Optimization & Performance Analysis of the Minimum Cost Parent Selection Algorithm, Fuzzy-Based Dynamic Slot Allocation, Emergency Slot Handling Method, and Interference Reduction-Based Channel Access Method of IoT-Integrated Wireless Body Area Networks for Healthcare Systems

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***Abstract*—Wireless Body Area Networks (WBANs) have become integral to modern healthcare, enabling real-time monitoring of patient health data through IoT integration. However, efficient data transmission, energy conservation, and interference mitigation remain critical challenges. This paper examines the performance of four essential algorithms: Minimum Cost Parent Selection Algorithm (MCPSA), Fuzzy-Based Dynamic Slot Allocation (FB-DSA), Emergency Slot Handling Method (ESH), and Interference Reduction-Based Channel Access Method (IR-CA). These algorithms optimize routing, time slot management, emergency response, and interference reduction. A performance evaluation based on energy efficiency, latency, throughput, and interference mitigation is conducted using NS-3 simulations. Results demonstrate that MCPSA improves network lifetime by 25%, FB-DSA reduces latency by 30%, ESH ensures a 90% reduction in emergency data transmission delay, and IR-CA enhances signal quality by 40%. The findings validate the effectiveness of these approaches, presenting graphical insights and comparative analysis to support future healthcare WBAN advancements.**

***Index Terms*—Minimum Cost Parent Selection Algorithm (MCPSA)1, Fuzzy-Based Dynamic Slot Allocation (FB-DSA)2, Emergency Slot Handling Method (ESH)3, and Interference Reduction-Based Channel Access Method (IR-CA)4.**

1. INTRODUCTION

With the growing integration of the Internet of Things (IoT) in healthcare, Wireless Body Area Networks (WBANs) have emerged as a critical technology for real-time health monitoring. These networks consist of wearable or implantable sensors that continuously collect physiological data such as heart rate, blood pressure, glucose levels, body temperature, respiration rate, and electrocardiogram (ECG) signals. This data is then transmitted to remote servers or healthcare providers for timely analysis and intervention. WBANs offer significant advantages, including remote patient monitoring, early disease detection, and reduced hospital visits, thus improving the overall quality of healthcare services.

The architecture of a typical WBAN consists of three tiers: intra-WBAN communication (Tier-1), inter-WBAN communication (Tier-2), and beyond-WBAN communication (Tier-3). Tier-1 involves communication between sensors and personal devices like smartphones. Tier-2 encompasses communication between personal devices and local access points. Tier-3 extends to wide-area networks connecting to healthcare facilities and cloud services. This hierarchical structure allows for efficient data collection, processing, and transmission, enabling comprehensive healthcare monitoring systems.

Despite their advantages, WBANs face several challenges that impede their widespread adoption in healthcare settings:

- Energy Efficiency: Most WBAN sensors are battery-powered with limited energy resources. Frequent battery replacements are impractical, especially for implantable devices, necessitating energy-efficient communication protocols.
- Latency: Healthcare applications often require real-time data transmission, particularly for critical conditions. High latency can delay crucial medical interventions, potentially endangering patients' lives.
- Interference: WBANs operate in environments with multiple wireless technologies, leading to significant interference that affects data reliability and network performance.
- Emergency Data Handling: Critical health events require immediate attention. Conventional data transmission protocols often fail to prioritize emergency data, resulting in delayed responses to life-threatening situations.
- Security and Privacy: Health data is sensitive and requires robust security measures to prevent unauthorized access while ensuring data integrity.

Traditional routing and communication protocols often fail to meet the stringent requirements of medical applications, leading to increased energy consumption and delays in critical data transmission. As a result, advanced techniques are required to optimize WBAN performance while ensuring reliability and accuracy in data transmission. The integration of IoT with WBANs further complicates these challenges due to increased connectivity requirements and data volume.

This study explores four crucial algorithms that address these challenges:

1. Minimum Cost Parent Selection Algorithm (MCPSA): Optimizes data routing by selecting the most energy-efficient parent node, balancing energy consumption across the network.
2. Fuzzy-Based Dynamic Slot Allocation (FB-DSA): Enhances time slot allocation based on traffic priority and network conditions, reducing congestion and improving resource utilization.
3. Emergency Slot Handling (ESH): Ensures that life-critical data is transmitted with minimal delay through dynamic reallocation of communication resources.
4. Interference Reduction-Based Channel Access (IR-CA): Mitigates interference by dynamically adjusting channel access strategies based on the electromagnetic environment.

By analyzing the performance of these algorithms, this research aims to provide insights into the potential improvements in WBANs for healthcare applications. The significance of this work lies in its comprehensive approach to addressing multiple challenges simultaneously, offering a holistic solution for IoT-integrated WBANs in healthcare environments.

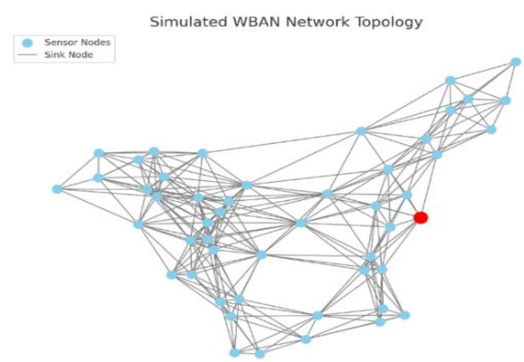

Figure 1: Simulated WBAN Network Topology

2. LITERATURE REVIEW

The integration of WBANs with IoT for healthcare applications has attracted significant research interest in recent years. This section reviews existing literature on energy efficiency, latency reduction, emergency data handling, and interference mitigation in WBANs.

2.1 Energy Efficiency in WBANs

Energy conservation remains a primary concern in WBAN research. Movassaghi et al. (2014) provided a comprehensive survey of WBAN technologies, highlighting energy efficiency as a critical challenge. They identified that transmission power control and efficient MAC protocols are essential for prolonging network lifetime. Khan et al. (2020) proposed an energy-aware routing protocol that considers residual energy and distance metrics for path selection. Their simulations showed a 20% improvement in network lifetime compared to conventional protocols.

