energy efficiency, adaptive superframe, queuing algorithm.

I. INTRODUCTION

In recent years, developed countries have encountered substantial obstacles in providing sustainable healthcare services and fostering wellness, mainly due to the increasing aging population and the rising prevalence of chronic ailments such as cardiovascular illnesses, kidney disease, diabetes, and various types of cancer. The World Health Organization (WHO) forecasts that by 2030, diabetes will rank among the leading causes of mortality, with an estimated allocation of up to 15 % of the national healthcare budget towards diabetes care [1]. Moreover, the aging population is a key factor driving the rise in chronic diseases [2], [3]. By 2050, the proportion of people aged 60 and above is expected to double, reaching 23.6 % in the United Kingdom, 35.6 % in Japan, and exceeding 20 % globally [4]. Healthcare providers are increasingly exploring the potential of digital health technologies for remotely monitoring and treating patients via Internet-connected sensors

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and medical devices. The Wireless body area network (WBAN) is the critical enabler of remote health monitoring. WBAN is a communication network that enables human-computer interaction through wireless sensor devices. It is defined in the IEEE 802.15.6 standard [5]. WBAN consists of miniature wearable devices or Implantable Medical Devices (IMDs). It monitors vital patient parameters such as body temperature, blood pressure, and heart rate [6], [7]. These sensor devices exploit short-range wireless communication technology to gather and transmit bio-signals from the body to a remote server or network coordinator for additional processing and services [8].

WBAN has various applications in both medical and non-medical domains, encompassing healthcare, professional sports, military operations, consumer electronics, gaming, entertainment, and security [9], [10]. In addition, WBAN is a specific type of Wireless Sensor Network (WSN), which has notable distinctions despite sharing some similarities [11], [12]. While both networks have overlapping features, research conducted on WSN cannot be directly extrapolated to WBAN due to their unique requirements and challenges [13]. In particular, WBAN stands out by addressing specific needs associated with network-body connection, a facet not catered by WSN technology [14]. WSN, in contrast, is distinguished by its large-scale, autonomous nature and can be deployed in fixed or distributed configurations [15], [16].

Medium Access Control (MAC) protocols significantly impact WBAN performance. Energy conservation is a primary concern in designing MAC protocols due to the energy limitations of battery-powered body sensor devices. Several studies conducted in [17], [18], [19], [20], and [21] have examined energy-efficient solutions at the MAC layer to prolong the operational lifespan. However, these approaches overlooked the Quality of Service (QoS) requirements, such as packet delay, Packet Delivery Ratio (PDR), and network throughput. Failure to meet application-specific QoS criteria can degrade the effectiveness of WBAN, regardless of prolonged operational longevity. Moreover, the demands for QoS change significantly across different WBAN applications. For instance, non-medical applications require packet delay that are less than 250 ms, whereas medical applications necessitate stricter limitations, with delay below 125 ms [22], [23].

The exponential growth of the Internet of Things (IoT) has increased the need to manage diverse traffic priorities in heterogeneous WBAN. Data from numerous sensing devices must be transferred simultaneously and immediately to a network coordinator (hub), each with different QoS and reliability criteria. The traffic rate is usually low during periodic situations (non-emergency cases) and becomes very high during emergency conditions. Unlike periodic data, emergency data necessitate rapid delivery with maximum reliability and minimal delay. Therefore, it is essential to develop a QoS-aware and adaptive MAC protocol that adapts to dynamic medical traffic and addresses the distinct traffic requirements of sensor nodes in WBAN.

A. MOTIVATION

The MAC layer manages and controls the times when the sensors can access a shared WBAN communication channel. For communication purposes, a hybrid channel access approach, which integrates the contention-access, scheduled-access, and polling-access techniques, is essential for optimizing the WBAN performance. The heterogeneous nature of the WBAN sensors generates various types of data containing vital signs information, including periodic, emergency, and on-demand data. This traffic must be prioritized and treated according to the priority level by tuning the network operation parameters associated with the MAC layer. Poor traffic prioritization in the service differentiation can lead to several issues, such as starvation of low-priority data classes and underutilization of network resources. Effective traffic prioritization during channel access is necessary to ensure fairness support and meet the stringent QoS requirements. The QoS assures high-quality performance and provides end-to-end support so that the traffic load is not starved. Additionally, a significant limitation of many MAC protocols proposed in [24], [25], and [26] is that they are not designed to be QoS-aware. The heterogeneous nature of vital signs information significantly influences the priority-based traffic during channel access. The QoS control must communicate different data types effectively and efficiently.

WBAN requires high data rates to transmit emergency traffic promptly. However, existing MAC protocols rely on pre-allocated static slot allocations, which must be customized for such scenarios. The primary limitation of static slot allocation is that each sensing device must use the channel in its designated time slots, regardless of its need. This can lead to inefficient resource utilization, particularly when a sensor experiences persistent deep fading. In addition, the MAC protocol determines the wireless channel usage and is responsible for conflict detection and processing of nodes, priority control, time slot allocation, and transmission order of nodes. For this purpose, an efficient MAC protocol must incorporate an adaptive superframe structure that enhances the superframe utilization and employs dynamic slot allocation based on varying traffic load requirements.

Therefore, this paper proposes a QoS-aware MAC protocol that supports dynamic medical traffic in WBAN, named Adaptive MAC (ADT-MAC) protocol. The proposed MAC protocol employs a hybrid channel access method and adaptive superframe structure with a dynamic slot allocation mechanism to eliminate network congestion and enhance overall WBAN performance while providing the required QoS. Moreover, the performance of the protocol and comparison with state-of-the-art protocols is evaluated comprehensively. The performance metrics include PDR, packet delay, network throughput, and energy consumption.

B. MAIN CONTRIBUTIONS

The main contributions of this work are as follows:

- The proposed ADT-MAC protocol introduces a hybrid and adaptive superframe structure to accommodate dynamic medical traffic that addresses both periodic and emergency traffic requirements.

- A dynamic slot allocation strategy is implemented to enhance QoS performance by prioritizing periodic traffic across three priority levels, which are high, medium, and low.
- An M/M/1 queuing algorithm with non-preemptive priority is modeled using the SimEvents in MATLAB simulators to validate the packet delay for each priority queue, providing a robust mathematical framework for performance analysis.
- The performance of the proposed ADT-MAC protocol is evaluated using the Castalia simulator based on the OMNeT++ platform. It is evaluated in comparison to the IEEE 802.15.6-MAC [5],DMTM-MAC [27], McMAC [28], and TA-MAC [29].

C. ORGANIZATION

The remainder of this paper is organized as follows: Section II outlines the fundamental framework of the IEEE 802.15.6 standard. Section III reviews existing research on MAC protocols tailored for WBAN applications, highlighting the current state-of-the-art and identifying gaps addressed by this study. Section IV constitutes the core of the paper, offering an in-depth description of the proposed MAC protocol. This section elaborates on the communication overview, underlying assumptions, and critical components, including data classification, connection procedure, adaptive superframe structure, and data transmission time. Additionally, an M/M/1 queuing algorithm with a non-preemptive priority is explained in this section. Section V presents the performance evaluation, detailing the simulation setup using Castalia and SimEvents simulators. Furthermore, a comparative performance analysis is conducted, juxtaposing the proposed MAC protocol against four protocols to highlight its advantages. Finally, Section VI concludes the paper, summarizing the findings and proposing potential directions for future research endeavours.

II. BASIC FRAMEWORK OF IEEE 802.15.6 STANDARD

Numerous wireless communication standards have been formulated for WBAN, such as IEEE 802.11 (Wireless Fidelity–Wi-Fi), IEEE 802.15.1 (Bluetooth), IEEE 802.15.4, and IEEE 802.15.6 [30], [31]. However, IEEE 802.11 is designed for high-speed communication and does not meet the low-power requirements of WBAN. Similarly, IEEE 802.15.1 limits the number of auxiliary nodes, while IEEE 802.15.4 cannot support high data rate applications exceeding 250 Kbps. In contrast, the low-power IEEE 802.15.6 standard is well-suited for WBAN, particularly in healthcare applications, as it enables reliability-sensitive applications, supports QoS requirements, and allows sensor devices to operate with minimal transmission power [32], [33], [34].

Task Group 6 (TG6) established the IEEE 802.15.6 standard to standardize communication among sensor devices [5]. The initial draft of the standard was published in 2010, with the final version released in 2012. This standard is applicable to both medical and non-medical fields, providing ultra-low-power, low-complexity, high-reliability, and short-range wireless communication in or near the human body at low frequencies [35]. Therefore, to enhance the performance of WBAN, we introduce a MAC protocol based on the IEEE 802.15.6 standard. The standard defines three bandwidths across three Physical (PHY) layers: Human Body Communication (HBC), Ultra-Wideband (UWB), and Narrowband (NB) [36]. The choice of the PHY layer depends on the WBAN applications, whether medical or non-medical contexts, and involves communication within, outside, or detached from the human body [37]. NB and UWB are based on Radio Frequency (RF) propagation, while HBC uses a non-RF method [37]. The NB-PHY supports seven frequency bands from 402 to 2483.5 MHz with 230 channels, 402 to 405 MHz dedicated to IMDs, and 2360 to 2400 MHz for medical applications. The UWB-PHY operates at 3494.4 to 9984 MHz, enabling high data rate and low power consumption. The HBC-PHY uses frequencies from 5 to 50 MHz, centered at 21 MHz. At the PHY layer, the standard manages radio transceiver activation and deactivation, Clear Channel Assessment (CCA) for the current channel, and data transmission and reception. According to IEEE 802.15.6, the hub or coordinator can use one of three access modes: (1) Beacon mode with beacon period superframe boundaries, (2) Non-beacon mode with superframe boundaries, and (3) Non-beacon mode without superframe boundaries. Beacon mode with beacon period superframe boundaries is the most useful as it synchronizes transmission among multiple sensing devices. A superframe is defined as the time interval between two consecutive beacons.

