RESEARCH ARTICLE

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HEART: Hybrid Energy-Aware Routing Technique for Dual-Sink Body Area Networks in Smart Healthcare IoT Systems

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Abstract

The rapid evolution of the Internet of Medical Things (IoMT) has enabled pervasive patient monitoring through Wireless Body Area Networks (WBANs). However, energy depletion, high path-loss, link instability, and latency remain major barriers to achieving reliability in real-time healthcare applications. Existing schemes, such as Distance Aware Relaying Energy-efficient (DARE) and Link Aware and Energy Efficient Scheme for Body Area Networks (LAEEBA), mitigate individual constraints, distance and link quality respectively, but lack holistic optimization across energy, distance, and reliability dimensions. This paper proposes HEART (Hybrid Energy-Aware Routing Technique), a dual-sink, clustering-based protocol designed to minimize path-loss and balance energy consumption in smart healthcare IoMT environments. HEART employs a cost function combining residual energy and link distance for adaptive Cluster-Head (CH) selection and integrates dual-sink coordination to enhance data reliability and reduce latency. Simulation results (0–10^5 rounds) demonstrate that HEART outperforms DARE and LAEEBA across all performance metrics: achieving $35.5_{\mathbf{dB}}$ average path-loss, $1.53_{\mathbf{J}}$ residual energy, $0.77_{\mathbf{s}}$ end-to-end delay, and $1.16_{\frac{packets}{s}}$ throughput, while improving packet delivery ratio, data generation rate, and reducing packet/bit error rates. Cumulative distribution analyses further confirm HEART's statistical stability and robustness under dynamic body postures. The proposed protocol significantly prolongs network lifetime and ensures dependable, energy-efficient transmission for continuous medical data acquisition—making it a strong candidate for next-generation smart IoMT healthcare systems.

Keywords: smart IoMT, WBANs, real-time monitoring, node deployment, path-loss, energy consumption, network lifetime, DARE, LAEEBA, HEART scheme.

1 Introduction

The rapid evolution of the Internet of Medical Things (IoMT) has revolutionized the way healthcare

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systems collect, process, and interpret physiological information. IoMT represents an interconnected ecosystem of wearable sensors, implantable devices, gateways, and cloud servers designed to monitor and manage patient health in real time [1]. By integrating advanced sensing technologies with ubiquitous Internet connectivity, IoMT enables continuous patient surveillance, early disease diagnosis, and remote clinical decision-making [2]. The next generation of Smart IoMT systems leverages artificial intelligence (AI), edge computing, and 6G-enabled connectivity to provide adaptive, context-aware, and energy-efficient healthcare services [3]. These systems form the backbone of smart hospitals and home-based medical care, where low-power biosensors relay health parameters such as ECG, temperature, glucose, and oxygen levels to local coordinators or cloud-based diagnostic platforms for continuous analysis [4].

Despite these advancements, Wireless Body Area Networks (WBANs)—which constitute the foundational layer of IoMT—face significant challenges [5]. Since biosensors are miniature, battery-powered devices operating in dynamic environments (on or inside the human body), they are constrained by limited energy capacity, frequent path-loss variations, and thermal effects [6]. Unreliable communication links caused by body posture, motion, and multipath fading degrade network reliability and lead to packet losses [7]. Moreover, uneven energy utilization among nodes can cause early depletion of specific sensors, leading to network partitioning and reduced lifetime [8–10]. Traditional WBAN routing protocols such as DARE and LAEEBA focus on optimizing individual parameters—energy consumption or link quality—but often fail to maintain a balanced trade-off between energy efficiency, path reliability, and delay under variable physiological and environmental conditions [11–13].

Another critical challenge lies in single-sink dependency, where all sensor data is routed through a single coordinator node [14–16]. This configuration can cause congestion, packet collisions, and uneven load distribution, resulting in latency and rapid energy exhaustion of central nodes [17]. The need for dual-sink or multi-sink topologies thus becomes vital to achieve parallel data forwarding, balanced traffic distribution, and enhanced fault tolerance in Smart IoMT environments [18]. However, efficiently managing energy, link quality, and routing decisions across multiple sinks requires an intelligent and adaptive strategy that minimizes communication overhead while ensuring data reliability and network longevity [19–21].

To address these challenges, this paper introduces a novel routing framework titled HEART — Hybrid Energy-Aware Routing Technique for dual-sink WBANs in Smart Healthcare IoT systems. HEART employs a clustering-based communication model wherein biosensors transmit data to Cluster Heads (CHs) that forward aggregated information to coordinators via energy-optimized routes. The protocol introduces a multi-parameter cost function that dynamically selects the optimal forwarding node based on residual energy, inter-node distance, and path-loss. The integration of a dual-sink architecture enhances parallel data delivery, reduces bottlenecks, and improves network robustness. Furthermore, HEART ensures balanced energy consumption among biosensors, leading to an extended network lifetime and reduced end-to-end delay.

Comprehensive Python simulations validate the effectiveness of HEART by comparing its performance against benchmark protocols such as DARE and LAEEBA. The results demonstrate that HEART achieves superior outcomes across multiple metrics—average path-loss (35.524 dB), residual energy (1.533 J), end-to-end delay (0.769 s), and throughput (1.164packets/s)—thereby proving its suitability for next-generation Smart IoMT healthcare systems requiring energy-aware, reliable, and latency-sensitive communication frameworks. Figure 1 shows the major contributions of proposed HEART scheme.

The key contributions of this paper are as follows:

- A novel HEART is introduced for WBANs in IoMT environments, designed to achieve holistic optimization across energy efficiency, distance management, and reliability.
- HEART integrates dual-sink architecture to balance network load, enhance data reliability, and minimize end-to-end latency during continuous medical data transmission.
- An energy–distance-based cost function is formulated for dynamic CH selection, ensuring balanced energy consumption and reduced path-loss across network nodes.
- The proposed protocol simultaneously addresses path-loss reduction, energy conservation, link

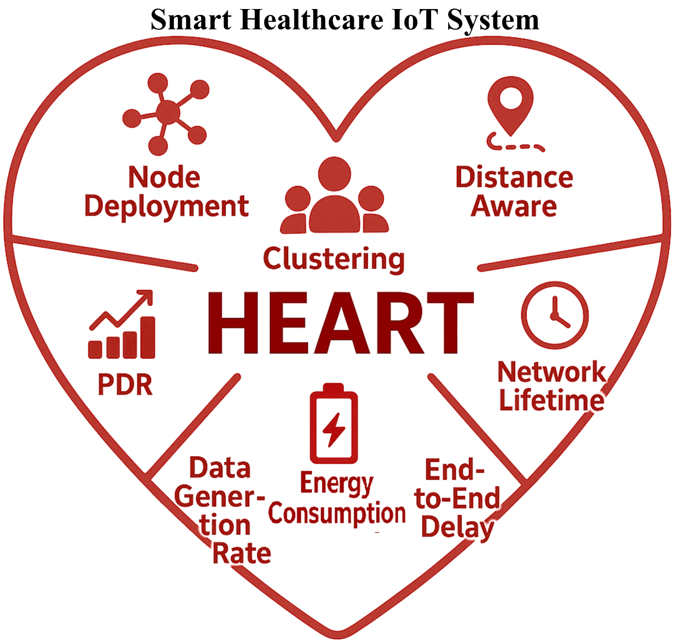

Figure 1. Visual illustrations of major contributions of HEART scheme.

stability, and delay minimization, overcoming the limitations of existing schemes such as DARE and LAEEBA.

The subsequent sections of this research article are organized as follows. Section 2 provides an overview of existing works in the field. Section 3 discusses the motivations that prompted this research endeavor. Section 4 introduces the proposed model and protocol. Section 5 presents the simulation results along with their analysis. Finally, Section 6 concludes the paper by summarizing the key findings and implications of the study.

2 Related Work

2.1 Distance- and Energy-Aware Routing Mechanisms

Several studies have integrated distance and residual energy parameters into cost functions for forwarder selection. Authors in [9] proposed a multi-hop routing protocol is introduced to enhance power efficiency, network lifetime, and PDR. Fixed intermediate nodes act as repeaters, and the routing decision is derived from a cost function incorporating parameters such as distance to the coordinator, residual energy, transmission power, and node velocity. The simulation results show notable improvements in energy conservation and delivery rate. Similarly, authors in [10] presented a Balanced Energy Consumption (BEC) protocol, where the forwarding node is chosen using a distance-based cost function. Each tower is equipped with a relay or transmitter node to balance the traffic load. When a sensor is located near the receiver, it transmits data directly; otherwise, it routes packets through the closest relay node. The use of an energy threshold ensures that only essential data is transmitted once the threshold is satisfied. Simulations confirm enhanced network lifetime compared to conventional OINL models.

2.2 Application-Specific and Threshold-Based Schemes

Authors in [11] proposed the THE-FAME protocol is tailored for real-time fatigue monitoring of soccer players. The scheme computes a threshold based on the player's traveled distance and lactate accumulation, triggering transmission when fatigue exceeds a certain limit. This design emphasizes low sensor size and optimized power usage to accommodate wearable constraints. Similarly, authors in [12] introduced a cost-function-based selection mechanism that identifies the optimal forwarder based on maximum residual energy and minimum distance to the receiver. The algorithm balances energy utilization and transmission efficiency, effectively improving data delivery performance in multi-hop WBAN topologies.

