

Original Article

Channel Allocation in WBAN: Dynamic TDMA-FDMA with Mobility Consideration

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Abstract - The need of Wireless Body Area Networks (WBANs) has raised due to technological advancements, cost-effective medical services, and the rising prevalence of diseases that require real-time health monitoring systems. The sensors involved in WBANs are affordable and portable, but resource-constrained. Sensors in WBANs for real health monitoring experience mobility along the body during activity, while some are implanted in the body to collect data, handling sensitive human medical information. Therefore, reliability and energy efficiency are critical performance metrics. Medium Access Protocol plays an important role in conserving energy and enhancing reliability in the dynamic environment of WBAN. Challenges of the WBAN in the MAC layer include static allocation, unfair channel allocation, and inefficient channel utilisation. We proposed a Dynamic TDMA-FDMA Channel Allocation protocol for a dynamic WBAN environment. The mobility of nodes, data rate, and data availability are factors in deciding on the channel allocation, helping to reduce idle waiting time and collisions. Highly mobile sensor nodes with unstable connections will access the channel frequently to maintain reliability. In terms of delay, reliability, and energy efficiency, the proposed MAC protocol outstrips the existing protocols.

Keywords - Medium Access Control protocol, Reliability, Energy-efficiency, Delay, WBAN, Mobility-aware.

1. Introduction

A type of Wireless Sensor Network (WSN) designed for body-centric applications is the Wireless Body Area Network (WBAN), which integrates portable devices and implanted sensors to monitor physiological data and track health conditions. It has gained recognition as a reliable approach to real-time health tracking remotely in ambulatory settings, as well as for early detection of abnormal health issues and rehabilitation monitoring.

In WBAN, miniature resource-constrained biosensors that are either implanted or placed on the body's surface are used to collect physiological data. These sensors transmit data to a sink node via a wireless medium, which then forwards the data to a remote doctor for diagnosis. There are three levels of communication within the WBAN: intra-band communication, which occurs among sensors attached or implanted in the body, and inter-band communication, which takes place between the sensors and the coordinator or sink node - a device without resource constraints. WBAN has unique characteristics compared to WSN, offering several

advantages for real-time monitoring, such as an ambulatory setup, improved healthcare, and reduced healthcare costs. However, this also introduces critical challenges, including energy efficiency, reliability, scalability, interference, security, and privacy. These issues must be addressed to enable WBANs to revolutionise health monitoring and maintenance. Numerous studies have focused on optimising energy use, securing sensitive medical data, and maintaining high reliability through techniques such as data compression [1-4] energy harvesting, mutual authentication protocols [5-9] encryption and decryption algorithms, and optimised routing protocols [10-14].

Sensor data is categorised into critical and normal data. Critical data is given higher priority and transmitted directly to the sink node, while normal data faces challenges like delayed delivery and unreliable transmission. The normal data must also be transmitted with lower latency, achievable through reliable routing protocols and efficient Medium Access Control MAC protocols. Unreliable routing can cause data to traverse excessive hops, increasing latency, while poor



MAC protocols significantly raise latency, cause collision issues, and lead to frequent retransmissions due to inadequate channel coordination. Excessive control packets also consume bandwidth, and idle listening to the channel results in energy drain from nodes.

1.1. Classification of MAC Protocol

MAC is the data link layer protocol that controls and manages how various devices get access to the shared channel to transmit their data without collision. It is classified as below[15],

1.1.1. Contention-based Protocol

All the nodes try to access the channel simultaneously without coordination, which will lead to a collision. When the collision occurs, the device will stop the transmission and wait. The contention-based protocol employs a collision avoidance algorithm to detect and resolve collisions.

1.1.2. Contention-Free Protocol

A scheduler is employed either in a distributed or centralised manner to allocate communication resources efficiently across network nodes. The scheduler divides the channel either into several frequency bands or timeslots to allocate them to the nodes. It will effectively reduce the collision.

1.1.3. Hybrid Protocol

The hybrid protocol allocates a synchronised timeslot over the time frame to a group of devices. Each device in the group accesses the channel using a contention-based protocol.

1.2. MAC Protocol for WBAN

The optimised cluster-based routing ensures improved energy efficiency, scalability, enhanced reliability, and extended network lifetime. Devices involved in monitoring human medical data are battery-powered and resource-constrained; therefore, designing a lightweight and robust MAC is essential for efficient and dependable communication among these devices. The MAC protocol manages the access to the channel by various devices, minimises collisions, reduces latency, and cuts energy consumption by limiting waiting times for channel access.

Key parameters that define a reliable MAC protocol include energy efficiency, latency, throughput, bandwidth utilisation, fairness among users, and scalability. Since sensors attached to the body move with it, the links between them can become unstable. Additionally, WBAN involves various sensors such as temperature sensors, blood sugar sensors, ECG, and EEG, among others, each with different data rates. For example, a blood glucose sensor may send data every half-hour, whereas an ECG sensor may transmit data every minute; therefore, assigning a fixed channel size to all sensors can lead to underutilisation or over-demand on the channel.

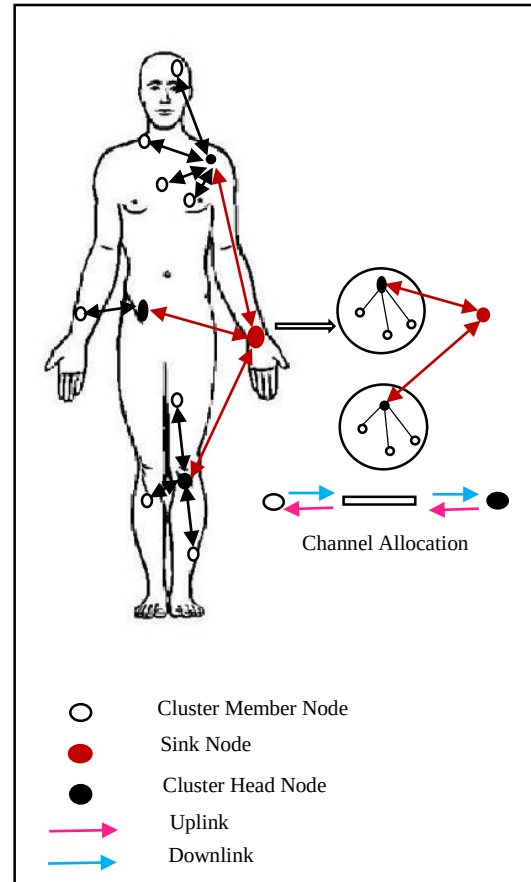


Fig. 1 Cluster-based topology of WBAN

An efficient channel allocation within a cluster-based network can further improve network performance. Consequently, designing a MAC protocol for WBAN should support its dynamic topology, include a duty cycle mechanism, be lightweight for resource-limited devices, and optimise bandwidth use for varying data rates. The WBAN, characterised by a dynamic topology and resource constraints, requires a real-time, adaptable channel allocation strategy to create an energy-efficient, reliable, and interference-free platform for continuous health monitoring. To boost the efficiency of the WBAN in the medical field, the MAC protocol to be developed should fulfil the following objectives,

- Employ effective mechanisms to minimise the transmission of collisions.
- Support low-power operation for energy-efficient communication.
- Designed for simplicity, requiring minimal code and memory.
- Ensure optimal channel utilisation across varying data rates.
- Adaptable to dynamic network protocol configuration.
- Scalable architecture accommodating extensive node deployment.