Figure 1 illustrates the superframe structure of IEEE 802.15.6 in beacon mode, which accommodates diverse traffic load requirements. It includes Exclusive Access Phases (EAP 1 and EAP 2), Random Access Phases (RAP 1 and RAP 2), Managed Access Phases (MAP 1 and MAP 2), Contention Access Phase (CAP), and two beacon frames. MAP phases are also referred to as Type I or Type II phases. At the start of each superframe, the hub transmits a beacon frame containing network management information, including Body Area Network Identification (BAN ID), synchronization, and medium access coordination. The hub can disable all access phases except RAP1, which is essential for node association and disassociation [27]. According to IEEE 802.15.6, RAP and CAP are reserved for normal data, while EAP is for the highest-priority data. MAP phases are allocated for scheduled uplink, downlink, and bilink transmission. The IEEE 802.15.6 standard defines eight distinct User Priorities (UP) based on traffic designation, ranging from UP_0 to UP_7, as shown in Table 1.

III. RELATED WORKS

Numerous strategies have been proposed to optimize WBAN performance concerning transmission delay, delivery probability, and energy efficiency, particularly under dynamic

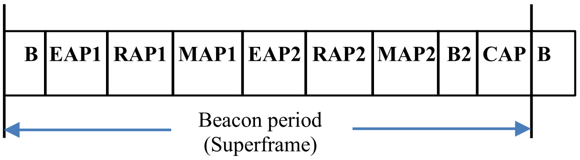


FIGURE 1. Beacon mode with beacon period [5].

TABLE 1. User priority mapping [5].

Priority	UP_i	Traffic Designation	Frame Type
Lowest	0	Background (BK)	Data
	1	Best Effort (BE)	Data
	2	Excellent Effort (EE)	Data
	3	Voice (VO)	Data
	4	Video (VI)	Data
	5	Medical data or network	Data and management
	6	High-priority medical data or network control	Data and management
Highest	7	Emergency or medical implant and even report	Data

network conditions and resource-constraint networks. Generally, two methods are used to analyze the performance of the WBAN MAC protocol, which are using numerical analysis and network simulation, as summarized in Table 2. Many of these studies adopt the IEEE 802.15.6 standard or its variants to satisfy diverse QoS requirements.

Recent research has focused on improving WBAN performance through various dynamic scheduling methods. For instance, in [38], the authors introduced a Dynamic Slot Scheduling (DSS) method using a temporal autocorrelation model to predict on-body channel status for future time slots, overcoming the limitations of Markov models and existing approaches that inadequately capture the intricate temporal variations in on-body channels. However, this method does not account for traffic prioritization in the network. Additionally, two TDMA-based methods have been proposed in [39], named Dynamic Scheduling Based on Sleeping Slots (DSBS) and Dynamic Scheduling Based on Buffer (DSBB) to support different traffic priority levels. Furthermore, [40] presented a priority-based method called a joint Throughput and Channel Aware (TCA) dynamic scheduling algorithm, which employs two priority classes to improve network performance. Nonetheless, these methods are restricted to two priority levels (normal and emergency) and require additional frameworks to extend the priority levels to accommodate multiple QoS levels.

An Adaptive MAC (A-MAC) protocol was created in [41] to modify the superframe structure and allocate slots dynamically based on data priority levels. A notable limitation of this work is its reliance on simulations using a self-developed event-driven system in MATLAB, which does not fully replicate real network environments. Thus, performance evaluation using system-level simulators such as NS-3, OPNET, and OMNeT++ is required to resemble a real network environment. The work in [42] presented a Demand-based Dynamic Slot Allocation (DDSA) algorithm to maximizes available time slot usage across all sensor devices and dynamically allocate slots according to priority. In addition, the authors in [27] developed a Dynamic Medical Traffic Management MAC (DMTM-MAC) that integrates dynamic slot allocation and modifies channel access mechanisms according to data priority levels. Although these efforts show significant potential for enhancing network efficiency, the QoS requirements for different priority levels are not adequately and sufficiently addressed.

Existing MAC protocols, such as Traffic Aware MAC (TA-MAC) [29], Priority-based Adaptive MAC (PA-MAC) [43], Multi-Constraints MAC (McMAC) [28], and QoS-driven MAC [44] address different traffic priority levels and QoS parameters within the network. These protocols effectively manage various priority levels and significantly reduce transmission delays for high-priority data. Despite outperforming their benchmarks, several challenges still need to be addressed. Specifically, TA-MAC, PA-MAC, and McMAC are based on the IEEE 802.15.4 standard, which lacks of traffic prioritization techniques to support diverse traffic types according to their QoS demands. A significant limitation of TA-MAC and PA-MAC is network performance degradation under heavy traffic loads due to the constrained number of Guaranteed Time Slots (GTS) available in the IEEE 802.15.4 standard [45]. This scarcity of GTS becomes particularly problematic as network traffic intensity increases. Furthermore, the QoS-driven MAC relies on numerical models, which fall short of real-world applicability due to simplified assumptions.

In [46], the authors proposed a Dynamic Slot Allocation with Non-Overlapping Back-off (DSA-NOBA) algorithm as a solution to reduce collisions in WBAN. This approach incorporates a DSA method to improve overall superframe utilization and expands Contention Windows (CW) for different traffic priorities. In addition, [47] proposes a method for allocating dedicated slots based on priority using a dynamic superframe structure of the IEEE 802.15.6 standard. The prioritization is established by the Criteria Importance Through Inter-Criteria Correlation (CRITIC) mathematical model. Furthermore, to provide effective service differentiation in heterogeneous WBAN, the authors in [48] have developed a dynamic CW, named Traffic-Aware IEEE 802.15.6 (TA-802.15.6). To address the issue of low-priority data, they introduce a starvation index parameter that dynamically adjusts the CW limits. Although the proposed numerical methods can yield potential results, they frequently rely on simplified assumptions that may not accurately represent real-world conditions. To investigate the actual performance, network simulators such as NS-2, NS-3, OPNET, and OMNeT++ are essential.

To the best of the authors' knowledge, no study comprehensively addresses the combination of an adaptive superframe structure, traffic prioritization, hybrid channel access method, QoS provisioning, IEEE 802.15.6 standard compliance, and numerical analysis through simulation. Therefore,

TABLE 2. Summarization of State-of-the-art MAC protocols.

References	Channel Access	IEEE Technology		Traffic Classification	QoS	Method	Limitations
		802.15.4	802.15.6				
DSS [38]	Scheduled		√	-	-	Network Simulator	No traffic classification and prioritization
DSBS, DSBB [39]	Scheduled	√	√	Normal and emergency	-	Network Simulator	Low performance in heterogenous traffic conditions
TCA [40]	Scheduled		√	1 and 0	-	Network Simulator	No traffic classification and prioritization
A-MAC [41]	Contention, Scheduled		√	Emergency, periodic and audio/video	-	MATLAB	Raise contention when multiple traffic types compete in a single CAP
DDSA [42]	Scheduled		√	Critical and non-critical	-	Network Simulator	Produce high packet loss
DMTM-MAC [27]	Contention, Scheduled, Polling		√	Periodic, urgent and on-demand	-	Network Simulator	Emergency traffic transmitted in EAP, which raise the contention problems
TA-MAC [29]	Contention, Scheduled	√		Emergency, on-demand, normal and non-medical	√	Network Simulator	Emergency traffic is penalized. Increases the risk of collision and transmission delay
PA-MAC [43]	Contention, Scheduled	√		Emergency, on-demand, normal and non-medical	√	Network Simulator	Performance degradation in high traffic loads due to contention complexity
McMAC [28]	Contention, Scheduled, Polling	√		Type 0 – Type 4	√	Network Simulator	Produce high delay and energy consumption
QoS-Driven [44]	Scheduled		√	Normal and abnormal context	√	Numerical Analysis	Channel state relies on two-state Markov model
DSA-NOBA [46]	Contention		√	UP(0) – UP(7)	-	Numerical Analysis	Increase collisions for high priority traffic due to short CW range
[47]	Contention, Scheduled		√	UP(0) – UP(7)	-	Numerical Analysis	Produce high delay
TA-IEEE 802.15.6 [48]	Contention		√	UP(0) – UP(7)	-	Numerical Analysis	Increase retransmission due to high collisions and channel fading
Proposed (ADT-MAC)	Contention, Scheduled, Polling		√	Emergency and Periodic with priority-based (High, medium, low)	√	Network Simulator	-

this study proposes a novel MAC protocol to adhere to these constraints, support traffic prioritization, and provision the QoS metrics.

IV. ADAPTIVE-MAC (ADT-MAC) PROTOCOL

This section details the proposed ADT-MAC protocol, comprising six components, which are communication overview and assumptions, traffic classification, connection procedure, adaptive superframe structure, data transmission time, and priority queuing model in SimEvents.

A. COMMUNICATION OVERVIEW AND ASSUMPTIONS

This paper examines a WBAN scenario for a patient with a chronic disease equipped with heterogeneous sensor devices. We consider a point-to-multipoint (star) network topology, as illustrated in Figure 2, where the WBAN is configured with a hub, or Full-Function Device (FFD), at the right hip, acting as a network coordinator. The WBAN consists of five wearable or IMDs-style sensor nodes positioned at the chest and the four extremities. These sensors are Reduced-Function Devices (RFDs) with direct communication capabilities with the hub. Hence, the central hub and WBAN sensor nodes use a single-hop communication architecture. Table 3 provides detailed information about the sensors.

The hub performs advanced functionalities such as synchronizing with nearby WBAN sensor nodes, allocating time slots, and exchanging control messages. On the other hand, the RFD sensor nodes are responsible for detecting and transmitting the gathered data to the central hub. The WBAN sensor nodes operate on battery power and have limited energy resources, while the hub is assumed to have an external power supply with higher processing capabilities. The hub receives data from the sensor nodes. Subsequently, it transmits the received data to a monitoring station or server through alternative networks, such as cellular, Wireless Local Area Network (WLAN), or wired connections. Nevertheless, this communication paradigm is beyond the scope of this work, as the main focus is to design a MAC protocol for a single-channel intra-WBAN transmission. The primary concern of our study is on the MAC layer of the sensor nodes, where the communication is organized into superframes. The network functions according to the IEEE 802.15.6 standard in beacon-enabled mode with superframes.