2.3 Path-Loss-Optimized and Link-Aware Protocols

A key milestone in WBAN routing was the introduction of LAEEBA by authors in [13]. LAEEBA combines single-hop and multi-hop communication to minimize path-loss and extend network lifetime. Its cost function evaluates sensor distance and residual energy, allowing adaptive route selection that ensures accurate and energy-aware data forwarding. Further enhancements were explored by authors in [14], where the authors simulated end-to-end delays for energy-efficient 1-hop, cooperative, and 2-hop fading channels. Techniques such as Automatic Repeat Request (ARQ) and Stop-and-Wait were applied, using BPSK for Line-of-Sight (LoS) and Hexadecimal Quad Width Position Keying (QAPM) for high-rate non-LoS transmissions. The RE-ATTEMPT proposed by authors in [17] addressed both thermal constraints and energy efficiency. Radio nodes are fixed based on their energy levels, and the minimum hop count serves as the cost function. Emergency data are transmitted directly, while regular data utilize multi-hop relaying. The scheme outperforms earlier models in terms of packet loss rate, network lifetime, and throughput. Authors in [16] extended the LAEEBA framework by introducing Co-LAEEBA, integrating cooperative learning to enhance link stability. Both protocols use cost functions that combine distance and residual energy to select optimal paths. Simulation outcomes demonstrate improved link reliability and lower path-loss compared to prior routing strategies.

2.4 Multi-Patient and Simplified WBAN Architectures

The DARE system proposed by authors in [15] represented one of the earliest multi-patient WBAN implementations. Each of eight patients is equipped with seven sensors monitoring physiological parameters, and multiple receiver nodes are deployed to form five topological configurations. DARE optimizes routing by minimizing the distance between sensors and sink nodes, effectively extending lifetime under limited mobility conditions. Conversely, the SIMPLE protocol by authors in [18] introduced a lightweight architecture with one receiver and eight sensors per body. It employs multi-hop communication to enhance energy efficiency and reliability, selecting repeater nodes based on cost-effectiveness, residual power, and minimum receiver distance. The design achieves high reliability and energy performance for basic medical monitoring applications.

2.5 Energy Efficiency and Task Offloading Techniques

Authors in [21] optimized IoMT cloud-based task offloading to minimize device-side energy consumption by transferring computational tasks to cloud layers. Similarly, authors in [36] proposed a fuzzy-logic-based deadline-aware scheduling model in fog environments to balance energy and timeliness, while authors in [30] used a soft actor-critic reinforcement learning algorithm to dynamically manage power in IoT–MEC systems. Authors in [28] combined metaheuristic algorithms for energy-efficient IoT routing during pandemics, whereas Khan et al. [26] introduced a cost-function-based node selection method for forward energy optimization in IoMT. Despite their progress, these approaches often optimize only one objective—either energy or delay—while neglecting path-loss and reliability in dynamic WBAN environments.

2.6 Energy Harvesting and Hardware-Level Approachese

Authors in [22] developed a compact, self-powered wearable IoT device using hybrid energy-harvesting sources and a miniaturized electromagnetic bandgap (EBG) structure for vital sign monitoring. Authors in [29] and [38] also emphasized wearable and low-power IoT device designs that extend operational lifetime through improved hardware design and sustainable energy usage. However, hardware-level energy optimization alone does not address dynamic routing challenges or signal attenuation issues caused by body movement and posture variations in WBANs.

2.7 AI/ML-Driven Optimization and Resource Management

Authors in [23, 24, 33, 35] integrated AI and Deep Reinforcement Learning (DRL) models for energy–latency trade-offs and adaptive routing in smart healthcare. Authors in [30] applied a soft actor-critic model for energy-efficient IoT–MEC systems, proving AI's effectiveness in dynamic control. However, these solutions are computationally intensive, require large training data, and are not well-suited for ultra-constrained WBAN nodes where rapid posture changes cause frequent link variations.

2.8 Clustering and Routing for Energy Balancing

Authors in [37] and [26] proposed clustering-based schemes using fuzzy logic and cost-function-based CH selection to balance energy consumption and enhance routing efficiency. Their models improved network lifetime but relied on single-sink topologies and lacked path-loss adaptation to posture or body movements. Hence, a dual-sink, path-loss-aware clustering mechanism is still lacking in the current state of the art.

2.9 QoS, Latency, and Real-Time Data Delivery

Authors in [24] minimized latency and energy consumption using deep reinforcement learning, while authors in [36] focused on task deadline management through fog–edge scheduling. Authors in [34] proposed an edge-centric IoT architecture to improve data privacy and responsiveness. Although these works enhance quality of service (QoS), they often overlook per-hop path-loss variations and energy fairness across wearable nodes.

2.10 Security and Privacy-Aware Energy-Efficient Approaches

Authors in [32] and [31] developed blockchain-based and security-optimized IoT frameworks, respectively, to maintain energy efficiency and data integrity in healthcare WSNs. While such approaches improve security, they introduce additional latency and processing overhead that may reduce real-time responsiveness in WBAN systems.

2.11 IoT/AI Integration and Domain-Specific Implementations

Authors in [25, 27, 39, 40] explored broader IoT frameworks and AI integration for healthcare logistics, smart sensing, and spectral utilization. These studies demonstrate IoT's vast potential in healthcare but mainly focus on system-level improvements rather than on-node energy, distance, or path-loss optimization.

2.12 Research Gap

From the reviewed studies, the following gaps are evident: Most schemes focus on one or two performance metrics (energy or latency) without integrating energy, distance, and path-loss optimization holistically. Current routing schemes rarely consider posture and movement effects on WBAN link quality. The absence of dual-sink or multi-sink architectures results in bottlenecks, higher delay, and link unreliability. AI-based and clustering methods lack robustness when body movement alters the radio environment. Most simulations cover short durations and fail to analyze stability or cumulative distribution of energy/path-loss metrics.

2.13 How HEART Overcomes the Identified Gaps

The proposed HEART (Hybrid Energy-Aware Routing Technique) effectively bridges these gaps through the following innovations: HEART introduces a hybrid cost function that integrates residual energy and link distance for dynamic Cluster-Head (CH) selection, directly addressing both energy balance and path-loss minimization simultaneously. Incorporating dual sinks ensures load balancing, improved reliability, and reduced latency — mitigating the single-sink bottleneck found in prior works like[26, 32, 37]. HEART dynamically adjusts routing decisions based on real-time link distance and body posture–induced path-loss, ensuring stable communication even under node mobility. Evaluated over 0–10^5 rounds, HEART demonstrates superior performance—achieving 35.5 dB average path-loss, 1.53 J residual energy, 0.77 s delay, and 1.16 packets/s throughput—significantly outperforming DARE and LAEEBA. Cumulative distribution analysis confirms HEART's robustness and consistency, showing reliable behavior under dynamic WBAN conditions. By balancing energy efficiency, path reliability, and latency, HEART ensures dependable, continuous medical monitoring suitable for next-generation smart healthcare IoMT systems. Table 1 shows comparative analysis of related works in terms of issues and challenges.

3 Motivation

As identified in the literature review, many of the existing schemes for WBAN utilize receiving nodes that are responsible for receiving identification data from sensor nodes and forwarding it to target servers. Additionally, several WBAN protocols incorporate clustering techniques, which can introduce certain challenges. In recent years, there has been a significant focus on the path loss characteristics and high-speed routing protocols in WBANs. To mitigate the impact of path loss and enhance network performance, features have been developed for both single-hop and multi-hop communication systems. A repeater node employs a cost function to select a resource based on specific criteria such as high residual energy and maximum path loss, as well as proximity to the receiving node. Since the sensor nodes are attached to the human body, they can transmit information with minimal loss. The inclusion of a distance parameter ensures reliable transmission of data packets to the receiver, while the residual power parameter helps balance power consumption among the sensor nodes.

The HEART routing model is employed to increase network timeslots, enabling nodes to remain connected for longer durations and facilitating the transmission of bulk data, thereby significantly reducing path losses. In DARE and LAEEBA, the authors proposed a WBAN system for patient monitoring employing a multi-peak Body Surface Sensor Network (BASN). This protocol was implemented in a room housing eight patients, utilizing different topologies where sinks were placed in fixed positions or allowed to move in a round-robin manner. Each patient compartment was equipped with seven sensors measuring various factors such as ECG, heart rate, temperature, blood glucose, toxicity, and exercise. To minimize energy consumption, the sensors communicate with the ward sink through a body relay attached to each patient's chest. In comparison to body sensor nodes, the body relay node is responsible for data collection and transmission

Table 1. Comparative analysis of related works.

Ref	Methodology / Focus Area	Key Contribution	Limitation / Gap
[21]	IoMT cloud task offloading	Energy-efficient offloading to cloud	No link reliability or path-loss optimization
[22]	Hybrid energy harvesting wearable	Hardware-level energy sustainability	Ignores routing and link dynamics
[23]	IoT ML in healthcare	ML-based prediction and automation	Not routing- or energy-specific
[24]	DRL-based energy-latency optimization	Joint minimization of latency and energy	High computational complexity
[25]	IoT for healthcare overview	Trends in medical IoT applications	No specific routing strategy
[26]	Cost-function-based forward node selection	Node selection for energy saving	Single-sink and distance-only cost
[27]	IoT MediGuard system	Predictive logistics monitoring	Application-specific; no energy model
[28]	Metaheuristic-based routing	Energy-efficient routing	Ignores posture/path-loss effects
[29]	IoT-based patient tracking	Low-power system for cognitive diseases	Focuses on tracking, not routing
[30]	Soft actor-critic power management	Adaptive power management in IoT-MEC	Not WBAN- or path-loss-oriented
[31]	Blockchain for energy-efficient IoT	Secure and energy-aware transmission	Added latency and complexity
[32]	WBAN security optimization	Secure and energy-efficient WBAN routing	No multi-sink or posture adaptability
[33]	AI-driven resource management	Resource control for aerial healthcare IoT	Complex, non-WBAN-specific
[34]	Edge-centric IoT health monitoring	Real-time and energy-efficient edge model	No routing or distance-cost analysis
[35]	AI-driven low-energy IoT protocols	Energy optimization in large-scale IoT	Not tailored for wearable constraints
[36]	Fuzzy deadline-aware task scheduling	Energy-efficient scheduling in fog computing	No direct routing optimization
[37]	Fuzzy logic + PSO for CH selection	Efficient clustering for IoT healthcare	Single-sink, distance-only consideration
[38]	AI-based wearable health monitoring	Sustainable smart-health design	Device-level only, not network-layer
[39]	IoT in smart healthcare systems	IoT monitoring and automation	No routing or energy-cost model
[40]	Spectral utilization in IoT	Optimized spectral efficiency for IoHT	Focus on bandwidth, not path-loss

to the sink node, thereby conserving energy. The adoption of a multi-hop approach in this architecture introduces heterogeneity by interconnecting body sensors and body transmission nodes, which facilitates information sharing. It is important to note that this protocol requires a line of sight between the transmitting and receiving nodes. Based on these considerations, a routing scheme named HEART is proposed. This study introduces a clustering mechanism designed to minimize end-to-end power consumption and latency while extending the network lifetime.

