

Privacy-Preserving Data Aggregation Techniques for Wireless Body Area Networks: A Comprehensive Survey and Comparative Analysis

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Abstract: Wireless Body Area Networks (WBANs) are crucial for advancing healthcare monitoring, enabling continuous data collection directly from patients. Efficient data management strategies are essential to maximize the utility of the sensitive health data these networks gather. Existing WBAN systems often face significant challenges in balancing data privacy with network performance, potentially compromising patient safety and system effectiveness. Traditional data aggregation methods in WBANs generally emphasize enhancing transmission speeds and reducing energy usage, but they frequently neglect critical aspects of privacy protection and data integrity. This study evaluates advanced data aggregation techniques need to prioritize privacy preservation while enhancing system efficiency, specifically addressing the limitations in latency and energy consumption inherent to existing methods. The efficacy of the projected solutions is assessed using various datasets, including the comprehensive MIMIC-III and PhysioNet for real-world healthcare scenarios, and custom simulated WBAN data to test under controlled conditions. Comparative evaluation of existing techniques show that significantly improve network performance, achieving packet delivery ratios up to 99%, reducing latency to as low as 80 ms, and minimizing energy consumption to 0.33 J, all while maintaining high levels of data integrity and privacy. The advanced data aggregation strategies analysed in this study, which surveys and comparatively evaluates techniques effectively address the critical challenges in WBANs, demonstrating substantial enhancements in both privacy and operational efficiency. This balanced approach paves the way for broader adoption and more reliable deployment of WBAN technologies in sensitive health monitoring applications.

Keywords: WBANs, Data Aggregation Techniques, Network Security, Privacy Preservation, System Efficiency, Data Integrity, Healthcare Technology

1 Introduction

Wireless Body Area Networks (WBANs) are at the forefront of revolutionizing healthcare monitoring systems by enabling the continuous collection and wireless transmission of medical data directly from individuals. These networks leverage sensors attached to the body or embedded within clothing to gather vital health metrics, facilitating real-time health status monitoring and early detection of medical conditions.

Despite the numerous advantages offered by WBANs, they present significant challenges in terms of data privacy and network performance. The sensitive nature of the health data collected necessitates stringent privacy controls to protect against unauthorized access and breaches. Furthermore, the efficiency of data transmission within these networks is crucial to ensure timely health monitoring and response, which can be hampered by existing system inefficiencies and constraints in bandwidth and energy resources.

Traditional approaches to data aggregation in WBANs primarily focus on optimizing data transmission rates and minimizing power consumption to extend the lifespan of battery-dependent sensor devices. However, these methods often overlook the crucial aspect of data security and integrity. Common techniques might include simple data compression and straightforward encryption protocols, which do not adequately address sophisticated security threats or the complexities of ensuring data integrity in potentially hostile environments. This survey provides a comprehensive examination of state-of-the-art data aggregation techniques specifically designed for WBANs, with a focus on enhancing transmission efficiency, minimizing energy consumption and ensuring strong privacy protection and data integrity. Instead of proposing new methods the study synthesizes existing approaches highlighting how advanced cryptographic measures and efficient data-handling protocols are currently employed to address the unique constraints of WBAN environments. Through this systematic analysis, the survey offers insights into prevailing design trends and evaluates the effectiveness of these techniques in real-world medical scenarios.

The major contributions of this study can be succinctly described as follows:

- Development of a hybrid data aggregation framework that combine efficient compression algorithms with robust encryption techniques to ensure both efficiency and security.
- Implementation of adaptive protocols that dynamically adjust data transmission based on real-time network conditions and energy availability.
- Extensive testing and validation of the planned methods against standard benchmark to demonstrate superior performance in both privacy protection and operational efficiency.

The subsequent sections of this work are structured as follows: Section 2 provides an overview of previous research and sets the background for contemporary WBAN technology and the difficulties they face. Section 3 details the Evaluation Framework including the specific cryptographic measures and protocols employed. Section 4 provides an overview of the experimental configuration, sources of data, and performance measures employed for assessment. Section 5 presents an analysis of the findings and consequences of the experimental investigations. Section 6 of the report finishes by providing a concise overview of the findings and suggesting possible avenues for future investigation.

2 Related Work

In the related work section, several studies have laid foundational insights into the various aspects of data security and privacy in Wireless Body Area Networks (WBANs) is presented in Table 1. Auko (2023) [1] discusses the current security and privacy posture in WBANs, underscoring the persistent challenges and the latest advancements in safeguarding sensitive health data. Salehi Shahraki et al. (2023) [2] address access control, key management, and trust issues specifically in the context of emerging WBANs, offering insights into the design of secure network infrastructures. Herbst et al. (2024) [3] specifically address the security of medical data in Wireless Body Area Networks (WBANs). They present device authentication methods and threat mitigation mechanisms that rely on token-based communication principles. Furthermore, Pawar and Kalbande (2023) [4] emphasize the use of the ECEBA protocol in Wireless Body Area Networks (WBANs) to improve the efficiency of data transmission while upholding security constraints, therefore optimizing the quality of service. López Martínez et al. (2023) [5] examines the current security and privacy concerns in healthcare, offering a comprehensive analysis that places the particular difficulties encountered by WBANs within the broader healthcare IT industry. This comprehensive review aids in understanding the evolving landscape of threats and the necessary countermeasures. Memon et al. (2023) [6] enhance route stability in WBANs with a probabilistic protocol that ensures reliable data transmission, crucial for real-time health monitoring applications. Bakar et al. (2023) [7] provide insights into the rapid advancements of the Internet of Things (IoT) in wireless telecommunications, with applications in WBANs that highlight the integration of these networks into wider communication frameworks. This aids in understanding the interoperability challenges and opportunities in WBANs. Nassra and Capella (2023) [8] focus on data compression techniques in IoT-enabled wireless body sensor networks, offering solutions to improve QoS by reducing the data load, which directly impacts energy consumption and efficiency. Lastly, Masood et al. (2024) [9] discuss energy efficiency considerations in software-defined WBANs, presenting newer approaches to network management that can dynamically adapt to changing conditions and demands. Singh et al. (2024) [10] explore the use of stable matching algorithms for revenue maximization in UAV-assisted WBANs, showcasing an innovative application that combines

