Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 9s (2025)

An Energy-Delay Optimized Model for Efficient WBAN Communication in Iot-Enabled Autism Monitoring

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Article History:

Received: 12-01-2025

Revised: 15-02-2025

Accepted: 01-03-2025

Abstract:

Wireless Body Area Networks (WBANs) have revolutionized healthcare by enabling continuous monitoring of physiological parameters, making them crucial for managing conditions like autism, where real-time data collection and analysis are vital. However, WBANs face challenges such as energy inefficiency, high delay, and communication overhead, particularly in dynamic IoT environments with mobility and emergency scenarios. This study addresses these challenges by proposing an Energy-Delay Optimized Data Communication Model (EDODCM) for WBANs. The primary objective is to enhance energy efficiency, increase network lifetime, reduce end-to-end delay, and minimize communication overhead while ensuring reliable data transmission from wearable sensors to gateways. The EDODCM employs an unequal clustering approach, an optimized duty-cycling mechanism, multi-hop routing for normal and emergency scenarios, and a TDMA-based Optimized Medium Access Control (TDMA-OMAC) for efficient data aggregation and transmission. Simulation results demonstrate that EDODCM improves average energy efficiency by 24.52%, extends average network lifetime by 20.1%, reduces average end-to-end delay by 9.65%, and decreases average communication overhead by 22.18% compared to existing approaches. The novelty of this work lies in its adaptive routing strategies for dynamic scenarios and its focus on integrating WBANs within IoT for real-time autism monitoring. These findings highlight EDODCM's potential for scalable and efficient WBAN communication, paving the way for improved healthcare solutions.

Keywords-WBAN, IoT, autism, energy efficiency, delay optimization, clustering, TDMA-OMAC, real-time monitoring, healthcare technology.

1. Introduction

Autism Spectrum Disorder (ASD) is a complex developmental condition that manifests through challenges in social interaction, communication, and a propensity for repetitive behaviours. In recent years, it is seen that some ASD individuals experience profound difficulties in verbal communication and require extensive support, while others might demonstrate exceptional skills in specific areas yet struggle with subtler aspects of social interaction [1], [2]. This diversity in presentation makes ASD a highly individualized condition that defies a one-size-fits-all approach to understanding or managing it. Moreover, symptoms of ASD typically appear within the first three years of life, with early signs sometimes evident even in infancy, such as a lack of response to their name or limited eye contact [3].Although there is no definitive cure for ASD, early diagnosis and intervention have been shown to make a substantial difference in the quality of life and developmental progress for individuals with this condition [4]. Specific designed therapeutic strategies, such as behavioural interventions, speech and language therapy, and sensory integration techniques, can enhance their ability to communicate, interact, and navigate daily life [5]. Recent statistics from the Centres for Disease Control and Prevention (CDC) highlight that approximately 1 in 36 children in the United States is diagnosed with ASD [6], a figure that reflects its growing prevalence and underscores the urgent need for improved diagnostic, monitoring, and therapeutic tools. This increased prevalence necessitates an evolving framework of support systems that can accommodate the diverse and dynamic needs of the ASD population.

Furthermore, individuals with ASD often exhibit heightened or diminished responses to sensory stimuli, such as lights, sounds, textures, or smells, which can significantly affect their behaviour and emotional regulation [6], [7]. Monitoring these sensory responses provides essential insights into behavioural patterns, allowing caregivers and healthcare professionals to create interventions designed for every individual's specific needs. For instance, understanding how a child reacts to different sensory inputs can inform strategies to reduce anxiety, improve focus, or enhance participation in social and learning environments [8].Recent advancements in technology, particularly in the realms of the Internet of Things (IoT) and Wireless Body Area Networks (WBAN), have opened new avenues for healthcare applications, including ASD management and monitoring [9], [10]. WBANs, which utilize sensors placed on or near the body, are designed to collect real-time data on physiological and behavioural parameters [11]. For individuals with ASD, these sensors can track movements, physiological responses, and other sensory indicators, providing caregivers with a detailed, objective understanding of sensory processing over time. By doing so, they enable personalized intervention strategies based on accurate, data-driven insights.