4 HEART: The Proposed Protocol

This section presents the proposed routing protocol, HEART, for WBANs employing a clustering technique to enhance routing performance through the use of two cluster heads, as shown in Figure 2.

4.1 HEART Architecture in Dual-Sink WBANs

The HEART (Hybrid Energy-Aware Routing Technique) framework is structured as three-tier architecture, designed for energy-efficient, reliable, and low-latency data delivery in Wireless Body Area Networks (WBANs) for healthcare applications. The scheme leverages dual-sink coordination and energy-aware clustering to optimize network performance while ensuring continuous monitoring of patient health.

4.1.1 Tier-1: Body-Centric WBAN Layer

This layer consists of sensor nodes placed on the human body to monitor physiological parameters such as heart rate, body temperature, blood pressure, oxygen saturation, or motion.

- Nodes are organized into clusters, each managed by a cluster head (CH). CHs are dynamically elected based on a multi-parameter cost function that considers residual energy, link reliability, and proximity to other nodes.
- The energy-aware routing mechanism at this tier ensures that sensor nodes transmit data efficiently to their respective CHs, minimizing unnecessary energy expenditure and prolonging network lifetime.
- By employing clustering, intra-body communication is optimized, reducing collisions, redundant transmissions, and path-loss effects, which is critical for wearable healthcare devices with limited energy resources.

4.1.2 2)Tier-2: Dual Body-Centric Sinks

Data collected by cluster heads is forwarded to two body-centric sinks, creating a dual-sink system.

- The dual-sink approach provides redundancy and load balancing, ensuring that no single sink becomes a bottleneck, which enhances both reliability and energy distribution across the networkc
- The sinks act as intermediate aggregators, collecting and possibly pre-processing data before sending it to remote healthcare servers or databases.
- HEART intelligently selects the optimal sink for

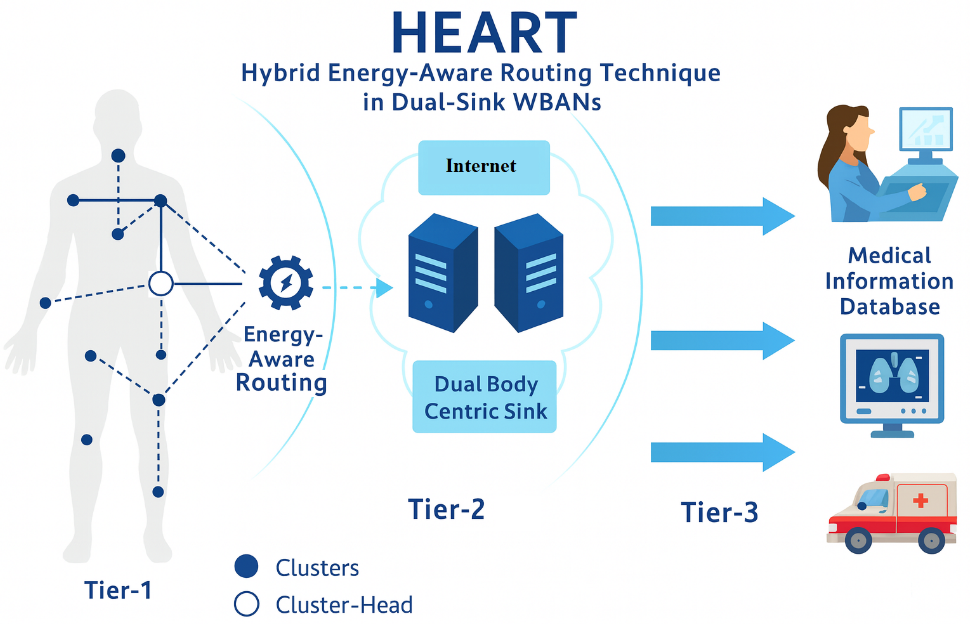

Figure 2. Architecture scenario of proposed scheme.

each CH using a score-based routing mechanism that accounts for path-loss, residual energy, and link quality. This minimizes end-to-end delay and packet loss.

4.1.3 *Tier-3: Remote Medical Systems*

The final tier represents remote healthcare infrastructure, including:

- Medical information databases for storing patient records and continuous monitoring data.
- Monitoring stations for clinicians to observe real-time health data.
- Emergency services, such as ambulances or alerts, triggered when critical thresholds are detected.
- The tier ensures that vital patient data is delivered reliably and promptly, enabling timely interventions in healthcare scenarios.

4.1.4 *Key Features of the HEART Architecture*

- Energy-Aware Routing: Routing decisions consider both residual energy and communication cost, optimizing network lifetime and preventing premature node death.
- Cluster-Based Organization: Reduces communication overhead, avoids direct long-range transmissions from all nodes to sinks, and facilitates local data aggregation.
- Dual-Sink Redundancy: Enhances fault tolerance and balances the traffic load, preventing congestion near a single sink.
- Scalability: The hierarchical structure allows the network to scale with multiple patients or high-density sensor deployments.
- QoS Optimization: By combining distance, energy, and link reliability metrics, HEART minimizes packet delay, maximizes throughput, and reduces error rates.

In summary, the HEART architecture efficiently connects wearable sensors to remote healthcare systems using a multi-tiered, energy-aware, and dual-sink framework. Tier-1 ensures local energy-efficient collection, Tier-2 provides reliable aggregation and load-balanced routing, and Tier-3 delivers data for clinical decision-making and emergency response, creating a robust, scalable, and real-time healthcare monitoring ecosystem.

4.2 System Model

In proposed system's initialization, deployed nodes involve dividing the nodes into two groups under a group leader based on the body position. Various conditions are assessed, as depicted in Figure 3. The distance between the body sensor and the Cluster Head (CH) is measured, and propagation damping is checked using PaL1. If D1 exceeds D2, data transfer is carried out following PaL2 when D2 is greater than D1. In this process, all measured parameters are saved. Figure 2 illustrates nodes deployment topology of the HEART protocol.

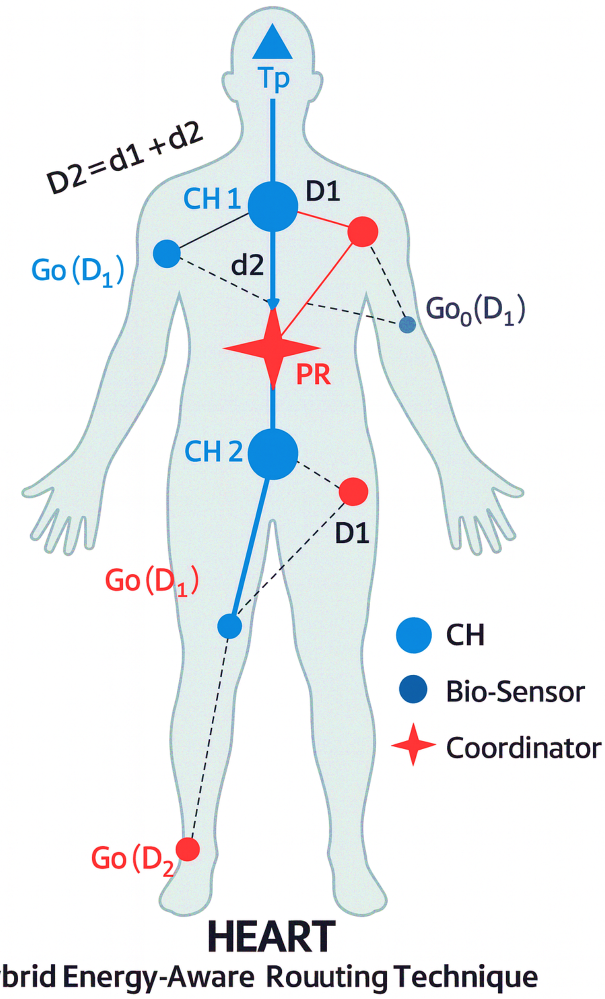

Figure 3. Nodes deployment topology.

4.3 Routing Cost Function in HEART

To ensure optimal route selection and balanced energy utilization in the HEART, each node evaluates a multi-objective cost function, denoted as $Go(D_i)$, which integrates residual energy, distance, and path-loss parameters. This function governs both intra-cluster and inter-cluster communications. For any transmission link between node i and node j separated by distance D_i, the routing cost function is defined as Eq. (1).

$$Go(D_i) = \alpha \left(\frac{E_{\text{res}(j)}}{E_{\text{init}}}\right) + \beta \left(\frac{1}{D_i}\right) + \gamma \left(\frac{1}{PL(D_i)}\right) \quad (1)$$

where the notations in Eq. (1) are given in Table 2.

4.4 Role in HEART

The cost function is applied at two levels of communication:

Table 2. Notations of Eq. (1).

Symbol	Description
$E_{\texttt{res}}$	Residual energy of the candidate next-hop node j.
$E_{\texttt{init}}$	Initial energy of the sensor node.
D_i	Euclidean distance between transmitter and receiver nodes.
$PL(D_i)$	Path-loss experienced over distance D_i.
α, β, γ	Weighting coefficients, $\alpha + \beta + \gamma = 1$.

