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A Novel Algorithm for Enhancing Fault Tolerance and Reliability in Wireless Body Area Networks

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Abstract

In wireless body area networks, routing presents a significant challenge due to factors such as scattering, the effects of body tissues, multidimensional structures, topology changes, thermal influences, and multi-hop data transmission. Although numerous studies have proposed various approaches to enhance this critical aspect, several unresolved issues persist. Among these challenges, the absence of effective solutions for fault tolerance and ensuring the integrity of transmitted data remains prominent. Most previous research has primarily focused on improving quality of service, often overlooking the vital aspects of fault tolerance and data reliability. Given the sensitivity of information in WBANs, addressing these factors is crucial for advancing this communication technology. This paper introduces a two-stage solution designed to support fault tolerance and ensure data integrity. The first stage establishes the foundation for reliable routing, while the second stage employs a multi-segment decomposition technique to enhance fault tolerance and data reliability. Simulations conducted using OPNET software demonstrate the superiority of the proposed method in improving key performance metrics, including reduced data loss, higher successful reception rates, lower end-to-end delay, and enhanced network throughput, compared to existing methods.

1. Introduction

Wireless Body Area Networks (WBANs) represent a groundbreaking advancement in medical and healthcare technologies. Comprising a collection of sensor nodes placed on or beneath the skin, these networks monitor vital signs and transmit them to a control center. Beyond their medical applications, WBANs are utilized in fields such as sports, military monitoring, and firefighting. However, their most critical and sensitive application remains within the healthcare domain due to its unique characteristics and stringent requirements.

Despite their promise, WBANs face significant challenges stemming from their distinctive architecture and stringent operational constraints. One of these challenges arises from the dynamic structure of WBANs, which is influenced by the constant changes in the human body, thereby increasing the likelihood of network errors and instability. This makes fault tolerance and reliability critical concerns [1]. Ensuring fault tolerance and reliability, particularly in terms of service delivery and data exchange, is vital given the life-critical nature of the information transmitted through these networks. Existing nodes and algorithms in WBANs often fall short of fully addressing these demands [2-4].

The importance of this issue can be analyzed from two perspectives:

1. Significance of Transmitted Information:

The data transmitted in WBANs includes medical information and vital signs, making data integrity an indispensable requirement [5-7].

2. Nature and Characteristics of WBAN Technology:

Unlike other technologies, WBANs exhibit a dynamic and variable architecture influenced by changes in the human body. This variability exacerbates the risk of errors and instability, intensifying the need for fault tolerance and reliability [8]. Furthermore, constraints on network elements and the necessity for multi-hop data exchanges amplify these challenges, emphasizing the need for tailored solutions. Consequently, ensuring fault tolerance and reliability in service delivery and data exchange becomes one of the most critical aspects of WBAN technology, directly impacting human health and well-being.

Despite extensive research efforts to enhance fault tolerance and reliability, significant gaps persist. Previous studies have employed various techniques, such as evaluating reliability and quality-related metrics [9], multipath routing [10], and addressing energy efficiency as a primary factor in reliability and fault tolerance [11]. However, many of these studies have inadequately addressed the architectural dynamics and specific fault tolerance needs of WBANs. This oversight has resulted in reduced effectiveness and presents a significant barrier to achieving optimal outcomes in this field.

These challenges form the foundation of the proposed study, which aims to address the critical issues of ensuring fault tolerance and reliability in WBANs. The primary objective is to enhance these essential aspects of WBAN technology.

While previous studies have mainly focused on optimizing QoS or energy efficiency, they have often overlooked the critical aspects of fault tolerance and data integrity. This gap is particularly important in healthcare-oriented WBAN applications where uninterrupted and accurate data delivery is vital. The proposed protocol directly addresses this gap by combining a reliable routing development phase with a fault-tolerant multi-segment decomposition phase. In this way, the study introduces a novel approach that not only improves network reliability but also ensures continuous service delivery under fault conditions, highlighting its novelty compared to prior research.

The structure of this paper is organized as follows: Section 2 reviews related work on WBANs, Section 3 introduces the proposed protocol, Section 4 presents the evaluation and simulation results, and Section 5 concludes with a discussion of findings and future research directions.

2. Related Work

This section reviews key recent studies in the field of WBANs to highlight the significance of the research topic and the need for the proposed study to address fundamental issues in this domain.

In [12], a ring-based service enhancement method for WBANs was proposed. This two-step approach first configures nodes into a predefined ring structure and then evaluates nodes based on energy, temperature, and position to select the optimal node for service delivery and data exchange. While this method reduces overhead and delay, it lacks reliability in service delivery, is unstable in fault scenarios, does not ensure data integrity, and is vulnerable to changes in network architecture.