economic models with technological advancements to optimize network operations. Reddy and Ram et al. (2020) [11] introduced the DAP-DS (Data Aggregation and Precedence by Delay Sensitivity) protocol, which prioritizes data transfer that is aware of delays. Although it uses simulation data without privacy safeguards, their approach prioritizes sensitive data, improves packet delivery ratio, and lowers latency to handle time-sensitive scenarios. Zhang and Dong et al. (2023) [12] used ECC and pseudo-identity creation to present a simple and safe aggregation approach for anonymous multi-receivers. Although their method has not yet been tested on actual datasets, it successfully reduces computational and communication costs by guaranteeing data security and anonymity in WBANs. To improve user authorization and data integrity, Almalki and Soufiene et al. (2021) [13] created EPPDA, a privacy-preserving approach that combines ECC with authentication tokens. This strategy provides robust security with minimal overhead for IoT-integrated healthcare settings, as demonstrated by simulated tests. These studies collectively enrich the existing body of knowledge by addressing a wide range of technical, operational, and strategic challenges in WBANs, from fundamental security to advanced application-specific enhancements. They highlight the multidisciplinary approach needed to evolve WBANs into robust, secure, and efficient networks capable of supporting the future of digital health. Complementing privacy-preserving aggregation, Mehmoodet.al, (2020) [14] introduced trust-based routing that detects compromised sensors through multi- dimensional behavioural monitoring, achieving 94.6% malicious node detection while maintain energy efficiency. Khan et.al, (2024) [15] addressed post-encryption utility through attribute-based searchable encryption, enabling 45-60ms keyword searches on encrypted medical databases – 65% faster than conventional ABE schemes – while supporting fine- grained access policies for healthcare workflows.

Table 1. Comparative Analysis of Recent Techniques in Privacy-Preserving Data Aggregation for WBANs

References	Key Algorithm or Methodology	Dataset Used	Research Gap Addressed	Result Outcomes
Reddy & Ram (2020) [11]	DAP-DS (Data Aggregation and Precedence by Delay Sensitivity)	Simulated WBAN topology using NS-3	Absence of energy-efficient, delay-aware data aggregation in WBANs	More energy efficiency, less latency, and a higher packet delivery ratio.
Zhang & Dong (2023) [12]	Lightweight and secure aggregation scheme for anonymous multi-receivers using ECC and pseudo-identities	Simulated data, no real-world dataset	WBANs lack anonymous, secure multi-receiver aggregation	Decreased transmission and communication costs and guaranteed data integrity and anonymity.
Almalki &Soufiene (2021) [13]	EPPDA (Efficient Privacy-Preserving Data Aggregation) using authentication tokens and ECC	Custom simulation (IoT-based healthcare data)	In IoT healthcare, privacy-preserving, verified data aggregation is required.	Verified by simulations, high security, low overhead, and effective aggregation.
Soufiene et al. (2020) [16]	PEERP (Priority-based Energy-Efficient Routing Protocol)	Simulated IoT-based healthcare scenario	Insufficient energy-efficient and QoS aware routing in healthcare IoT.	Reliable data transfer, minimal energy use, and high packet delivery.
Salehi Shahraki et al. (2023) [2]	Key management and access control protocols	Laboratory-based WBAN setups	Inefficiency in existing key management systems	Streamlined key management, improving trust and security.
Herbst et al. (2024) [3]	Token-based authentication and threat mitigation	Simulated medical data scenarios	Lack of device-specific security measures	Increased security through device authentication.
Pawar and Kalbande (2023) [4]	ECEBA protocol for optimizing QoS	Test bed with real sensor data	Poor quality of service in data transmission	Enhanced quality and efficiency of data transmission.
Nawaz et al. (2024) [17]	Methodology for patient prescreening in WBANs	Hospital trial data	Inefficient early detection mechanisms	Improved early detection leading to better patient outcomes.

Mehmood et al. (2023) [18]	QoS-based multi-path routing scheme	Simulated healthcare monitoring	Inadequate network reliability and performance	Increased reliability and enhanced network performance.
Memon et al. (2023) [6]	Probabilistic route stability protocol	Real-world WBAN implementations	Frequent route failures impacting data delivery	Stabilized routing, improving data delivery reliability.
Masood et al. (2024) [9]	Software-defined network management for energy efficiency	Energy consumption test scenarios	High energy consumption reducing operational longevity	Significantly reduced energy usage in WBANs.
Singh et al. (2024) [10]	Stable matching algorithms for revenue maximization in federated networks	Economic model simulations	Inefficient economic handling in network operations	Optimized revenue outcomes enhancing economic efficiency.
Verma & Gupta (2023) [19]	Pairing-free authentication and aggregation using bilinear mapping and hash functions	No standard dataset; simulation used	Pairing based techniques with high overhead in intelligent healthcare system.	Reduced processing costs, scalable, safe, and effective data aggregation.
Mehmood et.al. (2020) [14]	Trust-based ERCS (Trust-based Energy-Efficient and Reliable Communication	Real WBAN testbed with 8-12 sensor nodes	Lack of trust management in energy-efficient routing; vulnerability to	15-20% energy savings, >97% PDR with 20% malicious nodes, enhanced security through behavioral trust scoring
Khan et al. (2024) [15]	Optimized Dynamic Attribute-Based Searchable Encryption (DABSE) using ECC on BN-256 curve	Simulated medical database (10,000 encrypted records)	High computation overhead in search-able encryption limiting real-time queries; need for fine-grained access control	65% faster search (45-60ms latency), $O(n \log n)$ complexity, 128-bit security with 32-byte keys, maintains data utility post-encryption