Despite their potential, these systems face significant challenges, particularly in energy consumption and data communication efficiency [12], [13]. Sensors, which often rely on battery power, must operate continuously to provide uninterrupted monitoring. However, limited battery life can significantly restrict the duration and reliability of monitoring [14]. Furthermore, inefficient data transmission methods can result in communication overhead and delays, increased power consumption, and data loss, which compromise the effectiveness of the monitoring system [15]. These limitations pose a barrier to the seamless and real-time delivery of actionable insights that caregivers and healthcare providers rely upon. To overcome these challenges, there is an urgent need for a robust data communication model designed specifically for WBAN systems in ASD monitoring. Such a model must optimize energy consumption, extend sensor lifespan, and ensure efficient, low-delay data transmission. Addressing these issues will not only enhance the functionality of monitoring systems but also significantly improve the ability of caregivers and healthcare professionals to respond effectively to the needs of individuals with ASD. Hence, this work presents an Energy-Delay Optimized Data Communication Model (EDODCM) for efficient data collection from WBAN sensors in IoT environment with better energy efficiency, reduced communication overhead and latency. the contributions of the work are as follows:

- The proposed EDODCM minimizes energy consumption in WBAN sensors by optimizing the data transmission process and by optimized Cluster Head (CH) selection.
- EDODCM incorporates delay optimization approach on basis of priority to ensure timely delivery of sensory data. By prioritizing critical data packets and reducing transmission delays, the model supports real-time monitoring of physiological and behavioural parameters, which is vital for effective ASD management.
- The EDODCM introduces a technique to streamline data communication between WBAN sensors and processing units, reducing unnecessary data exchanges. This enhances the system's scalability and reliability, making it suitable for prolonged use in ASD monitoring applications.
- The work provides a detailed evaluation of the EDODCM in terms of network lifetime, energy consumption, communication overhead, and average End-to-End Delay (EED). Comparative analysis with existing WBAN data communication models demonstrate the superior performance of EDODCM, particularly in scenarios demanding continuous and accurate monitoring.

The manuscript is structured to provide a comprehensive overview of the proposed work. Section II discusses the existing WBAN approaches developed in recent years for various scenarios. Section III introduces the proposed EDODCM in detail, explaining the inter- and intra-cluster data communication strategies for efficient transmission of sensor data to the gateway. Section IV presents the results of ELDCM, focusing on its performance in terms of energy consumption, delay, and communication overhead, compared with existing methods. Finally, Section V concludes the study and outlines potential directions for future research.

2. Objective

Development of an effective sensory information collection mechanism using optimized classification techniques.

3. Methods

The Figure 1 illustrates the data communication process using WBAN sensors (sensing nodes) in an IoT environment towards IoT gateway. In this environment, WBAN sensing nodes are attached to the human body to monitor sensory and physiological parameters and transmit the collected data. Further, the Figure 2 shows the complete process of how EDODCM collects data from WBAN sensors integrated within the IoT environment. In this work, the IoT environment employs an unequal clustering approach with three distinct cluster sizes: small (Cluster $\mathbb{A}$), medium (Cluster $\mathbb{B}$), and large (Cluster $\mathbb{C}$). The WBAN sensor within each cluster communicates/transmits their data to the CH through intra-cluster data communication. Once data is gathered at the CH, inter-cluster data communication/transmission occurs, where CHs share information with other CHs, which is critical in facilitating data transmission across the network. After the data has been aggregated at the CH level, it is transmitted to an IoT gateway. This gateway acts as the intermediary, ensuring the collected information is forwarded to the processing servers. As the communication process from the medium and large clusters CHs to the IoT gateway requires higher energy consumption, this results in increased delay and communication overhead, especially for larger clusters. To address these challenges, the EDODCM optimizes the data transmission process by reducing energy consumption during communication, minimizing EED and decreasing communication overhead by employing efficient routing technique designed for WBANs for normal and emergency scenarios.

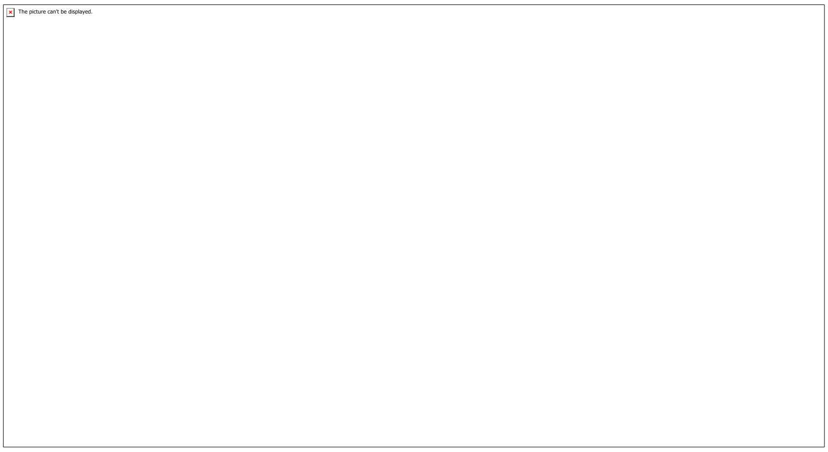

Figure 1. Architecture of WBAN Data Collection Method using IoT Environment.