In [13], a novel method for single-hop and multi-hop data exchanges in WBANs was introduced. Single-hop exchanges occur directly without intermediaries, while multi-hop interactions rely on metrics such as delay, remaining energy, connection stability, and signal quality. Although this method optimizes energy consumption, it does not guarantee fault tolerance, lacks mechanisms to handle architectural changes, and suffers from reduced data exchange reliability.

A two-step service enhancement approach was also presented in [14], focusing on ring-based node configuration and evaluation. Nodes are assessed based on energy, temperature, and position to select the best candidate for service delivery. While reducing overhead and delay, this method shares similar limitations to [12], including instability in fault scenarios and vulnerabilities in architectural changes.

In [15], an energy-focused service enhancement and communication reliability method was proposed. Routing decisions are based on a composite factor derived from distance and energy metrics, selecting intermediate nodes with minimal cost for data routing. While improving reliability, the method lacks optimization, fails to manage architectural changes, and does not provide fault coverage.

A routing protocol prioritizing real-time and fault-sensitive services was introduced in [16]. Real-time services are routed through the most efficient paths, while fault-sensitive services prioritize reliable paths. Despite effectively distinguishing and supporting service types, the method struggles with fault scenarios, architectural changes, and data integrity issues.

A multi-factor routing and service delivery method leveraging learning-based approaches was proposed in [17]. Decisions are based on factors such as distance, congestion, energy, and communication reliability. While reducing overhead and supporting multi-factor decision-making, this method is limited by its lack of fault recovery mechanisms and instability under architectural changes.

In [18], an energy-aware and architecture-aware routing method was introduced. It evaluates network architecture changes and selects routes based on these changes, distance, and remaining energy. Although this approach improves architecture analysis capabilities, it lacks fault coverage mechanisms and fails to ensure service reliability.

A bee colony algorithm-based method was proposed in [19], focusing on evaluating path costs and analyzing energy consumption. Nodes requesting data transmission initiate routing by spreading bee agents across the network. While this method reduces path costs and improves efficiency, it is unreliable under fault conditions and susceptible to architectural changes.

Opportunistic routing was explored in [20], aiming to mitigate network architectural changes caused by patient movements. Although this approach enhances service efficiency and maintains performance under architectural variations, it lacks mechanisms for addressing critical service needs, ensuring fault tolerance, and guaranteeing data integrity.

Distinct node deployment architectures were discussed in [21], emphasizing energy optimization and extending network lifetime. Despite these benefits, the method lacks provisions for critical service requirements and architectural resilience.

In [22], a coordinate-based node evaluation and distance matrix method was introduced. Nodes compute a distance matrix and weight component for routing. However, this approach faces challenges such as reduced data reliability, increased errors, and suboptimal service delivery.

Lastly, a demand-driven routing mechanism based on the DSR protocol was presented in [23]. The three-phase design—route request, route reply, and route maintenance—provides a structured approach to routing but suffers from data reliability issues, instability under architectural changes, and neglects essential service factors.

While these studies have contributed to WBAN advancements, most are ineffective in ensuring fault tolerance, leading to significant performance degradation. The proposed study aims to address these limitations and improve fault tolerance in WBANs.

3. Proposed Protocol

To analyze the design and performance of the proposed protocol, the wireless body area network is modeled as a graph, represented as Graph = (E, F). Table 1 outlines key concepts associated with the graph model and the significant parameters related to WBANs.

- E: Represents body sensors, where sensor nodes are deployed within the body's coverage area. Each maintains a unique routing table and neighbor table that are updated based on the status of neighboring sensors and routing processes within the protocol.
- F: Denotes the bidirectional and symmetrical links between sensors. A link exists if and only if both sensors and are within each other's transmission range and act as neighbors. Each link is associated with a cost component, representing the communication cost between sensors and. This cost varies based on the quality and reliability of the adjacent sensors.

$$\text{Graph} = (\mathrm{E},\mathrm{F}) \rightarrow \left\{\begin{matrix} \mathrm{E} = \{\mathrm{e_k}|\mathrm{e_1},\dots,\mathrm{e_k}|,\mathrm{Pda}\} \\ \mathrm{F} = \mathrm{e} \cup \mathrm{e} \rightarrow \mathrm{F} \Subset \mathrm{e} \times \mathrm{e} \rightarrow \mathrm{F} = \{\mathrm{f_{i,j}},\mathrm{f_{j,u}},\dots,\mathrm{f_{u,k}}\} \end{matrix}\right\} \quad (1)$$