Assuming that all sensor nodes and hub are within the transmission range of each other and able to communicate directly, any possible hidden node problems are disregarded. External interference is assumed to be negligible, as interference mitigation schemes are typically relevant in two-hop star topologies within individual WBAN. Notwithstanding, the potential for packet loss resulting from channel fading, packet collisions, or buffer overflow is prominent in WBAN environments.

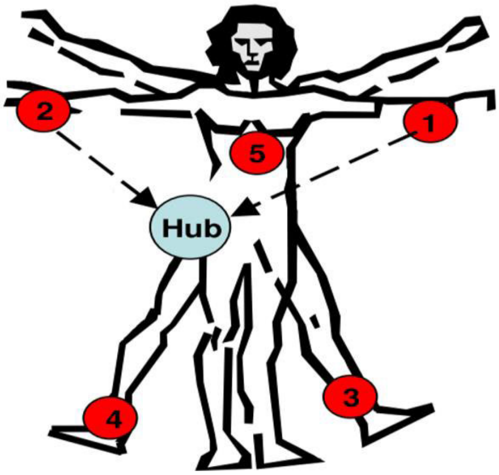


FIGURE 2. Single-hop star topology network [49].

TABLE 3. Sensors information.

Device	Sensor Type	Location	Traffic Classification
Hub	Network coordinator	Rip hip	-
Node (1)	Pulse oximeter (SPO$_2$)	Left wrist	Emergency
Node (2)	Blood pressure	Right wrist	Periodic
Node (3)	Motion sensor	Left ankle	Periodic
Node (4)	Skin temperature	Right ankle	Periodic
Node (5)	Electrocardiogram (ECG)	Chest	Emergency

B. TRAFFIC CLASSIFICATION

The ADT-MAC protocol is designed to provide QoS support for dynamic medical traffic requirements in WBAN by addressing both periodic and emergency events. Typically, the traffic rates are stable and relatively low during periodic monitoring (1 to 20 p/s), but can surge to very high levels during emergencies (50 to 100 p/s) [24]. On-demand traffic, such as voice and video, is triggered by user-initiated actions or healthcare requests [50]. For example, a remote doctor may initiate a video call or voice communication with a patient deploying WBAN devices, prompting the terminals to stream data. Voice packets are typically modeled using a Constant Bit Rate (CBR), as they generate packets at fixed intervals [51]. Voice data is encoded using a CBR codec, for instance, a G.726 encoder, which produces packets at a consistent rate. Conversely, video packets are characterized by irregular or bursty arrivals, which are often modeled using a Poisson distribution. Video encoded with a Variable Bit Rate (VBR) codec produces variable packet sizes and generation rates, with more complex scenes generating higher packet volumes and creating a traffic pattern similar to Poisson arrivals [52].

The ADT-MAC protocol employs the CBR model for periodic traffic and the Poisson model for emergency scenarios, which is inherently applicable to on-demand traffic as well. Since QoS requirements for vital sign monitoring can fluctuate between periodic and emergency situations, traffic classification is inherently context-dependent. To address this variability, health sensing data is categorized into four distinct traffic types, as summarized in Table 4.

- Type–0 (T0): T0 traffic refers to emergency data with stringent QoS requirements, particularly in terms of packet delay and reliability. This type of traffic is event-driven, typically triggered by life-threatening conditions. For instance, a severe drop in oxygen saturation or sudden abnormalities in heart activity may indicate critical health issues that necessitate immediate intervention. In such cases, T0 traffic demands rapid and highly reliable transmission to support timely medical responses.
- Type–1 (T1): T1 traffic requires soft QoS criteria, encompassing real-time medical data such as systolic and diastolic pressure measurements. Significant fluctuations in these parameters, such as high blood pressure or hypotension can indicate severe conditions like a stroke or shock. Thus, T1 traffic must be delivered with high reliability within specific deadlines.
- Type–2 (T2): T2 traffic involves continuous real-time medical data, such as skin or body temperature monitoring, necessitating high-reliability delivery within specified deadlines. Applications in this category typically have less stringent energy consumption, delay, and reliability constraints than T1 applications.
- Type–3 (T3): T3 traffic encompasses applications generating low data rate traffic, such as motion or gyroscopic sensors. These applications exhibit comparatively relaxed energy consumption, delay, and reliability requirements in relation to T1 and T2 applications.

TABLE 4. Traffic classification.

Traffic Classification	Traffic Type	Traffic Event	UP$_i$
Emergency	T0	Emergency medical data	7
Periodic	T1	High-priority medical data	6
	T2	Medium-priority medical data	5
	T3	Low-priority medical data	4

C. CONNECTION PROCEDURE

In this study, establishing a connection between a sensor node and the network is a prerequisite for transmitting sensor data to the hub. The time-sequence diagram of the connection procedure is depicted in Figure 3. The connection process employs the RAP, which uses a CSMA/CA method to transmit the connection request frame to the hub. According to the IEEE 802.15.6 standard, the hub can configure all access phases to zero, except for RAP, which is necessary for node association and disassociation with the network.

A disconnected node begins the frame transactions when it receives a beacon frame from the hub. The node transmits a connection request frame to the hub, identifying Unconnected_NID as the Sender Identifier (ID) field in the MAC header and providing the required allocation size for each slot interval. In the Recipient ID field of the Immediate Acknowledgment (I-ACK) frame, the hub replies with a Connected_NID. Upon receiving the authorized Node Identifier (NID) through the I-ACK frame, the node's association state transitions to UNCONFIRMED until the connection assignment frame is received. In order to fulfill the required link allocation and finish the connection process, the hub transmits a connection assignment frame that includes the link assignment Information Element (IE). The IE defines the start and end points of the allocation interval, which determines the authorized scheduled uplink interval by the hub during the scheduled-access period. After receiving the connection assignment frame, the node promptly responds with an I-ACK frame and modifies its linking status to CONNECTED. After completing the connection procedure for each node, the hub must transmit a beacon frame to all sensor nodes within the network to start the data transmission process.

Certain sensor nodes experience challenges in establishing a connection with the WBAN. The problems primarily arise from two factors: (1) The inability to transmit or receive connection requests or assignment frames, particularly in scenarios involving a high number of nodes or when encountering significant signal attenuation due to deep fading or body shadowing. (2) Failure to detect the hub's initial beacon due to delayed arrival or wake-up. To mitigate these issues, the ADT-MAC protocol includes a RAP phase in each superframe for handling the connection procedure in WBAN. The unconnected nodes remain awake to receive subsequent beacons and initiate the connection requests during the next RAP phase. Since all nodes and the hub share a common time reference with sequentially numbered slots, the hub can accurately determine the interval start and end for each node. This approach ensures efficient management of connection intervals and robust communication.

D. ADAPTIVE SUPERFRAME STRUCTURE

ADT-MAC protocol adopts an adaptive superframe structure that exploits a hybrid channel access method to optimize resource utilization while satisfying diverse QoS requirements. To accommodate dynamic medical traffic loads, the ADT-MAC protocol modifies the superframe structure of the IEEE 802.15.6 standard. It operates in one of the following three superframes, namely Superframe–1, Superframe–2, and Superframe–3, as illustrated in Figure 4.

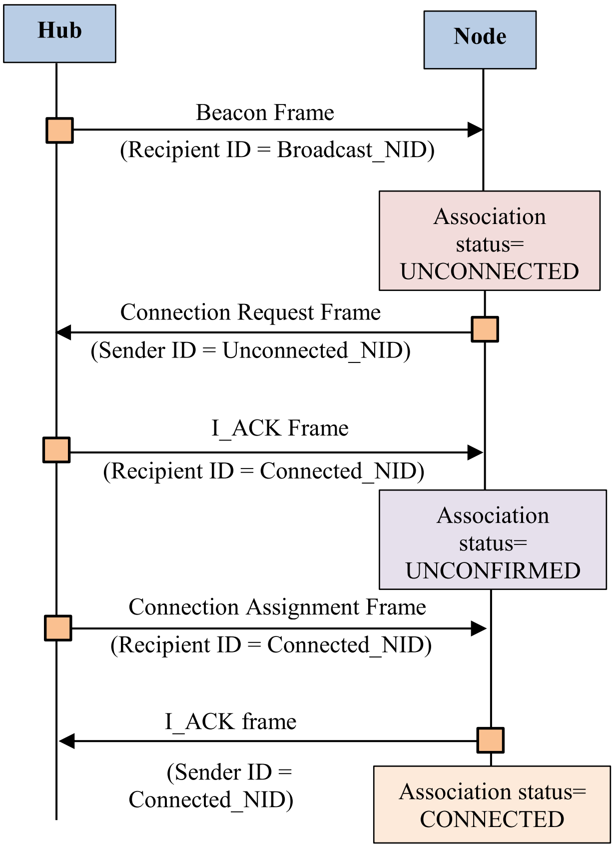
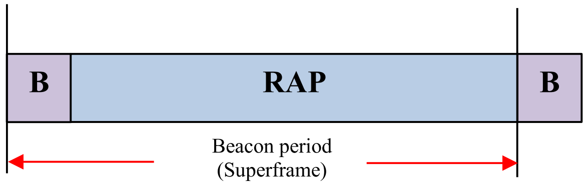


FIGURE 3. Connection procedure.

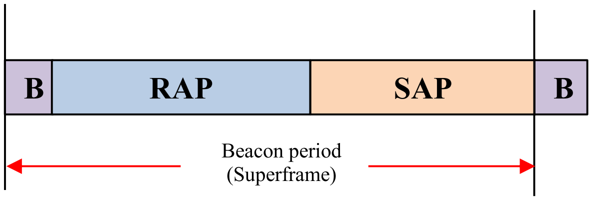
During the beacon phase, the hub broadcasts a beacon frame to all sensor nodes in the network to achieve clock synchronization. Upon receiving the beacon, each node synchronizes its operations with the hub. Before data transmission, sensor nodes undergo connection request and connection assignment procedures in the RAP slots using the CSMA/CA scheme to join the communication network. The superframe structure relative to this initialization phase only consists of the beacon and RAP periods, as depicted in Figure 4(a). The ADT-MAC protocol allocates a fixed RAP size, as defined by the IEEE 802.15.6 standard. RAP must consistently present in each superframe to ensure a dedicated portion for facilitating connection establishment and enhancing the overall communication process. After all sensor nodes are integrated into the WBAN, data transmission begins based on dedicated slots assigned according to the node priority levels, following a TDMA scheme.