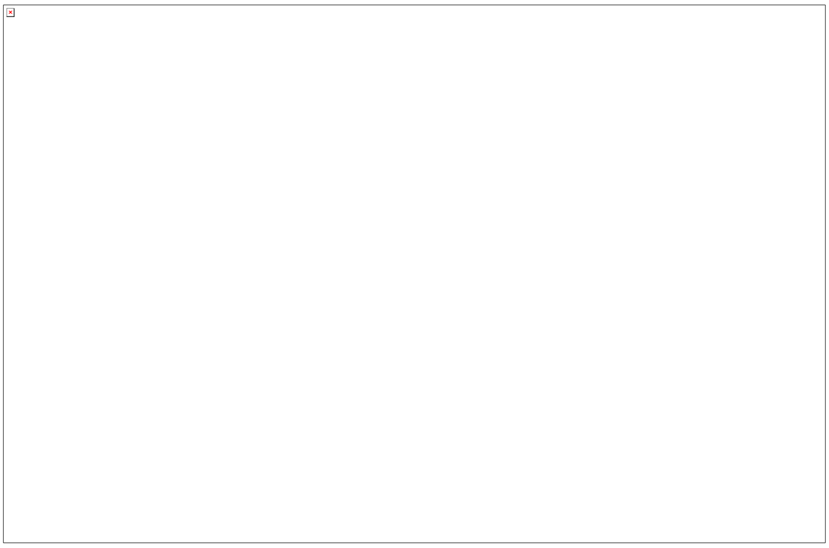

Figure 2.EDODCM Data Collection process from WBAN sensing nodes integrated within the IoT network.

As EDODCM is built on unequal-clustering approach, it helps in balancing energy consumption and handles load distribution between WBAN sensor nodes. In this work, if more WBAN sensor nodes exist in a cluster, then the size of cluster will be big, else will be small. In EDODCM, the WBAN sensor nodes first collect information and then transmit it towards CHs, and then CHs transmit it to IoT gateway for which this work presents a novel intra-cluster and inter-cluster data communication approach.

Intra-Cluster Communication Approach

In intra-cluster communication approach, one WBAN sensor node within the cluster is elected to serve as a CH, where the elected CH transmits data to other CHs. The process of electing CH is done on basis of cost-function denoted as K_y. The K_y is dependent on WBAN sensing node initial energy denoted as $\mathcal{E}$, total nodes present in a cluster denoted as X_v, average distance among nodes denoted as $M_{\rightarrow}$. The K_y also relies on the weights of $\mathcal{E}$, X_v, and $M_{\rightarrow}$ denoted as D_e, D_x and D_m respectively. From these parameters, the K_y and $M_{\rightarrow}$ are evaluated using Eq. (1) and Eq. (2) respectively.

$$K_y = \frac{M_{\rightarrow} * D_m}{(X_v * D_x) * (\mathcal{E} * D_e)} \qquad (1)$$

$$M_{\rightarrow} = {}^{K_h}/_{\mathcal{A}} \qquad (2)$$

In Eq. (2), K_h denotes overall distance among every WBAN sensing nodes and $\mathcal{A}$ denotes distance among every WBAN sensing nodes neighbors. From the Eq. (1) and Eq. (2), it is seen that, when a WBAN sensing node has least energy and less neighboring WBAN sensing nodes within a cluster, that WBAN sensing node is elected as CH.Further, this work presents an optimized duty-cycling approach which works on basis of distance of WBAN sensors nodes from CH. Consider N_C total WBAN sensing nodes present in a cluster, then the optimized duty-cycling approach denoted as ODC is evaluated using Eq. (3).

$$ODC = \frac{e^{-\frac{d_{SNCH}}{d}}}{\sum_{n=1}^{N_C - 1} e^{-\frac{d_{SNCH}}{d}}} \qquad (3)$$

In Eq. (3), d_{SNCH} is distance among the WBAN sensing node and CH and d is distance threshold. The Eq. (3) helps in conflict-free data-aggregation by allowing the WBAN sensing node to transmit data efficiently in a sequential way.Also, this approach helps to periodically put WBAN sensing nodes into sleep mode when not sensing and for transmitting data towards CH.

Inter-Cluster Communication Approach

Further, in inter-cluster data communication, i.e., data transmission from CH to CH, this work presents a novel multi-hoprouting approach for normal and emergency scenarios. Consider the established connection from WBAN sensing node to CH and from CH to CH as t which has path of transmission denoted as l. Also consider$\mathcal{SD}(t)$ as connection established from transmitter to receiver and$\mathcal{DS}(t)$ as connection established from receiver to transmitter. From this the hop-routing can be evaluated using Eq. (4).

$$\mathcal{G}_l = \sum_{t \in l} \mathcal{SD}(t) * \mathcal{DS}(t) \qquad (4)$$

In Eq. (4), $\mathcal{G}_l$ denotes hop-count for transmission of data and $\mathcal{SD}(t) * \mathcal{DS}(t)$ denotes the data transmission delivery-ratio. For evaluating the average number of hops per unit of distance, the inverse of $\mathcal{G}_l$ is considered denoted as $\bar{\mathcal{G}}_l$, which is evaluated using Eq. (5).