A robust dynamic channel allocation protocol has been proposed, which enables the devices to utilise the channel efficiently without unnecessary waiting times, improves channel utilisation, and reduces interference. The mobility of the nodes, the data rate of each device and data availability are the critical parameters that are considered while designing the MAC protocol for the dynamic WBAN network to energy-efficiently and reliably deliver the data to the destination node. As the body moves, the sensors attached to the body also moves that affects the communication link between the nodes. Hence, priority for the channel allocation is estimated based on the weighted mobility score, which is calculated by considering the mobility rate and data rate of the sensor. The node with a weighted mobility scores higher than 0.5 will get a dynamic TDMA slot, while the node with less than 0.5 will get a shared FDMA sub-band. The order of the nodes allowed to access the channel are based on the priority value. Hence, efficient channel utilization is achieved by integrating dynamic TDMA and dynamic FDMA.

1.3. Contribution of the Paper

This research primarily focuses on enhancing the reliability and energy efficiency for real-time health monitoring through a novel channel allocation method. The significant contribution of this paper is,

- Designing a dynamic channel allocation protocol for the intra-BAN layer of WBAN, considering the mobility score, data rate and data availability.
- Proposing a duty cycle mechanism that would be adapted to the proposed channel allocation protocol.
- The developed protocol is validated by comparing with existing protocols.

The outline of this paper is arranged as below. ie, Section 2 indicates an extensive review and critical analysis of the existing work related to this research. Section 3 presents a detailed proposed methodology. Section 4 presents the simulation and performance evaluation. Section 5 directs the way for future work.

2. Literature Survey

In WBAN, the MAC protocols have a crucial role in managing how devices access the shared communication medium, ensuring efficient and reliable data transmission. Designing the MAC protocol for WBAN involves considerations such as low power consumption, low latency, and emergency traffic management. MAC protocols are classified into asynchronous and synchronous types. Synchronous MAC protocols manage device access to the shared channel using a predetermined allocation schedule to guarantee QoS and reduce collisions, while asynchronous MAC protocols allow devices to access the channel randomly. Asynchronous MAC protocols rely on techniques like carrier sensing and collision detection to minimise collisions.

Synchronous MAC protocol offers several advantages, such as guaranteed QoS, reduced collisions, and predictable latency. The asynchronous MAC protocols offer more flexibility, adaptable to the dynamic network conditions. In high-traffic networks, synchronous MAC protocols provide better performance in terms of throughput and reliability, while asynchronous MAC protocols experience increased delay and collisions.

2.1. S-MAC

S-MAC [16] is a hybrid technique that uses CSMA/CA with a sleep-wake schedule to reduce idle listening and conserve energy. The sleep-wake cycle is synchronised using Request-To-Send (RTS) and Clear-To-Send (CTS) control packets at the start of each active period. The active period has a fixed duration, with a variable sleep interval. It employs a fixed duty cycle, which potentially causes higher energy usage owing to fixed listening periods and increased delays during data transmission caused by fixed sleep intervals. Figure 2 illustrates the synchronization between the sender and receiver in S-MAC protocol.

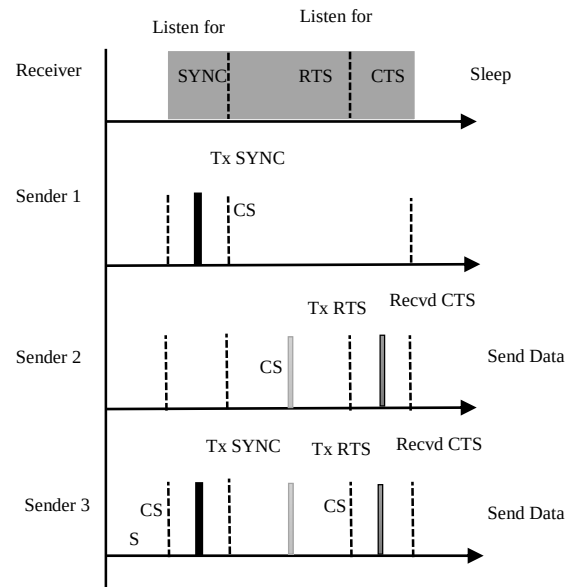


Fig. 2 Synchronization between sender and receiver in S-MAC

2.2. T-MAC

T-MAC [17] that dynamically adjusts the active periods of nodes to minimise idle listening time. It achieves this by allowing nodes to sleep when there is no traffic to send and wake periodically to update communication requests. It introduces the concept of early sleep when no events occur, to avoid unnecessary idle listening. In [18], two scheduling methods are suggested to improve the reliability and energy efficiency of the WBAN. Dynamic scheduling based on buffer involves putting a node to sleep during its active period, especially if it has a larger number of data packets stored in its buffer, with sleep duration depending on buffer size. The

approach based on sleeping slots assigns more slots to nodes with a higher number of packets, which may have accumulated during prior active sessions. Larger buffers result in more slots being allocated to those nodes.

2.3. BEE-MAC

In BEE-MAC [19], an improved version of the TDMA MAC protocol is presented, which improves the energy efficiency of sensor nodes. It comprises three phases: a setup phase for cluster formation and cluster head selection; an announcement phase, in which each member node requests its required slots from the cluster head; and a scheduling phase, where the cluster head allocates slots based on requests and broadcasts the schedule only once per frame. This method reduces control overhead by broadcasting the schedule just once and saves the energy resource of the cluster head.

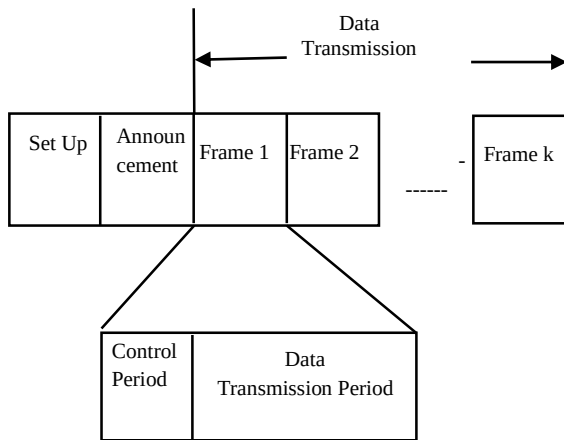


Fig. 3 Cycle of BEE-MAC protocol

2.4. ES-MAC

ES-MAC[20] is planned to enhance the energy efficiency of the cluster head by reducing its idle listening time. The cluster head activates its radio at the beginning of the frame for a specified duration, receives data packets from the designated node during its slot, and switches off its radio when no data packets are received from that node, thereby minimising idle listening and conserving energy.

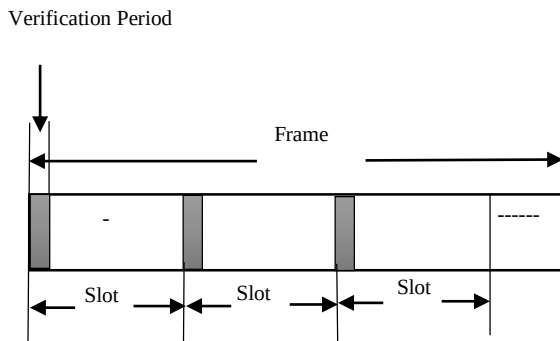


Fig. 4 Frame format for ES-MAC protocol

2.5. EE-DCAA

EE-DCAA [21] is introduced to improve QoS and extend network lifetime; it employs polling-based access to dynamically allocate slots to heterogeneous sensors within a WBAN. These sensors collect various data types from the human body to monitor health, with each sensor differing in data rate, type, and volume.

In [22], the scheduled allocation of channels is categorised into scheduled uplink, used by all nodes to send data to the hub; scheduled downlink, used by the hub to send frames to nodes; and scheduled bilink, for exchanging frames between nodes and the hub using scheduled polling access. A node obtains its slot by transmitting a connection request frame to the hub, which then responds with a connection assignment frame. The hub assigns scheduled access based on the node's data rate.