1) PERIODIC TRAFFIC ($4 \leq UP \leq 6$)

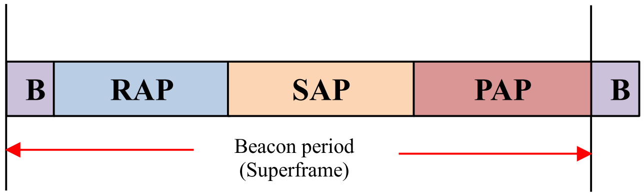
In ADT-MAC protocol, periodic traffic is classified into three types, namely T1, T2, and T3, as outlined in Table 4. To achieve traffic prioritization, the data types are mapped in



a) Superframe-1



b) Superframe-2



c) Superframe-3

FIGURE 4. **Adaptive superframe structure of ADT-MAC.**

the following order: T1 $- >$ Priority-1 (P1), T2 $- >$ Priority-2 (P2), and T3 $- >$ Priority-3 (P3), respectively. Sensor nodes transmitting periodic traffic follow a CBR model. For WBAN medical applications, where normal traffic is typically periodic, a TDMA-based approach is well-suited, as sensor nodes access the medium in a duty cycle. Although the scheduling complexity is considered a major drawback of TDMA-based MAC protocols in scalable networks [53], this is not a significant concern for WBAN, which is a short-range and non-scalable network. To manage periodic traffic, the superframe consists of a beacon, RAP, and Scheduled Access Period (SAP), as shown in Figure 4(b). As described in **Algorithm 1**, in SAP, the ADT-MAC protocol employs a priority-based TDMA scheme with a dynamic slot allocation strategy, ensuring that CBR traffic is efficiently served. The allocation slots are adjusted based on sensor node requirements, such as traffic priority and traffic rate. This approach allows for flexible scheduling within each TDMA round rather than relying on a fixed or static transmission order. In addition, the proposed MAC protocol prioritizes sensor nodes with higher-priority traffic over lower priority, ensuring better QoS performance. By adapting to varying traffic priority and traffic rates, the proposed MAC protocol efficiently allocates resources and enhances overall network performance and reliability.

2) EMERGENCY TRAFFIC (UP = 7)

In emergencies, the traffic rate of sensor nodes increases and becomes random, following a Poisson model [44]. Initially, the WBAN operates under normal conditions with sensor nodes using a CBR traffic model, where each node selects a traffic rate within the range of 1 to 20 p/s, with static inter-arrival time. When an emergency is detected, the traffic rate switches abruptly from CBR to a Poisson distribution with exponentially distributed inter-arrival times. This model can also be applied to video traffic, as it accurately represents the bursty and sporadic nature of on-demand video data transmission. Figure 4(c) shows the superframe structure for managing emergency traffic, which comprises a beacon, RAP, SAP, and Polling Access Period (PAP). The first transmission uses TDMA access, while subsequent transmissions utilize polling access. During SAP, emergency packets are transmitted immediately if a slot is available. If the slot is occupied by periodic traffic, the emergency node can seize the slot, with periodic traffic deferring its transmission. ADT-MAC manages the emergency traffic in a preemptive manner. When the hub receives a packet with the More Data field set to one ($\mathit{More\ Data} = 1$), indicating that a sensor node has additional data to transmit, it allocates an extra time slot to the respective sensor node. The hub communicates this by embedding future poll messages in the ACK packet, notifying the node that a poll will be sent in the next available slot. Each poll allocates a single time slot, allowing nodes to receive multiple polled slots within a superframe based on their transmission needs. This mechanism, facilitated by the PAP, ensures efficient resource allocation and timely data delivery for sensor nodes with pending transmissions.

ADT-MAC protocol adaptively selects the superframe structure based on the traffic types of the nodes. The transition between different superframe structures is depicted in Figure 5. The first transition, T_{1-2}, occurs from Superframe-1 to Superframe-2. The Superframe-2 manages both periodic and emergency traffic, with emergency traffic being prioritized in a preemptive manner. In this phase, emergency nodes can seize slots allocated to periodic traffic. Given the high rate of emergency traffic, the hub detects a ($\mathit{More\ Data} = 1$), which indicates additional data transmission requirements from the sensor nodes. In response to this condition, the hub initiates the second transition, T_{2-3}, which involves the inclusion of a beacon, SAP, and PAP phases. This superframe structure facilitates the transmission of additional emergency traffic packets using a polling-based method. Once the emergency situation is resolved, the hub reverts to the previous superframe structure through the T_{3-4} transition to transmit periodic traffic.

3) ALGORITHM 1

Let S_i represent the slots assigned to each node N_i, and E_i denote the additional slots allocated to N_i. The minimum number of slots each node can receive is defined as S_{min}. The threshold rule is as follows: if the total number of nodes in the network is less than eight ($N < 8$), each node N_i receives at least two slots ($S_{min} = 2$); otherwise, each node receives at least one slot ($S_{min} = 1$) or no slots are allocated to any node. At the start of each TDMA round, the hub guarantees

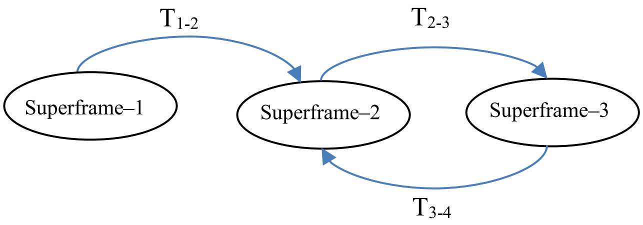


FIGURE 5. State transition diagram.

the allocation of S_{min} to each N_i. The hub then sorts the nodes based on their priority levels and traffic rates. For the next round, slots are assigned using the formula $S_i = S_{min} + E_i$ for each N_i. During the allocation process, the hub subtracts E_i from the total of available extra slots, $E_s \longleftarrow E_s - E_i$. After this first allocation, if $E_s > 0$, the hub assigns one additional slot to each node, $S_i = S_{min} + 1$, until $E_s = 0$. The number of extra slots E_i assigned to each node N_i depends on the total available extra slots E_s and is proportional to the node's contribution to the overall traffic. The relationship is defined as

$$E_i = \left(\frac{T_i}{T_{total}}\right) x E_s \tag{1}$$

where T_i is the traffic rate of node N_i and T_{total} is the sum of the traffic rates of all nodes.

E. DATA TRANSMISSION TIME

The structure of the Physical Layer Protocol Data Unit (PPDU) defined by IEEE 802.15.6 is depicted in Figure 6. According to the PHY technologies demonstrated in IEEE 802.15.6, the total duration of a packet transmission in time, T_{packet} is comprises of the symbols of the Physical Layer Convergence Protocol (PLCP) preamble ($N_{preamble}$), PLCP header (N_{header}), and Physical Layer Service Data Unit (PSDU) which is expressed as

$$T_{packet} = T_s \times \left(N_{preamble} + N_{header} \times S_{header} + \frac{N_{total}}{log_2(M)} \times S_{PSDU}\right) \tag{2}$$

where T_s is symbol duration, $N_{preamble}$ and N_{header} is the length of the PHY layer preamble PLCP header in bits, S_{header} is the spreading factor of the PLCP. The symbol M, is the modulation constellation size and S_{PSDU} is the spreading factor of PSDU.

N_{total} is the number of interleaved bits, which is computed as

$$N_{total} = N_{PSDU} + N_{CW} \times (n - k) + N_{pad} \tag{3}$$

N_{PSDU} is the actual payload and is calculated as

$$N_{PSDU} = N_{MACHeader} + N_{MACFrameBody} + N_{FCS} \tag{4}$$

Finally, N_{pad} is the number of pad bits which is evaluated as

$$N_{pad} = log_2(M) \times \frac{(N_{PSDU} + N_{CW} x (n - k))}{log_2(M)} - (N_{PSDU} + N_{CW} \times (n - k)) \tag{5}$$

where the MAC header, $N_{MACHeader}$ consists of 7 octets, $N_{MACFrameBody}$ is the actual payload which can be maximum up to 256 bytes, and N_{FCS} is the number of frame check sequence composed of two octets. N_{CW} is the Bose–Chaudhuri–Hocquenghem (BCH) code word which is equal to N_{PSDU}/k, where k is the message bits for the selected BCH code. N_{CW} is set to zero for the case of un-coded transmission. The term $(n - k)$ is the number of parity bits, where $n = 63$ and $k = 51$ [5], [54]. For un-coded transmission, N_{pad} will be always equal to 0.

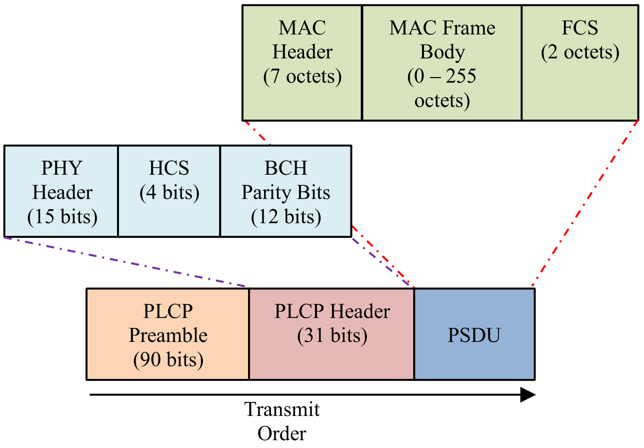


FIGURE 6. NB-PHY layer frame structure in IEEE 802.15.6 standard.

The mean time for successful transmission, T_x and time duration for unsuccessful transmission attempt, $T_{failure}$ is obtained by the following [55], [56], [57]

$$T_x = T_{data} + T_{ACK} + T_{SIFS} \tag{6}$$

$$T_{failure} = T_{data} + T_{SIFS} + T_{preamble} + T_{timeout} \tag{7}$$

where T_{SIFS} is the Short Inter Frame Space (SIFS) duration, T_{ACK} is the time duration of the ACK frame, $T_{preamble}$ is the time to receive the preamble and $T_{timeout}$ is the time out duration.