$$\bar{\mathcal{G}}_l = \frac{1}{\sum_{t \in l} \mathcal{SD}(t) * \mathcal{DS}(t)} \qquad (5)$$

Further, consider a normal scenario, where the sensory data has to be sent periodically to monitor the autism patients. Also, consider an emergency scenario where an autism patient requires immediate attention, then in this scenario, it is important to send sensory information to the IoT gateway, having highest priority. Hence, for normal scenarios, a $\mathbb{U}$ path is established and for emergency scenarios, a $\mathbb{N}$ path is established. Both the $\mathbb{U}$ path and $\mathbb{N}$ path is evaluated using Eq. (6) and Eq. (7) respectively.

$$\mathbb{U} = \frac{\mathbb{L}}{\mathbb{L}+\mathbb{J}}\mathbb{G} \qquad (6)$$

$$\mathbb{N} = \frac{\mathbb{J}}{\mathbb{J}+\mathbb{L}}\mathbb{G} \qquad (7)$$

In Eq. (6) and Eq. (7), $\mathbb{L}$ and $\mathbb{J}$ denotes the WBAN sensing node flag variable, i.e., $\mathbb{L}$ gives $flag = 0$ for normal scenarios and $\mathbb{J}$ gives $flag = 1$ for emergency scenarios. Also, the $\mathbb{G}$ denotes the multi-hop routing approach which is obtained using Eq. (8).

$$\mathbb{G} = \mathbb{U} + \mathbb{N} \qquad (8)$$

Using Eq. (8), the multi-hop is established for normal and emergency scenarios. Further, when there are more clusters and CHs, there are chances of increased delay and packet-failure rate during emergency scenario data transmission.

TDMA-based Optimized MAC approach

For reducing packet-failure rate and delay during data transmission from WBAN sensing node to CH and CH to CH, this work presents a TDMA-based Optimized Medium Access Control (TDMA-OMAC) approach.As, TDMA-OMAC helps in evaluating packet-failure rates by providing a structured and deterministic communication framework that eliminates collisions, reduces retransmissions, and offers consistent intervals for real-time analysis. Its ability to isolate and monitor failures in individual time slots makes it a powerful method for evaluating and improving packet-delivery in IoT environment. Hence, in this work theTDMA-OMACevaluatespacket-failure rate denoted as L_{r}^{p} using Eq. (9).

$$L_{r}^{p} = 1 - \left(1 - L_{r}^{b}\right)^{\mathcal{B}_{\hbar}} \quad (9)$$

In Eq. (9), L_{r}^{b}denotes mean Bit-Error-Rate (BER) for the communication channel which is evaluated by considering Signal-to-Noise Ration (SNR) denoted as γ for distance s, i.e., from WBAN sensing node to CH and CH to CH. Also, $\mathcal{B}_{\hbar}$ represents the data collected from WBAN sensing nodes and transmitted towards CH and further transmitted to other CH, so that it can be transmitted to IoT gateway. The $\mathcal{B}_{\hbar}$ is represented using Eq. (10).

$$\mathcal{B}_{\hbar} = \sum_{o=1}^{N_C} b_o \qquad (10)$$

In Eq. (10), b_o denotes the information in bits collected by WBAN sensing nodes, which is transmitted to CH and further to IoT gateway and N_C denotes total WBAN sensing nodes present in a cluster.Moreover, finding the best path for transmitting data from a WBAN sensing node to CH and from the CH to the IoT gateway is essential for optimizing energy use, minimizing delay, reducing packet loss, and ensuring reliable communication. Hence, the best route for data transmission is evaluated using Eq. (11).

$$L_{\mathcal{M}} = \mathcal{E}_v + \mathcal{G}_l + \bar{\mathcal{G}}_l + L_{r}^{p} \qquad (11)$$

In Eq. (11), $L_{\mathcal{M}}$ denotes best route for data transmission, $\mathcal{E}_v$ denotes the energy-level of WBAN sensing nodes which also includes CHs, $\mathcal{G}_l$ denotes hop-count for transmission of data, $\bar{\mathcal{G}}_l$ denotes inverse of $\mathcal{G}_l$, and L_{r}^{p} denotes packet-failure rate.Moreover, as most of the MAC approaches are used for enhancing IoT networks environment by reducing energy and communication overhead, providing better delay[24], the presented TDMA-OMAC optimizes the process of transmission of packets among CHs for transmitting it to IoT gateway for emergency scenarios, having better energy efficiency, delay and less communication overhead. The complete process of TDMA-OMAC is presented in Algorithm 1.