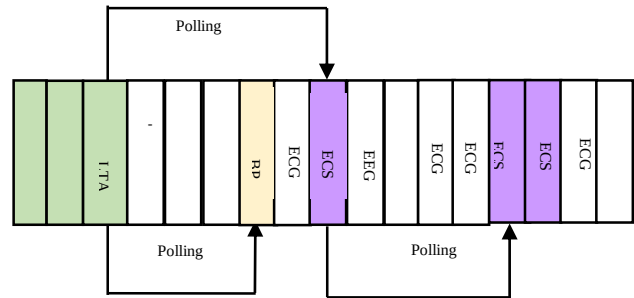


Fig. 5 Super frame structure of EE-DCAA protocol

2.6. SRE-MAC

SRE-MAC [23] employs the SG-TLO algorithm to select the optimal cluster node and uses a contention phase alongside variable-size TDMA to allocate the spectrum among nodes. The transmission phase is used to send data, and nodes change to sleep mode in their inactive periods to preserve energy.

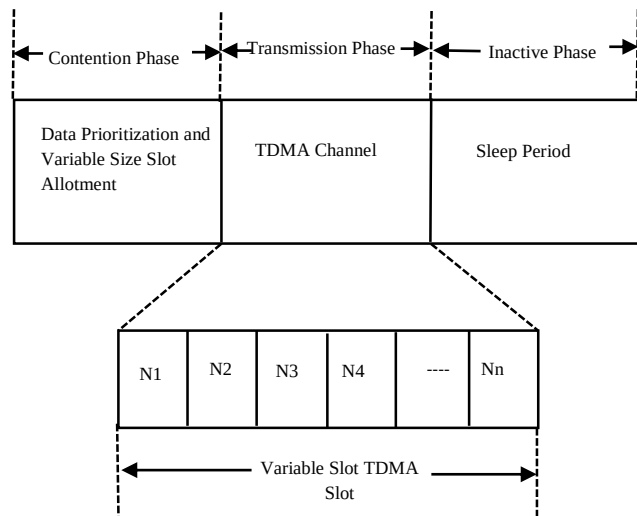


Fig. 6 Frame structure of SRE-MAC protocol

2.7. TDMA-MAC

In [24], the MAC protocol includes a beacon, a random-access phase, and a scheduled access phase. During the random-access phase, each node requests a connection and receives an assignment. The coordinator broadcasts the beacon to all connected nodes to maintain clock synchronization. Each sensor transmits its data during its scheduled time slot, while unconnected nodes send connection requests using a contention-based approach during the random-access phase.

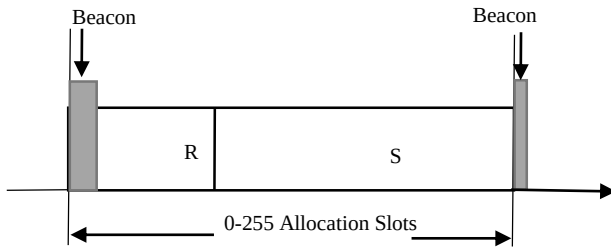


Fig. 7 Super frame of TDMA-MAC

2.8. DMTM-MAC

In DMTM-MAC [25], which acquires dynamic and correlation-related knowledge of medical data and bases its decisions on this information, it allocates channels to each node. Additionally, the type of data generated by the node, its QoS constraints, and the channel allocation priority are also determined based on the node's context.

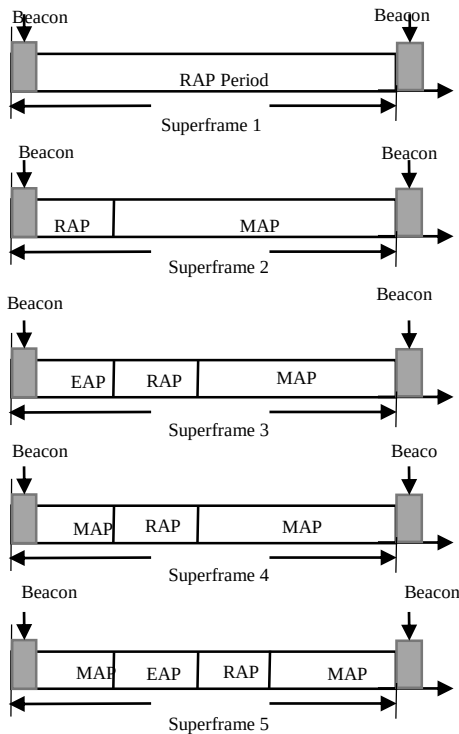


Fig. 8 Superframe structure of DMTM-MAC protocol

2.9. MVDR

In MVDR MAC [26] protocol, to enhance the energy efficiency and to prioritize the emergency medical data. It classifies the data according to the patient's physiological condition as high critical data, critical data and normal data. Based on the type of data, data rate and packet size, the priority value is calculated. Based on the priority value, the slot is assigned, and transmission rate is adjusted. If the data is high critical data, then the data are transmitted through GTS allocation in Contention Free Period with increased transmission rate, reducing the packet loss and transmission delay. If the data is critical data, then the data are transmitted through GTS allocation in Contention Free Period, while the data is normal, then it is transmitted in the Contented Period. The protocol does not address body mobility and dynamic channel conditions.

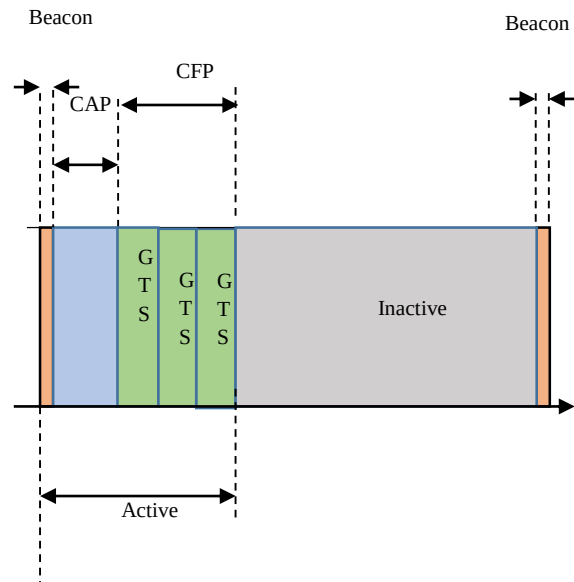


Fig. 9 Super frame structure of MVDR protocol

2.10. MC-HYMAC

In MC-HYMAC [27], a multichannel hybrid MAC protocol that combines Contention- based and contention-free channel access mechanisms.

The protocol classifies the data into emergency data and normal data; the emergency data are transmitted using TDMA for scheduled, contention-free transmission, while the normal data through CSMA/CA through contention- based channel access.

It also employs adaptive power control, dynamic timeslot, multi-channel communication to reduce the transmission delay and energy consumption. It also employs a finite state Markov model to analyse the state transitions of each sensor to estimate the energy consumption and channel access efficiency of each sensor. The multi-channel communication increases computation and the synchronisation overhead.

Table 1. Comparison of various MAC protocols

Mac Protocol	Mechanism	Advantages	Limitation
S-MAC	Fixed Duty-Cycle, Periodic Synchronisation among Neighbours.	Simple design reduces idle listening.	Not adaptive to traffic load.
T-MAC	Adaptive Duty Cycle with a timeout mechanism.	Adaptive to traffic load.	Causes early sleep result in packet miss.
BEE-MAC	Uses Beacon frame for scheduling, synchronisation, and traffic indication.	Minimise Idle Listening, Good Synchronization.	Beacon Overhead, Low Scalability.
ES-MAC	Uses adaptive sleep scheduling with traffic awareness.	Better Trade-off between the energy saving and throughput	Synchronization Overhead, Limited Scalability.
EE-DCAA	Dynamic channel allocation and duty cycling.	Minimises the collisions, supports the mobility of nodes.	Overhead of dynamic channel allocation.
SRE-MAC	Rearrangement of the sleep schedule to avoid collisions.	Minimises the collision and improves the throughput.	Synchronization overhead.
DMTM-MAC	Dynamic slot allocation for multiple traffic modes.	Prioritizes the traffic, Efficient Handling of Heterogeneous Data.	Complexity in traffic classification and control overhead.