ADT-MAC protocol allows for one retransmission attempt if the initial transmission fails. In our simulation, a 128-byte packet requires 1 ms for transmission using BAN radio. The packets transmission time, T_{data} is calculated as

$$T_{data} = \frac{L}{R} = \frac{(128 \times 8)bits}{1024Kbps} = 1ms \tag{8}$$

where L is the packet size in bits and R is the packet rate in Kbps.

In the ADT-MAC protocol, all packets require acknowledgment. The total transmission time for each packet, T_x including transmission, acknowledgment, and radio state transition times ($T_{data} + T_{ACK} +$ radio state transition times), is 1.16 ms. This includes the radio state switching times between transmission and reception, plus two SIFS, as formulated in (6). Based on the simulation parameter in Table 5, the slot allocation length is 10 ms, allowing for the transmission of up to eight packets per slot. Therefore, we assume that each slot can accommodate eight packets.

F. PRIORITY QUEUING MODEL IN SIMEVENTS

WBAN requires robust queuing strategies to prioritize emergency packets and ensure effective QoS for high-priority traffic. As discussed in [57] and [58], priority queuing models are crucial for fulfilling QoS requirements in wireless networks. These models classify packets into priority queues, where the schedulers process higher-priority packets before lower-priority packets.

This section introduces a non-preemptive M/M/1 queuing algorithm to determine the packet delay for each priority queue of periodic traffic in the ADT-MAC protocol. Our proposed algorithm is modeled using SimEvents, which is a specialized simulator for constructing and analyzing discrete-event system models. SimEvents is an extension of MATLAB, which provides a comprehensive library of pre-built blocks, such as queues, servers, gates, and switches, that can be interconnected in a block diagram similar to Simulink models. This tool facilitates the collection and analysis of performance metrics such as waiting time, resource utilization, and network throughput, which are essential for network operation optimization and performance evaluation.

To the best of our knowledge, no prior studies have used SimEvents as a mathematical framework for WBAN performance analysis. Thus, we developed our proposed mathematical model using SimEvents. The model prioritizes emergency packets over non-emergency packets, adhering to a non-preemptive priority rule where ongoing transmissions are not interrupted.

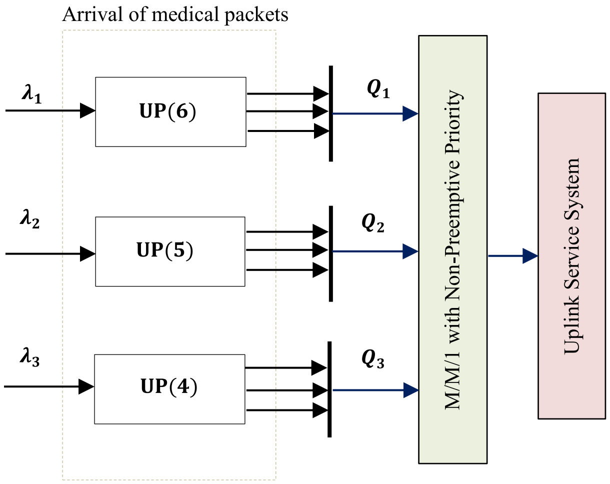


FIGURE 7. Queuing model architecture of ADT-MAC.

We consider three types of traffic arriving at the sensor node, categorized into k-priority queues, Q_k, where $k = 1, 2, 3$, with Q_1 representing the highest-priority. The architectural framework of the queuing model for ADT-MAC is presented in Figure 7, with its implementation in SimEvents depicted in Figure 8. Traffic arrivals at sensor nodes are modeled using Poisson distribution, simplifying queue performance analysis. We denote the Poisson traffic arrival rate of queue-k at time t as $\lambda_k(t)$. The inter-arrival time of a Poisson traffic arrival process is an exponential random variable represented as

$$\lambda_k(t) = \frac{1}{(Mean\ Inter - arrival)} \tag{9}$$

In our proposed scheme, sensor nodes enter idle state after completing scheduled transmission slots while other nodes are scheduled for transmission. From a queuing perspective, this idle state is viewed as the server's vacation. Each queue takes T_{slot} to complete one frame transmission, which is written as

$$T_{slot} = T_x = T_{data} + T_{ACK} + T_{SIFS} \tag{10}$$

Thus, the service rate, $\mu_k(t)$ of the queue-k at the time t is given as

$$\mu_k(t) = \frac{1}{T_{slot}} \tag{11}$$

where, the service time is defined as the total time to transmit a packet, T_{slot} including the time to transmit a data packet, T_{data}, SIFS duration, T_{SIFS} and the time of acknowledgment packet, T_{ACK}.

V. PERFORMANCE EVALUATION

The performance of the ADT-MAC protocol is compared against IEEE 802.15.6-MAC [5], DMTM-MAC [27], McMAC [28], and TA-MAC [29]. These protocols are selected for comparison due to their conceptual similarities with the main features of the proposed scheme. DMTM-MAC is a recent protocol that prioritizes emergency traffic and employs a dynamic superframe structure based on traffic demand, which is aligned with the traffic-adaptive approach of ADT-MAC. McMAC and TA-MAC focus on traffic classification to address diverse QoS requirements, which is a core aspect of ADT-MAC. IEEE 802.15.6-MAC is chosen as a benchmark, as the ADT-MAC protocol is based on its superframe structure. Additionally, the unresolved problems of fixed slot allocation in IEEE 802.15.6 standard for WBAN communication necessitate its inclusion in the performance evaluation of the proposed protocol.

This study does not include a scalability test, as it focuses on a single WBAN MAC protocol for intra-WBAN communication with a limited number of sensor nodes in a small deployment area. Scalability is typically addressed in large-scale sensor networks through inter-WBAN communication, where multiple WBANs coexist within the same area.

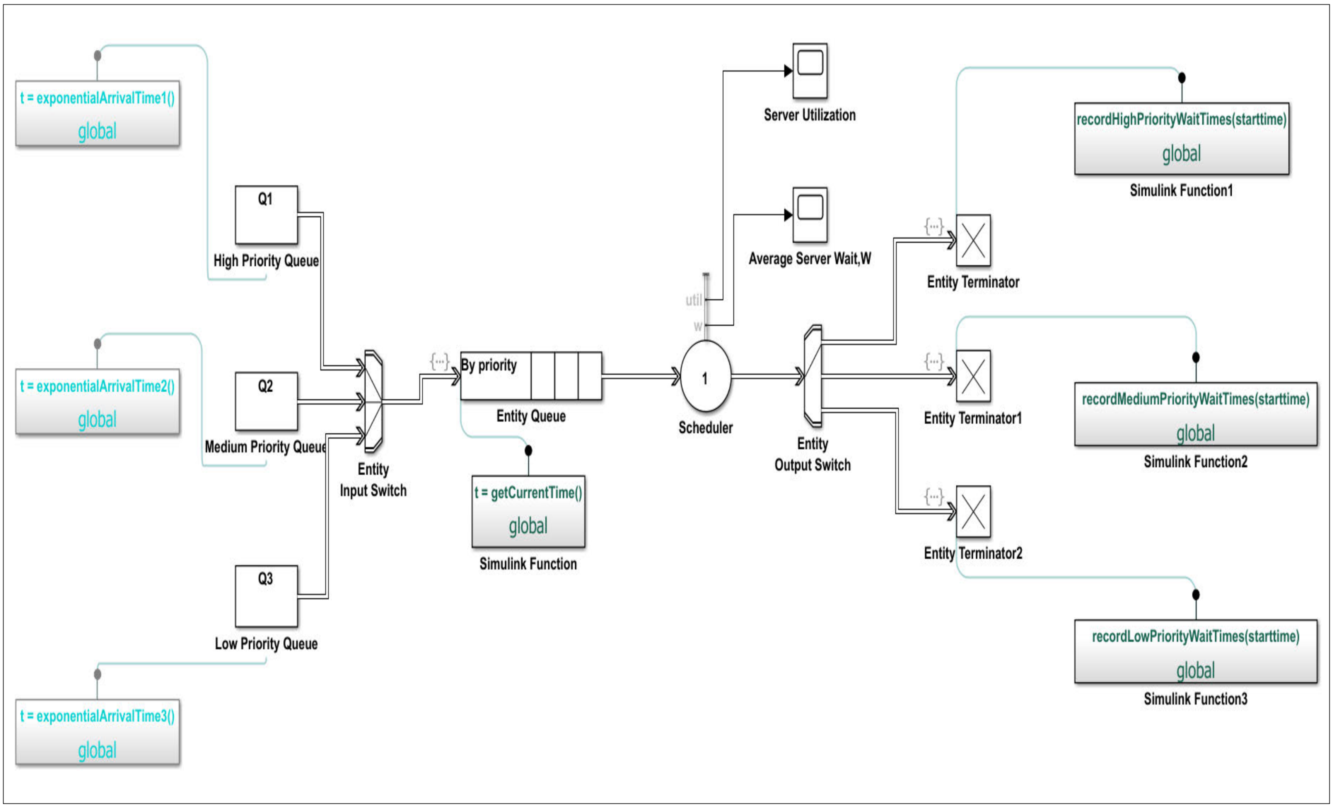


FIGURE 8. Queuing model of the ADT-MAC in SimEvents.

In real-world implementation, scalability poses several challenges, such as increased signal interference among WBAN, which can reduce throughput, increase energy consumption, and diminish network efficiency. Additionally, ensuring seamless integration of WBAN sensors across diverse software platforms and operating systems remains a significant challenge from an interoperability perspective. The following sub-sections present the simulation setting, metrics for evaluating the ADT-MAC, results, and discussion.

A. SIMULATION SETTING

The performance of the ADT-MAC protocol is evaluated using a two-fold simulation approach.