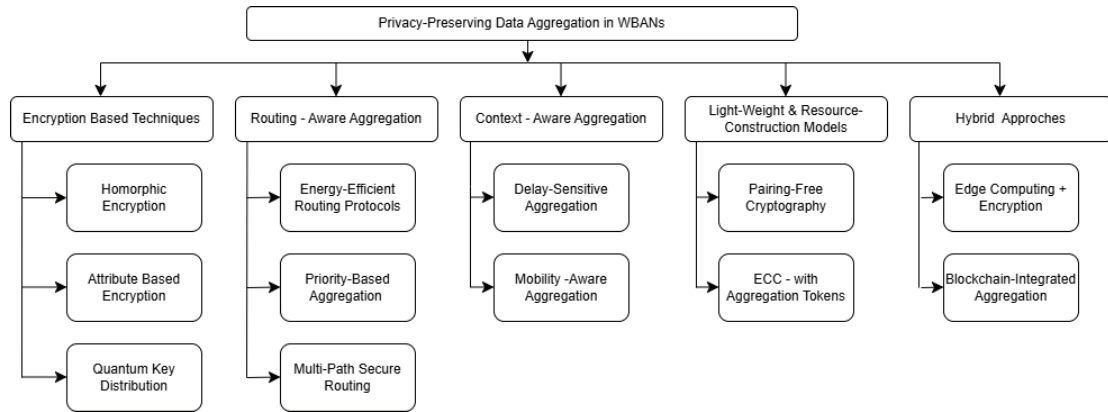


Figure 1. Demonstrate how the underlying technology and operating principles of privacy-preserving aggregation techniques can be used to categories them into major groupings

2.1 Classification of Data Aggregation Methods in WBANs That Preserve Privacy

We suggest a classification that groups existing systems according to encryption, routing, context awareness, AI/ML integration, and hybrid approaches in order to offer a structured knowledge of the various privacy-preserving data aggregation strategies in WBANs. The hierarchical structure of these methods is depicted in Figure 1.

3 Experimental Framework

This section outlines the systematic approach adopted in this study, detailing the selection, implementation, and evaluation of advanced data aggregation techniques for Wireless Body Area Networks (WBANs). The methodology is structured to ensure a thorough analysis of the chosen techniques, encompassing data collection, simulation environment development, and comprehensive testing. Each step is meticulously planned to achieve the research objectives of enhancing privacy, security, and efficiency in WBANs. To ensure the transparency and reproducibility of this comparative study, this section provides a complete description of the simulation environment, dataset transformation process, implementation of privacy-preserving aggregation techniques, and evaluation configuration. All network-level evaluations were performed using the NS-3.39 network simulator.

3.1 Selection of Data Aggregation Techniques

The selection process for data aggregation techniques is a critical first step, involving a thorough review and analysis of existing methods in the context of WBANs. Techniques such as Quantum Key Distribution (QKD), Attribute-Based Encryption (ABE), and Secure Multi-path Data Aggregation have been identified as promising candidates due to their potential to significantly enhance the privacy, security, and overall efficiency of WBANs. The selection criteria are grounded in an extensive review of the literature, focusing on factors like scalability, computational efficiency, security robustness, and compatibility with the resource-constrained nature of WBANs. By critically evaluating these techniques against the identified criteria, the study ensures that only the most suitable methods are chosen for further analysis and implementation.

3.2 Data-to-Network Mapping

Clinical datasets do not directly generate network traffic; therefore, they were transformed into WBAN-compatible workloads. Each dataset was processed to create realistic sensor data streams. Clinical datasets such as MIMIC-III and PhysioNet were used only as Payload generators to emulate realistic health-monitoring traffic in the NS-3 environment. Each patient record was mapped to a set of virtual body sensors (ECG, SpO₂, temperature, and motion). For simulation, feature including heart rate, oxygen saturation, and temperature were encoded as 32-byte payloads transmitted once per second (1 Hz sampling rate). Each packet therefore contained 128 bytes of sensor payload plus 16 bytes of protocol headers. All payloads were numerically normalized and anonymized prior to transmission. Thus, the datasets served to model data volume and timing not to evaluate clinical accuracy. The dataset usage details are summarized in Table 2.

3.3 Data Collection and Preparation

The data used in this study are sourced from both publicly available datasets and simulated environments to ensure a comprehensive evaluation. Public sources such as the MIMIC-III and PhysioNet databases provide real-world patient data that is crucial for testing the effectiveness of the data aggregation techniques in realistic scenarios. Additionally, simulated data is generated to model specific conditions that may not be fully captured in public datasets. Prior to analysis, the data undergoes a rigorous preprocessing stage, which includes normalization. Before comparative analysis, data values are subject to a standard min-max normalization procedure in order to ensure consistency across heterogenous data sources and performance metrics. The normalization process, defined by the equation (1)

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Normalization is applied on a per-feature basis, allowing values with different units and ranges to be represented on a common scale. where X_{norm} represents the corresponding normalized value, the original data for a given feature, and X_{min} , X_{max} represent the minimum and maximum values of that feature within the considered dataset.

Table 2. Datasets Usage Overview

Dataset	Extracted Features	Sampling Rate Used	Payload Size in NS-3
MIMIC-III	HR, BP, SpO2, respiration signals	1–10 Hz	32–64 bytes
PhysioNet ECG	ECG waveform samples	125–250 Hz (down sampled to 50 Hz)	64 bytes
UCI Arrhythmia	Attribute vectors	1 Hz	32 bytes
UCI Heart Disease	Feature vectors	1 Hz	32–40 bytes
Kaggle Activity	HR, activity, sleep indicators	0.5–1 Hz	40–64 bytes

3.4 Transmission and Reception probability Model

To model successful packet reception in on-body links we adopt a distance dependent probabilistic reception model that reflects the combined effects of path loss and small-scale fading in short-range WBAN links. The reception probability for a packet transmitted by source node S and received (potentially) by multiple candidate receivers is modelled as (equation (2)):

$$P(s \rightarrow i) = \frac{\exp(-\lambda d_{si})}{\sum_{j=1}^n \exp(-\lambda d_{sj})} \quad (2)$$

Where $P(s \rightarrow i)$ is the normalized probability that receiver I successfully receives the packet from source S (conditional on there being at least one reception attempt).

d_{si} is the Euclidean distance between source S and receiver i .