Most of the Existing MAC protocols exhibit significant critical limitations, which make them unsuitable for energy-efficient and reliable continuous health monitoring in WBAN environments. Most of the protocols use static timeslots or frequency bands, which leads to resource underutilization when the nodes are inactive, or collisions occur, and delayed delivery of data when the traffic is bursty. Additionally, the mobility of the nodes is not taken into consideration during channel allocation.

The dynamic behaviour of the node causes an unstable link between the nodes, synchronization errors and retransmissions, which adversely impact overall network performance. The contention-based protocols suffer from high energy consumption due to idle listening, overhearing and collisions, while the schedule-based protocols suffer from high consumption due to frequent synchronization. Another important challenge is that the existing protocols cannot ensure the stringent QoS, such as low latency and high reliability, which are required in medical applications.

The aforementioned limitations emphasise the strong motivation for developing a new MAC protocol that is mobility-aware, energy-efficient, and capable of supporting heterogeneous traffic requirements in WBAN. In Real-time health monitoring WBAN, the packet loss or delay may compromise patient safety, making reliability a primary concern. At the same time, the extreme energy constraints of wearable and implantable sensors require minimal power consumption to prolong network lifetime. Considering that mobility is an intrinsic characteristic of humans, the MAC layer must dynamically adapt to topology changes, variable channel conditions, and fluctuating traffic demands. Therefore, there is a clear need for a change in existing MAC protocols through the design of a dynamic TDMA-FDMA protocol with mobility awareness, which can allocate time

slots and frequency bands dynamically, thereby ensuring efficient spectrum utilization, extended network lifetime, low delay, and reliable delivery of critical medical data.

3. Proposed System

WBAN is a network setup consisting of miniature-sized biosensors deployed inside or outside the body to collect the vital signals of humans to have real-time monitoring of their health condition. Sensors attached to or embedded in human body parts move with the body, making the link between nodes unstable. Additionally, the sensors involved in human medical data collection are diverse; they have different data rates, collect various types of data, and have different transmission ranges. Therefore, efficient channel allocation with the least idle waiting time for channel access can effectively reduce latency and improve energy efficiency. Existing TDMA slot allocation techniques assign the entire channel to each sensor for fixed time slots. When these techniques are used in WBAN, they result in inefficient channel use, longer waiting times for channel access, and increased data retransmissions. The FDMA slot allocation method allows multiple users to access the channel simultaneously by dividing it into several non-overlapping bands, each allocated to a different user. It results in limited scalability, inefficient for handling mobility nodes. As a result, dynamic slot allocation based on mobility has been proposed for mobility-based WBAN to achieve more efficient channel allocation, enhance reliability, increase energy efficiency, and minimise interference and collisions.

3.1. Network Model

The sensors in the WBAN are clustered using the best clustering algorithm to form a cluster-based topology. The dynamic TDMA-FDMA MAC protocol is designed for intra-cluster communication in WBANs to efficiently allocate channels, as WBANs comprise heterogeneous biosensors. The

sensors attached or embedded inside the body are grouped into clusters with a clustering algorithm, and the best cluster head node is selected using cluster head selection algorithm. Initially, all the cluster member nodes turn on their radio for listening. The channel allocation process involves three phases- Request for Information (RFT), Channel Allocation Schedule (CAS), and Sleep Period (SP). During the RFT phase, the cluster head node uses a token-based polling scheme to collect the information, such as data rate, data availability, from each of its member nodes. At the CAS phase, the cluster head prepares the channel allocation schedule for its member nodes using the information collected during the RFT phase and the mobility score of each member node, which it calculates and sends the schedule information to its member nodes using a token-based polling scheme. At the Sleep phase, except the node for which the channel is allocated to send its data, all the member nodes turn off their radio and set the low-power timer for enabling a precise wake-up schedule to conserve energy.

3.2. Request for Information (RFT)

During this phase, the cluster head node initiates a token-based polling message to collect information such as data rate and data availability from each of its member nodes. After initiating the token-based polling message, the cluster head enters sleep mode with its radio off but remains in low-power listening to receive the response, which conserves energy. The token-based polling scheme is a communication strategy where a single message (referred to as a token) is initiated by the cluster head that passes sequentially among member nodes in the cluster to collect the information. This scheme has several advantages over the traditional method, particularly for resource-constrained devices. In the traditional method, each member node sends its information through an individual message to its cluster head, leading to high energy consumption, increased channel contention and potential collisions. But in the token-based polling scheme, a single message is circulated sequentially among the member nodes, and each member node appends its information to the message when it arrives. It is a highly efficient, scalable strategy that avoids collision, reduces the bandwidth usage and transmission overhead.

3.3. Channel Allocation Schedule (CAS)

The cluster head uses its low-power listening strategy to wake up on receiving the token-based polling message from its cluster member node. Data rate, data availability and mobility score of a node are important parameters involved in the channel allocation decision.

Data rate and data availability are obtained from the token-based polling message from its member node, while the mobility score for each of its member nodes is calculated by the cluster head based on the already received data. The cluster head uses the following strategy to allocate the channel for each of its member nodes.

Each timeslot is dynamically allocated either to:

- A dynamic node (node with a higher mobility score) and a node with a higher data rate that utilises the entire channel, or
- A group of static nodes sharing a specific time slot using FDMA with unequal frequency bands based on data rate and data availability.

The Cluster head node uses the estimated mobility score to classify its member nodes as static or dynamic. If a node has a high mobility score, it will have an unstable link, so the entire timeslot channel is allocated to that node. If the node is static (i.e., a node with a lower mobility score), it will have a stable link, making it suitable for reliable data transmission. Therefore, the channel is shared by two static nodes using the FDMA technique with unequal frequency band sizes based on data rate and data availability. Moreover, if a node exhibits a higher data rate, then the entire channel of a timeslot is allocated to that particular node, and the static nodes with a lower data rate can share the channel using the FDMA technique. The data rate and mobility score are involved in the decision of channel allocation method, i.e. either an entire channel of a timeslot or a shared FDMA sub-band of a timeslot is allocated. The sorting of nodes for channel allocation is based on priority, which considers the mobility score and data rate of each node.

The node with a higher mobility score and higher data rate is given higher priority (1 is referred to as higher priority and 7 as the lowest priority). When two nodes have the same mobility score and data rate, the node with the lesser residual energy is given higher priority. Table 2 presents the channel allocation parameters for the decision of channel allocation, either an entire slot or a shared frequency sub-band. The duration of the timeslot allocated to a dynamic node or multiple static nodes accessing the entire channel, and the amount of frequency allocation to the static nodes, depends on the data rate and data availability of the nodes. All the member nodes switch to sleep mode outside their assigned time slots, with their active time - including listening in the RFI, CAS, transmitting, and receiving of data. This reduces unnecessary waiting time, ultimately saving the energy of each node.

3.3.1. Estimation of Mobility Score

The cluster head node estimates the mobility score of each of its member nodes using the variance of Received Signal Strength Indicator (RSSI).

$$M_s = \alpha \cdot \frac{RSSI_{Var}}{RSSI_{Max-Var}} \quad (1)$$

α is the tuning weights that lie in $\epsilon (0,1)$. $RSSI_{Max}$ is the maximum observed RSSI value, $RSSI_{Max-Var}$ will normalize the score so that strong signals with low variance yield lower mobility scores.