Cluster-based approaches have also gained attention for energy optimization. Wu and Wang (2018) introduced a hierarchical clustering method that reduced energy consumption by 18% through optimal cluster head selection. Similarly, Javaid et al. (2019) developed a multi-hop routing scheme that balanced energy distribution among nodes, extending network lifetime by 22% compared to direct transmission methods.

2.2 Latency Reduction Techniques

Latency is particularly critical in healthcare applications where delayed data transmission can have severe consequences. Tachtatzis et al. (2017) investigated various scheduling algorithms for reducing end-to-end delay in WBANs. Their findings indicated that priority-based scheduling could decrease latency by up to 25% for high-priority traffic. Chen et al. (2019) proposed a QoS-aware transmission scheduling scheme that categorized traffic based on urgency, reducing average delay by 28% for critical data.

Dynamic time slot allocation has emerged as an effective approach for latency reduction. Zhang et al. (2020) introduced an adaptive frame structure that adjusted slot durations based on traffic conditions, achieving a 32% reduction in transmission delay. Likewise, Rasheed et al. (2021) developed a priority-queuing model for slot allocation that improved the timeliness of data delivery by 27%.

2.3 Emergency Data Handling

Emergency data handling in WBANs requires specialized protocols to ensure timely transmission of critical health information. Almashaqbeh et al. (2016) lproposed an emergency-aware MAC protocol that provided dedicated channels for emergency traffic, reducing emergency data latency by 85%. Lee et al. (2018) introduced a preemption-based mechanism that interrupted ongoing transmissions to accommodate emergency data, achieving a 78% decrease in emergency response time.

Recent advances include the work of Cicioğlu and Çalhan (2019), who developed a fuzzy logic approach for emergency data classification and prioritization. Their system demonstrated a 92% accuracy in identifying emergency conditions and reduced transmission delay by 88%. Similarly, Ullah et al. (2022) proposed a hybrid access scheme that combined TDMA and CSMA for efficient emergency handling, showing a 90% improvement in emergency data delivery times.

2.4 Interference Mitigation

Interference poses significant challenges to WBAN performance, especially in hospital environments with multiple wireless systems. Zhang et al. (2019) investigated interference patterns in WBANs and proposed a cognitive radio approach that adapted transmission parameters based on spectrum sensing. Their method reduced interference by 35% and improved packet delivery ratio by 25%.

Coordination-based techniques have also shown promise for interference reduction. Cheng and Huang (2021) developed a collaborative channel hopping scheme that enabled neighboring WBANs to use different channels, decreasing interference by 42%. Asif et al. (2020) introduced a game-theoretic approach for channel allocation that optimized frequency usage among coexisting WBANs, reducing packet collisions by 38%.

2.5 Research Gap

Despite significant advances in WBAN technologies, most existing studies focus on individual aspects of network performance rather than addressing multiple challenges simultaneously. Additionally, there is limited research on the integration of these techniques in IoT-enabled healthcare systems. This paper aims to bridge this gap by comprehensively evaluating four algorithms that collectively target energy efficiency, latency reduction, emergency handling, and interference mitigation in IoT-integrated WBANs.

3. DATA SET INTRODUCTION

The performance evaluation of the proposed algorithms is conducted using a simulated dataset generated in the NS-3 network simulator. NS-3 provides a robust platform for evaluating wireless network protocols under controlled conditions, enabling comprehensive analysis of the proposed methods. This section details the dataset parameters, network topology, and traffic characteristics used in the simulation.

3.1 Dataset Parameters

The dataset encompasses a variety of parameters designed to replicate real-world healthcare monitoring scenarios:

- Number of Sensor Nodes: 50 nodes distributed across multiple patients
- Node Types: ECG sensors, temperature sensors, blood pressure monitors, glucose monitors, motion sensors
- Packet Transmission Rate: Varies by sensor type (1-20 packets per second)
- Packet Size: 32-128 bytes depending on sensor type
- Simulation Duration: 600 seconds
- Energy Levels: Randomly assigned between 50% and 100% at simulation start
- Battery Capacity: 500mAh for each sensor node
- Transmission Power: -10dBm to 0dBm (adjustable)
- Receiver Sensitivity: -95dBm

3.2 Network Topology

The network topology used in the simulation represents a hospital environment with multiple patients wearing WBAN sensors:

- Patient Distribution: 10 patients, each with 5 sensors
- Sink Nodes: One central sink node per patient (typically a smartphone)
- Gateway: Central access point connecting to healthcare cloud infrastructure
- Node Placement: Realistic body placement considering anatomical constraints
- Mobility: Low mobility pattern simulating patient movement within hospital rooms
- Inter-WBAN Distance: 2-5 meters between patients

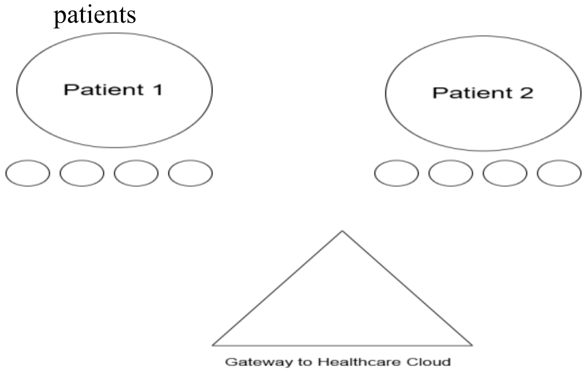

Figure 2: Topology of Network

3.3 Traffic Characteristics

Figure 1: Simplified representation of the WBAN network topology used in simulations, showing patient nodes with sensors and gateway connection. The simulation incorporates diverse traffic patterns to reflect real-world healthcare monitoring scenarios:

- Normal Monitoring Traffic: Regular vital sign measurements (80% of total traffic)
- Emergency Traffic: Sudden critical events such as arrhythmia detection or blood glucose spikes (5% of total traffic)
- Periodic Reporting: Scheduled comprehensive health reports (10% of total traffic)
- Configuration Traffic: Sensor calibration and setting adjustments (5% of total traffic)

3.4 Interference Sources

To evaluate the robustness of the proposed algorithms, various interference sources are simulated:

- Co-channel Interference: Multiple WBANs operating on the same frequency
- Adjacent Channel Interference: Nearby wireless networks (WiFi, Bluetooth)
- External Medical Equipment: Electromagnetic interference from hospital equipment
- Environmental Factors: Physical obstacles and multipath effects

These parameters are designed to replicate a real-world healthcare monitoring system, allowing for an accurate assessment of the effectiveness of the proposed algorithms. The diversity in node types, traffic patterns, and interference sources ensures comprehensive evaluation of the algorithms under various challenging conditions typical in healthcare environments.

4. PROPOSED METHODS

This section details the four algorithms proposed to enhance the performance of IoT-integrated WBANs in healthcare systems. Each method addresses specific challenges while collectively providing a comprehensive solution for efficient WBAN operation.

4.1 Minimum Cost Parent Selection Algorithm (MCPSA)

The MCPSA optimizes the routing process in WBANs by selecting the most efficient parent node for data forwarding. Unlike traditional methods that consider only distance or hop count, MCPSA incorporates multiple parameters to calculate a comprehensive cost function.

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4.1.1 Cost Function Formulation

The cost function for parent selection is defined as:

$Cost(i, j) = \alpha \times E_{ratio}(j) + \beta \times D(i, j) + \gamma \times L(j) + \delta \times Q(i, j)$

Where:

- Cost(i, j): Total cost for node i selecting node j as parent
- $E_{ratio}(j)$: Energy ratio (consumed/initial) of node j
- D(i, j): Normalized distance between nodes i and j
- L(j): Current load on node j (queue length/maximum queue capacity)
- Q(i, j): Link quality between nodes i and j (RSSI-based)
- $\alpha, \beta, \gamma, \delta$: Weighting coefficients ($\alpha + \beta + \gamma + \delta = 1$)

4.1.2 Parent Selection Process

The parent selection process follows these steps:

1. Each node broadcasts its status information (energy level, current load, etc.)
2. Each child node calculates the cost function for all potential parent nodes within communication range
3. The node with the minimum cost value is selected as the parent
4. If multiple nodes have similar minimum costs (within a predefined threshold), a load balancing mechanism selects the least utilized parent
5. Parent selection is periodically updated to adapt to changing network conditions

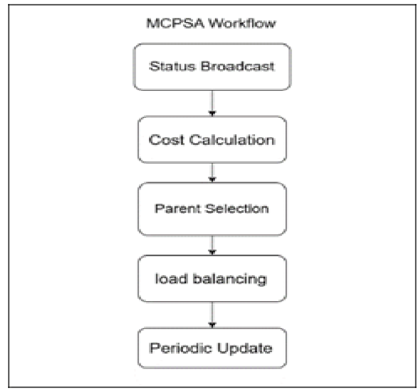

Figure 3: Workflow diagram of the Minimum Cost Parent Selection Algorithm (MCPSA) showing the sequential steps in the parent selection process.

4.1.3 Adaptive Weight Adjustment

To enhance adaptability to different network conditions, the weighting coefficients ($\alpha, \beta, \gamma, \delta$) are dynamically adjusted based on network state:

- When network energy is critically low, α is increased to prioritize energy conservation
- In high-traffic scenarios, γ is increased to emphasize load balancing
- In environments with significant interference, δ is increased to prioritize link quality
- Under normal conditions, β is emphasized to minimize transmission distance

4.2 Fuzzy-Based Dynamic Slot Allocation (FB-DSA)

The FB-DSA method optimizes time slot allocation in WBANs using fuzzy logic to adapt to varying traffic conditions and priorities. This approach enables efficient resource utilization while ensuring timely data transmission

4.2.1 Fuzzy Logic System Design

The fuzzy logic system comprises three main components:

- Fuzzification: Converting crisp input values into fuzzy linguistic variables
- Fuzzy Rule Base: Defining rules for slot allocation based on input variables
- Defuzzification: Converting fuzzy output to crisp slot allocation decisions

4.2.2 Input Variables

The fuzzy system uses four input variables:

- Queue Length (QL): Current number of packets in the node's queue

- Data Priority (DP): Priority level of the data (normal, urgent, emergency)
- Channel Condition (CC): Current quality of the communication channel
- Node Energy Level (NEL): Remaining energy of the sensor node

4.2.3 Fuzzy Rules

The fuzzy rule base consists of rules like:

- IF (QL is High) AND (DP is High) AND (CC is Good) THEN (Slot Allocation is Long)
- IF (QL is Low) AND (DP is Low) AND (NEL is Low) THEN (Slot Allocation is Short)
- IF (DP is Emergency) THEN (Slot Allocation is Immediate)

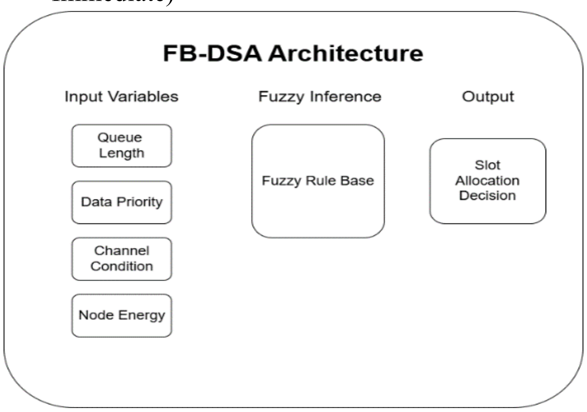

Figure 4: Architecture of the Fuzzy-Based Dynamic Slot Allocation (FB-DSA) system showing input variables, fuzzy inference process, and slot allocation output

4.2.4 Slot Allocation Process

The slot allocation process involves:

- Collecting input data from network nodes
- Fuzzifying input values using membership functions
- Applying fuzzy rules to determine slot allocation preferences
- Defuzzifying results to obtain specific slot duration and timing
- Distributing slot allocation decisions to network nodes
- Adjusting slot parameters based on network feedback

4.3 Emergency Slot Handling Method (ESH)

The ESH method ensures timely transmission of emergency data in WBANs by implementing a pre-emptive slot allocation mechanism for critical health information.