The graph is formally defined as:

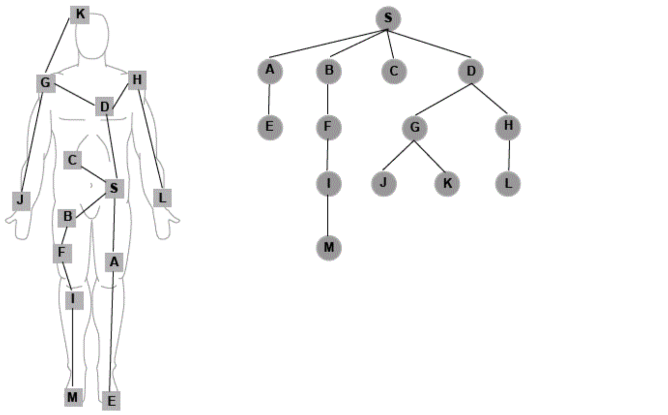

Figure 1. Body topology graph

In the graph depicted in Figure 1, the changes in the body sensor network's connectivity graph (network topology) vary dynamically based on the states of the human body. The network in question comprises specific sensor nodes designed for application in the human body environment. Additionally, each node can function as both a router and a host. The interactions and exchanges between the network sensors occur within a symmetrical and bidirectional framework. Each sensor node possesses a unique identifier, and the network contains a single sink node.

A sensor node *n* is considered a neighbor to node *m* under the protocol if the following conditions are met: (1) the distance between nodes *n* and *m* is less than 10 cm; (2) node *n* is located closer to the sink than node *m*; and (3) the distance between node *n* and node *m* is shorter than the distance between node *m* and the sink.

Path loss between the transmitter and receiver is one of the most critical factors influencing routing and data transmission in wireless body area networks. Path loss is evaluated as a function of distance, as detailed in Equation (2) [17]. It is defined in relation to signal attenuation and the absorption coefficient of body tissues and is assessed accordingly.

$$\text{Past Lost}_{\text{db}}^{\text{lm}}(\text{Dist}_{\text{lm}}) = \text{Pas t Lost}_{0,\text{db}}^{\text{lm}} + 10\text{nx}_{\text{lm}}\log_{10}\left(\frac{\text{D}_{\text{lm}}}{\text{D}_{0,\text{lm}}^{\text{lm}}}\right) + \varepsilon \quad (2)$$

In the above equation, the component $\text{Past Lost}_{\text{db}}^{\text{lm}}(\text{Dist}_{\text{lm}})$ represents the path loss coefficient between the transmitting and receiving nodes, defined in decibels. $\text{Past Lost}_{0,\text{db}}^{\text{lm}}$ Corresponds to the path loss at a reference distance$\text{Dist}_{0,\text{nm}}$, nx_{lm} represents the path loss exponent, and the component ε is a normal random variable used to account for deviations caused by body tissues. The energy consumption of sensors and the wireless body area network in this protocol is limited to the energy consumed for transmissions and receptions. Equations (3) and (4) provide the details of energy consumption during data transmission and reception in wireless body area networks.

$$\text{Eng}_{\text{Rec}} = \text{p}.[\text{Eng}_{\text{elec}}] \quad (3)$$

$$\text{Eng}_{\text{Sed}} = \text{w}.\left[\text{Eng}_{\text{elec}} * \text{Eng}_{\text{amp}}(\text{n}_{\text{lm}})\text{Dist}_{\text{lm}}^{\text{n}_{\text{lm}}}\right] \quad (4)$$

In Equation (2), the component Eng_{Rec} represents the energy required to receive a message, *p* denotes the number of bits in the received message, and Eng_{elec} corresponds to the energy required to process a single bit of data. In Equation (3), the component Eng_{Sed} represents the energy required to transmit a data message, while $\text{Eng}_{\text{amp}}(\text{n}_{\text{lm}})$denotes the energy required to amplify the transmission, determined based on the distance ratio between the transmitting and receiving nodes. Additionally, Dist_{lm} represents the distance between the transmitter and receiver nodes.

3.1. Protocol Phases

The proposed protocol consists of two primary phases designed to achieve fault tolerance and ensure data reliability in WBANs: the routing development phase and the fault-tolerant service phase. Both phases are essential to meeting the protocol's objectives.

Phase 1: Routing Development:

This phase represents the initial step in the proposed protocol, designed to establish a foundation for the suggested routing mechanism with the goal of enhancing network reliability. Upon activation of the network, the sink node broadcasts an initialization message to all network nodes (body sensors) within its transmission range. Any node within the sender's transmission range receives this message.