RSSI Variance

RSSI is the measure of the power level of the received signal by the receiving device. RSSI variance is the degree of fluctuation or inconsistency in the RSSI value across multiple measurements or over time. Low RSSI Variance indicates the link is stable and consistent, while higher RSSI variance indicates an unstable link.

$$RSSI_{Var} = \frac{1}{N} \sum_{j=1}^N (RSSI_j - RSSI_M)^2 \quad (2)$$

$RSSI_{Var}$ refers to the RSSI Variance, $RSSI_j$ refers to the RSSI value of the j^{th} signal, $RSSI_M$ refers to the average RSSI value of N signals. RSSI variance helps determine the link quality.

3.3.2. Data Rate

Sensors of different types are positioned on the body to gather distinct physiological data. Each sensor functions with a unique and distinct data rate, which is sampled at different frequencies tailored to its specific purpose. The data rate of the sensors has a significant role in determining the design and performance of the MAC protocol. Some sensors in WBAN, such as temperature sensors, respiration sensors, generate low and periodic data, while ECG sensor produces a higher data rate stream.

The increased data rate of the sensor creates the demand for the bandwidth of the channel and channel access, which directly affects the channel allocation schedule, energy consumption.

3.3.3. Weighted Mobility Score

The priority value for sorting the sensors for the channel allocation is estimated using the weighted mobility score, which integrates the mobility score and the data rate of a sensor. As the mobility score and the data rate work on different scales, normalization is applied to rescale the values into a common range, which allows both parameters to have a fair contribution in estimating the final score.

$$X_{Norm_value} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (3)$$

The relative importance of each parameter is decided by assigning certain weights to each of them based on how much they influence the final result. The mobility score has critical importance because it affects the stability of the link, hence, it has given higher weight compared to that of the data rate.

$$Mobility\ score_{Norm} = \frac{mobility\ score - mobility\ score_{min}}{mobility\ score_{max} - mobility\ score_{min}} \quad (4)$$

$$Data\ rate_{Norm} = \frac{data\ rate - data\ rate_{min}}{data\ rate_{max} - data\ rate_{min}} \quad (5)$$

$$Weighted\ Mobility\ Score\ (WMS) = \alpha_1 Mobility\ score_{Norm} + \alpha_2 * Data\ rate_{Norm} \quad (6)$$

Where $\alpha_1 + \alpha_2 = 1$; $\alpha_1 > \alpha_2$, α_1 is the weight assigned to the mobility score, and α_2 is the weight assigned to the data rate. The weighted mobility score gives the ranking value that helps to decide order of the sensor for the channel allocation.

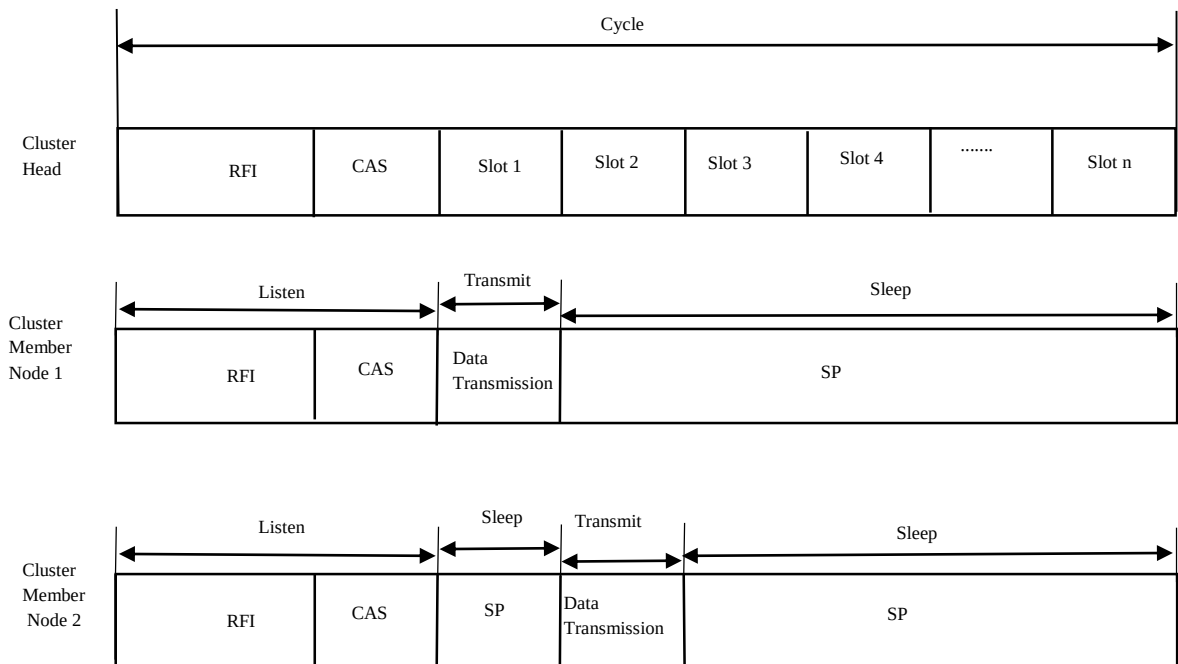


Fig. 10 Time slot division for cluster member nodes and cluster head

3.3.4. Dynamic Length of the Timeslot

The length of the time slot allocated to each of the sensor is dynamic, which is based on the data availability of the sensor.

The sensor with the maximum data can get the longer timeslot, while the sensor with the minimum data will get a shorter timeslot.

$$\text{Timeslot Length}_i = \frac{\text{Data of Node}_i}{\sum_{i=1}^n \text{Data of Node}_i} * \text{Total length of a frame} \quad (7)$$

Where n = number of cluster member nodes, Timeslot Length_i gives the length of the timeslot required for cluster member node i . Data of Node_i is the data availability of the node i .

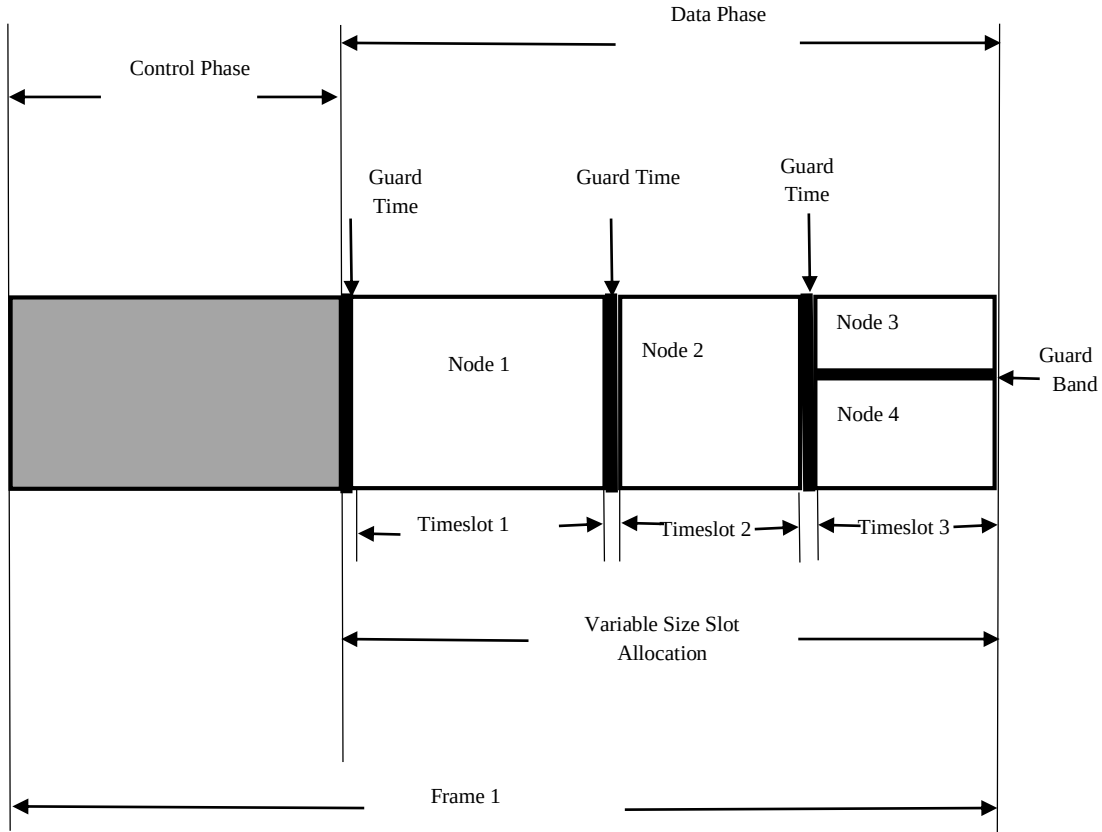


Fig. 11 Frame structure of dynamic TDMA-FDMA with mobility consideration protocol

