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ENERGY-EFFICIENT ROUTING PROTOCOLS FOR WIRELESS BODY AREA NETWORKS: A REVIEW

Surender Singh[1], Amreen Kaur[2] and Jaspreet Kaur[3]

[1,2,3]Department of Computer Science and Engineering, BGIET, Sangrur, 148001, India

[*]Corresponding Author: Surender Singh

ABSTRACT

Wireless Body Area Networks (WBANs) have emerged as a crucial technology for healthcare monitoring, enabling real-time patient monitoring with minimal human intervention. These networks consist of sensor nodes that continuously track vital physiological parameters and wirelessly transmit data to remote medical servers. However, energy efficiency remains a critical challenge due to the limited power resources of sensor nodes, affecting the longevity and reliability of WBAN deployments. Efficient routing protocols play a key role in managing power consumption, reducing communication overhead, and enhancing network lifetime while ensuring quality of service (QoS) parameters such as reliability, latency, and security. This paper provides a comprehensive review of various energy-efficient routing protocols designed for WBANs, analyzing their mechanisms, strengths, and limitations. The classification of these protocols into cluster-based, temperature-aware, QoS-aware, and cross-layer approaches offers a structured comparison of their effectiveness in different medical scenarios. Additionally, we present a detailed comparative analysis based on key performance metrics such as energy consumption, network lifetime, and reliability. Furthermore, we discuss existing challenges in WBAN energy efficiency, including security concerns, real-time data transmission constraints, and scalability issues. Lastly, we explore potential research directions, emphasizing the integration of energy harvesting techniques and blockchain-based security frameworks to enhance the sustainability and robustness of WBANs. This review aims to provide insights into future advancements in energy-efficient WBAN routing protocols, supporting optimized healthcare applications and remote patient monitoring systems.

1. INTRODUCTION

Wireless Body Area Networks (WBANs) are specialized wireless sensor networks designed for healthcare applications, enabling continuous monitoring of physiological parameters such as heart rate, blood pressure, body temperature, and glucose levels [1]. These networks consist of wearable or implantable sensor nodes that communicate wirelessly with a central coordinator or remote healthcare system. WBANs play a crucial role in modern telemedicine by supporting remote healthcare services, early disease detection, and emergency response systems [2][3].

Despite their potential, WBANs face significant challenges, with energy efficiency being one of the most critical [4]. Sensor nodes operate on limited battery power, and frequent battery replacements are impractical, particularly in implantable devices. The primary source of energy depletion in WBAN nodes is communication, which includes data transmission, reception, and processing [5]. Inefficient energy management can result in premature network failure, data loss, and degraded quality of service (QoS) [6][7].

To address these challenges, energy-efficient routing protocols have been developed to optimize data transmission while minimizing power consumption. These protocols use various strategies such as clustering, temperature-aware mechanisms, QoS-aware techniques, and cross-layer optimization to extend network lifetime and enhance performance [8][9]. Clustering-based protocols, such as LEACH and its variants, reduce communication overhead by aggregating data at cluster heads before forwarding it to the base station [10]. Temperature-aware routing protocols, such as TARA and LTR, help prevent excessive heating of nodes, ensuring patient safety [11]. QoS-aware approaches prioritize critical healthcare data, minimizing delays while optimizing power usage [12]. Cross-layer routing mechanisms enhance communication efficiency by integrating multiple network layers [13].

This paper presents a comprehensive review of energy-efficient routing protocols in WBANs, analyzing their strengths, limitations, and effectiveness in different medical applications. Additionally, it discusses current challenges and explores potential improvements to enhance the efficiency and reliability of WBAN communication.

1.1 Challenges in WBAN Energy Efficiency

- **Limited battery capacity:** Sensor nodes rely on small, non-replaceable batteries, making frequent battery replacements or recharging impractical, especially for implantable devices. This necessitates highly efficient power management strategies [14][15].

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- **High energy consumption in data transmission:** Wireless communication is the primary source of energy depletion in WBANs [16]. Frequent data transmission to a central hub or external device, combined with factors like transmission distance, interference, and environmental conditions, further impacts energy efficiency [17][18].
- **Trade-off between energy efficiency and QoS:** Maintaining reliable data transmission without excessive power consumption is challenging [19]. Real-time healthcare applications demand low latency, high throughput, and minimal packet loss, all while conserving energy [20].
- **Heat generation from sensors:** Continuous operation of WBAN nodes, particularly implantable devices, can cause temperature rise, posing risks to patient safety. Excessive heat may lead to tissue damage or discomfort, necessitating temperature-aware routing protocols to mitigate these effects [21][22].
- **Interference and network congestion:** Multiple WBANs operating in close proximity, such as in hospitals, can experience communication interference and congestion. This affects both energy efficiency and data reliability. Adaptive frequency selection and dynamic power control can help minimize these disruptions [23][24].
- **Security and energy trade-offs:** Ensuring data privacy and security requires cryptographic operations, which increase energy consumption [25]. Lightweight encryption techniques and energy-efficient security protocols are essential to protect sensitive medical data while preserving network longevity [26].
- **Node failure and energy balancing:** Energy depletion of sensor nodes can lead to network disruption and degraded performance. Load balancing techniques and predictive energy management approaches help distribute power consumption evenly across nodes, preventing premature failures [27].
- **Energy harvesting limitations:** While technologies such as piezoelectric, thermoelectric, and RF energy harvesting offer potential solutions, their efficiency depends on environmental and physiological conditions. Advancements in hybrid energy harvesting and intelligent power management are essential for prolonging WBAN lifespan [28][29].