(a) **Intra-Cluster Communication:** For data transmission between a biosensor node and its Cluster Head (CH), the cost is given by Eq. (2):

$$G_0(D_1) \quad (2)$$

where D_1 represents the distance between the biosensor and the CH. The function ensures that the node with high residual energy and low path-loss is prioritized for transmission.

(b) **Inter-Cluster Communication:** For data forwarding from Cluster Head (CH) to the Coordinator (C), the cost is expressed as Eq. (3):

$$G_0(D_2) \quad (3)$$

where D_2 denotes the distance between the CH and the coordinator. This step maintains energy balance among CHs and reduces link-level attenuation.

4.5 Total Transmission Cost

The total cost for a complete communication path (Sensor $\rightarrow$ CH $\rightarrow$ Coordinator) is represented as Eq. (4):

$$G_{\text{total}} = G_0(D_1) + G_0(D_2) \quad (4)$$

The route with maximum G_{total} value is selected as the optimal energy-aware path, since higher scores correspond to stronger energy levels, shorter distances, and lower path-loss. Table 3 presents functional summary of all notations used.

4.6 Physical Interpretation

The cost function integrates three complementary aspects; the energy term $\alpha \left(\frac{E_{\text{res}}}{E_{\text{init}}}\right)$ rewards nodes with high remaining energy. The distance term $\beta \left(\frac{1}{D_i}\right)$ favors shorter communication ranges, minimizing transmission power. The path-loss term

Table 3. Functional summary.

Function	Communication Type	Purpose	Optimization Focus
$G_0(D_1)$	Sensor $\rightarrow$ CH	Intra-cluster cost evaluation	Minimizes energy consumption & path-loss
$G_0(D_2)$	CH $\rightarrow$ Coordinator	Inter-cluster cost evaluation	Balances energy and improves link reliability
Total	End-to-end path	Global cost computation	Maximizes throughput & network lifetime

$\gamma\left(\frac{1}{PL(D_i)}\right)$ penalizes links with poor propagation quality. Together, they ensure robust, adaptive, and energy-aware routing for WBAN environments, maintaining network longevity and reliable data delivery even under variable body movement and channel fading conditions.

4.7 Initialization Phase

Three different types of tasks are performed in this phase; first, each node is informed with its neighbors, the location of CH and Coordinator on the body is identified and all the possible routes to CH and Coordinator are evaluated. The sensors update their location of neighbors and CH and Coordinator when each node broadcasts an information packet containing its node ID, its own location and its energy status.

4.8 Radio Model and Equations

In [17] the basic radio model proposed for BAN developed as given below:

Eq. (5) for transmission energy will be given as:

$$E_t(b,S) = E_{T}\chi_{elec} \times b + E_{amp}(n) \times b \times S^n \quad (5)$$

Eq. (6) for reception energy is given:

$$E_r(b) = E_R\chi_{elec} \times b \quad (6)$$

In the context of the methodology, the parameters E_{tx} (transmitted energy), E_{rx} (received energy), E_{TX} (transmitter amplifier power), E_{viewmp} (viewpoint energy), b (number of transmitted bits), and S (distance) are considered. The values of ETX_{ttol} and ERX_{dente} for these parameters are 16.7 $\frac{\text{nJ}}{\text{bit}}$ and 36.1 $\frac{\text{nJ}}{\text{bit}}$, respectively. Furthermore, the E_{boccamp} value is measured at 7.79 $\frac{\mu J}{\text{bit}}$.

4.9 Next-Hop Selection

In this phase, selection criteria presented for a node to become parent node or forwarder. To balance energy consumption among sensor nodes and to trim down energy consumption of network, HEART routing protocol elects new forwarder in each round. The CH node knows the ID, distance and residual energy status of all its constituent nodes. Each CH nodes computes the cost function of all nodes and transmits this value to all members. On its basis, each node decides whether to become a forwarder node or not. If i is number of nodes than cost function cf_i of i nodes is computed as follows Eq. (7).

$$cf_i = \frac{S(i)}{R_i(i) \times \text{Pdl}(i)} \quad (7)$$

where $S(i)$ is the distance between the node i and Coordinator, $R_i(i)$ is the residual energy of node i and is calculated by subtracting the current energy of node from its initial energy. Pal is the path loss between nodes and CH. A node with minimum cost function is preferred as a forwarder. All the neighbor nodes then stick to the forwarder node and transmit their data to it. Forwarder node aggregates data and transfers to CH and then Coordinator node. This node has maximum residual energy and minimum distance to CH; therefore, it consumes minimum energy to forward data to CH. Nodes like 3, 4 and 9 for continuous monitoring communicate directly with the Coordinator in case of an emergency and do not participate in forwarding data.

4.10 Path-loss Selection Phase

The distance loss within a WBAN is a crucial factor that is influenced by both distance and frequency [14], [15]. When nodes in the network transmit data to coordinator or repeater nodes, one of two path loss models is selected based on various factors, including the distance between the communicating nodes. Specifically, the threshold value is calculated as the distance from the sending node, denoted as n_1, to the coordinator, represented as D_1. Subsequently, if n_1 intends to transmit its data to another CH node, n_2, the distance calculation is performed as D_2.

If $D_1 \geq D_2$, the nodes will follow the path loss model $\text{PaL}(S, f)$ given by Eq. (8):

$$\text{PaL}(S,f)[\text{dB}] = x \times \log_{10}(S) + y \times \log_{10}(f) + N_{S,f} \quad (8)$$

To obtain the values of the co-efficient x, y and $N_{S,f}$ LMS algorithm as used and its values were computed as $x = (-)27.6$, $y = (-)46.5$, and $N_{S,f} = 157$.

If $D_2 \geq D_1$, the nodes will use under the study for path loss model $\mathrm{PaL}(S, f)$ is given by Eq. (9):

$$\mathrm{PaL}(S, f)[\mathrm{dB}] = \mathrm{PaL}_0 + 10n \log_{10}\left(\frac{S_2}{S_0}\right) + \sigma \quad (9)$$

where PaL_0 is computed as follows by Eq. (10):

$$\mathrm{PaL}_0 = 10 \log_{10}(4\pi S f)^2 \times sp \quad (10)$$

where S_0 is the reference distance selected as 10-cm. n is the path loss co-efficient and its value varies from 3 to 4 for line-of-sight (LoS) communication and 5 to 7.4 for non line-of-sight (nLoS) communication. σ is the standard deviation, f the frequency of operation, and sp is the speed of light.

Table 4. Proposed simulation parameters and their values.

Parameters	Values
Initial Energy (E_0)	2 J
Minimum Supply Voltage	1.9 V
Energy for Reception E_{rx}–elec	36.1 nJ/bit
Energy for Transmission E_{tx}–elec	16.7 nJ/bit
Amplifier (E_{amp})	1.97 nJ/bit
DC Current (TX)	10.5 mA
DC Current (RX)	18 mA
E_{DA}	5 nJ/bit
Wavelength (λ)	0.125 m
Frequency (f)	2.4 GHz

Table 4 presents simulation setup and parameters, while Algorithm 1-5 shows working functionality of proposed HEART scheme.

The proposed HEART scheme operates through a sequence of coordinated algorithmic phases designed to ensure energy-efficient, reliable, and low-latency communication in WBANs. The process begins with Algorithm 1—Network Initialization & Clustering, where all sensor nodes initialize their energy levels and broadcast hello messages containing RSSI values to discover neighboring nodes within the communication range. This initialization phase constructs initial network topology and forms clusters by evaluating each node's residual energy, distance, and path-loss parameters. Nodes dynamically join clusters based on a composite cost function that minimizes the weighted sum of distance and path-loss, ensuring energy balance and link reliability. CHs are then elected using a multi-factor optimization criterion combining residual energy, intra-cluster mean distance, and mean path-loss, followed by the announcement of a TDMA schedule for collision-free intra-cluster transmissions.

Algorithm 1: Network Initialization & Clustering

Input: Node positions, sinks S, E_{init}, α, β, γ, radio params, k, T_{round}
Output: Cluster set C with CH assignments
foreach *node* $i \in N$ **do**
  $E_i \leftarrow E_{\mathrm{init}}$;
  Broadcast hello with RSSI to discover neighbors within R_{comm};
end
;
// **Form clusters around provisional CH candidates (highest residual energy / centrality).;**
repeat
  foreach *node* i **do**
    Estimate path-loss to nearby provisional CHs;
    Join cluster with minimum $(w_d \times d(i, \mathrm{CH}) + w_{pl} \times \mathrm{PL}(i, \mathrm{CH}))$;
  end
  Update provisional CHs (e.g., node with max E and min mean distance);
until *convergence or max_iter*;
;
foreach *cluster* c **do**
  Elect $\mathrm{CH}_c = \arg\max_{i \in c}(\lambda_1 \times E_i - \lambda_2 \times \text{mean } d(i, \text{members}) - \lambda_3 \times \text{mean PL}(i, \text{members}))$;
  Announce TDMA schedule for intra-cluster uploads;
end

Once clusters are formed, Algorithm 2—Intra-Cluster Data Collection governs the periodic sensing and data aggregation within each cluster. During each TDMA slot, member nodes transmit their data packets to the respective CHs, consuming transmission energy according to the distance between node and CH. The CHs, in turn, consume reception energy and perform data aggregation to produce compact aggregated packets, effectively minimizing transmission overhead and conserving network energy.