Table 2. Channel allocation parameter of dynamic TDMA-FDMA with mobility consideration protocol

Sensors	Data Rate	Data Rate _{Norm}	Mobility Score	Mobility Score _{Norm}	Weighted Mobility Score (WMS)	Priority	Channel Allocation
ECG sensor	50 kbps	0.49	0.7	1	0.847	1	Complete channel
Pulse Oximeter	10 kbps	0.09	0.1	0.14	0.125	5	Shared FDMA sub-band
Temperature Sensor	3 kbps	0.02	0	0	0.006	6	Shared FDMA sub-band
Glucose Monitor	1 kbps	0	0	0	0	7	Shared FDMA sub-band
EMG	100 kbps	1	0.4	0.57	0.699	2	Complete channel
Respiration rate	5 kbps	0.04	0.2	0.29	0.215	4	Shared FDMA sub-band
Blood pressure	7 kbps	0.06	0.3	0.43	0.319	3	Shared FDMA sub-band

Table 3. Description of the fields in the sync message

Field	Size (Bytes)	Explanation
Message type	1	Indication of sync message
Cluster ID	1	Unique Cluster ID
Cluster Head ID	1	Cluster Head ID
Frame Number	1	Frame number to identify the order
Frame Duration	2	Duration in milliseconds of the particular frame
Timestamp	4	Cluster head node current time (for synchronization)
Node Allocation Table (per Cluster Member Node and repeated for the number of Cluster Member nodes).	8	<ul style="list-style-type: none"> Cluster Member ID Slot Number Slot Start Time Slot Duration Mobility Flag (1 for mobility node, 0 for static node) Frequency band (will not be present for mobility node)
Guard Time	1	Fixed time of 2 milliseconds
Next SYNC Interval	2	The interval until the next SYNC frame will be broadcast.
CRC	2	Error Detection Code

3.3.5. Synchronization Mechanism

Maintaining the time sync is a critical factor in the TDMA system because it ensures that each node transmits within its designated timeslot without overlapping with other nodes. It prevents collisions, optimises the bandwidth usage and allows for minimal guard time between the timeslots to improve the overall efficiency. At the start of each frame, there is a fixed timeslot for the control phase. During this period, all the nodes are preconfigured to wake up and request the slot by sending the amount of residual data availability to the cluster head. When the cluster head receives the request from all its member nodes, and updates any changes in the mobility score and data availability. Based on the updated information, it schedules the time slot allocation and sends the schedule as a synchronisation message. Table 3 describes each field and the size of each field in the sync message.

The sync message contains a Header field which includes the Message type, Cluster ID, Cluster Head ID, Frame Number, Frame Duration, and Timestamp. The next comes the Payload field, which includes Node Allocation Table {Cluster Member Node ID, Slot Number, Slot Start Time, Slot Duration, Mobility Flag, and frequency band} and finally the Footer field, which includes Guard time, Next SYNC interval, and CRC. The fields of the Node Allocation Table are repeated for the number of Cluster Member Nodes present. Each node, on receiving the sync message, will synchronise its local clock, store its allocated timeslot to wake up, and then enter sleep mode. Hence, the frame size of the synchronization

message is 10 bytes for the header, $8 \times K$ bytes for the Node Allocation Table (K refers to the number of member nodes in the cluster) and 5 bytes for the footer. Figure 12 represents the frame format of the synchronization message sent by the cluster head to its cluster member nodes. The guard time plays a vital role in ensuring reliable communication. It is a small buffer period added at the start of the timeslot to account for the timing uncertainties caused by clock drift between the cluster head and its member nodes, propagation delay, and variations due to node mobility. It prevents interference and improves the reliability. Lack of guard time results in overlap with the timeslot of an adjacent node when a node wakes up or begins transmitting data slightly too early or too late. The guard band is an unused slice of spectrum placed between the two active frequency channels allocated to the static nodes to minimise the interference and to improve the signal clarity. This protocol introduces a two-tiered hybrid channel access mechanism, combining dynamic time slot allocation for mobile nodes with shared traffic-adaptive FDMA for static nodes. This design improves spectrum utilisation, fairness, and QoS guarantees, making it suitable for heterogeneous WBAN environments with varied node mobility profiles.

3.4. Sleep Period (SP)

All the member nodes except the node to which the channel is allocated will go to sleep mode. Each member node will switch to sleep mode when it is outside its assigned timeslots, RFT phase and CAS phase. This helps to reduce the waiting time the node, which ultimately saves energy.

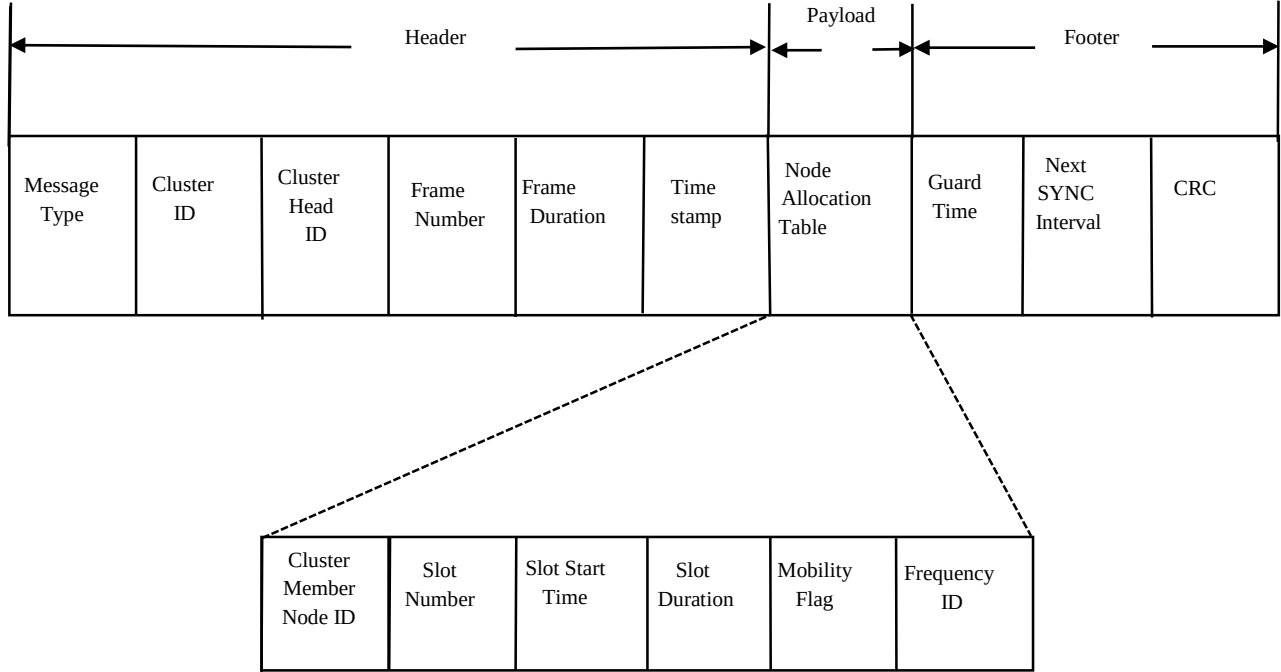


Fig. 12 Frame format of synchronization message

Table 4. Algorithm of efficient channel allocation in the cluster-based sensor network using dynamic TDMA–FDMA with mobility consideration