2. CLASSIFICATION OF ENERGY-EFFICIENT ROUTING PROTOCOLS

Energy-efficient routing protocols in WBANs can be broadly classified into the following categories:

1. **Cluster-Based Routing Protocols**: These protocols enhance energy efficiency by organizing nodes into clusters, where cluster heads aggregate and transmit data, reducing direct communication between individual nodes and the sink. This approach conserves energy and balances load by periodically rotating cluster heads. Notable examples include LEACH-WBAN, H-HEED, and RE-ATTEMPT [30]. However, excessive clustering may introduce communication delays and increase overhead due to cluster maintenance.
2. **Temperature-Aware Routing Protocols**: Designed to prevent overheating of sensor nodes, these protocols select paths that minimize temperature accumulation. Continuous operation of nodes can lead to localized heating, posing risks to tissue safety. Protocols such as TARA, LTR, and HPR dynamically adjust transmission routes based on node temperature profiles to enhance patient safety [31]. However, prioritizing thermal management may compromise network latency and packet delivery efficiency.
3. **QoS-Aware Routing Protocols**: These protocols aim to balance energy efficiency with quality-of-service (QoS) requirements, ensuring reliable and timely data transmission. QPRD and priority-aware WBAN routing consider factors such as packet delay, packet loss, and data priority [32]. They are particularly beneficial for real-time applications, such as critical health monitoring, where low latency and high data integrity are essential. However, maintaining an optimal trade-off between energy efficiency and QoS metrics remains a challenge.
4. **Cross-Layer Routing Protocols**: By integrating multiple network layers, these protocols optimize energy consumption and communication performance. Cross-layer approaches such as RL-WBAN and Co-LAEEBA dynamically adjust transmission power, data rates, and routing paths to extend network lifetime while maintaining QoS requirements [33]. Although highly efficient, cross-layer optimization introduces computational complexity and may require additional processing resources.

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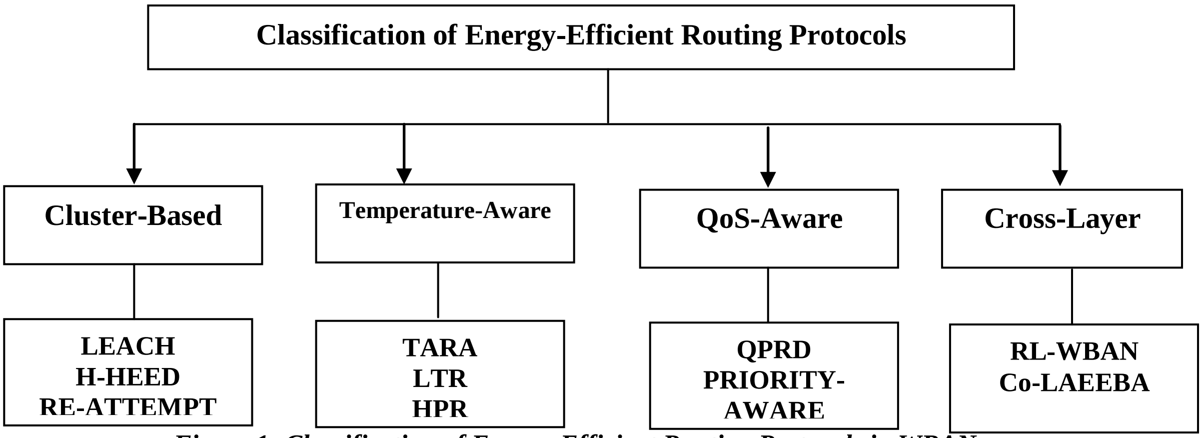

Figure 1: Classification of Energy-Efficient Routing Protocols in WBANs

3. Comparative Analysis of Energy-Efficient Routing Protocols

This section presents a comparative analysis of energy-efficient routing protocols in WBANs, highlighting their performance based on key parameters such as energy consumption, network lifetime, delay, and scalability. The table below provides a structured comparison:

Table 1: Comparative Analysis of Energy-Efficient Routing Protocols

Protocol	Energy Consumption	Network Lifetime	Latency	Reliability
LEACH	Low	Moderate	High	Moderate
TARA	Moderate	High	Low	High
REAR	High	Moderate	Low	High
CORM	Low	High	Moderate	High