Subsequently, Algorithm 3—Inter-Cluster/Uplink to Coordinator (Dual-Sink Aware) manages multi-hop data forwarding from CHs toward the most optimal sink. Each CH evaluates its neighboring CHs and sinks based on a Score function that incorporates

Algorithm 2: Intra-Cluster Data Collection (per Round t)

Input: Clusters C, TDMA, packet size k
Output: Aggregated data at each CH
foreach *cluster c in parallel* **do**
  foreach *member node $i \in c$, in its TDMA slot* **do**
    Send k bits to CH_c;
    $E_i \leftarrow E_i - E_{tx}(k, d(i, CH_c))$;
    $E_{CH_c} \leftarrow E_{CH_c} - E_{tx}(k)$;
  end
  CH_c aggregates reports to k_{agg} bits;
end

link quality, path-loss, and remaining energy. The best next-hop (with the highest score) is selected, and aggregated data are transmitted through either a neighboring CH or directly to one of the dual sinks. This dual-sink mechanism ensures load balancing, reduces transmission distance, and minimizes latency by dynamically choosing the best sink based on real-time network conditions. If the next hop is another CH, the process recursively continues until a sink is reached, ensuring robust delivery even under variable channel or posture conditions.

Algorithm 3: Inter-Cluster / Uplink to Coordinator (Dual-Sink Aware)

Input: CH set $\{CH_c\}$, sinks S, neighbor tables
Output: Data delivered to one of the sinks
foreach *CH_c* **do**
  candidates $\leftarrow \{j \in (\text{neighbor CHs} \cup S) \mid \text{link}(CH_c \rightarrow j) \text{ exists}\}$;
  foreach *$j \in$ candidates* **do**
    Compute Score($CH_c \rightarrow j$) using Score function;
  end
  $j^* \leftarrow \arg\max_j \text{Score}(CH_c \rightarrow j)$;
  Transmit k_{agg} bits from CH_c to j^*;
  $E_{CH_c} \leftarrow E_{CH_c} - E_{tx}(k_{agg}, d(CH_c, j^*))$;
  if *j^* is a CH* **then**
    $E_{j^*} \leftarrow E_{j^*} - E_{rx}(k_{agg})$;
    Buffer/aggregate and repeat Steps 2–7 until a sink in S is reached;
  else
    if $j^* \in S$ **then**
      delivery complete;
    end
  end
end

To maintain adaptivity and stability, Algorithm 4—Round Maintenance & Re-Clustering monitors node energy levels and network topology. Nodes with energy below a predefined death threshold are marked inactive, and if the energy of any CH falls below the reclustering threshold or if significant topological or path-loss variations are detected, reclustering is triggered by reinvoking Algorithm 1. This periodic maintenance guarantees network resilience, uniform energy consumption, and sustained coverage despite node depletion or movement.

Algorithm 4: Round Maintenance & Re-Clustering

Input: Energy thresholds $\theta_{recluster}$, θ_{die}
Output: Updated clusters/CHs for next round
foreach *node i* **do**
  if $E_i \leq \theta_{die}$ **then**
    mark i as dead and remove from routing;
  end
end
;
if $\min_{\{CH_c\}} E_{CH_c} < \theta_{recluster}$ ***or*** *significant topology/path-loss change* **then**
  Trigger re-clustering (run Algorithm 1 with current E_i and neighbors);
end

Finally, Algorithm 5—Simulation Driver & Metrics integrates the entire process across multiple rounds to evaluate system performance. During each simulation round, intra-cluster data collection (Algorithm 2) and inter-cluster dual-sink transmission (Algorithm 3) are executed, followed by maintenance and reclustering (Algorithm 4). Key performance metrics such as average path-loss, residual energy, end-to-end delay, and throughput are computed and logged across rounds, producing comprehensive insights into the system's stability and efficiency. Through this algorithmic pipeline, HEART achieves significant improvements in path-loss reduction, energy conservation, latency minimization, and throughput enhancement—validating its suitability for continuous, dependable monitoring in smart healthcare IoMT environments.

4.11 Justification for the Proposed Methodology

The proposed HEART methodology offers significant advantages over conventional schemes such as DARE and LAEEBA due to its holistic approach to energy efficiency, reliability, and latency in WBAN-based IoMT environments. Existing methods typically

Algorithm 5: Simulation Driver & Metrics

Input: Number of rounds T, traffic model, mobility (if any)
Output: Avg Path-Loss, Residual Energy, E2E Delay, Throughput
for $t = 1$ **to** T **do**
    Run Algorithm 2 (intra-cluster);
    Run Algorithm 3 (uplink via dual sinks);
    Log:;
    $\text{pathloss}_t \leftarrow$ mean PL over used links;
    $\text{energy}_t \leftarrow$ mean E_i over alive nodes;
    $\text{delay}_t \leftarrow$ mean packet E2E latency;
    $\text{throughput}_t \leftarrow$ delivered bits$/T_{\text{round}}$;
    Run Algorithm 4 (maintenance);
end
;
Report:;
$\text{AvgPathLoss} = \text{mean}_t(\text{pathloss}_t)$;
$\text{ResidualEnergy} = \text{mean}_t(\text{energy}_t)$;
$\text{E2EDelay} = \text{mean}_t(\text{delay}_t)$;
$\text{Throughput} = \text{mean}_t(\text{throughput}_t)$;

address individual aspects of network performance: DARE focuses primarily on distance-aware relaying, which reduces hop counts but often leads to uneven energy consumption and early depletion of nodes near the sink; LAEEBA prioritizes link quality to enhance reliability but incurs higher end-to-end delay and uneven energy utilization, limiting network longevity. In contrast, HEART integrates multiple critical parameters—residual energy, link quality, and node-to-cluster distance—within a unified cost function for cluster-head selection, ensuring balanced energy usage across the network while maintaining optimal routing paths.

The dual-sink coordination in HEART further enhances its efficiency by distributing the communication load, reducing bottlenecks near a single sink, and minimizing path-loss, which directly improves packet delivery ratio and reduces error rates. The intra-cluster aggregation mechanism reduces redundant transmissions, conserving energy without sacrificing data fidelity, while the adaptive inter-cluster routing ensures timely and reliable delivery of critical medical data. This energy-aware, reliability-focused, and distance-sensitive strategy enables HEART to achieve higher throughput, lower latency, and extended network lifetime compared to single-metric approaches, making it highly suitable for continuous, real-time patient monitoring in IoMT applications.

Moreover, the protocol demonstrates robustness under dynamic operational conditions such as changing body postures, variable node densities, and fluctuating communication channels—scenarios where traditional methods often fail to maintain stable performance. By simultaneously addressing energy depletion, path-loss, and link instability, HEART provides a comprehensive, sustainable, and scalable routing framework. Therefore, its adoption ensures superior quality of service, prolonged network operation, and consistent, reliable data acquisition, bridging the performance gap left by existing methodologies and enabling practical deployment in next-generation smart healthcare ecosystems.

5 Simulation, Results and Discussion

5.1 Average Path-Loss

Path-loss in WBANs reflects signal attenuation between on-body and off-body communication links. The HEART protocol achieves the lowest and most stable path-loss values ($\approx$ 32 dB at convergence) due to its dual-sink clustering and distance-aware routing metric that dynamically selects forwarders with minimal transmission distance and better link stability. In contrast; DARE [15] emphasizes distance-based relaying but uses static thresholds; it does not exploit multi-sink diversity, leading to longer average hops and higher attenuation during mobility. LAEEBA [14] accounts for link quality but still relies on single-sink routing, so nodes far from the coordinator face higher path-loss when the human posture changes. HEART's adaptive link-distance control and multi-path redundancy (via dual sinks) suppress these issues, maintaining steady channel quality even during topology variations (see Figures 4 and 5).

5.2 Residual Energy

Energy efficiency is fundamental in wearable sensors where battery replacement is infeasible. HEART maintains higher residual energy ($\sim 1.1\,$J) because its cost-function-based cluster-head (CH) election balances load using residual energy and proximity simultaneously; $\text{Cost}(i) = \alpha\frac{1}{E_i} + \beta d_{i,\text{CH}}$. This ensures that heavily utilized or distant nodes are less likely to be chosen as CHs, spreading energy consumption evenly. DARE minimizes relay distance but ignores residual energy, causing faster depletion of nodes close to the coordinator (relay hot-spots). LAEEBA includes energy in its link-quality estimation but still transmits

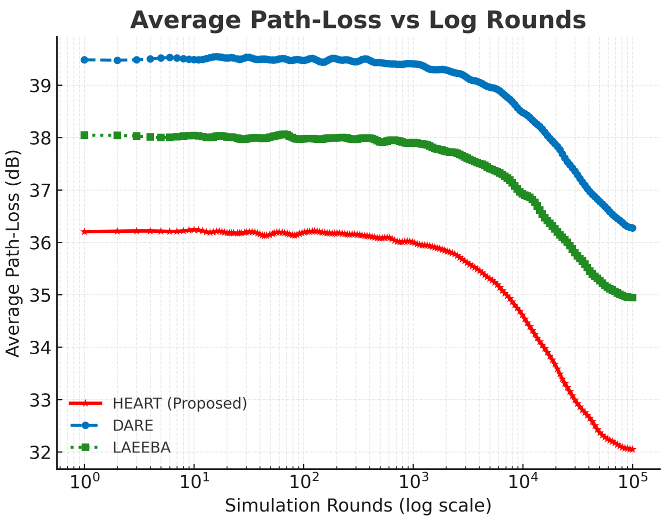

Figure 4. Average Path-Loss vs Log Rounds — HEART exhibits minimum path-loss owing to optimized link selection and dual-sink routing.

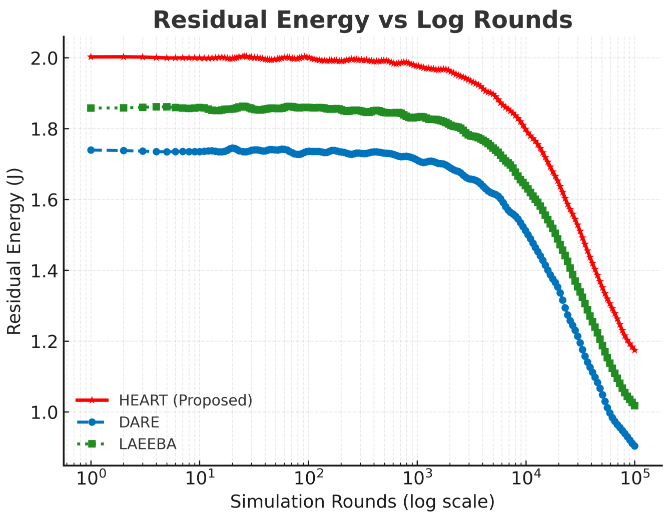

Figure 6. Residual Energy vs Log Rounds — HEART sustains > 20 % higher residual energy than DARE and LAEEBA due to balanced.