First, Castalia and OMNeT++ simulators are used to assess the key performance metrics, such as PDR, packet delay, network throughput, and energy consumption. Castalia is chosen for performance evaluation as it supports the WBAN by offering the IEEE 802.15.6 standard, which is not supported by the other simulators. It provides a specific scenario for WBAN and the basic characteristics of the IEEE 802.15.6 standard. For these reasons, the Castalia open-source simulator is used as the simulation tool for the evaluation experiments. The attained results are compared with benchmark protocols under identical network conditions to ensure a fair comparison. For IEEE 802.15.6-MAC, the superframe structure employs a fixed slot size, comprising a beacon, five EAP slots for emergency traffic, five RAP slots for connection establishment, and 15 TDMA-MAP slots for periodic traffic.

We simulate a WBAN using a single-hop scenario and a star topology network consisting of a hub and five sensor nodes, as shown in Figure 2. A similar network configuration is also used in [39]. Each sensor node carrying periodic traffic transmits a 105-byte data packet, including overhead, to the hub. Emergency traffic is modeled using a Poisson distribution. Table 5 outlines the simulation parameters for ADT-MAC. The superframe consists of 32 slots per beacon period, with each slot having a duration of 10 ms, which are used in [27] and [39]. The receiver sensitivity is -87 dBm, and the transmission power is -10 dBm. The Body Area Network (BAN) Radio is used for a simulation duration of 300 seconds, with three repetitions to mitigate the randomness of time deviations in packets transmitted by the application layer. The radio chipset functions in the 2.4 GHz frequency spectrum to send data at a rate of 1,024 Kbps, providing reliable wireless connectivity. The maximum capacity of the MAC buffer is 48 packets. All the parameters mentioned are set by referencing [59]. The SAP and PAP slots are dynamically adjusted based on hub-collected information. The RAP length is fixed following the specifications outlined in the IEEE 802.15.6 standard, with two RAP slots allocated for effective WBAN operation. In addition, the study assumes non-temporal path loss variations during the simulation.

The application layer generates both periodic and emergency traffic. Periodic traffic, which represents the normal situation, uses a CBR model, with sensor nodes generating between 1 to 20 p/s to simulate low to moderate traffic conditions [20]. On the other hand, emergency traffic follows a Poisson model to simulate random packet arrivals, with the traffic rate set between 50 to 100 p/s to approximate very high traffic conditions [39]. The emergency scenarios occur during two distinct simulation periods, as shown in Table 6, with two nodes (Node 1 and Node 2) designated for emergency situations.

TABLE 5. Simulation parameters.

Parameters	Value
Frequency Band	2.4 GHz
Simulation Area	3 x 3 m^2
Radio	BAN Radio
Simulation Time	300 s
Number of Nodes	6 (1 hub and 5 sensor nodes)
Periodic Traffic Model	CBR
Emergency Traffic Model	Poisson
Traffic Rate for Periodic Traffic	1–20 p/s
Traffic Rate for Emergency Traffic	50–100 p/s
Superframe Length	32 slots
RAP Length	2 slots
SAP Length	15 slots
PAP Length	15 slots
Slot Size	10 ms
Transmission rate	1,024 Kbps
MAC Buffer Size	48 packets
Receiver Sensitivity	-87 dBm
Transmission Power	-10 dBm
IEEE 802.15.6-MAC Related Configurations	
RAP Length	5 slots
EAP Length	5 slots
TDMA Length	15 slots

TABLE 6. Emergency traffic scenarios.

Time Period (s)	Mean Inter-Arrival (s)	Traffic Rate (p/s)
50 – 100	0.02	50
150 - 250	0.0125	80

Second, we modeled an M/M/1 queueing algorithm with non-preemptive priority using SimEvents in MATLAB simulator to establish a mathematical framework for evaluating the ADT-MAC protocol. Priority queues are distinguished by traffic events to compute the key performance metric, which is packet delay. To validate the accuracy of our proposed model in provisioning the QoS requirements, the results are compared with packet delay measurements obtained from the Castalia simulator. Table 7 presents the mapping of periodic traffic to the queue prioritization. Packet arrivals at each queue follow independent Poisson processes with rates λ_1, λ_2, and λ_3, aligned with packet rates defined in the Castalia simulator. Sensor nodes are assumed to operate under saturated traffic conditions, implying that each node always has at least one packet in its queue ready for transmission. This assumption simplifies the analysis by ensuring continuous packet flow and enabling the investigation of dynamic queuing and prioritization mechanisms under heavy traffic conditions.

TABLE 7. Mapping of periodic traffic to queue prioritization.

Priority Queue	Traffic Type	Priority Level	UP_i	Arrival Rate (p/s), λ_k
Q_1	T1	High (P_1)	6	20
Q_2	T2	Medium (P_2)	5	10
Q_3	T3	Low (P_3)	4	5

B. PERFORMANCE METRICS

In order to achieve an energy-efficient MAC protocol with the desired QoS requirements, the performance of the ADT-MAC protocol is evaluated using the key parameters, namely PDR, packet delay, network throughput, and energy consumption [28], [44].

1) PACKET DELIVERY RATIO (PDR)

The PDR is the ratio of the total number of packets received by the receiver node to the number of packets generated by the sender nodes. Network reliability is analyzed by measuring the PDR, with higher values indicating better protocol performance. Mathematically, the PDR is represented as

$$PDR = \frac{N_{PktRx}}{N_{PktTx}} x100\% \tag{12}$$

where the N_{PktRx} and N_{PktTx} represent the total number of packets received and generated, respectively.

2) PACKET DELAY

The packet delay of a sensor node is the average time taken from the generation of a packet at the sensor node to its reception at the hub. A lower packet delay indicates better performance of the protocol. It is calculated as

$$Delay = \frac{\sum_{i=1}^{N} \sum_{j=1}^{P_{succ_i}} delay_j}{\sum_{i=1}^{N} P_{succ_i}} \tag{13}$$

where N is the number of sensor nodes, P_{succ_i} is the number of successfully delivered packets for the i-th sensor, and $delay_j$ is the j-th packet delivery delay of the i-th sensor.

3) NETWORK THROUGHPUT

The network throughput is defined as the average data transmitted per second, measured in bits per second (bps). It is evaluated as

$$Throughput = \frac{N_{pkt} x L_{pkt}}{t_{sim}} \tag{14}$$

where t_{sim} represents the simulation duration in seconds, and N_{pkt} and L_{pkt} signifies the length of data packets in bits.

4) ENERGY CONSUMPTION

The total energy consumption, E_{total} of a sensor node is the sum of the energy consumed during its communication time across three operational states, which are, transmitting, receiving, and idle. Lower total energy consumption indicates better protocol performance. It is computed as

$$E_{total} = E_{tx} + E_{rx} + E_{idle} \tag{15}$$

where E_{tx}, E_{rx}, and E_{idle} denote the energy consumed in transmitting, receiving, and idle, respectively. In the idle state, a node is inactive to allow other nodes to transmit.

C. RESULTS AND DISCUSSION

The first part of this sub-section presents the performance of the ADT-MAC protocol with varying number of nodes using Castalia and OMNeT++. The ADT-MAC protocol is analyzed and compared with IEEE 802.15.6-MAC [5],DMTM-MAC [27], McMAC [28], and TA-MAC [29]. The comparison has been made in terms of packet delay, PDR, network throughput, and energy consumption. Two types of traffic are considered such as periodic and emergency. Periodic traffic is modeled using a CBR, and emergency traffic follows Poisson distribution. The second part demonstrates the performance of a mathematical framework based on the M/M/1 queuing algorithm with a non-preemptive priority using SimEvents in MATLAB to validate key QoS metrics. The analysis focuses on packet delay across priority queues. The effectiveness of the ADT-MAC protocol in ensuring QoS for different traffic priorities within a WBAN environment is confirmed by comparing the average packet delay obtained from the Castalia simulations and the SimEvents model.

1) PERFORMANCE EVALUATION OF ADT-MAC PROTOCOL FOR VARYING NUMBER OF NODES

The performance of ADT-MAC is evaluated with respect to the increasing number of nodes, which vary from 2 to 12. The simulation is performed in the presence of both periodic and emergency scenarios, with Node 1 and Node 2 carrying the emergency data, as described in Table 6. Considering that each packet requires about $1.16168 \approx 1.16$ ms from the transmission to acknowledgment, therefore each time slot can accommodate up to eight packets.

Figure 9 illustrates the average PDR of the ADT-MAC protocol in comparison to other existing MAC protocols. The results demonstrate that the ADT-MAC is the most reliable protocol and exhibits the lowest packet drop rate. Although PDR decreases as the number of sensor nodes increases due to channel access failures and buffer overflows, ADT-MAC consistently outperforms the other protocols. This superior performance is due to its dynamic slot allocation mechanism during the SAP, which employs a TDMA-based approach to ensure higher slot utilization for periodic traffic. Furthermore, ADT-MAC utilizes a priority-based channel access strategy in the SAP to minimize packet drop in the network. The TDMA-polling access scheme, employed for emergency traffic, further enhances the reliability of ADT-MAC. The proposed scheme increases the probability of successful transmission for both emergency and periodic traffic through efficient slot utilization.

As shown from the results, DMTM-MAC, TA-MAC, and McMAC are less reliable compared to the proposed scheme, as they allow some sensor nodes to access the channel using the CSMA/CA mechanism. As the number of nodes increases, these protocols experience performance degradation due to channel congestion and packet collisions, leading to buffer overflows and increased packet loss. On the other hand, ADT-MAC mitigates these issues by adopting a TDMA-based approach for periodic traffic and a TDMA-polling technique for emergency traffic, which reduces collisions, idle listening, and overhearing. IEEE 802.15.6-MAC exhibits the lowest PDR as the number of nodes increases, mainly due to its fixed slot size in the superframe structure. The fixed slot allocation cannot adapt to unpredictable traffic patterns and varying channel conditions in WBAN communication. Moreover, each sensor node is allocated a fixed number of slots in each superframe, irrespective of its traffic requirements, which leads to slot wastage. Additionally, the emergency traffic is transmitted using CSMA/CA during the EAP, which causes packet collision, increases packet loss, and, therefore, deteriorates the performance of the IEEE 802.15.6-MAC. Furthermore, when the emergency traffic becomes high, the transmission of emergency traffic will deteriorate because the fixed-sized EAP cannot communicate all the data. These factors explain why it performs worse than the other protocols.