Algorithm 1: TDMA-OMAC for efficient CH-to-CHcommunication.			
Step 1	**Start**		
Step 2	**CH Selection:** Evaluate K_y using Eq. (1) to identify CHs for all clusters. The CH set is denoted as $\mathcal{D}$.Sort CHs by cluster size, prioritizing nodes with lower energy and fewer neighbors, resulting in a CH set $[\beta_1, \beta_2, \beta_3, \dots, \beta_D]$.		
Step 3	**For Each Round**		
Step 4		Compute $\mathcal{G}_l$ and $\bar{\mathcal{G}}_l$ using Eq. (4) and Eq. (5) to find the optimal hop.	
Step 5		Determine the scenario (normal or emergency) using Eq. (8)	
Step 6		**If** emergency scenario	
Step 7			Transmit data to IoT gateway using best path $L_{\mathcal{M}}$ using Eq. (11).
Step 8			Evaluate packet-failure rate $L_{\prime}^{p}$using Eq. (9).
Step 9		**Else**	
Step 10			Transmit data IoT gateway using the best route $L_{\mathcal{M}}$ using Eq. (11).
Step 11		**End if**	
Step 12	**End For**		
Step 13	**Stop**		

Energy Consumption, Delay and Communication Overhead Evaluation

Further, the energy consumption for transmission of data from WBAN sensors to IoT gateway is primarily influenced by three factors, i.e., intra-cluster communication (WBAN sensing nodes to CH), inter-cluster communication (CH-to-CH or CH-to-IoT gateway), and WBAN sensing node operations, which includes sensing, processing, and transmitting data. Hence, from this, the total energy consumption E_{total} in the network is evaluated using Eq. (12)

$$E_{total} = \sum_{n=1}^{N_C} \left(E_{Sense} + E_{process} + E_{transmit} \right) + \sum_{c=1}^{C} E_{CH} \qquad (12)$$

In Eq. (12), E_{Sense} denotes energy consumed by WBAN sensing nodes for sensing data, $E_{process}$ denotes energy consumed by WBAN sensing nodes for processing data, $E_{transmit}$ denotes energy consumed by WBAN sensing nodes for transmitting data to CHs, C denotes total number of clusters and E_{CH} denotes energy consumed by CHs for aggregation, inter-cluster communication, and

Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 32 No. 9s (2025)

transmission to the IoT gateway. The energy consumed by a WBAN sensing node to transmit data to the CH, i.e., energy for intra-cluster data communication is evaluated using Eq. (13).

$$E_{transmit} = N_C \cdot P_t \cdot T_{SNCH} \quad (13)$$

In Eq. (13), P_t denotes power required for transmission, T_{SNCH} denotes time required for WBAN sensing nodes to transmit data to CH. Further, the energy consumed by the CH to transmit aggregated data to other CHs or the IoT gateway, i.e., energy for inter-cluster data communication is evaluated using Eq. (14).

$$E_{CH} = P_{CH} \cdot T_{CH} + E_{agg} \quad (14)$$

In Eq. (14), P_{CH} is power required for CH to transmit aggregated data, T_{CH} is time required for CH to transmit data and E_{agg} is the energy consumed by CH for data aggregation which is evaluated as $E_{agg} = \lambda \cdot S_{agg}$, where λ denotes energy coefficient for aggregation and S_{agg} denotes size of aggregated data. The energy consumed by WBAN sensing nodes for sensing data is evaluated using Eq. (15)

$$E_{Sense} = N_C \cdot P_S \cdot T_{Sense} \quad (15)$$

In Eq. (15), P_S denotes power required for sensing data and T_{sense} is time required for sensing. Using Eq. (13), Eq. (14) and Eq. (15), when substituted in Eq. (12), the total energy consumption E_{total} is obtained as presented in Eq. (16).

$$E_{total} = \sum_{n=1}^{N_C}\left(P_s \cdot T_{Sense} + P_t \cdot T_{SNCH} + E_{process}\right) + \sum_{c=1}^{C}\left(P_{CH} \cdot + T_{CH} + \lambda \cdot S_{agg}\right) \quad (16)$$

The EDODCM main objective is to minimize E_{total} while ensuring reliable communication by adjusting the parameters P_t, P_{CH}, T_{SNCH}, T_{CH} and S_{agg}. Additionally, the ODC in (Eq. (3)) helps reduce unnecessary energy consumption by putting nodes into sleep mode when idle. The total network delay $\mathcal{L}$ in this work is evaluated using Eq. (17).

$$\mathcal{L} = \sum_{h=1}^{H}\left(\frac{P_h}{R_h} + D_p\right) \quad (17)$$

In Eq. (17), H is total number of hops in the path, P_h is the size of the packet transmitted at hop h (in bits), R_h is data-transmission rate at h (in bits/second) and D_p is processing delay at each node (in seconds). The total communication overhead $\mathcal{C}$ is evaluated using Eq. (18).