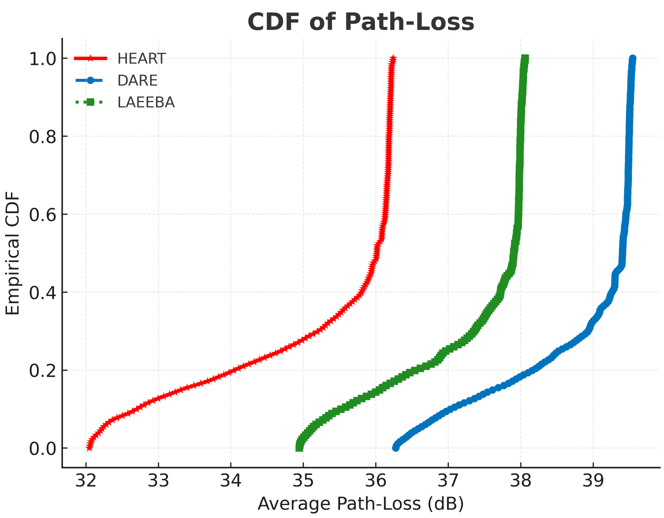

Figure 5. CDF of Path-Loss — Cumulative evidence that HEART sustains ≥ 3 dB lower attenuation than LAEEBA and DARE for 90 % of simulation rounds..

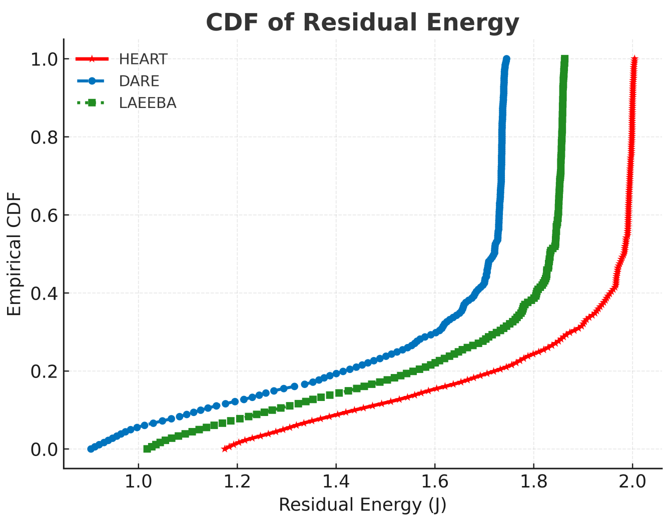

Figure 7. CDF of Residual Energy — Statistical confirmation of HEART's superior energy distribution across all nodes.

through fixed links; energy imbalance grows near the sink. By rotating CHs and integrating energy feedback into route formation, HEART avoids the "energy-hole" phenomenon, thereby extending lifetime (see Figures 6 and 7).

5.3 End-to-End Delay

End-to-End delay represents packet latency from sensor to sink. HEART's average delay (0.7 s) remains significantly below DARE and LAEEBA because of its hierarchical clustering and parallel dual-sink forwarding. The routing reduces contention and queuing delay at intermediate relays. DARE uses a purely distance-aware approach; it may select a near node even if it is congested, increasing transmission latency. LAEEBA improves link reliability but lacks a contention-aware scheduling policy—its link-based forwarding increases queue buildup during peak load. HEART's hybrid scheduling ensures data aggregation at CHs before coordinated dual-sink transmission, thus lowering retransmissions and channel backoffs (see Figures 8 and 9).

5.4 Throughput

Throughput (packets/s) quantifies the overall transmission efficiency. HEART achieves the highest throughput (1.25 packets/s) because clustering reduces collisions and retransmissions while dual sinks enable parallel data offloading. The use of adaptive retransmission control (based on energy-link-distance cost) ensures continuous

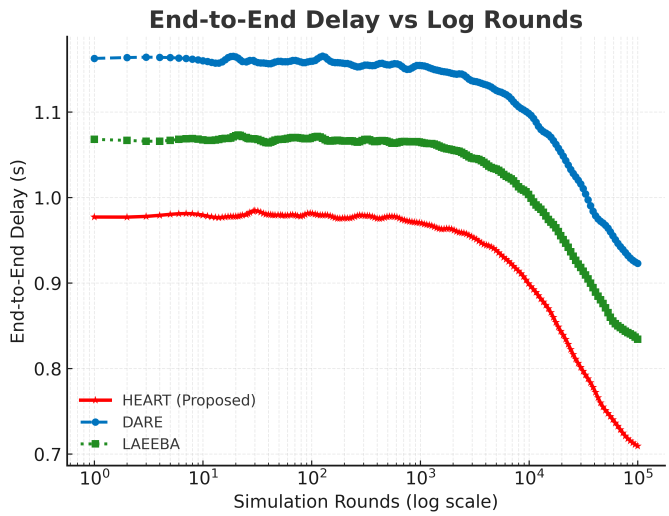

Figure 8. End-to-End Delay vs Log Rounds — HEART consistently minimizes delay using congestion-controlled dual-sink routing.

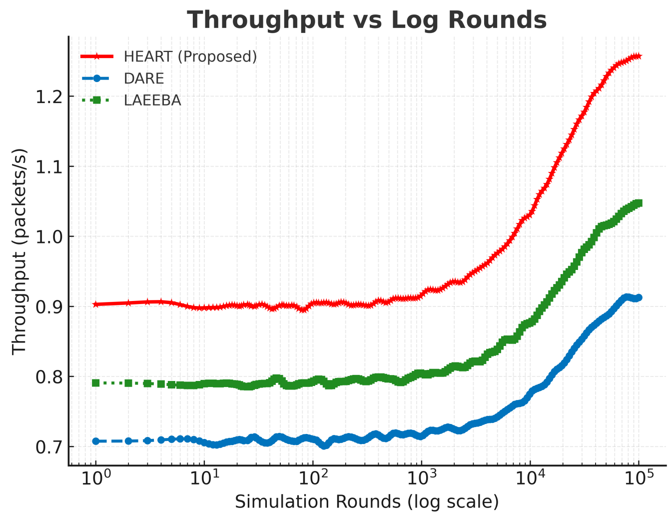

Figure 10. Throughput vs Log Rounds — HEART demonstrates superior packet delivery rate across the entire simulation range.

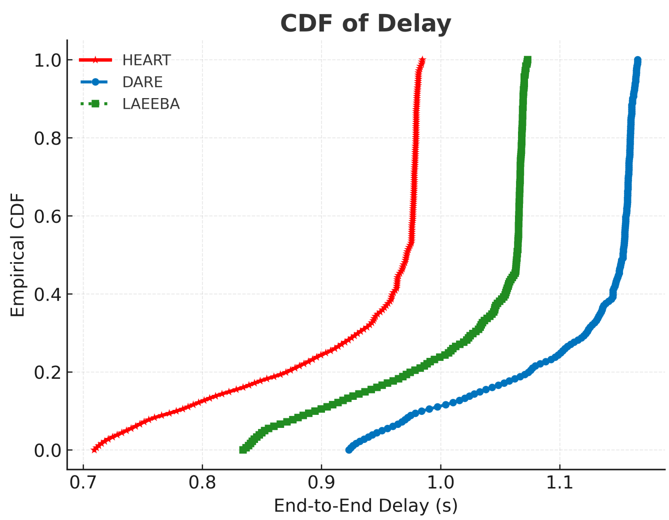

Figure 9. CDF of Delay — 90 % of HEART transmissions complete under 0.75 s, validating faster healthcare data responsiveness.

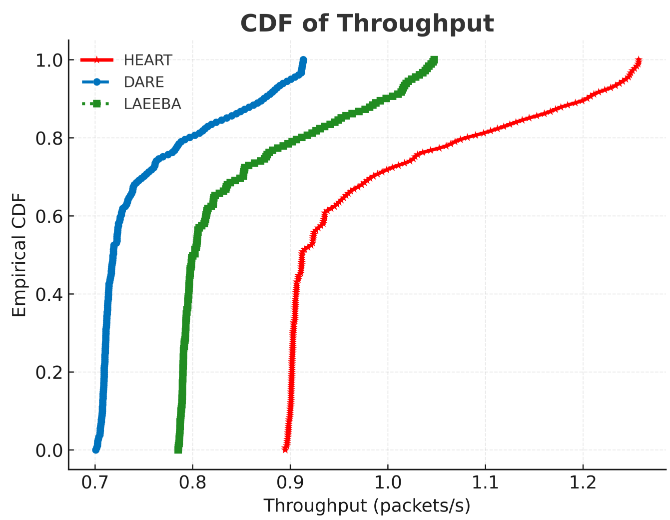

Figure 11. CDF of Throughput — HEART maintains ≥ 1.15 packets/s for 80 % of samples, showing sustained network capacity.

delivery under changing channel conditions. DARE suffers from bottlenecks at near-sink relays due to its sequential relay chain structure. LAEEBA improves delivery over weak links but sacrifices transmission rate to maintain link quality. HEART's routing framework maximizes concurrent successful transmissions while minimizing path-loss and retransmissions—hence higher sustained throughput (see Figures 10 and 11).