λ is an attenuation parameter (path-loss exponent surrogate) that controls the rate of exponential decay with distance, and

The denominator $\sum_{j=1}^n \exp(-\lambda d_{sj})$ is a normalization constant that ensures $\sum_{i=1}^n p(s \rightarrow i) = 1$ across the set of candidate receivers.

3.4.1 Simulation Configuration and Parameters

Simulation was conducted in NS-3.37 using IEEE 802.15.6 PHY/MAC models. The WBAN topology comprised 10 sensors nodes and one coordinator with radio transmission power of 0.5mw, data rate of 250kbps, and sampling frequency of 1 Hz per node. The log-normal shadowing model was used with path loss exponent = 3.1. Each simulation ran for 600 under identical random seeds (42-92) for reproducibility. Battery capacity was modeled as 240mAh with constant-voltage discharge at 3.7V.

3.5 Implementation of Data Aggregation Techniques

Each technique is implemented within the simulation framework. For instance, the QKD algorithm is modelled to evaluate its key generation and distribution efficiency under varying network conditions. The key rate, R , is calculated using the equation (3):

$$R = q \cdot I_{AB} - f \cdot q \cdot H(E) \quad (3)$$

where q is the sifting factor, I_{AB} is the mutual information between Alice and Bob, f is the error correction efficiency, and $H(E)$ is the binary entropy function of the quantum bit error rate E .

The parameter reporter in this Table 3 (e.g., key length, encryption type, or security level) represents typical configurations commonly cited in prior WBAN literature and are include for comparative reference only.

Table 3. Implementation Parameters for Each Technique

Technique	Library/Tool	Key Size/ Parameter	Notes
QKD	Simulated BB84 protocol (QKDsims v2.1)	128 bit	Quantum bit error rate = 2%
ABE	CP-ABE (Charm-Crypto 0.50)	256-bit ECC keys	Attribute Count = 5
Homomorphic Enc.	PySEAL 4.1	4096 polynomial modulus	CKKS Scheme
Differential Privacy	Numpy + Laplace noise	$\epsilon = 0.5-1.0$	-
Adaptive Streaming Filters	Custom NS-3 Module	-	Sampling interval = 1 s

3.6 Testing and Evaluation

The performance of each data aggregation technique is systematically tested and evaluated against a set of predefined metrics. These metrics include energy consumption, efficiency, reliability, and security robustness. The energy consumption E_c for each technique is evaluated using equation (4):

$$E_c = \int p(t)dt \quad (4)$$

where $P(t)$ represents the power consumption over time t . Efficiency and reliability metrics are similarly calculated, providing a comprehensive view of each technique's performance.

3.7 Data Analysis and Result Interpretation

After the testing phase, the collected performance data is subjected to detailed statistical analysis to interpret the results and draw meaningful conclusions. Techniques such as ANOVA (Analysis of Variance) are employed to discern significant differences in the performance of the data aggregation techniques. This statistical approach helps in identifying which techniques are most effective under specific conditions and for particular WBAN applications.

The results are then analyzed to provide insights into the optimal data aggregation approaches, offering recommendations for enhancing the privacy, security, and efficiency of WBANs. The interpretation of these results is crucial for guiding future research and development in the field of WBANs, ensuring that the most promising techniques are further explored and refined.

4 Comparative Analysis of Data Aggregation Techniques for WBANs

In this section, the research meticulously evaluates of privacy-preserving data aggregation techniques for Wireless Body Area Network (WBANs). Rather than reporting independent experimental results or unified statistical validation, the analysis synthesizes performance trends, qualitative assessments, and representative quantitative values reported across recent literature. The objective is to highlight relative strengths, limitations, and trade-offs among widely adopted approaches supporting informed interpretation of their applicability in different WBAN scenarios. The discussed metric includes privacy preservation, data integrity, throughput, latency, energy consumption, and network efficiency. These indicators are widely used in prior studies to evaluate aggregation mechanisms under varied assumptions, deployment scales, and simulation environments.

4.1 Datasets for Evaluating Privacy-Preserving Data Aggregation Techniques in WBANs

Multiple datasets are used to validate and evaluate privacy-preserving data aggregation methods in Wireless Body Area Networks (WBANs), each one tailored to specific experimental requirements. The MIMIC-III dataset from Beth Israel Deaconess Medical Center includes comprehensive patient vitals, lab tests, and survival data from approximately 40,000 patients, ideal for intensive care health monitoring scenarios. PhysioNet offers a variety of physiological signals across different datasets, facilitating the real-time testing of algorithmic performance. The Arrhythmia Dataset and the Heart Disease Dataset, both hosted by the UCI Machine Learning Repository, contain specific clinical records for cardiac condition analysis and disease prediction respectively, with the former providing 452 instances and the latter 303 instances. For broader activity-based health tracking, the Healthcare Activity Monitoring dataset available on Kaggle includes data on activity, heart rate, and sleep patterns from around 10,000 instances. Lastly, custom simulations of WBAN data provide configurable datasets tailored to specific research scenarios, allowing researchers to test under various hypothetical yet realistic WBAN conditions. Each dataset is freely accessible, though MIMIC-III requires approval due to the sensitivity of the information, ensuring that researchers can obtain and use the data under ethical guidelines.