Algorithm: Efficient channel allocation in the cluster-based sensor network

Input:

A set of sensor nodes N , set of cluster head nodes C_H and their cluster member nodes C

1. for each cluster C_k in C_H do
2. All cluster members in C_k wake up and start listening.
3. C_k sends a token-based polling message to its member nodes
4. cluster member nodes attaches its data to the queue in the token-based polling message
5. C_k receives the token-based polling message from its member nodes
6. for each cluster member node $C_{k,i}$ in C_k do
7. if $WMS \geq 0.5$
8. $AC_{k,i} \leftarrow$ complete channel allocated
9. else
10. $AC_{k,i} \leftarrow$ shared channel allocated
11. computes $Mobility\ score_{Norm(i)} = \frac{mobility\ score_i - mobility\ score_{min}}{mobility\ score_{max} - mobility\ score_{min}}$
12. computes $Data\ rate_{Norm(i)} = \frac{data\ rate_i - data\ rate_{min}}{data\ rate_{max} - data\ rate_{min}}$
13. compute $WRS_i = \alpha_1 * Mobility\ score_{Norm(i)} + \alpha_2 * Data\ rate_{Norm(i)}$
14. compute $Timeslot\ Length_i = \frac{Data\ of\ Node_i}{\sum_{i=1}^n Data\ of\ Node_i} * Total\ length\ of\ a\ frame$
15. end for
16. $AC_{k,i}$ gives complete channel allocation or shared channel allocation
17. WRS_i gives the order of the sensor to access the channel
18. $Timeslot\ Length_i$ gives the length of the timeslot allocated to each sensor
19. Cluster head node prepares the schedule based on $AC_{k,i}$, WRS_i , $Timeslot\ Length_i$ and send it to its member nodes through a synchronization message.
20. end for

Output:

The channel has been allocated efficiently with minimum waiting time.

Table 5. Simulation parameter

Parameter	Value
Number of sensors in WBAN	9 (1- sink node, 1- cluster head and 7 cluster member nodes)
Simulation Area	2m * 2m
Simulation time	200 s
Frequency Band	2.4 GHz ISM
PHY data rate	970 kbps
Frame Duration	250 ms
Guard time, Guard frequency	2 ms, 100 kHz
Weighted Mobility Score (WMS)	> 0.5 is treated as a mobility node with a high data rate
Data Packet Size	250 Bytes

4. Simulation and Result

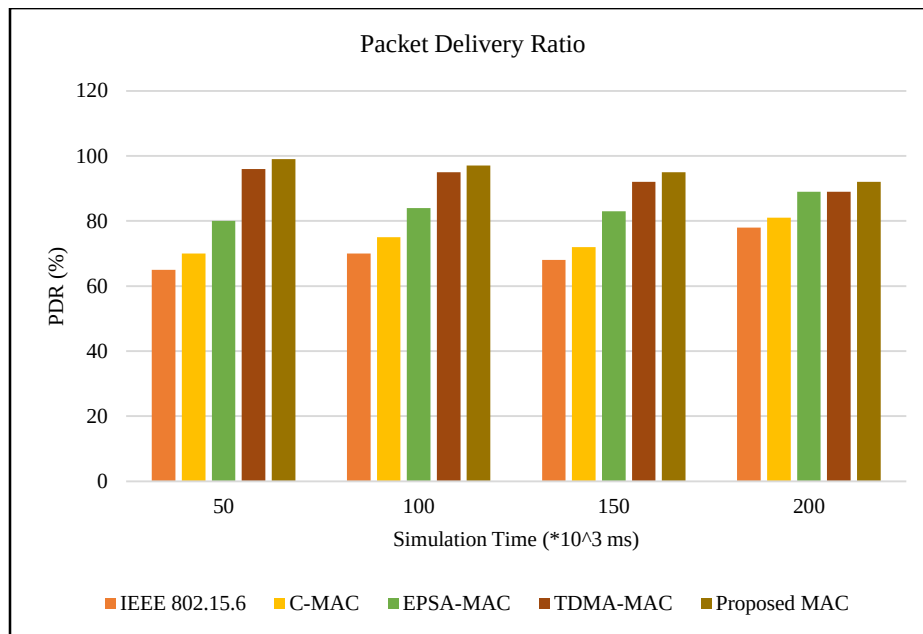
The proposed Mobility-Aware Dynamic TDMA–FDMA protocol was simulated using the NS-3 platform, which provides a flexible environment for developing and evaluating custom MAC protocols in WBAN. The custom Mobility module is used to represent sensor movement and uses RSSI variance to find the mobility score of each node in WBAN. To model energy consumption, NS-3's Basic Energy Source and Radio Energy Model, thereby providing a realistic estimation of network lifetime under the proposed protocol. It is assumed that multiple sensors are either embedded or surface-mounted on the body for acquiring medical data and transmitting it to the sink via the cluster head.

The cluster head functions as a coordination node and efficiently allocates the communication channel to its members to minimise waiting times and collisions, thereby conserving energy and ensuring reliable data transmission. The efficiency of the proposed protocol is systematically assessed and compared with IEEE 802.15.6 [28], TDMA-MAC, EPSA-MAC [29], and C-MAC [30] in terms of

reliability, measured by the Packet Delivery Ratio (PDR), delay, and energy efficiency.

4.1. Packet Delivery Ratio

One of the key parameters regarding the performance of WBAN in the medical field is reliability. Reliability is measured by Packet Delivery Ratio (PDR), which quantifies the proportion of packets received by the destination relative to those packets sent by the source. In the proposed protocol, the cluster head efficiently allocates the channel to each member node based on their mobility, data rate, and data availability. Each node transmits its data during the designated timeslots and switches to sleep mode when the channel is allocated to other nodes. A higher PDR indicates greater reliability. Additionally, node mobility creates unstable connection links, leading to packet loss. Therefore, mobile nodes are allocated larger or more frequent time slots to reduce retransmissions. Figure 13 represents the comparison of the PDR percentage of the proposed MAC protocol with the existing MAC protocol.

**Fig. 13 Comparison of the packet delivery ratio percentage**

4.2. Delay

The MAC protocol should be designed to reduce the delay, thereby enhancing transmission reliability. In the MAC layer, the delay is mainly caused by idle waiting time to access the channel and unfair allocation of the channel. The parameter delay has to be handled carefully; otherwise, it can lead to poor resource utilisation. In the Proposed MAC

protocol, nodes are scheduled to transmit their data in a desired timeslot. The cluster head node fairly allocates the channel to each member node based on data rate and data availability to reduce the delay. Moreover, the proposed MAC protocol guarantees consistent and predictable transmission times, which effectively minimises the average delay. Figure 14 represents the comparison of the Delay.