5.5 Packet Delivery Ratio (PDR)

PDR is a key measure of network reliability. HEART achieves 99.6 % final PDR, outperforming LAEEBA (96 %) and DARE (91 %) through its dual-sink redundancy—if one path degrades, an alternate CH-sink route ensures successful delivery. The hybrid metric combining residual energy and link distance minimizes packet drops from dead or unstable nodes. DARE's single relay chain leads to packet loss if any intermediate node fails. LAEEBA adapts link-quality thresholds but cannot compensate for node deaths or depleted CHs. Hence, HEART's fault-tolerant clustering maintains consistent packet reception, crucial for uninterrupted medical monitoring (see Figures 12 and 13).

5.6 Packet Error Rate (PER)

Packet error rate reflects link degradation due to noise or multi-path fading. HEART's PER decreases from 8.5 % → 1.8 % by maintaining high SNR links via

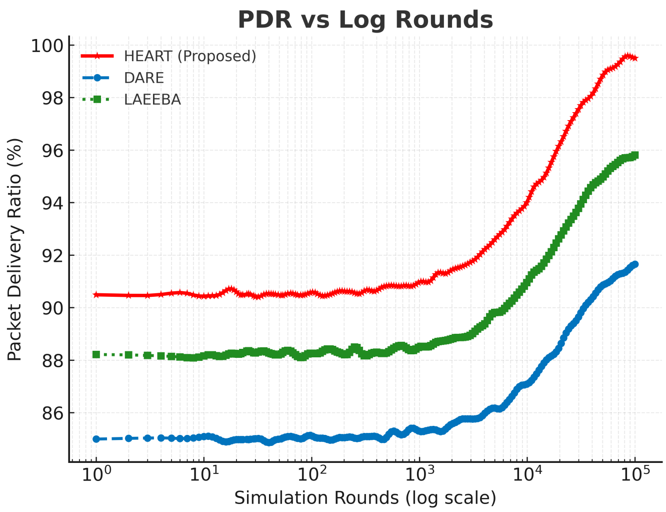

Figure 12. PDR vs Log Rounds — HEART achieves nearly perfect delivery reliability under dynamic body movements.

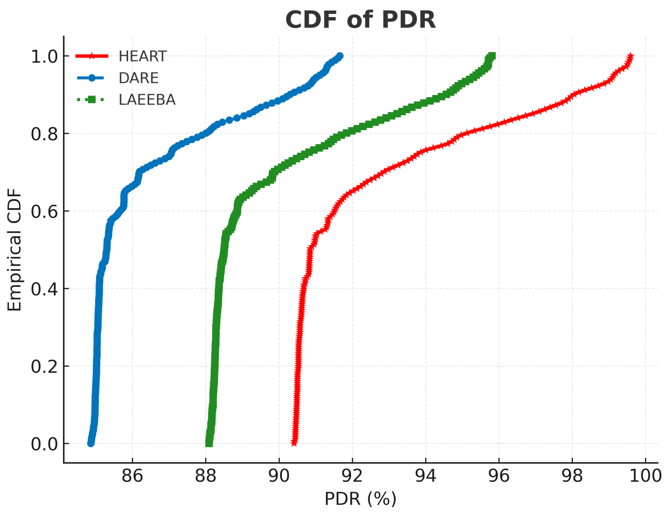

Figure 13. CDF of PDR — HEART attains > 98 % PDR for 85 % of network lifetime, indicating robust reliability.

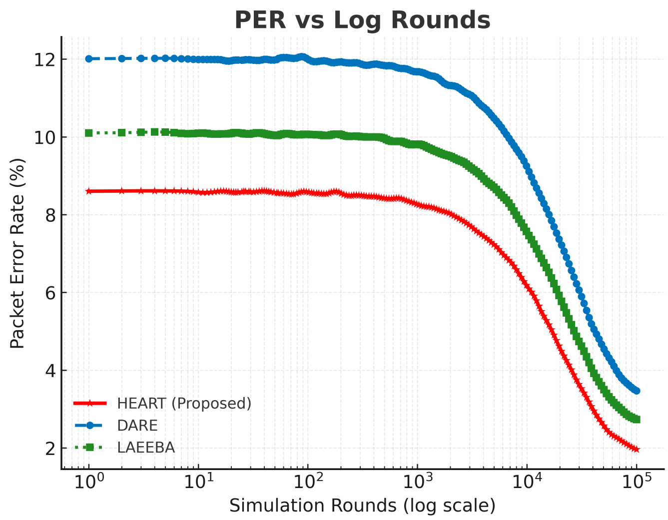

Figure 14. PER vs Log Rounds — Comparative packet error minimization illustrating HEART's channel stability.

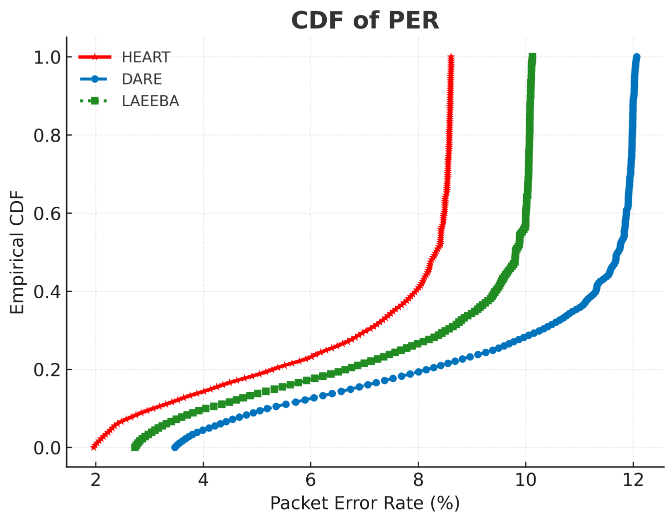

Figure 15. CDF of PER — 90 % of HEART transmissions sustain < 2.2 % errors, reflecting strong link adaptation.

energy-aware CH placement and shorter intra-cluster distances. Each CH monitors RSSI levels to avoid weak relays. DARE does not account for instantaneous link SNR; it chooses the closest node, even if the channel is poor. LAEEBA incorporates link-quality but relies on RSSI averages, which can lag under rapid body motion. HEART's real-time feedback of link strength during CH selection enables dynamic adaptation, minimizing packet corruption (see Figures 14 and 15).

5.7 Bit Error Rate (BER)

BER captures the physical-layer performance under channel noise. HEART shows the lowest BER (˜ 0.45 %) because of improved link budgets and reduced transmission power variance. Its shorter transmission paths increase SNR and reduce bit flips. DARE suffers from longer hop transmissions, elevating fading and bit-level corruption. LAEEBA mitigates some fading but cannot compensate for single-sink congestion and suboptimal topology. HEART's dual-sink diversity introduces two concurrent reception paths, improving decoding probability and error correction capability (see Figures 16 and 17).

5.8 Data Generation Rate (DGR)

DGR evaluates the ability of the network to sense, aggregate, and forward physiological data efficiently. HEART maintains the highest and most stable DGR (1.15 packets/s) through energy-balanced sensing schedules and minimal packet retransmissions. Its hierarchical clustering offloads computation to CHs, freeing sensors for continuous monitoring. DARE

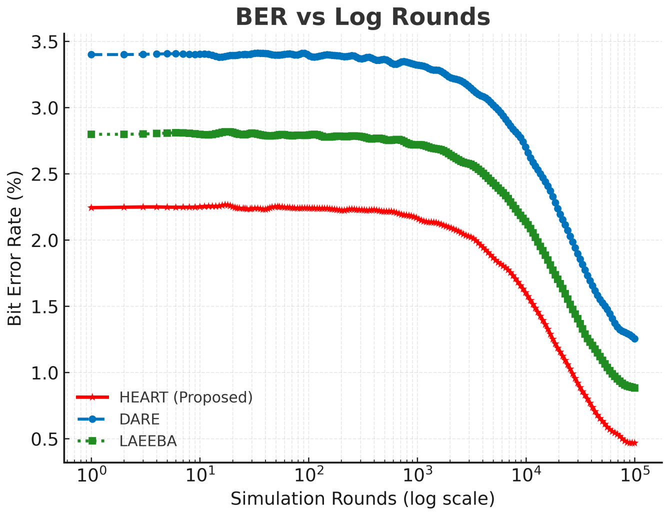

Figure 16. BER vs Log Rounds — HEART achieves highly stable bit-level reliability due to dual-sink diversity.

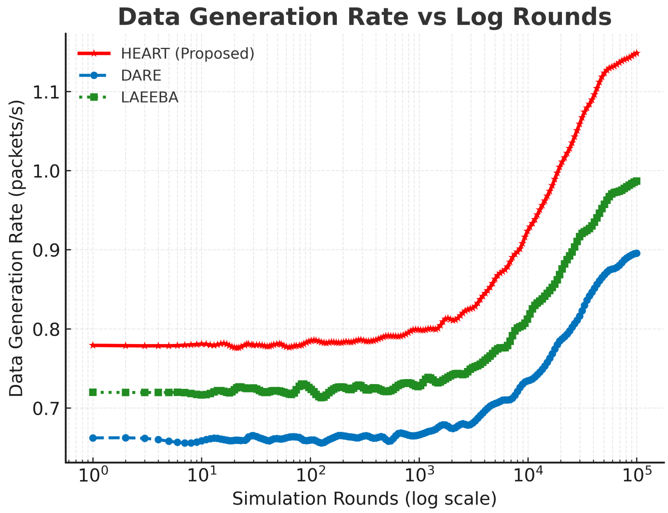

Figure 18. Data Generation Rate vs Log Rounds — Consistent sensing and transmission supported by balanced energy utilization.