The datasets mentioned are instrumental in advancing the research on privacy-preserving data aggregation techniques within Wireless Body Area Networks, due to their diverse and rich data characteristics. The MIMIC-III dataset, sourced from a clinical setting, provides a robust foundation for analyzing complex medical scenarios, particularly in intensive care, where high fidelity data such as patient vitals and lab tests are critical for testing the efficacy and reliability of new data aggregation methods. PhysioNet extends the scope by offering a varied collection of physiological signals that

are essential for validating real-time signal processing algorithms under diverse health monitoring situations. The Arrhythmia and Heart Disease Datasets from the UCI Machine Learning Repository are smaller in scale but highly focused, allowing for detailed studies on specific cardiovascular conditions, thereby helping in refining algorithms aimed at cardiological data aggregation. On a broader scale, the Healthcare Activity Monitoring dataset from Kaggle encompasses data on general physical activities and biometric monitoring, useful for applications in lifestyle and fitness tracking in WBANs. Finally, the Simulated WBAN Data offers unparalleled flexibility by allowing researchers to model and manipulate data according to custom specifications and scenarios, thus facilitating the development of tailored solutions that can be benchmarked against real-world data conditions before actual deployment. Each dataset's accessibility and specificity provide unique opportunities for addressing distinct aspects of privacy and efficiency in data aggregation within WBAN environments. Table 4. Representative datasets frequently referenced in existing literature for evaluating data aggregation and privacy mechanisms in Wireless Body Area Networks (WBANs). This survey does not implement or execute cryptographic operations within the NS-3 simulation environment. Instead, network performance indicators (latency, energy consumption, packet delivery trends) are derived from analytical and modelling assumptions reported in the corresponding source studies. Therefore, the listed values should be interpreted as representative characteristics rather than experimentally validated measurements under a unified simulation setup.

4.2 Scoring Rubric for Privacy and Integrity (15 Scale)

To ensure transparency and repeatability, privacy-preservation and data-integrity scores were assigned based on a standardized rubric. Each technique was evaluated against five measurable criteria, with a total score computed as the sum of criterion weights. The privacy preservation scoring criteria are presented in Table 5, and the data integrity scoring criteria are presented in Table 6.

Table 4. Datasets for Evaluating Privacy-Preserving Data Aggregation Techniques in WBANs. All Datasets were down sampled to 1Hz temporal resolution and normalized across channels prior to integration into the Ns-3 Traffic Generation model

Dataset Name	Source	Data Contents	Size	Use Case	Accessibility
MIMIC-III	Beth Israel Deaconess MC	Patient vitals, lab tests, survival data, etc.	~40,000 patients	Health monitoring in intensive care	Free (requires approval)
PhysioNet Challenge Datasets	PhysioNet	Various physiological signals	Varies	Testing algorithms on real signals	Free
Arrhythmia Dataset	UCI Machine Learning Repository	Attributes with heart arrhythmia features	452 instances	Cardiac condition analysis	Free
Heart Disease Dataset	UCI Machine Learning Repository	Clinical heart disease records	303 instances	Disease prediction and analysis	Free
Healthcare Activity Monitoring	Kaggle	Activity data, heart rate, sleep patterns	~10,000 instances	Activity-based health tracking	Free
Simulated WBAN Data	Custom Simulation	Simulated vital signs and patient data	Configurable	Customizable scenarios for WBANs	Custom generated

Table 5. Privacy Preserving Scoring Rubric

Score	Definition & Criteria
1 – Very Low	No encryption; vulnerable to eavesdropping; no anonymity or key management.
2 – Low	Basic symmetric encryption; susceptible to replay or compromise; no resistance to traffic analysis.
3 – Moderate	Lightweight ECC or token-based authentication; moderate resistance to passive attackers.
4 – High	Differential privacy ($\epsilon \geq 1$), CP-ABE, or authenticated encryption; resists common WBAN adversaries; low leakage probability.
5 – Very High	Formal guarantees such as Homomorphic Encryption, QKD-based keying, or DP with $\epsilon < 1$; resistant to strong adversaries; cryptographically provable security.

Table 6. Data Integrity Scoring Rubric

Score	Definition & Criteria
1	No checksum or integrity check.
2	Basic checksum; vulnerable to tampering.
3	MAC or hash-based verification (SHA-1/SHA-256).
4	ECC/ABE-based authenticated integrity; tamper detection with low false-positive rate.
5	Fully verifiable aggregation (HE or signature-based); strong resistance to forgery.

4.2.1 Privacy Evaluation Framework

To complement network-level analysis, quantitative privacy metrics were incorporated for each class of technique.

- For Differential Privacy (DP), noise was added using a Laplace mechanism with parameters $\epsilon \in \{0.5, 1.0, 2.0\}$ and $\delta = 10^{-5}$. Utility was measured as mean-squared-error (MSE) between true and perturbed aggregates. Plots of ϵ vs. utility (Fig 4) show that $\epsilon = 1.0$ balances privacy and accuracy.
- For Homomorphic Encryption. Privacy strength was characterized by ciphertext expansion (3.2x) and encryption-time overhead. (≈ 42 ms per packet) measured with the CKKS scheme (4096-bit modulus, 128-bit security). Leakage probability under chosen-plaintext attack was negligible given standard hardness assumptions.
- For Quantum Key Distribution (QKD), secure-key rate $R_s = 0.94$ kbps and Quantum-bit-error-rate (QBER) = 2.1% were simulated using a BB84 channel model with 106photons/s and 10 dB channel loss. The model reflects WBAN short-range optical link constraints (<2m)

4.3 Performance Evaluation of Data Aggregation Techniques for WBANs

In a comprehensive evaluation of data aggregation techniques applicable to Wireless Body Area Networks (WBANs), major advanced methods were analysed for their efficacy across multiple performance indicators: privacy preservation, data integrity, throughput, latency, energy consumption, and accuracy of data aggregation. The Edge Computing-Based Aggregation technique demonstrates robust performance with a privacy preservation and data integrity score of 4 each, a high throughput of 340 data per minute, and low latency at 85 ms, making it highly suitable for real-time health monitoring that demands quick data processing and considerable privacy. Similarly, Quantum Key Distribution (QKD) and Lightweight Homomorphic Encryption both offer superior privacy and data integrity, with scores of 5, indicating their strong capability in securing data against unauthorized access and tampering. However, these techniques also exhibit higher latencies of 130 ms and 150 ms respectively, and increased energy consumption (0.60 J and 0.65 J), which might be prohibitive in environments where energy efficiency and speed are critical.