$$\mathcal{C} = \sum_{n=1}^{N_C}\left(\eta_{agg} + \eta_{ctrl} + \eta_{fail}\right) \quad (18)$$

In Eq. (18), η_{agg} is overhead due to data aggregation at CHs, η_{ctrl} is the overhead because of data and η_{fail} is overhead due to retransmissions caused by packet-failure rate. The η_{agg}, η_{ctrl}, and η_{fail} are evaluated using Eq. (19), Eq. (20) and Eq. (21) respectively.

$$\eta_{agg} = \alpha \cdot \left(\frac{D_{SNCH}}{N_C}\right) \quad (19)$$

$$\eta_{ctrl} = \beta \cdot C_{Ctrl} \quad (20)$$

$$\eta_{fail} = \gamma \cdot L_{r}^{p} \cdot \mathcal{B}_{\hbar} \quad (21)$$

In Eq. (19), Eq. (20) and Eq. (21),$\alpha$is aggregation factor, D_{SNCH} is the total data transmitted by WBAN nodes to CH, β is control data frequency factor,C_{ctrl} is the total size of control packets transmitted between nodes, CHs, and the gateway, γ denotes retransmission factor, L_{f}^{p} is packet-failure rate (Eq. (9)) and $\mathcal{B}_{\hbar}$ is total data transmitted in bits (Eq. (10)).This presented EDODCM combines clustering, duty-cycling, multi-hop routing, and a TDMA-based MAC protocol to optimize data transmission for WBAN sensing nodes to IoT gateway. The approach ensures energy efficiency, low delay, and communication overhead under both normal and emergency scenarios. By dynamically selecting CHs and leveraging optimized routes, the system enhances performance in IoT-integrated healthcare environments. The results of the EDODCM in terms of energy consumption, delay and communication overhead using Eq. (16), Eq. (17) and Eq. (18) respectively, is discussed in next section.

4. Results

To evaluate the performance of the proposed EDODCM and the existing DC-ACO approach [22], simulations were conducted using the SENSORIA simulator [25]. The simulation parameters are summarized in Table 1. The network was simulated for a total of 100 rounds, with the number of WBAN nodes varying between 50 and 300. Each data packet had a size of 80 bytes, and the transmission range was set between 10 to 25 meters, ensuring a realistic communication environment. The data rate was fixed at 50 kbps, while the mobility rate ranged from 0 to 50 m/s to mimic dynamic scenarios. The simulation area covered a 50×50 m² space, representing a typical Autism WBAN deployment. The IEEE 802.11 MAC protocol was utilized to manage medium access control. Each WBAN node was initialized with an energy level of 100 Joules, providing a uniform starting point to assess energy efficiency and network performance. These simulation settings were chosen to provide a comprehensive evaluation of the models in terms of energy consumption, network lifetime, communication overhead, and delay under diverse network conditions.

Table 1. Simulation Parameters

Simulation Parameters	**Value**
Total Rounds	100
WBAN nodes	50~300
Data Packet Size	80 bytes
Transmission Range	10m-25m
Data Rate	50 kbps
Mobility Rate	0-50 m/s
Area Considered	50×50
MAC Protocol	IEEE 802.11
Initial Energy	100 Joules

5. Discussion

1.1 Network Lifetime

This section presents the network lifetime performance of EDODCM compared with DC-ACOP. The results are presented in Figure 3, where the results demonstrate better network lifetime performance for proposed EDODCM compared to the existing DC-ACO model across various scenarios. For a network with 50 nodes, EDODCM extended the network lifetime to 4425 seconds, surpassing DC-ACO's network lifetime performance, i.e., 3898 seconds. As the network size increased to 300 nodes, EDODCM maintained its superior performance, achieving a network lifetime of 3864 seconds compared to DC-ACO's network lifetime performance, i.e., 2698 seconds. The average improvement in network lifetime across all scenarios was 20.1%, with the most significant gains observed in larger networks. This improvement is attributed to EDODCM's unequal clustering approach, which balances energy consumption and load distribution, particularly in clusters with higher node density. Additionally, the optimized duty cycling and presented routing approach reduces unnecessary energy consumption, further contributing to extended network longevity.These findings emphasize EDODCM's potential to address the critical challenge of limited energy resources in WBANs, ensuring sustainable and efficient data transmission. The results validate EDODCM as a robust solution for applications requiring prolonged network operation, particularly in healthcare scenarios where uninterrupted monitoring is essential.