The average PDR performance for emergency and periodic traffic across varying numbers of nodes is depicted in Figure 10. DMTM-MAC experiences significant packet drops for emergency traffic, as it relies on CSMA/CA during the EAP period, which results in increased collisions and retransmissions. In contrast, through its TDMA-polling mechanism for emergency traffic, ADT-MAC mitigates the limitations of CSMA/CA and achieves a higher PDR. Additionally, ADT-MAC achieves a high PDR for periodic traffic due to its priority-based channel access strategy during SAP, which further reduces packet loss in the network.

Figure 11 illustrates the average packet delay performance across five MAC protocols. The results indicate that the ADT-MAC protocol consistently outperforms its benchmarks and exhibits the lowest average packet delay at varying numbers of sensor nodes. The superior performance of the proposed scheme is due to its dynamic slot allocation using a TDMA-based approach for periodic traffic, which effectively reduces contention, lowers collision probability, and minimizes packet retransmissions. Furthermore, in emergency

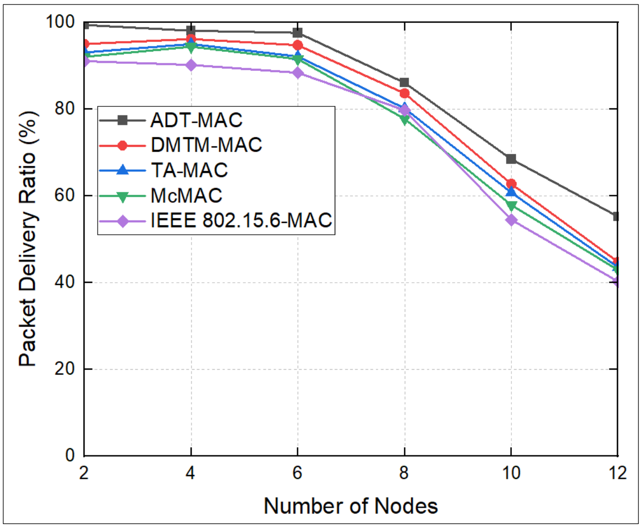


FIGURE 9. Average PDR.

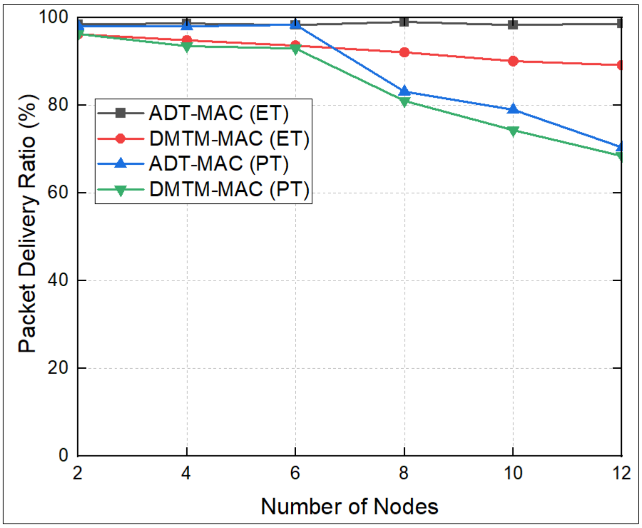


FIGURE 10. Average PDR for emergency (ET) and periodic (PT) traffic.

situations, the ADT-MAC protocol further enhances the WBAN performance by employing a TDMA-polling access scheme that dynamically allocates additional time slots for high data rate transmission.

In contrast, DMTM-MAC, TA-MAC, and McMAC rely on the CSMA/CA mechanism during the contention-access period to reserve time slots, resulting in increased packet delay. These protocols require sensor nodes to continuously monitor the channel for availability before transmitting, contributing to higher delay. DMTM-MAC performs better than TA-MAC and McMAC because it uses TDMA scheme for periodic traffic transmission, which creates a balanced solution, although CSMA/CA is used for emergency traffic transmission. In fact, TA-MAC only uses the CSMA/CA scheme for data transmission and experiences a higher probability of collisions, leading to more retransmissions and longer packet delays. It can be noticed that the performance of IEEE 802.15.6-MAC exhibits the highest packet delay among the compared protocols. This is due to its fixed slot allocation in the superframe structure and reliance on CSMA/CA for channel access, which raises collision probability as the number of nodes increases. This leads to higher contention, packet retransmission, and packet delay. Additionally, emergency traffic is transmitted only during EAP, further increasing the packet delay due to contention, packet collisions, and retransmission.

As can be seen from Figure 12, the ADT-MAC protocol achieves a lower average packet delay for emergency traffic compared to DMTM-MAC. ADT-MAC uses a TDMA-polling scheme for emergency traffic. In contrast, DMTM-MAC relies on CSMA/CA during the EAP, leading to increased packet collisions, retransmissions, and higher packet delay. In addition, the proposed ADT-MAC demonstrates superior performance in handling periodic traffic, which benefits from priority-based channel access and dynamic slot allocation during the SAP using a TDMA approach. This effectively mitigates contention, reduces collision probability, and minimizes retransmissions. Consequently, ADT-MAC outperforms DMTM-MAC in terms of average packet delay for periodic and emergency traffic.

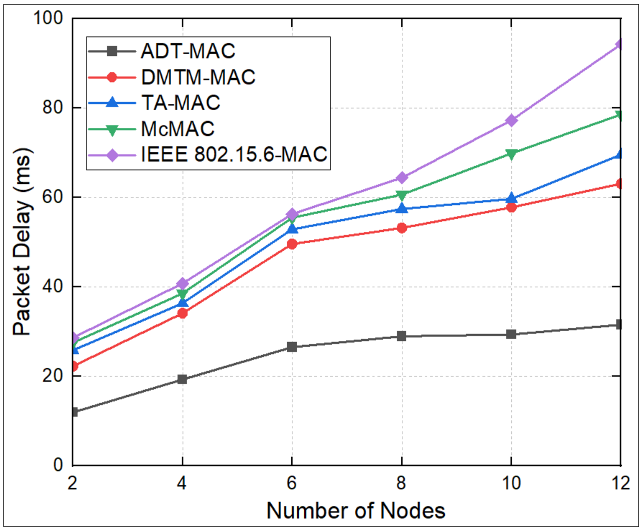


FIGURE 11. Average packet delay.

Figure 13 depicts that the ADT-MAC protocol achieves higher average network throughput compared to other MAC protocols. The network throughput of all protocols increases as the number of sensor nodes rises, which also leads to an increase in the PDR. However, as more sensor nodes are added, the likelihood of collisions and encountering busy channels during the CSMA/CA phases also increases, thereby degrading the overall network throughput for the benchmark MAC protocols. In contrast, the ADT-MAC protocol employs a TDMA-based for periodic traffic and TDMA-polling scheme for emergency traffic, which ensures

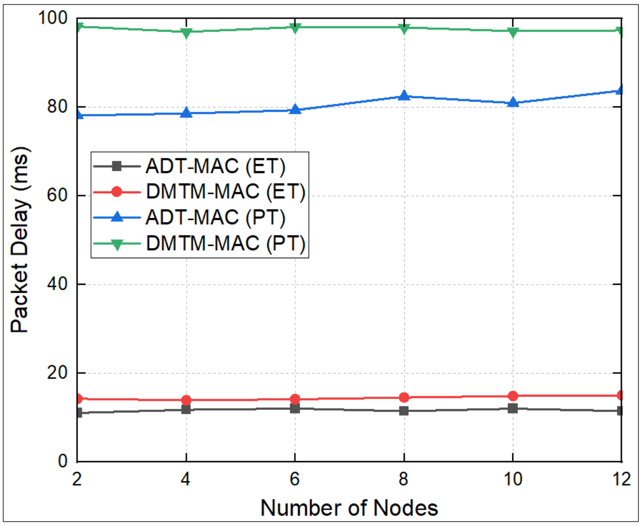


FIGURE 12. Average packet delay for emergency (ET) and periodic (PT) traffic.

higher network throughput even with a larger number of sensor nodes.

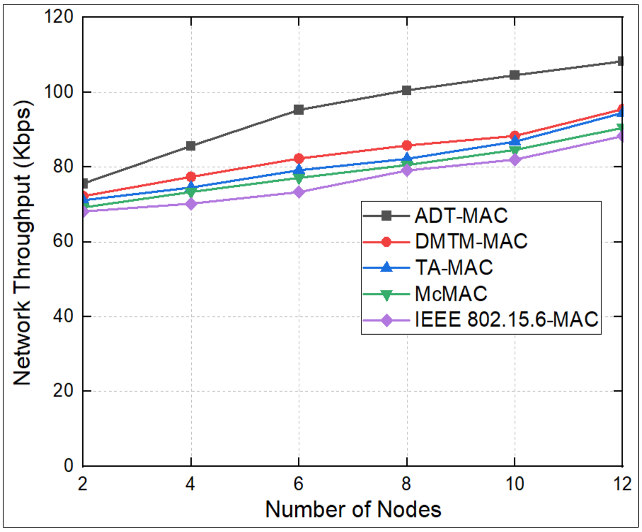


FIGURE 13. Average network throughput.

As shown in Figure 14, the ADT-MAC protocol achieves lower energy consumption compared to DMTM-MAC, TA-MAC, McMAC, and IEEE 802.15.6-MAC across varying numbers of sensor nodes. Energy consumption generally varies according to the behavior of the sensor nodes, with high-traffic networks consuming more energy than low-traffic networks. However, ADT-MAC demonstrates a slight reduction in energy consumption as the number of sensor nodes increases. This reduction is primarily due to two factors: First, each sensor node is allocated a minimum of two slots, and with only 15 scheduled slots available, the network cannot accommodate more than five nodes. Consequently, some nodes do not receive slots for transmission, which reduces overall energy usage. Second, ADT-MAC employs a TDMA-based mechanism with polling access, which allows sensor nodes to conserve energy by entering idle mode when other nodes are scheduled for transmission and avoiding unnecessary packet retransmissions. Furthermore, time slots are allocated based on the specific requirements of each sensor node, which minimizes idle listening and reduces energy dissipation.