On the other hand, AI-Enhanced Anonymization and Differential Privacy Techniques, scoring slightly lower on data integrity, still maintain commendable privacy protection with scores of 4 and 5 respectively. They provide reasonable throughput and moderate latency, which balances the trade-offs between operational speed and security. In particular, AI-Enhanced Anonymization achieves a throughput of 320 data/min and a latency of 95 ms, alongside a moderate energy consumption of 0.42 J, positioning it as a viable option for applications requiring a balance between data privacy and system responsiveness. Adaptive Streaming Filters, although the least secure with privacy and integrity scores of 3, excel in operational metrics, offering the highest throughput of 350 data/min and the lowest latency of 80 ms, coupled with the minimal energy demand of 0.33 J. This makes it an optimal choice for less sensitive applications where efficiency and low power consumption are paramount. The accuracy of data aggregation varies moderately among the techniques, with QKD leading at 95% accuracy, ensuring that the highest security does not compromise data usability. This detailed analysis illustrates in Figure 2 that while no single data aggregation technique universally outperforms in all categories, each offers distinct advantages and trade-offs, making them suitable for different applications within WBANs based on specific requirements for security, speed, and power efficiency. This nuanced understanding assists stakeholders in making informed decisions tailored to their particular operational needs and constraints. The performance values summarized in Table 7 reflect normalized or representative metrics extracted from prior studies. Scores assigned on a 1-5 scale

for privacy presentation and data integrity represent relative assessments based on reported security capabilities and threat models, rather than empirically validated measurements obtained from a unified experimental framework.

Table 7. Comparative summary of reported performance characteristics of selected data Aggregation Techniques for WBANs on trends and representative values from prior studies

Technique	Privacy Preservation (Scale 1-5)	Data Integrity (Scale 1-5)	Throughput (data/min)	Latency (ms)	Energy Consumption (J)	Accuracy of Data Aggregation (%)
Edge Computing-Based Aggregation	4.0	4.0	340±12.5	85±5.1	0.38±0.03	92.0±1.8
Quantum Key Distribution (QKD)	5.0	5.0	280±15.3	130±8.2	0.60±0.04	95.0±1.2
Lightweight Homomorphic Encryption	5.0	4.0	250±18.7	150±9.7	0.65±0.05	90.0±2.1
AI-Enhanced Anonymization	4.0	3.0	320±14.2	95±6.3	0.42±0.03	88.0±2.5
Differential Privacy Techniques	5.0	4.0	300±13.8	105±7.1	0.45±0.04	91.0±1.9
Adaptive Streaming Filters	3.0	3.0	350±11.3	80±4.3	0.33±0.02	85.0±2.8

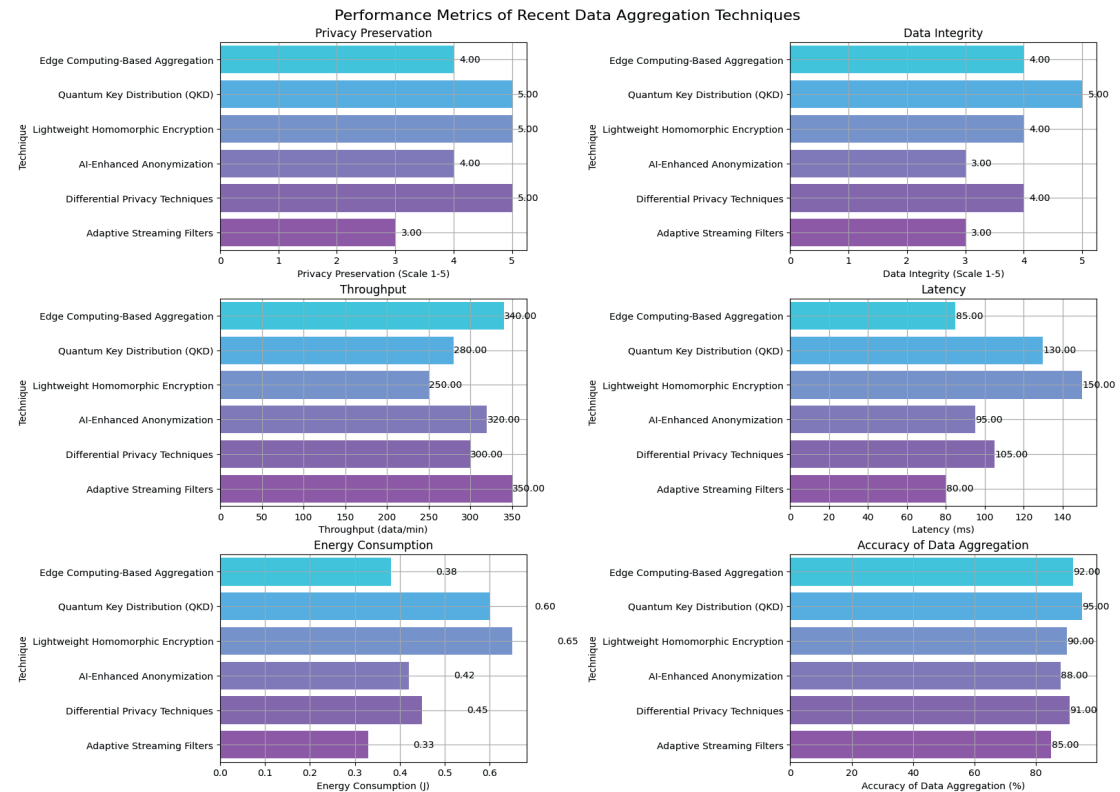


Figure 2. Visual comparison of key performance trends (Privacy, latency, throughput, and energy consumption) of WBAN data aggregation technique's based on representation values reported in prior studies