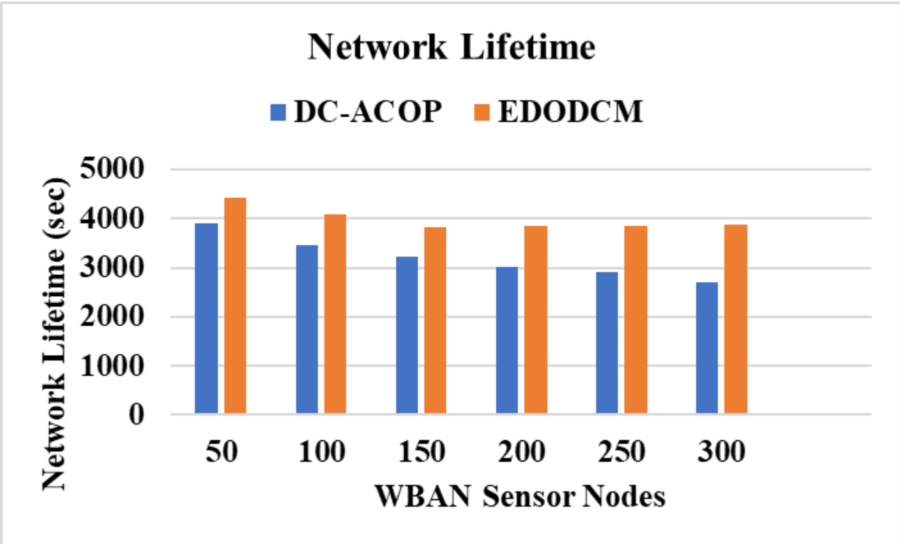

Figure 3. Network Lifetime Performance by varying WBAN sensor nodes.

1.2 Energy Efficiency

This section presents the energy efficiency performance of EDODCM compared with DC-ACOP. The results are presented in Figure 4, where the results demonstrate better energy efficiency for proposed EDODCM compared to the existing DC-ACO model across various scenarios. For a network size of 50 nodes, EDODCM achieved an energy efficiency of 50.74%, significantly outperforming DC-ACO's energy efficiency, i.e., 35.87%. As the network size increased, EDODCM consistently maintained higher energy efficiency, reaching 60.78% for a network of 300 nodes, compared to DC-ACO's 49.87%. The average improvement across all scenarios for EDODCM was notable, with an average energy efficiency of 24.52% compared to DC-ACO. The consistent performance gains indicate that EDODCM can handle increasing network sizes without substantial degradation in energy efficiency, a critical factor for WBAN applications where sensor nodes are resource-constrained. The results also emphasize that EDODCM is particularly effective in minimizing energy consumption in larger networks, where challenges like increased communication overhead and latency are more pronounced. The findings validate the robustness of EDODCM in optimizing energy utilization while maintaining reliable and efficient data communication, making it a promising solution for energy-sensitive IoT environments integrating WBANs.

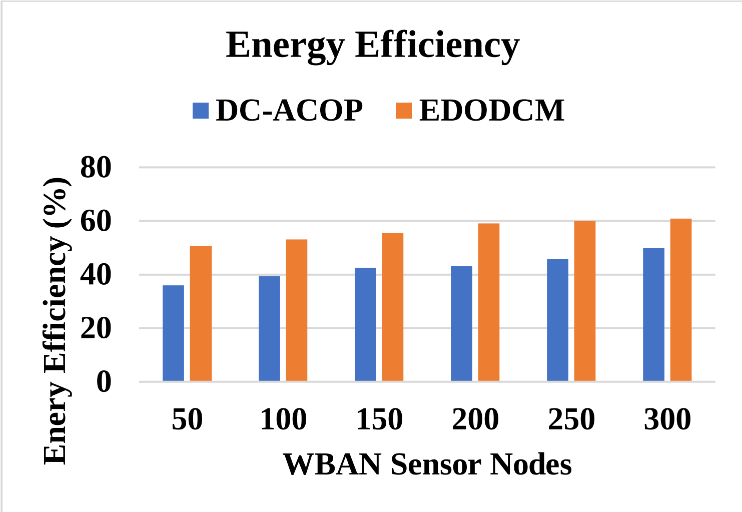

Figure 4. Energy Efficiency Performance by varying WBAN sensor nodes.

1.3 End-to-End Delay

This section presents the EED performance of EDODCM compared with DC-ACOP. The results are presented in Figure 5, where the results demonstrate the significant reduction in communication delay achieved by the proposed EDODCM model compared to the DC-ACO approach across various network sizes. For network with 50 nodes, EDODCM reduced the EED from 133.51 seconds in comparison with DC-ACOEED of 124.51 seconds, reflecting an improvement of 6.74%. As the network size increased, the EDODCM achieved EED of 161.41 seconds for 300 nodes, compared to 183.41 seconds for DC-ACO, resulting in an improvement of approximately 11.99%.The average EED reduction across all network configurations was 9.65%, highlighting the model’s consistent effectiveness. This improvement was attributed to EDODCM’s optimized intra-cluster and inter-cluster communication approaches, which minimized latency by streamlining data transmission paths and employing efficient routing approach. Furthermore, the TDMA-OMAC approach ensured orderly and collision-free communication, reducing retransmissions and delays, particularly in larger and denser networks.The reduction in EED achieved by EDODCM is critical for real-time applications such as healthcare monitoring, where timely data transmission can be a matter of urgency. These results validate EDODCM's ability to deliver faster and more reliable communication, enhancing the overall performance and responsiveness of WBAN-based IoT systems.