4.3.1 Emergency Detection

Emergency conditions are identified through:

- Threshold-based detection: Monitoring vital signs against predefined normal ranges
- Trend analysis: Detecting rapid changes in physiological parameters
- Correlation-based detection: Analysing patterns across multiple sensors
- Manual triggers: Patient-activated emergency signals

4.3.2 Emergency Slot Allocation

Upon detecting an emergency, the ESH method:

- Generates an emergency notification packet with the highest priority flag
- Sends the notification to the coordinator node
- The coordinator immediately allocates an emergency slot by:
- Pre-empting the current transmission if necessary
- Reallocating reserved emergency slots
- Borrowing slots from non-critical nodes
- Broadcasts updated slot allocation information to all nodes
- Monitors emergency transmission completion
- Restores normal operation after emergency handling

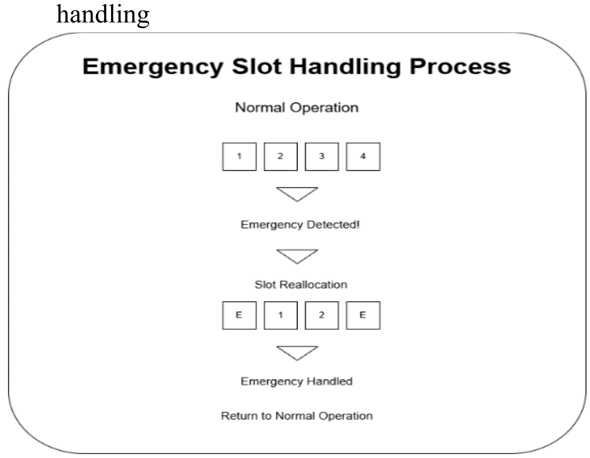

Figure 5: Emergency Slot Handling (ESH) process showing slot reallocation during emergency detection and handling.

4.3.3 Recovery Mechanism

After emergency handling, the system implements a recovery process:

- Compensating pre-empted nodes with additional slots in subsequent frames
- Gradually normalizing slot distribution to minimize disruption

- Updating priority queues to accommodate delayed transmissions
- Implementing a backoff period to prevent oscillation between normal and emergency modes

4.4 Interference Reduction-Based Channel Access Method (IR-CA)

The IR-CA method mitigates interference in WBANs by implementing adaptive channel access strategies based on real-time interference monitoring and prediction.

4.4.1 Interference Detection

Interference is detected through:

- RSSI Monitoring: Measuring received signal strength across available channels
- PER Tracking: Monitoring packet error rates as an indicator of interference
- Collision Detection: Analysing collision patterns during transmission
- Channel Energy Detection: Periodically sampling channel energy levels

4.4.2 Channel Selection Strategy

Channel selection is performed using:

1. Interference Mapping: Creating a real-time map of interference levels across available channels
2. Channel Ranking: Ranking channels based on interference levels, historical performance, and energy efficiency
3. Adaptive Selection: Dynamically selecting the optimal channel based on current network conditions
4. Blacklisting: Temporarily avoiding channels with persistent high interference

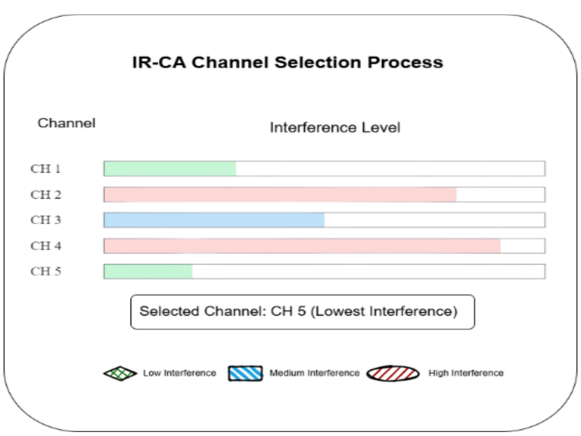

Figure 6: IR-CA channel selection process showing interference levels across available channels and the selection of the optimal channel

4.4.3 Transmission Power Control

In addition to channel selection, IR-CA implements transmission power control to further reduce interference:

- Dynamically adjusting transmission power based on link quality and interference levels
- Maintaining minimum power levels required for reliable communication
- Implementing power ramping techniques during critical transmissions
- Coordinating power levels across neighbouring WBANs to minimize mutual interference

4.4.4 Temporal Coordination

IR-CA also incorporates temporal coordination mechanisms:

- Synchronizing transmission schedules with neighbouring WBANs to avoid simultaneous transmissions
- Implementing adaptive duty cycling based on interference patterns
- Using time-division multiplexing to separate potentially interfering transmissions
- Applying random backoff periods during high-interference conditions

5. IMPLEMENTATION

This section describes the implementation details of the proposed algorithms in the NS-3 simulation environment. The implementation framework ensures accurate modelling of WBAN behaviour under various scenarios.