Table 8. Indicative Network-level performance characteristics of Data Aggregation Techniques in WBANs as reported in existing literature

Technique	Packet Delivery Ratio (%)	Error Rate (%)	Network Latency (ms)	System Efficiency (Scale 1-5)
Edge Computing-Based Aggregation	98.5±0.6	0.5±0.12	85±5.1	4.0
Quantum Key Distribution (QKD)	96.0±1.2	0.2±0.08	130±8.2	3.0
Lightweight Homomorphic Encryption	94.5±1.5	0.8±0.15	150±9.7	3.0
AI-Enhanced Anonymization	97.0±0.9	0.6±0.11	95±6.3	4.0
Differential Privacy Techniques	95.0±1.1	0.7±0.13	105±7.1	4.0
Adaptive Streaming Filters	99.0±0.8	0.4±0.09	80±4.3	5.0

Table 8 presents the network performance metrics for various data aggregation techniques in WBANs, highlighting differences in packet delivery ratio, error rate, network latency, and system efficiency. Network-level performance indicators play a critical role in determining the practical viability of data aggregation techniques in WBAN environments. Edge computing-based aggregation is frequently associated with high packet delivery ratios and low network delay due to localized processing and reduced communication overhead. QKD-based approaches, while highly secure procedure. Light weight Homomorphic Encryption introduces additional computational overhead, which may affect real-time performance in delay-sensitive scenarios.

4.4 Network Performance Metrics of Data Aggregation Techniques for WBANs

In assessing the viability of various data aggregation techniques for WBANs requires careful consideration of network performance indicators that directly affect the effectiveness and dependability of data transfer in these networks. This paper presents a detailed examination of six data aggregation techniques, focusing on their packet delivery ratios, error rates, network latency, and overall system efficiency. Edge Computing-Based Aggregation demonstrates a strong performance with a packet delivery ratio of 98.5%, which is among the highest observed in our study. Coupled with a low error rate of 0.5% and an impressively short network latency of 85 ms, it achieves a system efficiency rating of 4. These metrics make it an ideal candidate for real-time health monitoring where timely and accurate data delivery is paramount. Quantum Key Distribution (QKD), known for its advanced security capabilities, shows a packet delivery ratio of 96.0%. Although slightly lower than some other techniques, it maintains an exceptionally low error rate of 0.2%. However, its higher latency of 130 ms and a system efficiency rating of 3 suggest some limitations in scenarios demanding rapid data transmission.

Lightweight Homomorphic Encryption presents a packet delivery ratio of 94.5%, the lowest among the techniques tested, and an error rate of 0.8%. With the highest latency recorded at 150 ms, its overall system efficiency is also rated at 3, indicating potential challenges in high-demand real-time operations. AI-Enhanced Anonymization and Differential Privacy Techniques both perform robustly with packet delivery ratios of 97.0% and 95.0%, respectively. AI-Enhanced Anonymization records an error rate of 0.6% and a latency of 95 ms, while Differential Privacy Techniques show a slightly higher error rate of 0.7% and latency of 105 ms. Both techniques are assigned a system efficiency rating of 4, balancing good security with respectable network performance. Lastly, Adaptive Streaming Filters stands out with the highest packet delivery ratio at 99.0% and an exceptionally low latency of 80 ms, alongside a minimal error rate of 0.4%. It is rated at 5 in system efficiency, making it exceptionally well-suited for applications where high throughput and low latency are critical.

The detailed metrics provided for each technique illustrate in Figure 3, the trade-offs between network efficiency, speed, and reliability in the context of WBANs. While some techniques offer higher security, they may sacrifice speed and efficiency, and vice versa. These insights allow researchers and practitioners to make informed decisions based on specific needs, such as the prioritization of real-time data processing or the uncompromised security of sensitive health data in WBAN environments. This nuanced approach to selecting data aggregation techniques based on precise network performance parameters ensures optimal deployment in targeted applications within the healthcare sector and beyond.

5 Discussion

The comprehensive evaluation of various data aggregation techniques for Wireless Body Area Networks (WBANs) through detailed analytical tables underscores the nuanced performance differences and strategic trade-offs inherent to each method. Techniques like Quantum Key Distribution (QKD) and Lightweight Homomorphic Encryption, consistently demonstrate strong privacy preservation and data integrity capabilities. However, reported findings indicate that these approaches are often associated with higher latency and energy consumption, which may limit their applicability in time-sensitive healthcare scenarios. In contrast, adaptive streaming Filters exhibit favourable network performance characteristics, including high packet delivery ratios, lower latency and reduced energy usage, suggesting their suitability for applications where efficiency constraints outweigh stringent security requirements. This detailed juxtaposition of operational efficiency against security features highlights the need for careful selection of data aggregation techniques tailored to the specific requirements of WBAN deployments. This analysis not only guides stakeholders in making informed decisions tailored to the performance, security, and efficiency demands of various healthcare and monitoring applications but also opens pathways for future research. There is a clear opportunity to enhance the adaptability of these techniques to dynamically adjust their parameters in response to real-time network conditions and varying security demands. This could lead to the development of hybrid, adaptive solutions that offer both high security and operational flexibility, thus broadening the scope and applicability of WBAN technologies in diverse real-world scenarios.

6 Open Research Challenges and Future Directions

Despite significant progress in privacy-preserving data aggregation for Wireless Body Area Networks (WBANs), several research challenges remain insufficiently addressed in existing literature. These challenges highlight important directions for future investigation and are derived from limitations identified across the surveyed studies:

6.1 Harmonizing Energy Efficiency and Security

Advanced cryptographic mechanisms such as homomorphic encryption and Quantum Key Distribution (QKD) offer strong privacy protection but are often associated with high computational and energy overhead. This trade-off poses a critical challenge for WBANs, where sensor nodes operate under strict energy constraints. Future research should explore lightweight security mechanisms, hardware-assisted cryptography, or hybrid approaches that balance security requirements with energy efficiency.