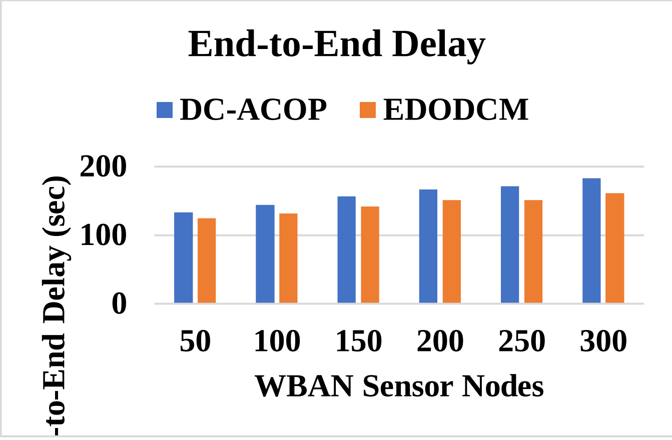

Figure 5. End-to-End Delay Performance by varying WBAN sensor nodes.

1.4 Communication Overhead

This section presents the communication overhead performance of EDODCM compared with DC-ACOP. The results are presented in Figure 6, where the results reveal a notable reduction in communication overhead achieved by the EDODCM model compared to the DC-ACO approach across various network configurations. For a network size of 50 nodes, EDODCM achieved communication overhead of 0.078 compared to 0.089 in DC-ACO, marking an improvement of 12.36%. Further, for 300 nodes, EDODCM achieved communication overhead of 0.12, compared to 0.1647 in DC-ACO, representing a significant reduction of 27.14%.On average, EDODCM consistently reduced communication overhead by 22.18% across all tested configurations. These improvements are primarily attributed to the model's optimized data aggregation approach, unequal clustering, and energy-efficient routing approach. The multi-hop routing mechanism used by EDODCM ensures efficient utilization of network resources, minimizing redundant transmissions and thus reducing communication overhead.The substantial reduction in communication overhead underscores EDODCM's ability to streamline data communication processes, making it more efficient for applications where minimizing overhead is crucial. This improvement enhances the scalability and performance of WBANs, particularly in scenarios requiring high reliability and low operational cost.

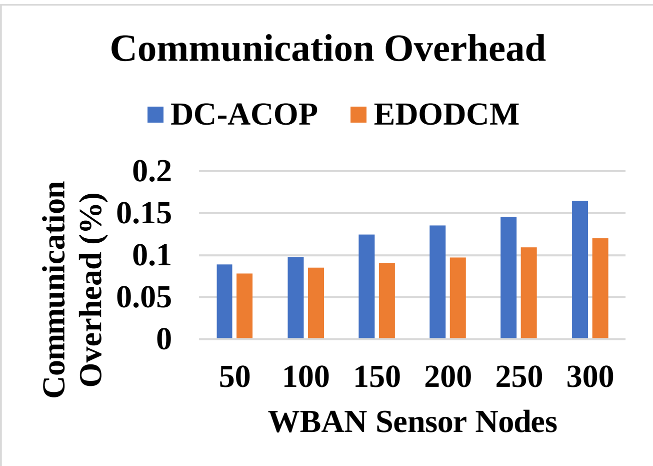

Figure 6. Communication Overhead Performance by varying WBAN sensor nodes.

6 Conclusion

In this work, an EDODCM for WBANs integrated into the IoT environment is proposed. WBANs, a critical technology for health monitoring systems, face challenges of energy inefficiency, high communication overhead, and increased delay, especially in dynamic scenarios involving mobility and emergency data transmission. Existing approaches like DC-ACO, while effective and provided better performance, have limitations in optimizing these parameters simultaneously. This study addresses these gaps with a novel unequal clustering-based communication model that enhances energy efficiency, reduces delay, and minimizes communication overhead. The proposed EDODCM employs an optimized duty-cycling mechanism, multi-hop routing for normal and emergency scenarios, and a TDMA-based Optimized Medium Access Control (TDMA-OMAC) approach to streamline data aggregation and transmission. Simulation results demonstrate that EDODCM outperforms DC-ACO across key metrics. The model improves average energy efficiency by up to 24.52%, extends average network lifetime by 20.1%, reduces average EED by 9.65%, and lowered average communication overhead by 22.18%. These improvements highlight the efficacy of EDODCM in addressing the complex requirements of WBANs in IoT environments. Future work will focus on incorporating advanced machine learning algorithms for predicting the collected Autism data.

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