Upon receiving the initialization message, each node extracts the message ID and verifies whether it has already received this message. Since the message is broadcast across the network, a node may receive the same message multiple times. To prevent redundant retransmissions and mitigate message duplication, the first action performed by a body sensor upon receiving the initialization message is to check for duplication. This verification is based on the message ID. Depending on the outcome of this verification, as illustrated in the activity diagram, two scenarios may arise:

1. The message is new: In this case, the receiving node stores the message information, updates its contents, and retransmits the message to its neighboring sensors in the network.
2. The message is a duplicate: In this case, the node compares the hop count specified in the received message with the hop count stored in its memory. If the hop count in the message exceeds the stored value, the node discards the message. Conversely, if the hop count is lower, the node updates its routing tables with the new information, refreshes the message contents, and retransmits the message to its neighboring sensors.

This iterative process continues until the initialization message has been received by all nodes in the network. As a result, body sensors identify their neighboring nodes and determine their relative position to the sink.

Subsequently, if a body sensor wishes to send data, it generates a route request packet and transmits it to all neighboring nodes. Upon receiving the route request, each neighboring node evaluates its own state and that of the sender relative to the sink (based on hop count) to determine its eligibility to participate in the routing process. The decision is based on the following conditions:

- The node is unsuitable for routing and data transmission: This condition occurs if the hop count of the recipient node to the sink exceeds the hop count of the sender node to the sink. In such cases, the node refrains from participating in routing, as its position is suboptimal for data exchange.

- The node is suitable for routing and data transmission: This condition occurs if the hop count of the recipient node to the sink is lower than the hop count of the sender node to the sink. In this case, the node generates a response message, evaluates its status (e.g., quality, stability, and reliability), appends this information to the response message, and transmits it back to the requesting node.

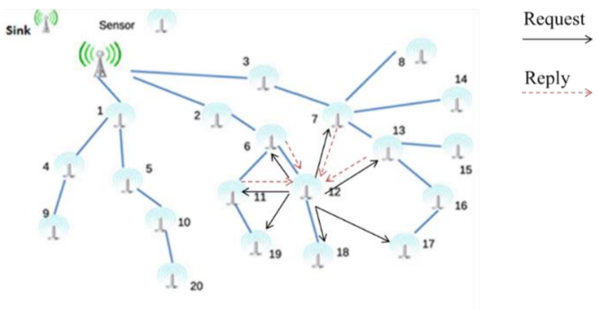

Figure 2. Protocol routing details

If the requesting sensor does not receive any response messages from neighboring nodes within a specified time period indicating the absence of neighboring nodes. The proposed protocol ensures stability and prevents the void problem by having the requesting node retransmit the request message with increased transmission power. This process is repeated until a suitable node in the vicinity of the requesting node is found and responds. The routing process is based on the exchange of request and response packets. The evaluation results of the candidate nodes' statuses are provided to the requesting node, enabling it to proceed with data transmission effectively.

Phase 2: Ensuring Service Fault Tolerance:
The primary objective of the second phase is to ensure the fault tolerance of transmitted services. To achieve this goal, this phase of the proposed protocol is designed and developed based on the concepts outlined in [24] and utilizes a solution known as multi-segment decomposition.

```
START
RECEIVE responses FROM neighboring
nodes
SELECT neighbor_node WITH
highest_priority BASED_ON
network_requirements
BEGIN multi_segment_data_exchange
   IF data_received_by_sink_node THEN
      CALL "Next Phase of Routing"
   ELSE
      RETRY data_exchange
   ENDIF
   IF network_activity_complete THEN
      BREAK
   ENDIF
END multi_segment_data_exchange
END
```

Figure 3. Pseudocode of the second phase of the proposed protocol

Based on the flowchart depicted in Figure 3, this phase is invoked after the requesting sensor receives response messages to facilitate data transmission. For this purpose, upon receiving the response messages, the requesting node evaluates the status of the candidate nodes and selects the top k nodes as routing nodes. Equation (5) provides the details of this evaluation and prioritization process.

$$PI_j = (\alpha_1 \times R) + (\alpha_2 \times S) + (\alpha_3 \times Q) \qquad (5)$$

In the above equation, PI_j represents the importance and value of node j among other nodes, while $\alpha 1$, $\alpha 2$, and $\alpha 3$are adaptive coefficients of the equation components (such that their sum equals one).