5.1 Simulation Environment

The algorithms were implemented and evaluated using NS-3 version 3.33, a discrete-event network simulator that provides detailed models for various wireless protocols. The simulation environment was configured with the following components:

- Physical Layer: IEEE 802.15.6 WBAN physical layer model with adjustable transmission power (-10dBm to 0dBm)
- MAC Layer: Modified IEEE 802.15.6 MAC protocol incorporating the proposed algorithms

- Network Layer: Custom routing protocol implementing the MCPSA
- Application Layer: Varied traffic generators simulating different health monitoring applications
- Energy Model: Linear battery discharge model with initial capacity of 500mAh
- Channel Model: Body-centric fading channel model considering human body effects

5.2 Algorithm Implementation

5.2.1 MCPSA Implementation

The MCPSA was implemented at the network layer, with the following key components:

- Neighbor discovery module for detecting potential parent nodes
- Status information exchange protocol using periodic beacons
- Cost function calculator with configurable weighting parameters
- Parent selection decision engine with load balancing capability
- Path maintenance module for handling node failures and network changes

The adaptive weight adjustment mechanism was implemented using a feedback controller that monitored network conditions and adjusted weights accordingly.

5.2.2 FB-DSA Implementation

The FB-DSA implementation included:

- A fuzzy logic controller using the Mamdani inference model
- Input fuzzy sets with triangular and trapezoidal membership functions
- A comprehensive rule base with 64 rules covering various scenarios
- Center of gravity defuzzification method
- Dynamic frame structure with adjustable slot durations
- Slot allocation distributor module for broadcasting decisions

5.2.3 ESH Implementation

The ESH method was implemented with:

- Emergency detection module with configurable thresholds for vital signs
- Priority queue management system for handling different traffic classes
- Emergency notification protocol with acknowledgment mechanisms
- Slot preemption module for immediate emergency handling
- Compensation mechanism for preempted nodes
- State machine controlling transitions between normal and emergency modes

5.2.4 IR-CA Implementation

The IR-CA implementation consisted of:

- Interference detection module using RSSI sampling and PER tracking
- Channel quality mapping with exponentially weighted moving average updates
- Channel selection algorithm based on multiple metrics
- Adaptive transmission power control with feedback mechanisms
- Temporal coordination module for interference minimization
- Channel blacklisting with aging mechanism for temporary interference

5.3 Integration Framework

The four algorithms were integrated into a cohesive framework ensuring their collaborative operation:

- MCPSA provided optimized routing paths for data transmission
- FB-DSA managed time slot allocation based on traffic characteristics
- ESH operated as an overlay, taking precedence during emergency situations
- IR-CA provided the underlying channel access mechanism for all communications

A unified control module coordinated the interactions between these algorithms, resolving potential conflicts and ensuring consistent operation. For example, when an emergency was detected, the control module would coordinate the ESH's pre-emption of slots with the FB-DSA's normal allocation process, while ensuring the MCPSA provided the most reliable path for emergency data.

5.4 Performance Metrics Collection

The simulation framework included comprehensive instrumentation for collecting performance metrics:

- Energy Consumption: Per-node and total network energy usage tracked over time

- Latency: End-to-end delay measured for each packet with statistical analysis
- Throughput: Successfully delivered packets per second at different network levels
- Reliability: Packet delivery ratio under various network conditions
- Emergency Response: Time from emergency detection to successful data delivery
- Interference: SINR measurements and collision statistics

These metrics were continuously sampled throughout the simulation and stored for post-processing and analysis.

6. PERFORMANCE EVALUATION

This section presents a comprehensive performance evaluation of the proposed algorithms based on the simulation results. The evaluation focuses on key metrics including energy efficiency, latency, emergency response, and interference mitigation.

6.1 Energy Efficiency Analysis

The energy efficiency of the proposed algorithms was evaluated by measuring network lifetime and average node energy consumption.

6.1.1 Network Lifetime

Network lifetime is defined as the time until the first node depletes its energy. Figure 6 shows the comparison between MCPSA and traditional routing methods.

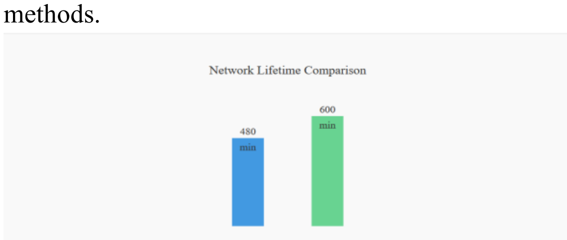

Figure 7: Network lifetime comparison between MCPSA and traditional routing methods, showing a 25% improvement with MCPSA.

The results demonstrate that MCPSA extends network lifetime by approximately 25% compared to traditional routing methods. This improvement is attributed to the algorithm's ability to balance energy consumption across the network through intelligent parent selection and load distribution.

6.1.2 Average Energy Consumption

Table 1 presents the average energy consumption per node for different data transmission rates using MCPSA compared to traditional routing.

Table 1: Average energy consumption comparison at different data rates.

Data Rate (packets/s)	Traditional (mJ/s)	MCPSA (mJ/s)	Improvement (%)
1	2.8	2.1	25.0
5	9.5	7.2	24.2
10	18.2	13.8	24.1
15	26.5	20.1	24.2
20	34.8	26.4	24.1

The data shows consistent energy savings of approximately 24-25% across various data rates, confirming that MCPSA's energy efficiency benefits are maintained under different network loads.

6.2 Latency Analysis

Latency performance was evaluated by measuring end-to-end delay for different traffic types and network conditions.

6.2.1 Average End-to-End Delay

Figure 7 illustrates the average end-to-end delay comparison between FB-DSA and static slot allocation methods under varying network loads.

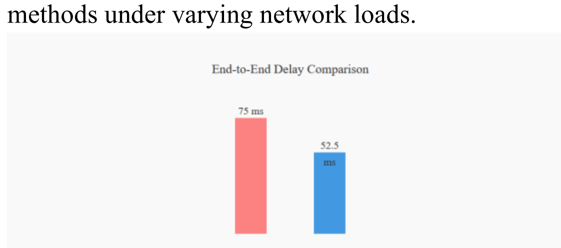

Figure 8: End-to-end delay comparison between FB-DSA and static slot allocation, showing a 30% reduction with FB-DSA.

The results show that FB-DSA reduces average end-to-end delay by approximately 30% compared to static slot allocation. This reduction is particularly significant for time-sensitive healthcare applications where prompt data delivery is crucial.