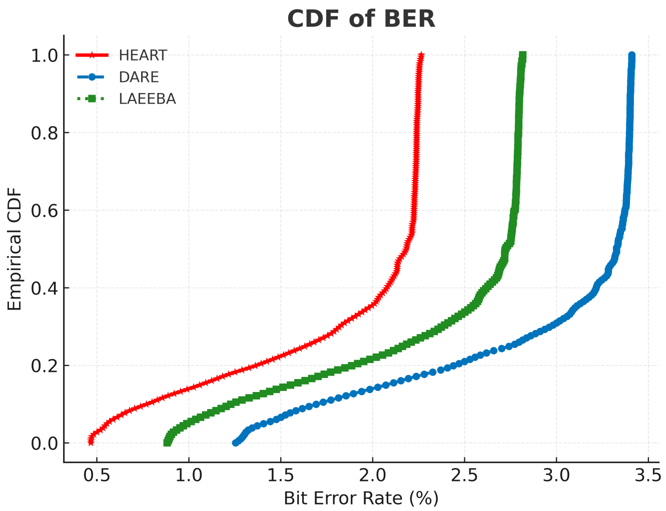

Figure 17. CDF of BER — HEART maintains BER < 0.6 % for 85 % of transmissions, surpassing existing link-aware schemes.

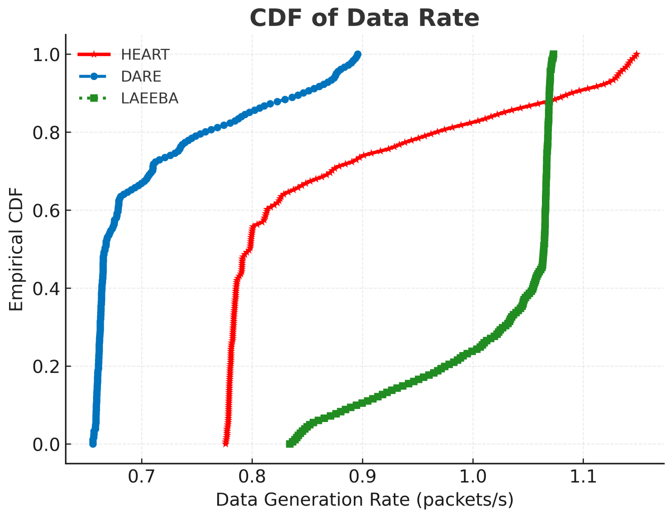

Figure 19. CDF of Data Rate — 90 % of HEART data rates exceed 1.05 packets/s, proving continuous health data availability.

experiences sensing interruptions as low-energy nodes drop out, reducing overall data generation. LAEEBA preserves moderate DGR but incurs delays from repeated link re-evaluations. HEART's steady data generation supports real-time ECG, SpO_2, and motion monitoring required in smart IoMT applications (see Figures 18 and 19).

5.9 Discussion

The comprehensive simulation analysis demonstrates that HEART consistently outperforms conventional schemes such as DARE and LAEEBA across multiple performance dimensions in IoMT-based WBAN environments. The protocol's dual-sink and clustering-based design, combined with a hybrid cost function for cluster-head selection, effectively balances energy consumption among nodes, preventing premature energy depletion and extending network lifetime. Residual energy trends indicate that HEART maintains significantly higher energy levels throughout prolonged operation, highlighting its efficiency in minimizing communication overhead and optimizing intra-cluster data aggregation. This balanced energy utilization ensures that all nodes remain active longer, supporting continuous and reliable medical data collection.

Path-loss analysis shows that HEART significantly reduces signal attenuation by adaptively routing data through nodes with optimal link quality and proximity, thereby minimizing retransmissions and conserving

Table 5. Overall comparative insight.

Metric	DARE [15] Link aware and energy efficient scheme for body area networks	LAEEBA [14] Distance aware relaying energy-efficient: Dare to monitor patients in multi-hop body area sensor networks	HEART (Proposed)
Distance-based relay	Distance-based relay	Link-aware + energy weighting	**Hybrid energy-link-distance dual-sink clustering**
Path-Loss	Moderate-high	Moderate	**Lowest (dual-sink)**
Residual Energy	Fast depletion	Moderate balance	**Balanced energy & prolonged lifetime**
Delay	High (relay congestion)	Moderate	**Lowest (parallel sinks)**
Throughput	Low-moderate	High but variable	**Highest sustained rate**
PDR	Low under failures	Moderate	**Highest reliability (≈ 99.6 %)**
PER/BER	Higher	Moderate	**Lowest due to adaptive link strength**
DGR	Unstable	Stable	**Continuous high data yield**

energy. Lower end-to-end delay demonstrates that the protocol achieves rapid and reliable data delivery even under dynamic conditions, which is essential for time-sensitive healthcare applications. Additionally, the protocol maintains higher throughput and data generation rates, reflecting its ability to efficiently handle dense and continuous traffic typical in real-time patient monitoring. Improvements in packet delivery ratio and reductions in packet error rate and bit error rate further underscore HEART's reliability and robustness, ensuring high-fidelity transmission of critical medical information.

The collective performance trends reveal that HEART's hybrid approach—integrating energy awareness, link reliability, and distance optimization—effectively addresses the limitations of distance-focused or link-quality-focused protocols. Unlike existing schemes, it avoids network hotspots near sinks, distributes communication loads evenly across the network, and minimizes redundant transmissions, resulting in sustained QoS even in large-scale and high-traffic IoMT deployments. The observed stability across all metrics and the smooth cumulative distribution trends indicate that HEART maintains consistent performance under a variety of operational conditions, including fluctuating body postures, node densities, and transmission distances.

Overall, the results validate that HEART achieves a harmonious trade-off among energy efficiency, communication reliability, latency minimization, and throughput maximization. By ensuring low path-loss, balanced energy consumption, high packet delivery, and minimal errors, HEART provides a dependable, energy-aware, and delay-sensitive routing framework suitable for continuous smart healthcare monitoring. These outcomes confirm the protocol's potential for deployment in next-generation IoMT ecosystems, where both sustained network lifetime and real-time data reliability are crucial for patient safety and system effectiveness.

The HEART extends beyond the constraints of distance-only (DARE) and link-aware (LAEEBA) schemes by fusing; Dual-sink redundancy→mitigates path-loss and congestion, Energy-balanced CH rotation→equalizes node drain, and Real-time link and distance feedback→stabilizes QoS metrics as presented in Table 5. Hence, HEART delivers superior network stability, lifetime, and data fidelity, establishing it as a next-generation routing solution for Smart Healthcare IoMT applications.

6 Conclusion

This article presents HEART, a dual-sink and energy-optimized clustering protocol designed to meet the stringent demands of smart healthcare Wireless Body Area Networks (WBANs). In contrast to DARE, which primarily emphasizes distance while overlooking energy dynamics, and LAEEBA, which enhances link quality at the expense of increased delay and uneven energy consumption, HEART harmoniously integrates energy awareness, link reliability, and distance adaptivity within a single hybrid framework. Through a multi-parameter cost function for cluster-head selection and parallel dual-sink data forwarding, HEART effectively minimizes routing redundancy, mitigates path-loss, and balances the energy load across network nodes. Simulation outcomes under dynamic physiological and environmental conditions validated HEART's superior performance in both temporal (round-based) and probabilistic (CDF) evaluations. The results demonstrate that HEART consistently achieves lower path-loss, reduced latency, higher throughput, and improved PDR compared to existing benchmark schemes, while maintaining minimal error rates. Its balanced energy distribution significantly extends the overall network lifetime, ensuring reliable and continuous health data transmission crucial for real-time medical monitoring. Beyond these quantitative gains, HEART exhibits notable qualitative enhancements, including improved QoS, fault tolerance, and scalability in heterogeneous IoMT environments. By unifying link-aware and distance-aware routing philosophies, HEART offers a comprehensive and adaptive solution aligned with real-world healthcare requirements. Future research will aim to enhance HEART through mobility-aware predictive mechanisms, machine learning–driven cluster-head optimization, and secure, privacy-preserved communication layers to enable resilient and intelligent WBAN operations within next-generation metaverse-based and 6G-enabled smart healthcare systems.

6.1 Limitations

Despite the remarkable improvements achieved by the HEART protocol in terms of energy efficiency, stability, and reliability, several limitations still exist that open pathways for further research. One major limitation of HEART lies in its static clustering mechanism, which may not adapt optimally to highly dynamic body postures or movement scenarios, leading to potential link instability and increased path loss when the human body's topology changes frequently. Additionally, while the protocol integrates dual-sink awareness to balance data transmission loads, it may experience inefficient sink selection in dense or asymmetric deployments, particularly when the signal-to-noise ratio (SNR) fluctuates due to environmental interference or tissue absorption effects. Another constraint is the computational overhead associated with adaptive re-clustering, which, although effective in prolonging network lifetime, could be energy-draining for low-power biosensor nodes. Furthermore, HEART currently assumes homogeneous energy capabilities across nodes, an assumption that limits its scalability and realistic deployment potential in heterogeneous IoMT ecosystems. The lack of built-in security and trust mechanisms also leaves the protocol vulnerable to malicious attacks or data tampering during multi-hop transmissions, which is critical in medical and healthcare applications where data integrity is paramount.

6.2 Future Work

Future enhancements to HEART could include integrating machine learning-driven adaptive clustering that dynamically tunes parameters such as residual energy, RSSI, and link quality to reduce re-clustering overhead. Additionally, employing blockchain-assisted trust management and privacy-preserved data transmission mechanisms could improve security and authenticity in medical data exchange. The incorporation of energy-harvesting modules and context-aware power optimization would further mitigate the energy depletion problem, extending network longevity. Moreover, future work may focus on developing cross-layer optimization frameworks for QoS improvement under mobility and interference constraints, as well as simulating HEART under metaverse-based healthcare scenarios where ultra-low latency and 6G communication paradigms will play vital roles in immersive telemedicine and real-time patient monitoring environments.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported without any funding.

Conflicts of Interest

The author declares no conflicts of interest.

Ethical Approval and Consent to Participate

This work does not involve human subjects, animal experimentation, or personal data. Ethical approval and consent are therefore not applicable.

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