As mentioned earlier, the primary objective of this phase is to ensure fault tolerance. This concept implies that the protocol is designed with capabilities that allow it to continue functioning correctly and continuously even in the presence of faults. This capability ensures seamless data exchanges and the accurate reception of transmitted data by the sink node.

To support such fault tolerance, the proposed protocol employs a technique called multi-segment decomposition. In this technique, the source sensor, within a distributed framework, divides the data it intends to send into k separate segments and transmits these k segments to the sink node via the selected node(s). Even if one or more segments are lost or encounter errors (depending on the configuration of the multi-segment decomposition technique), the sink node can reconstruct the original data and recover the lost parts upon receiving c segments out of the k total segments. This feature represents the most significant advantage of the protocol in supporting fault tolerance. However, it should be noted that if the number of lost segments exceeds a certain threshold (segment threshold), recovery will not be possible.

The set of equations in Equation (6) represents this concept. In these equations, the components Re_1 through Re_(m-1) are unknown values within the range of integers (randomly selected by the source sensor), Re0Re_0Re0 corresponds to the original data, b is a prime number greater than all the equation values, and u represents the factors through which the transmitted data is divided into k segments.

$$\mathrm{F(u) = (Re_{m-1}u^{m-1} + Re_{m-2}u^{m-2} + \cdots + Re_2u^2 + Re_1u + Re_0)\ Mod\ b} \quad (6)$$

To facilitate a better understanding, a comprehensive scenario illustrating the application of the multi-segment decomposition technique is presented below. Consider a scenario where a heart rate value of 10 is the original data to be transmitted. This scenario explains the multi-segment technique with three segments and a recovery capability of two (i.e., the original data is divided into three segments, but the sink node can reconstruct the data using any two segments).

The original data must therefore be divided into three segments. For this purpose, a polynomial equation is defined, and by assigning values to the component u, the original data is divided into three segments. Note that the values assigned to u must be prime numbers, and the Re components are randomly selected (in this scenario, Re is set to 4). Additionally, Re_0 represents the original data, and b is a prime number chosen to be greater than all values in the equation. Equation (7) provides the detailed process of this explanation.

$$\mathrm{F\ (u) = Re_1u + Re_0\ Mod\ b \rightarrow F(u) = 4u + 10\ Mod\ 11 \rightarrow \begin{bmatrix} F(1) = 4 + 10\ mod\ 11 \rightarrow F(1) = 3 \\ F(2) = 8 + 10\ mod\ 11 \rightarrow F(2) = 7 \\ F(3) = 12 + 10\ mod\ 11 \rightarrow F(3) = 0 \end{bmatrix}} \quad (7)$$

Suppose that during the transmission process, one of the packets encounters an error or a Packet Loss issue occurs, and the PDA node receives two out of the three sent segments. In this case, the destination node can recover the original data using the relationship (8), based on the concepts of multiple equations with multiple unknowns and Lagrange's interpolation. The details of this process are provided in equation (8).

$$\mathrm{F(u) = \begin{bmatrix} F(1) = 3 \\ F(2) = 7 \end{bmatrix} \rightarrow F(u) = Re_1u + Re_0\ Mod\ b \rightarrow \begin{bmatrix} Re_1 + Re_0 = 3 \\ 2Re_1 + Re_0 = 7 \end{bmatrix} \rightarrow \begin{bmatrix} -Re_1 - Re_0 = -3 \\ 2Re_1 + Re_0 = 7 \end{bmatrix} \rightarrow Re_1 = 4 \rightarrow \begin{bmatrix} (4 + Re_0)\ Mod\ 11 = 3 \\ (8 + Re_0)\ Mod\ 11 = 7 \end{bmatrix} \rightarrow Re_0 = 10} \quad (8)$$

The multi-segment technique used in this protocol is highly adaptable and compatible with network conditions and fault tolerance requirements. It effectively adjusts its performance according to the specific needs and requirements.

The computational complexity of the proposed protocol can be analyzed in two phases. In the routing development phase, each node processes routing requests from its neighbors, resulting in a complexity of $O(n \cdot d)$, where $n$is the number of nodes and $d$is the average number of neighbors. Since WBANs typically involve a limited number of nodes (5–17 in our experiments), this overhead remains minimal. In the fault-tolerant service phase, the multi-segment decomposition technique introduces a reconstruction process with complexity $O(k\log k)$, where $k$is the number of generated data segments. Given that $k$is relatively small in WBAN applications, the protocol achieves efficient execution suitable for real-time healthcare environments, ensuring both low processing delays and high reliability.