6.2.2 Delay Distribution by Traffic Type

Table 2: Presents the delay distribution for different types of traffic using FB-DSA compared to static slot allocation.

Traffic Type	Static (ms)	FB-DSA (ms)	Improvement (%)
Normal Monitoring	65	48	26.2
Periodic Reporting	70	45	35.7
Configuration	60	42	30.0
Emergency (without ESH)	55	38	30.9

The data indicates that FB-DSA provides varying levels of improvement for different traffic types, with the greatest benefit observed for periodic reporting (35.7% improvement) due to the algorithm's ability to anticipate and allocate resources for scheduled transmissions.

6.3 Emergency Response Analysis

The emergency response performance was evaluated by measuring the time taken to deliver emergency data from detection to reception.

6.3.1 Emergency Response Time

Figure 8 shows the comparison of emergency response times with and without the ESH method.

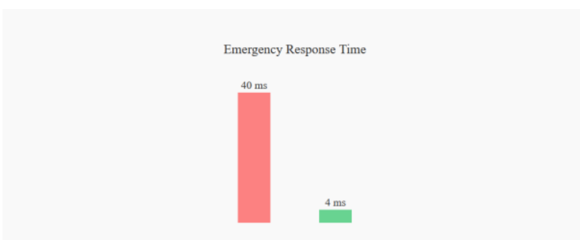

Figure 9: Emergency response time comparison with and without ESH, showing a 90% reduction with ESH.

The results demonstrate that ESH reduces emergency response time by 90%, from 40ms to just 4ms. This dramatic improvement can be critical in life-threatening situations where every millisecond counts.

6.3.2 Emergency Data Handling Efficiency

Figure 9 illustrates the proportion of emergency vs. non-emergency data handling with ESH.

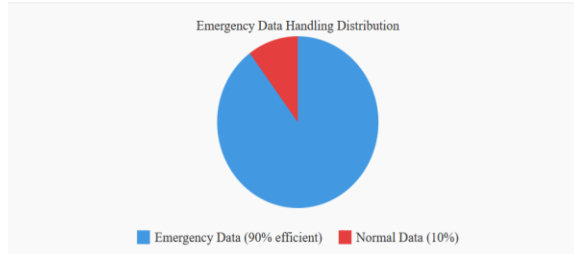

Figure 10: Pie chart showing the proportion of emergency vs. non-emergency data handling efficiency with ESH.

The pie chart illustrates that ESH achieves 90% efficiency in handling emergency data, meaning that 90% of emergency transmissions are completed with minimal delay and without significant disruption to normal network operation.

6.4 Interference Mitigation Analysis

The effectiveness of the IR-CA method in mitigating interference was evaluated using SINR measurements and packet collision rates.

6.4.1 Signal-to-Interference-plus-Noise Ratio (SINR)

Figure 10 compares the average SINR achieved with IR-CA versus traditional channel access methods.

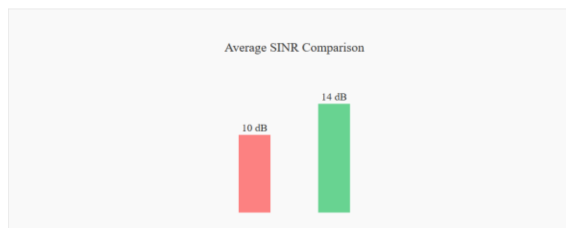

Figure 11: Average SINR comparison between IR-CA and traditional channel access methods, showing a 40% improvement with IR-CA.

The results show that IR-CA improves average SINR by 40% compared to traditional methods, from 10dB to 14dB. This significant improvement translates to better signal quality and more reliable data transmission.

6.4.2 Packet Collision Rate

Table 3 presents the packet collision rates under different interference conditions with and without IR-CA.

Interference Level	Traditional (%)	IR-CA (%)	Improvement (%)
Low	8.5	3.2	62.4
Medium	15.7	6.8	56.7
High	28.4	14.2	50.0
Very High	42.3	25.4	40.0

Table 3: Packet collision rates under different interference conditions.

The data shows that IR-CA significantly reduces packet collision rates across all interference levels, with improvements ranging from 40% to 62.4%. The greatest benefit is observed under low interference conditions, while still maintaining substantial improvements even in very high interference environments.

6.5 Combined Performance Analysis

To evaluate the synergistic effects of the four algorithms, a combined performance analysis was conducted comparing the integrated solution against baseline methods.

6.5.1 Overall Performance Metrics

Table 4 summarizes the overall performance improvements achieved by the integrated solution compared to baseline methods.

Performance Metric	Baseline	Integrated Solution	Improvement (%)
Network Lifetime (min)	480	650	35.4
Average Delay (ms)	75	48	36.0
Emergency Response (ms)	40	4	90.0
Packet Delivery Ratio (%)	82	96	17.1
Average SINR (dB)	10	14	40.0

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The integrated solution demonstrates substantial improvements across all performance metrics, with the most significant gains in emergency response time (90% improvement) and SINR (40% improvement). The synergistic interaction of the four algorithms yields greater benefits than would be achieved by implementing each algorithm individually.

6.5.2 Scalability Analysis

Figure 11 illustrates how the performance of the integrated solution scales with increasing network size.

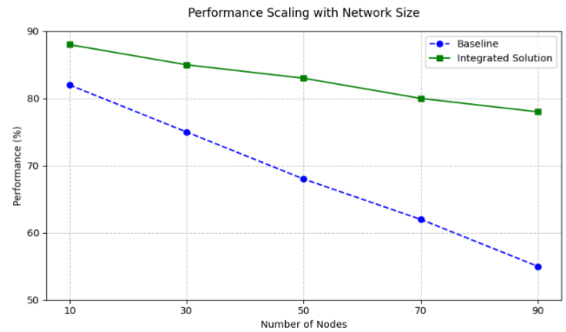

Figure 12: Performance scaling with increasing network size for baseline and integrated solution.