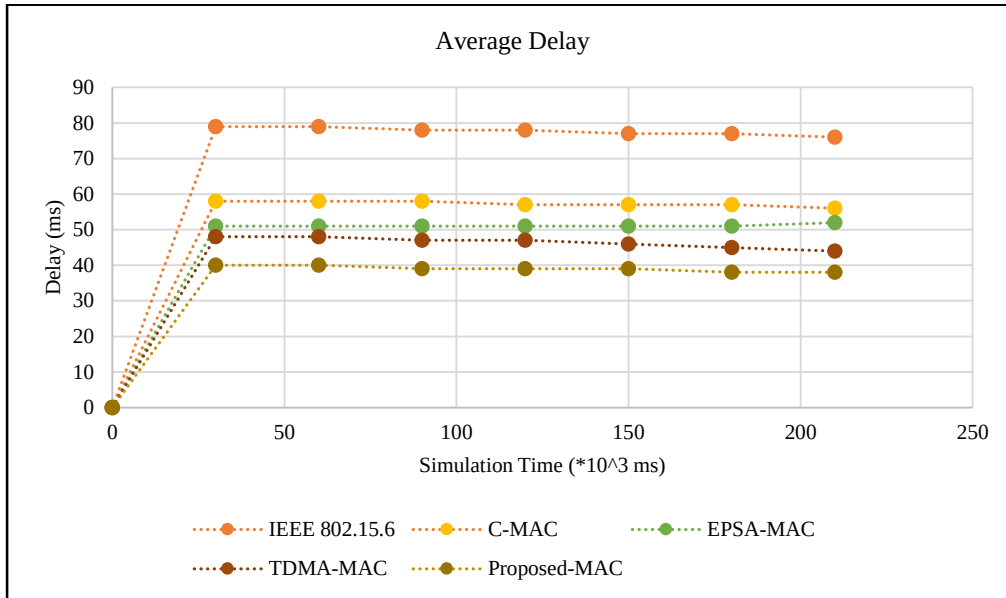


Fig. 14 Comparison of the delay

4.3. Energy - Efficiency

Since the battery-powered sensor nodes are resource-constrained, it is essential to use the energy efficiently to extend the network's lifespan. In the MAC layer, sensor energy is conserved by minimising idle waiting time and retransmissions.

During sleep mode, no energy is consumed, but idle waiting to access the channel uses energy that should be saved to preserve sensor power. The proposed MAC protocol is more energy-efficient, which would be more suited for devices with limited resources. Figure 15 represents the comparison graph of energy consumption.

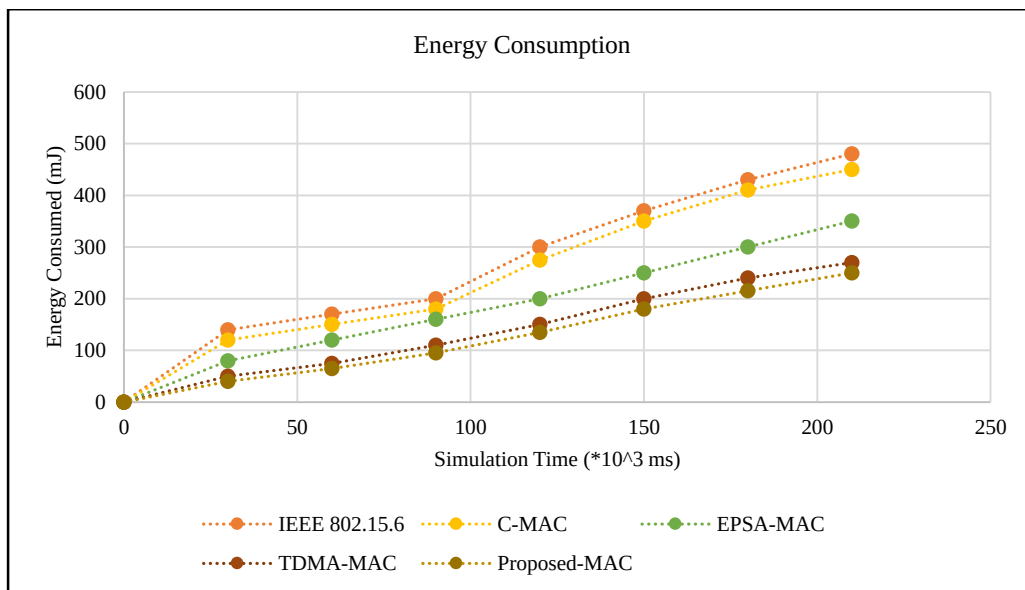


Fig. 15 Comparison of the energy consumption

4.4. Comparative Analysis

In EPSA-FMAC scheduling, the network coordinator node performs slot allocation before each frame transmission. Initially, standard TDMA allocation is performed, if any unused timeslot is identified by the network coordinator, it reassigns the empty timeslot to the waiting nodes. Hence, the waiting nodes should remain until it gets assigned to an empty timeslot. Moreover, the empty timeslot is segregated into smaller equal timeslots based on the number of weighting nodes. The proposed protocol combines the dynamic TDMA and shared FDMA for the heterogeneous sensor's dynamic nodes in WBAN. The scheduling of the channel is based on the weighted mobility score, which combines the mobility score and data rate of a node. The order of the nodes for the channel allocation is based on the weighted mobility score. The duration of the time slot for each node is based on the availability of the data of that node. The proposed protocol is suitable for a WBAN environment with heterogeneous sensors and a mobility environment. Moreover, the proposed protocol is a cluster-based network setup that supports high scalability. C-MAC protocol includes two phases with multiple acknowledgement that leads to more energy consumption. Moreover, sink node performs the scheduling, and it limits the scalability. It has synchronization overhead, which makes it unsuited for a WBAN environment. The proposed protocol

involves minimal sync message and support efficient duty-sleep mechanism, which makes it suited for energy-constrained and mobility-based WBAN environment. Though TDMA- MAC has enhancements in packet delivery ratio, delay and energy efficiency, it offers a static and periodic timeslot allocation strategy, which does not adapt well to the dynamic traffic from the heterogeneous nodes of WBAN and dynamic environment in WBAN. Moreover, contention-based Random-Access Phase introduces overhead, which reduces the overall efficiency of the protocol. The proposed protocol is developed for the resource-constrained, heterogeneous, dynamic WBAN network, which involves the data rate, mobility score in the calculation of priority that decides the order of nodes for channel allocation and also decides the dynamic TDMA slot or dynamic FDMA. IEEE 802.15.6 uses multiple channel access mechanisms involving CSMA/CA, TDMA and polling to achieve QoS. It supports traffic prioritization, it has limitations such as fixed scheduling, limited adaptability to dynamic traffic conditions and insufficient mobility management. The proposed protocol involves the mobility score as a priority for channel allocation. The node which has higher mobility has higher priority to access the entire timeslot for longer duration. Hence, the energy efficiency and reliability of the nodes can be effectively achieved.

Table 6. Comparative analysis of MAC protocol with WBAN essential parameters

Requirement Protocol	Reliability	Priority-based Scheduling	Energy-Efficiency	Scalability	Adaptive Bandwidth Allocation based on the traffic	Mobility Support	Support for Multiple Data Rates
EPSA-MAC	✓		✓				✓
C-MAC	✓		✓		✓		
TDMA-MAC	✓		✓		✓		
IEEE 802.15.6	✓	✓	✓				✓
Proposed Protocol	✓	✓	✓	✓	✓	✓	✓

The proposed protocol supports scalability by having cluster head node to perform the channel allocation schedule. Moreover, the scheduling is performed based on the mobility score, which is not addressed by the existing research work. The efficient channel utilization is achieved by considering the data rate of each sensor while performing the channel allocation. Table 6 illustrates the comparative analysis of the existing protocol with the proposed protocol in terms of parameters which are more essential for mobility based WBAN environment.

5. Conclusion

The WBAN in medical applications must meet strict requirements such as reliability, minimised delay, and energy efficiency. The proposed Mobility-Aware Dynamic TDMA-FDMA Channel Allocation protocol considers mobility as a critical factor when allocating channels. Additionally, it

assesses the sensor's data rate and the availability of data for slot allocation, which efficiently utilises channel resources and reduces delay. The proposed MAC protocol surpasses the existing protocols in reducing delay and improving reliability, energy efficiency, and suitability for resource-constrained sensor nodes. Future work will focus on developing a lightweight, mobility-aware data aggregation algorithm for resource-constrained cluster head nodes.

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Competing Interest

The authors declare no conflicts of interest.

Author's Contributions

Kavya developed the theory and performed the simulation of the proposed research work. All other authors involved in the implementation of this work. All the authors have reviewed and endorsed the article.

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