4. Analysis and Experiments

In this section, the performance of the proposed protocol is analyzed and evaluated in a real-world application. The outcome includes a detailed analysis of the strengths and weaknesses of the proposed protocol. The primary objective of presenting this protocol is to enhance the applications of wireless body area networks and to improve its performance in terms of reliability and fault tolerance in these networks. To evaluate the protocol, the OPNET software was used. The topology applied during the experiments is the one introduced in [6], and an overview of this topology is shown in Figure (4).

4.1 Evaluation criteria and Performance Evaluation

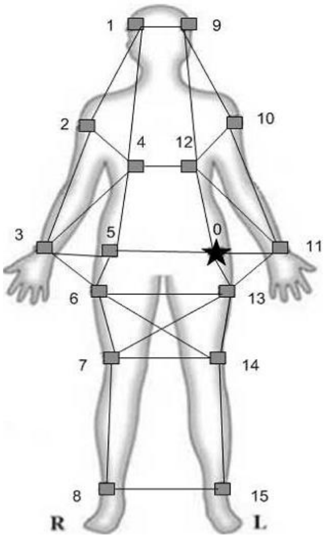

Figure 4. Topology of the body-bound wireless network in experiments

In Table 1, the performance metrics for modeling the wireless body area network are presented. The values assigned to the metrics are based on the standards of wireless body area networks, the assumptions of this technology, and the efficiency derived from similar studies, particularly the baseline reference. It is noteworthy that these metrics are considered for both scenarios configured similarly, with the only difference being the activity of the protocols.

The results obtained from the conducted simulations are presented and analyzed in detail for each outcome. It is worth noting that the experiments were repeated for various numbers of sensors to enhance the reliability and value of the simulations. The details of the variables evaluated in this section are shown in Table 2.

In Figure 5, the results of data exchange delays are presented, comparing the proposed protocol with the ELRW protocol. Both protocols (the proposed protocol and ELRW) are designed to enhance reliability and the quality of data exchanges in wireless body area networks. Accordingly, each protocol has formulated its solutions with distinct and unique methodologies aimed at improving service delivery in these networks.

Table 1. Parameters of simulation scenario settings

Parameter	Values	Description
Number of sensors	5-17	Sensors available in the network
Number of PDAs	1	Number of sink nodes in the network
Message destination	PDA	Final destination of the transmitted data
PDA placement location	Center of body	Placement considering the topology
Type of traffic and transport layer protocol	CBR (Constant Bit Rate), UDP	Type of network traffic and transport layer protocol
Message size	32 Byte	Volume and size of messages
Transmission power	10.5 mA	Base power for data transmission
MAC layer operation mode	802.15.4	Standard of the MAC layer
Node data transfer rate	100 kbps	Data transfer speed in the network
Topology variations	Standing, lying, sitting	Human state changes
Simulation time	600 seconds	Duration of the simulation run
Simulation start time	20 s	Time for interaction after initial configuration
Node buffer size	50 PK	Buffer size of the network sensors
Initial node energy	1 J	Initial energy of the network sensors
Energy required for receiving	16.7 nj/b	Energy consumption for receiving one bit
Energy required for transmission	31.6 nj/b	Energy consumption for transmitting one bit
Transmission amplification energy	1.97 nj	Energy consumption for transmission amplification

Table 2. Introduction of variables evaluated in experiments

Variable	Definition	Formula	Unit
Data Exchange Delay	Average time for data transmission	$\frac{\sum_{j=1}^{\text{No.of packet}} \text{Delay}_j}{\text{No. of send data}}$	Seconds
Instability Rate	Rate of route errors in interactions	$\frac{\sum \text{No. of Route Error}}{\text{Time } (s)}$	Count
Data Loss Rate	Percentage of lost data	$\frac{\text{No. of Packet Drop}}{\text{No. of Packet Send}} * 100$	Percentage

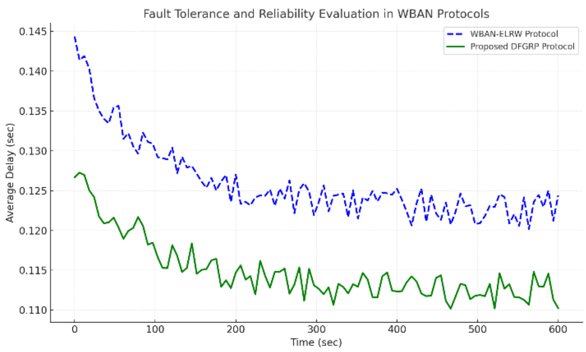

Figure 5. Results of Network Interaction Delay Rates

In this chart, the horizontal axis represents time (seconds), while the vertical axis shows the average network interaction delay (seconds). The green and blue lines represent the results of the proposed protocol and the ELRW protocol, respectively.