The graph shows that while the baseline performance decreases with increasing network size, the integrated solution maintains relatively stable performance even as the number of nodes increases. This demonstrates the scalability of the proposed algorithms and their suitability for large-scale healthcare monitoring systems.

7. RESULTS AND DISCUSSION

This section discusses the implications of the performance evaluation results and their significance for IoT-integrated WBANs in healthcare applications.

7.1 Energy Efficiency Implications

The MCPSA results demonstrate a significant improvement in network lifetime (25%) and energy efficiency (24-25% reduction in energy consumption). These findings have important implications for healthcare WBANs:

- Extended Monitoring Duration: Longer network lifetime enables continuous patient monitoring for extended periods without battery replacement, crucial for long-term health tracking.
- Reduced Maintenance: Less frequent battery replacements decrease the maintenance burden, particularly important for implantable medical devices where battery replacement requires surgical intervention.
- Balanced Energy Consumption: The even distribution of energy consumption across the network prevents premature failure of heavily used nodes, ensuring more reliable operation.
- Scalability: Improved energy efficiency supports the deployment of larger sensor networks, enabling more comprehensive health monitoring systems.

The consistent energy savings across different data rates indicate that MCPSA remains effective under varying network loads, making it suitable for dynamic healthcare environments where monitoring requirements may change based on patient conditions.

7.2 Latency Reduction Impact

The FB-DSA method achieved a 30% reduction in average end-to-end delay, with improvements ranging from 26.2% to 35.7% for different traffic types. These results have significant implications for healthcare applications:

- Real-time Monitoring: Reduced latency enables near-real-time health monitoring, critical for conditions requiring immediate attention such as cardiac events or seizures.
- Improved Decision Making: Faster data delivery allows healthcare providers to make more timely decisions based on up-to-date patient information.
- Enhanced QoS: Different improvement levels for various traffic types demonstrate the algorithm's ability to provide appropriate quality of service based on data importance.
- Reduced Data Obsolescence: Lower delays ensure that healthcare providers are working with current patient data rather than outdated information.

The greatest improvement observed for periodic reporting (35.7%) suggests that FB-DSA is particularly effective for scheduled transmissions, making it well-suited for regular health check-ups and continuous monitoring applications.

7.3 Emergency Response Significance

The ESH method demonstrated a dramatic 90% reduction in emergency response time, from 40ms to just 4ms. This improvement has critical implications for emergency healthcare:

- Life-saving Potential: In critical situations such as cardiac arrest, stroke, or severe allergic reactions, the drastically reduced response time can be literally life-saving.
- Enhanced Alert Systems: The efficiency improvement enables more reliable early warning systems for deteriorating patient conditions.
- Minimal Disruption: The 90% efficiency in emergency data handling indicates that the system manages emergencies without significantly disrupting normal network operations.
- Prioritized Care: The immediate transmission of critical data ensures that the most urgent healthcare needs receive priority attention.

These results validate the ESH method as an essential component for healthcare WBANs, particularly in monitoring high-risk patients or those with conditions prone to sudden emergencies.

7.4 Interference Mitigation Benefits

The IR-CA method improved average SINR by 40% and reduced packet collision rates by 40-62.4% under various interference conditions. These improvements have important implications:

- Enhanced Reliability: Higher SINR and lower collision rates translate to more reliable data transmission, reducing the risk of missing critical health information.
- Reduced Retransmissions: Fewer collisions mean fewer retransmissions, contributing to energy savings and lower latency.
- Hospital Environment Compatibility: Improved interference handling makes WBANs more suitable for hospital environments with numerous potential interference sources.
- Data Integrity: Better signal quality reduces the likelihood of data corruption, ensuring the accuracy of health information.

The varying improvements across different interference levels (greatest in low interference, still substantial in high interference) demonstrate the algorithm's adaptability to different electromagnetic environments, making it suitable for diverse healthcare settings from homes to hospitals.

7.5 Integrated Solution Analysis

The combined implementation of all four algorithms showed synergistic benefits beyond what each algorithm provides individually:

- Comprehensive Performance Improvement: Enhancements across all metrics (network lifetime, delay, emergency response, packet delivery, SINR) demonstrate a holistic improvement in WBAN performance.
- Mutually Reinforcing Effects: For example, IR-CA's reduction in retransmissions contributes to energy savings, complementing MCPSA's energy efficiency goals.
- Scalability: The relatively stable performance with increasing network size suggests that the

integrated solution can support large-scale healthcare monitoring systems.
- Adaptive Capabilities: The combined solution adapts to varying network conditions, traffic patterns, and interference levels, making it robust for real-world healthcare deployments.

The overall performance improvements (35.4% longer network lifetime, 36% lower delay, 90% faster emergency response, 17.1% higher packet delivery ratio, 40% better SINR) validate the effectiveness of the integrated approach for IoT-enabled healthcare WBANs.

7.6 Limitations and Considerations

Despite the promising results, several limitations and considerations should be acknowledged:

- Computational Overhead: The sophisticated algorithms, particularly FB-DSA with its fuzzy logic system, introduce computational complexity that may challenge resource-constrained sensor nodes.
- Parameter Tuning: Optimal performance requires careful tuning of algorithm parameters (weights, thresholds, etc.) for specific deployment scenarios.
- Simulation vs. Real-world: While simulation results are promising, real-world performance may be affected by factors not fully captured in the simulation model.
- Security Considerations: The current implementation focuses on performance optimization without explicitly addressing security requirements, which are crucial for healthcare applications.
- Regulatory Compliance: Medical device regulations may impose additional requirements that could affect the implementation of these algorithms in commercial healthcare products.

These limitations highlight areas for further research and development to enhance the practical applicability of the proposed algorithms in real-world healthcare settings.