In comparison, DMTM-MAC, TA-MAC, and McMAC exhibit higher energy consumption compared to the ADT-MAC, primarily due to the use of the CSMA/CA mechanism during the contention-access period. The continuous collisions detection and avoidance mechanisms inherent in the CSMA/CA approach lead to increased energy consumption. In WBAN, energy is primarily consumed through packet collisions and retransmissions. Moreover, when a large number of sensor nodes are densely deployed in a small area, the increased contention complexity leads to more collisions, which further dissipates energy through packet retransmissions. Among the other MAC protocols, IEEE 802.15.6-MAC demonstrates the highest energy consumption. This is attributed to its fixed slot size and CSMA/CA mechanism, which raises the collisions probability as the number of sensor nodes increases, resulting in higher contention and packet delay.

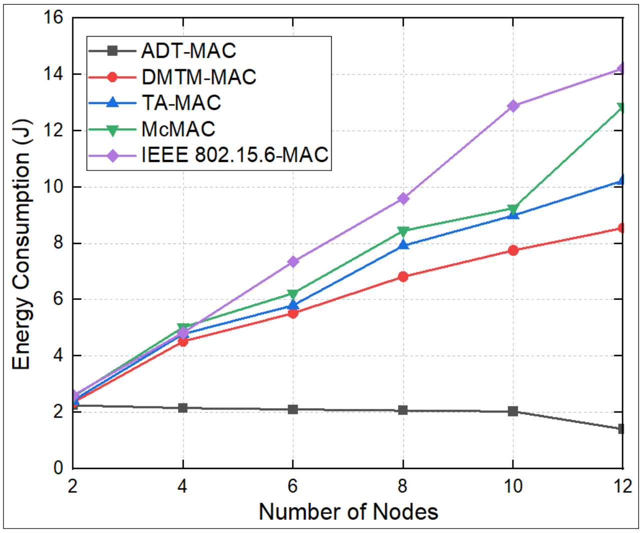


FIGURE 14. Average energy consumption.

Figure 15 illustrates the average energy consumption performance for emergency and periodic traffic across varying numbers of nodes. The results show that the ADT-MAC is more energy efficient than DMTM-MAC. This efficiency is due to the TDMA-based operation for periodic traffic and the TDMA-polling mechanism for emergency traffic in ADT-MAC, where sensor nodes transmit their packets within allocated time slots and remain inactive during other periods. On the other hand, DMTM-MAC uses CSMA/CA during the EAP for emergency traffic transmission, which leads to higher power consumption due to the continuous collisions detection and avoidance required by CSMA/CA. Thus, as the number of nodes increases, energy consumption in DMTM-MAC rises due to increased data processing demands.

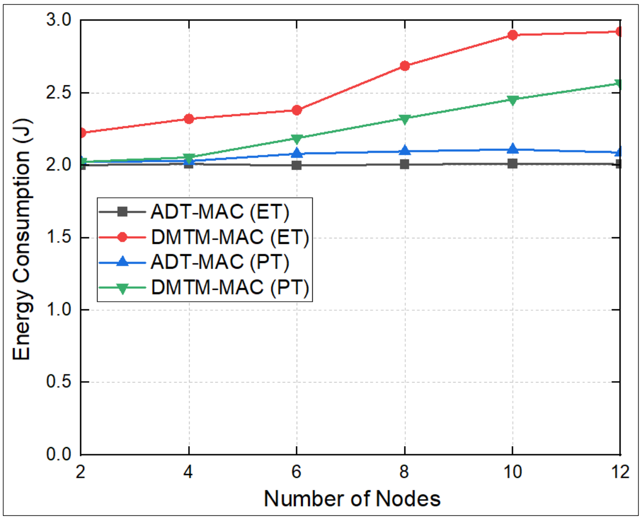


FIGURE 15. **Average energy consumption for emergency (ET) and periodic (PT) traffic.**

In WBAN, achieving high QoS requires reliable communication with minimal packet loss, low packet delay, and sufficient network throughput to support diverse traffic types, including periodic and emergency data. The proposed ADT-MAC protocol addresses the trade-offs between QoS and energy consumption through an adaptive superframe structure with a hybrid channel access method. It employs a TDMA-based approach for periodic traffic, ensuring efficient slot utilization and network throughput, even with increased sensor nodes. Furthermore, a TDMA-polling access scheme dynamically allocates additional time slots for high data rate transmission for emergency traffic, enhancing reliability and minimizing packet drops. Energy efficiency is achieved by reducing unnecessary retransmissions and idle listening through tailored slot allocations and allowing nodes to enter idle mode during inactive periods. Slot allocation constraints inherently limit the number of active nodes, further reducing energy consumption as unused nodes remain inactive.

2) PERFORMANCE EVALUATION USING AN M/M/1 QUEUING ALGORITHM WITH A NON-PREEMPTIVE PRIORITY

To validate the accuracy and efficiency of the ADT-MAC protocol, simulations are conducted for all three priority queues listed in Table 7, utilizing Castalia and SimEvents simulators. The results are shown in Figure 16, with a summary of the average packet delay obtained from both simulators presented in Table 8. The high-priority traffic (P_1 and Q_1) consistently exhibits the lowest average packet delay of 23.79 ms and 22.91 ms, respectively. In contrast, medium-priority traffic (P_2 and Q_2) shows slightly higher average packet delay of 44.07 ms and 45.17 ms, respectively. Meanwhile, low-priority traffic (P_3 and Q_3) experiences the highest average packet delay of 82.88 ms and 82.81 ms. These results demonstrate that P_1 and Q_1 exhibit the lowest average packet delay throughout the simulation, followed by P_2, Q_2, P_3, and Q_3.

This performance verifies that P_1 and Q_1 represent the high-priority traffic in the ADT-MAC protocol, where these packets are prioritized and transmitted first, followed by medium and low-priority traffic. Consequently, these packets experience smaller delay and shorter waiting times within the network, ensuring the timely delivery of emergency and time-sensitive medical data. Prioritizing high-priority traffic is crucial in scenarios where rapid data transmission can significantly impact patient outcomes, as delays in transmitting high-priority medical information could result in severe health risks. Additionally, the performance of the ADT-MAC aligns with theoretical expectations across different priority levels and effectively manages traffic prioritization, with high-priority packets experiencing lower delay compared to low-priority ones.

TABLE 8. **Comparison of average packet delay performance.**

Priority Level	Average Packet Delay (ms) - Castalia	Priority Queue	Average Packet Delay (ms) - SimEvents
P_1	23.79	Q_1	22.91
P_2	44.07	Q_2	45.17
P_3	82.88	Q_3	82.81

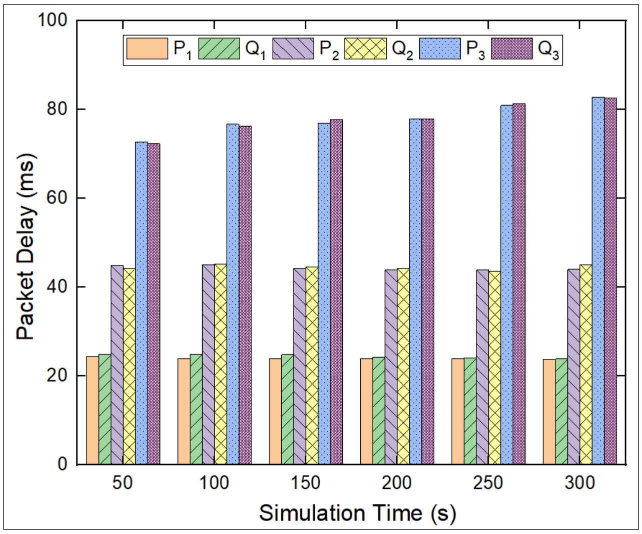


FIGURE 16. **Average packet delay obtained from Castalia and SimEvents.**

Furthermore, all traffic priority levels maintain an average delay below the 125 ms threshold specified in the IEEE 802.15.6 standard, demonstrating the ability of the protocol to meet stringent QoS requirements across all traffic classes. This behavior supports the theoretical analysis of the network performance. The close correspondence between results from Castalia and SimEvents validates the accuracy and reliability of the proposed non-preemptive M/M/1 queueing algorithm. The observed correlation between priority levels and packet delay highlights the significant impact of queuing priority on network performance metrics, underscoring the effectiveness of the non-preemptive priority queueing model in differentiating service levels.

VI. CONCLUSION AND FUTURE WORK

This paper introduces a novel ADT-MAC protocol designed specifically for WBAN applications to fulfill the QoS requirements of the IEEE 802.15.6 standard. The proposed protocol demonstrates enhanced QoS performance compared to the DMTM-MAC, TA-MAC, McMAC, and IEEE 802.15.6-MAC protocols through an adaptive superframe structure incorporating priority-based and dynamic slot allocation for dynamic medical traffic. Additionally, the ADT-MAC protocol reduces energy usage by implementing an efficient slot allocation method through TDMA and a polling approach. The average packet delay acquired through simulations in Castalia and SimEvents demonstrates effective traffic prioritization across both platforms, validating the effectiveness of the ADT-MAC protocol in managing diverse priority levels within a WBAN environment. The ADT-MAC adequately differentiates service levels based on traffic priority while adhering to the 125 ms delay threshold set by the IEEE 802.15.6 standard for all priority levels. By addressing the dynamic medical traffic through an adaptive, energy-efficient, and QoS-aware solution, ADT-MAC shows a promising solution for WBAN applications, particularly in healthcare scenarios requiring timely and reliable data transmission. As for our future direction, we recommend extending the ADT-MAC protocol to facilitate multi-hop communication, thus enhancing its applicability and scalability support for extensive WBAN deployments. The continuous advancement of the ADT-MAC protocol could also establish an IoT-enabled WBAN framework by connecting to cloud-based platforms or edge-computing systems powered by Artificial Intelligence (AI) and Deep Learning (DL) through IoT networks such as 4G/5G/6G technologies. This advancement enhances diagnostics, enables anomaly detection, and supports personalized healthcare solutions, positioning the ecosystem as a transformative approach to modern healthcare delivery.

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