The proposed protocol in this study effectively minimizes data exchange delay through robust routing quality support while maintaining stability to prevent unwanted events that could lead to increased delays. This efficient performance, combined with ensuring fault tolerance in data exchanges, results in reduced delays for the proposed protocol. In contrast, the ELRW protocol demonstrates effective routing quality support; however, it lacks strategies to maintain stability and provide fault tolerance. This shortcoming leads to increased disruptions caused by instabilities, ultimately resulting in higher delays for the ELRW protocol.

Figure 6 illustrates the network packet loss rate for the proposed protocol compared to the ELRW protocol. While the ELRW protocol focuses on mitigating packet loss by assessing and utilizing high-quality sensors for routing, this approach alone proves insufficient in managing packet loss effectively, especially given the critical nature of transmitted data. The proposed protocol addresses packet loss more comprehensively by ensuring continuity and service reliability. In its first step, it enhances routing with criteria such as stability, reliability, and quality to ensure the highest possible quality and dependability in data transmission.

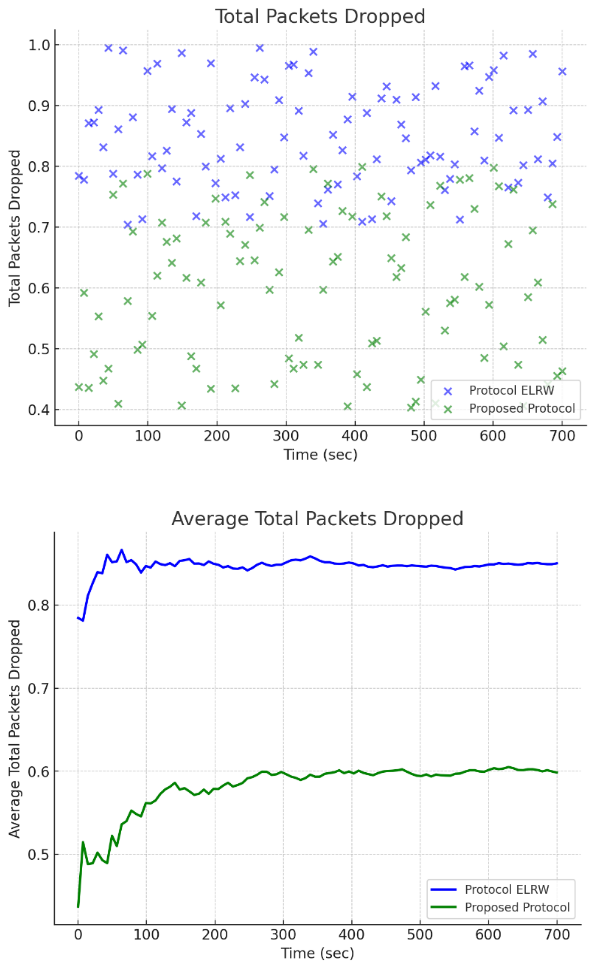

Figure 6. Network data loss rate results

In Figure 7, the instability rate results for the proposed protocol are compared with those of the ELRW protocol. Both protocols aim to enhance the reliability of data exchanges; however, the key distinction lies in the approach of the proposed protocol. Unlike ELRW, the proposed protocol not only focuses on quality-based routing but also incorporates capabilities such as stability analysis, management of topological changes, and fault-tolerance assurance. These advanced measures enable the proposed protocol to provide more reliable routing. Additionally, in the event of errors or failures during data transmission, the protocol efficiently handles such issues without causing adverse impacts, thereby maintaining service stability. This leads to a significant reduction in instability rates and an overall improvement in network performance under various conditions, whereas the ELRW protocol is limited to enhancing routing quality and lacks similar robustness against faults and topology changes.

Figure 7 illustrates the comparison of route instability between the Proposed Protocol and the ELRW Protocol. The graph on the left depicts the total number of route errors over time, while the graph on the right shows the average number of route errors during the simulation. The Proposed Protocol (represented in green) demonstrates significantly fewer errors compared to the ELRW Protocol throughout the simulation period. This highlights the stability and efficiency of the Proposed Protocol, which not only ensures quality-based routing but also incorporates mechanisms for analyzing stability, handling topological changes, and providing fault tolerance. In contrast, the ELRW Protocol, despite offering quality routing, lacks sufficient measures to address route failures, resulting in higher instability.