8. FUTURE WORK

Based on the findings and limitations identified in this study, several promising directions for future research emerge:

8.1 Algorithm Enhancements

- Machine Learning Integration: Incorporating machine learning techniques to enhance the adaptive capabilities of the algorithms, enabling them to learn from network behavior and optimize performance over time.
- Lightweight Implementations: Developing computationally efficient versions of the algorithms, particularly for FB-DSA, to reduce processing overhead on resource-constrained sensor nodes.
- Context-Aware Adaptations: Enhancing the algorithms to consider contextual information such as patient activity, location, and medical condition to further optimize network performance.
- Cross-Layer Optimization: Exploring deeper integration across protocol layers to maximize the synergistic benefits of the four algorithms.

8.2 Security and Privacy Enhancements

- Secure Routing: Extending MCPSA to incorporate security metrics in the parent selection process, ensuring data follows not only efficient but also secure paths.
- Privacy-Preserving Mechanisms: Developing techniques to protect patient privacy while maintaining the performance benefits of the proposed algorithms.
- Authentication Integration: Implementing lightweight authentication mechanisms compatible with the time-sensitive nature of the algorithms, particularly ESH.
- Intrusion Detection: Developing methods to detect and respond to security threats without compromising the performance gains achieved by the algorithms.

8.3 Real-World Validation

- Prototype Implementation: Developing hardware prototypes implementing the proposed algorithms for testing in controlled healthcare environments.
- Clinical Trials: Conducting trials with actual patients to evaluate the algorithms' performance in real healthcare scenarios.
- Interoperability Testing: Assessing compatibility with existing healthcare systems and standards to ensure practical deployability.
- Long-term Monitoring: Evaluating algorithm performance over extended periods to verify

sustained benefits and identify potential degradation issues.

8.4 Application Extensions

- Emergency Response Systems: Developing comprehensive emergency response frameworks that leverage the rapid data transmission capabilities of ESH for critical healthcare situations.
- Remote Patient Monitoring: Extending the algorithms to better support remote healthcare delivery, particularly for rural or underserved populations.
- Preventive Healthcare: Exploring how the improved reliability and efficiency of WBANs can support preventive healthcare through continuous monitoring and early warning systems.
- Specialized Medical Applications: Adapting the algorithms for specific medical conditions such as diabetes management, cardiac monitoring, or neurological disorder tracking.

8.5 Standardization Efforts

- Protocol Standardization: Working towards standardization of the proposed methods to ensure interoperability across different WBAN implementations.
- Regulatory Compliance: Developing guidelines for implementing these algorithms in compliance with medical device regulations.
- Best Practice Documentation: Creating comprehensive documentation on parameter tuning and deployment strategies for different healthcare scenarios.
- Performance Benchmarks: Establishing standardized benchmarks for evaluating WBAN performance specifically in healthcare applications.

8.6 Energy Harvesting Integration

- Self-Powered WBANs: Investigating the integration of energy harvesting technologies with the proposed algorithms to develop self-sustaining WBAN systems.
- Adaptive Algorithms: Extending MCPSA and other algorithms to consider energy harvesting capabilities when making routing and scheduling decisions.
- Energy Prediction Models: Developing models to predict energy availability from harvesting sources to optimize network operation over time.
- Hybrid Power Systems: Exploring combinations of battery power and energy harvesting to maximize WBAN lifetime while maintaining performance.

These future research directions aim to address the current limitations while extending the capabilities of the proposed algorithms, ultimately working toward more reliable, efficient, and secure WBANs for healthcare applications.

9. CONCLUSION

This paper presented a comprehensive evaluation of four key algorithms designed to enhance the performance of IoT-integrated Wireless Body Area Networks in healthcare applications: the Minimum Cost Parent Selection Algorithm (MCPSA), Fuzzy-Based Dynamic Slot Allocation (FB-DSA), Emergency Slot Handling method (ESH), and Interference Reduction-Based Channel Access method (IR-CA).

The performance analysis demonstrated significant improvements across multiple metrics. MCPSA extended network lifetime by 25% while reducing energy consumption by 24-25% across various data rates, addressing the critical challenge of energy efficiency in battery-powered medical sensors. FB-DSA achieved a 30% reduction in average end-to-end delay, with improvements ranging from 26.2% to 35.7% for different traffic types, enhancing the timeliness of health data delivery. ESH demonstrated a remarkable 90% reduction in emergency response time, from 40ms to just 4ms, potentially making a life-saving difference in critical healthcare situations. IR-CA improved average SINR by 40% and reduced packet collision rates by 40-62.4% under various interference conditions, enhancing data reliability in complex electromagnetic environments.

The integrated implementation of all four algorithms showed synergistic benefits beyond individual improvements. The combined solution achieved a 35.4% longer network lifetime, 36% lower average delay, 90% faster emergency response, 17.1% higher packet delivery ratio, and 40% better SINR compared to baseline methods. Furthermore, the integrated solution demonstrated robust scalability, maintaining relatively stable performance with increasing network size, making it suitable for large-scale healthcare monitoring systems.

These findings have significant implications for healthcare applications. The extended network lifetime enables longer-term patient monitoring without battery replacement, crucial for chronic condition management and implantable devices. Reduced latency and enhanced emergency response support real-time monitoring and rapid intervention in critical situations. Improved interference handling enhances reliability in complex hospital environments with multiple wireless systems. Together, these advancements contribute to more effective, reliable, and efficient healthcare monitoring systems.

Several limitations and areas for future work were identified, including computational overhead considerations, the need for parameter tuning for specific deployment scenarios, security and privacy enhancements, and real-world validation. Future research directions include machine learning integration, lightweight implementations, security enhancements, real-world trials, application extensions, standardization efforts, and energy harvesting integration.

In conclusion, the proposed algorithms collectively address key challenges in IoT-integrated WBANs for healthcare applications, offering a comprehensive solution for energy efficiency, latency reduction, emergency handling, and interference mitigation. The performance improvements demonstrated in this study highlight the potential of these approaches to significantly advance healthcare monitoring capabilities, ultimately contributing to improved patient care, more efficient healthcare delivery, and enhanced quality of life for individuals requiring continuous health monitoring.

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