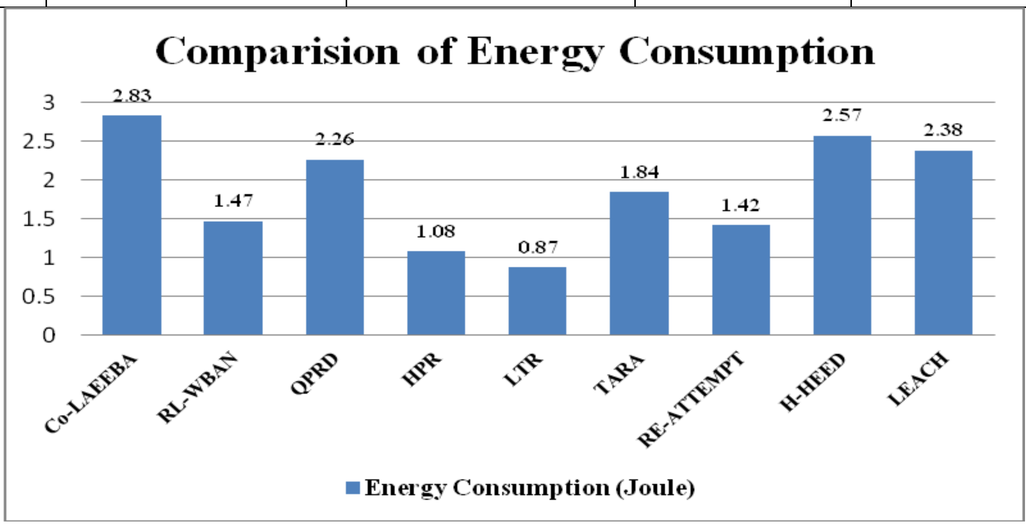

Figure 2: Comparison of Energy Consumption among Different Routing Protocols

Table 2: structured comparison between different routing protocols in WBAN

Protocol	Approach	Strengths	Limitations
LEACH	Cluster-Based	Reduces direct transmissions, improves energy efficiency.	High overhead in cluster formation.
H-HEED	Cluster-Based	Balances energy consumption among	Increased complexity due to frequent

		nodes.	re-clustering.
RE-ATTEMPT	Cluster-Based	Enhances reliability and minimizes retransmissions.	Additional processing overhead.
TARA	Temperature-Aware	Prevents hotspots in the network.	Higher latency due to temperature-based routing.
LTR	Temperature-Aware	Maintains energy efficiency and patient safety.	Trade-off between delay and energy efficiency.
QPRD	QoS-Aware	Ensures real-time data transmission.	Increased computation complexity.
RL-WBAN	Cross-Layer	Adapts routing based on real-time conditions.	Requires continuous learning and computation.
Co-LAEEBA	Cross-Layer	Efficient in load balancing and reliability.	Higher computational overhead.

Each protocol has distinct advantages and challenges, making them suitable for different WBAN applications. Cluster-based protocols offer energy efficiency but introduce communication overhead. Temperature-aware approaches prioritize patient safety but can lead to increased latency. QoS-aware protocols ensure timely data delivery but may require more processing power. Cross-layer techniques optimize multiple parameters but at the cost of complexity.

4. POTENTIAL IMPROVEMENTS

- **Security and Privacy Concerns**: Secure routing mechanisms are needed to prevent data breaches.
- **Real-Time Data Transmission**: Delay-sensitive applications require faster and more efficient routing.
- **Adaptive Protocols**: Protocols should dynamically adjust based on changing network conditions.
- **Integration with AI and Machine Learning**: AI-based energy prediction models could optimize routing decisions.
- **Scalability**: Future WBANs will include more sensors, requiring more scalable protocols.

5. FUTURE RESEARCH DIRECTIONS

Future research should focus on:

- Hybrid routing approaches that integrate multiple strategies.
- Advanced machine learning techniques for dynamic routing optimization.
- Energy harvesting methods to extend the lifespan of WBAN nodes.
- Blockchain-based security mechanisms for efficient data transmission.
- Improving fault tolerance in routing mechanisms to handle node failures efficiently.

6. CONCLUSION

In this paper, we provided a comprehensive review of energy-efficient routing protocols for Wireless Body Area Networks (WBANs). The growing demand for continuous health monitoring and real-time medical applications necessitates routing strategies that minimize energy consumption while ensuring reliable data transmission. By classifying existing protocols into cluster-based, temperature-aware, QoS-aware, and cross-layer approaches, we analyzed their performance, advantages, and limitations in WBAN environments. Energy efficiency remains a critical challenge due to the limited battery life of sensor nodes and the high power consumption of wireless communication. Our review identified key challenges such as interference, security trade-offs, real-time data transmission constraints, and network congestion. To address these issues, we explored potential improvements, including energy harvesting techniques, blockchain-based security solutions, and hybrid routing approaches that combine multiple strategies for enhanced performance.

Future advancements in WBAN technology should focus on adaptive routing solutions that dynamically optimize energy usage based on network conditions and patient-specific requirements. Additionally, implementing energy-efficient security mechanisms, such as lightweight cryptographic methods and blockchain-based authentication, can help mitigate security-

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energy trade-offs. Continued research in these areas will contribute to the development of more sustainable and reliable WBAN systems for next-generation healthcare applications.

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