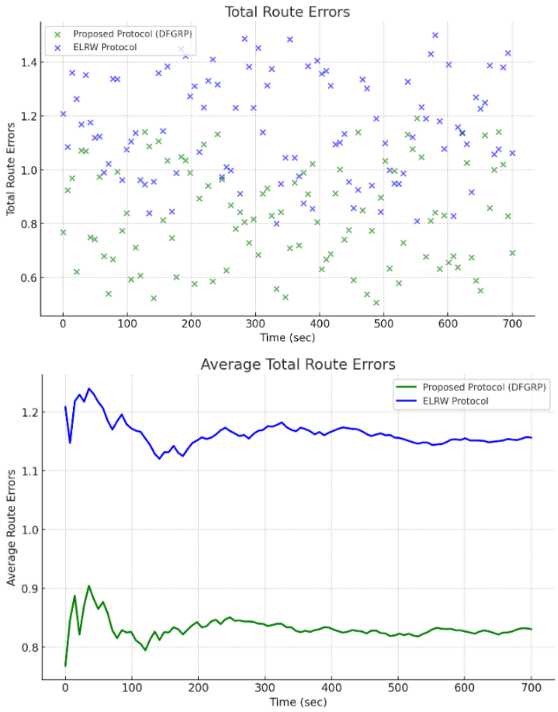

Figure 7. Results of instability rates of active pathways

Figure 8 presents a comparative analysis of the route instability rates between the Proposed Protocol (green) and the ELRW Protocol (blue). As illustrated, the Proposed Protocol consistently demonstrates lower instability rates throughout the simulation. This indicates its ability to maintain stable and reliable active routes, outperforming the ELRW Protocol, which experiences higher route errors due to its limited fault-tolerance measures. The green curve emphasizes the effectiveness of the Proposed Protocol in ensuring both stability and fault-resilient communication.

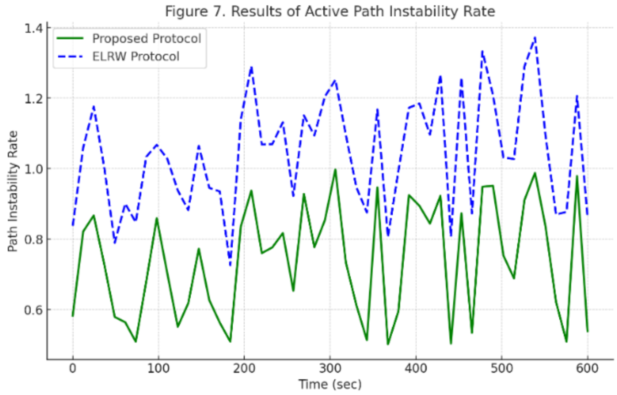

Figure 8. Results of Active Path Instability Rate

4.2 Analysis of the Proposed Protocol's Performance Compared to the ELRW Protocol

The proposed protocol is designed to enhance reliability and ensure fault-tolerant routing and data exchanges within wireless body area networks (WBANs). The simulation results, assessed through various routing and data interaction metrics, demonstrate the superior performance of the proposed protocol compared to the alternative ELRW protocol. Table 3 provides a comprehensive evaluation of the proposed protocol's effectiveness in contrast with the ELRW protocol, highlighting its significant improvements in reliability, fault tolerance, and overall network stability.

Table 3. General review and conclusion of simulation results

Metric	ELRW	Proposed Protocol	Improvement (%)
Instability Rate	1.26	1.03	$\left(1-\left(\frac{1.03}{1.26}\right)\right)*100=18.2$
Data Loss	6.25%	5%	$(6.25-5)*100=1.25$
End-to-End Delay	0.119 s	0.11 s	$\left(1-\left(\frac{0.11}{0.119}\right)\right)*100=7.6$

5. Conclusion and Future Work

The proposed protocol in this study is designed to ensure reliability and fault tolerance, demonstrating adaptability and flexibility to meet the demands of various conditions in wireless body area networks (WBANs). This adaptability stands out as one of its most significant and prominent features. To achieve this, the protocol has been developed in two phases. The first phase ensures reliable routing tailored to network conditions and requirements, while the second phase effectively guarantees fault tolerance. During the routing process, inappropriate sensors are excluded, ensuring service reliability and stability. Furthermore, by utilizing the capabilities of multi-segment analysis techniques, data interactions are carried out in a manner that not only guarantees fault tolerance but also maintains load balancing across exchange paths as much as possible. For future work, measures could be taken to enhance the protocol's performance by incorporating mechanisms for predicting the future status of sensors and ensuring the reliability of their links for subsequent interactions. Additionally, leveraging artificial intelligence techniques could further improve the protocol by reducing overhead and enhancing efficiency.

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