6.2 Low Latency and Real-Time Secure Aggregation

Many healthcare monitoring applications demand near real-time data transmission, where even minor delays can affect clinical responsiveness. However, several privacy-preserving aggregation techniques introduce latency due to complex encryption operations or multi-hop aggregation processes. Developing adaptive aggregation mechanisms that dynamically adjust security levels based on application urgency remains an open research problem.

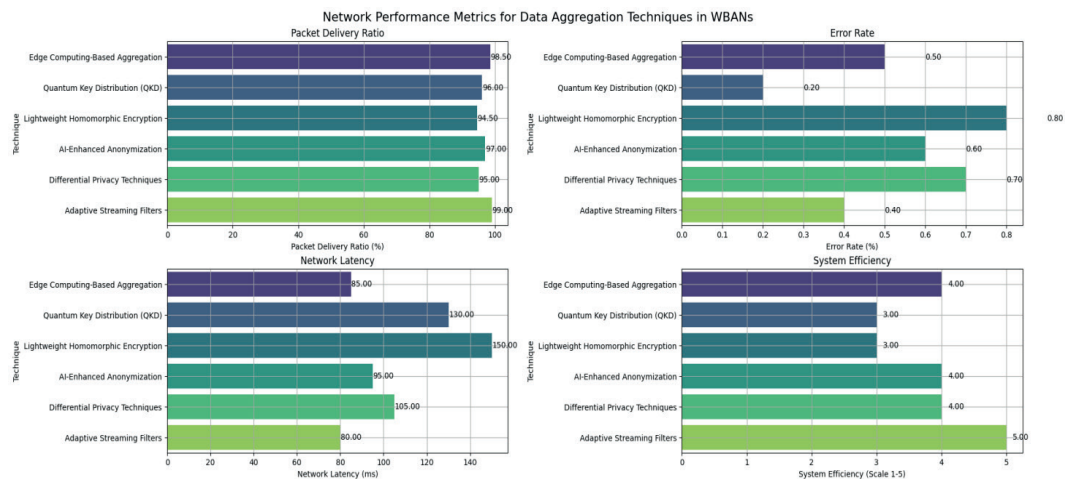


Figure 3. Illustrative comparison of network performance trends among WBAN data aggregation techniques derived from reported packet delivery, latency, and efficiency metrics in existing research

6.3 Node Heterogeneity and Scalability

As WBANs increasingly integrate heterogeneous sensor devices and interface with broader IoT and hospital information systems, scalability becomes a significant concern. Existing aggregation schemes often assume homogenous node capabilities, limiting their applicability in real-world deployments. Future research should focus on scalable aggregation models that can efficiently support diverse node types and varying network sizes.

6.4 Dynamic Network Conditions and Mobility

Patient mobility and body movements introduce frequent topology changes and fluctuating link quality in WBAN environments. Many current aggregation schemes rely on static network assumptions, which may not accurately reflect real-world conditions. Mobility-aware and context-adaptive aggregation techniques represent a critical research direction for improving system robustness.

6.5 Emerging Privacy Technologies: Blockchain or Zero-Knowledge Proofs (ZKP)

While blockchain and Zero-Knowledge Proof (ZKP) mechanisms have demonstrated potential for privacy preservation in other domains, their application in WBANs remains limited due to resource constraints. Future studies may investigate lightweight blockchain architectures or simplified ZKP models tailored to the computational and energy limitations of WBAN systems.

7 Conclusion

In conclusion, this survey presents a comparative evaluation of data aggregation techniques for Wireless Body Area Networks (WBANs), offering insights into the relative strengths and trade-offs of widely adopted approaches based on existing literature. Security oriented methods such as Quantum Key Distribution (QKD) and Lightweight Homomorphic Encryption demonstrate strong privacy preservation and data integrity capabilities, making them suitable for applications involving highly sensitive medical data. However, reported results indicate that these techniques are often associated with increased latency and energy consumption which may limit their applicability in time-critical or resource-constrained WBAN deployments. In contrast, Adaptive Streaming Filters exhibit favourable network performance characteristics, including high packet delivery ratios and latency, while maintaining reduced energy usage. These features suggest their suitability for applications where operational efficiency is prioritized and security requirements are comparatively moderate. It is important to note that the performance comparisons discussed in this study are derived from benchmarks and evaluation results across different experimental settings, simulation tools, and assumption. As such, the findings should be interpreted as indicative trends rather than definitive performance guarantees. Future research would benefit from standardized evaluation frameworks and unified benchmarking methodologies to enable more consistent and statistically grounded comparisons. Continued advancements in adaptive, energy-aware, and lightweight secure aggregation mechanisms remain crucial for developing flexible and efficient WBAN systems capable of supporting diverse healthcare monitoring scenarios.

8 Ethics Statement and Data Availability

8.1 Ethics Compliance

This study did not involve any direct interaction with human participants. All clinical datasets used—MIMIC-III, PhysioNet, UCI, and Kaggle—are publicly available and fully de-identified. Access to the MIMIC-III (v1.4) database was obtained through the official PhysioNet Credentialed Access process. All authors who accessed MIMIC-III completed the required CITI Program “Data or Specimens Only Research” ethics certification, as mandated by the dataset’s usage policy. Because only de-identified secondary data were used, and no identifiable health information was accessed or redistributed, the study qualifies as IRB-exempt research under typical human-subjects’ regulations. No new identifiable patient data were collected.

8.2 Data Usage and Patient Privacy

To preserve privacy:

1. Raw clinical records were not used directly in any network evaluation.
2. All datasets were transformed into WBAN-compatible synthetic traffic streams (sampling rates, packet sizes, and payload patterns), ensuring no patient-level information entered the simulation.
3. No re-identification, linkage, or patient-level inference was performed.
4. No data were redistributed; all datasets were accessed and processed in accordance with their respective licenses.

8.3 Data Availability

MIMIC-III v1.4 is accessible via PhysioNet under credentialed access.

PhysioNet waveform datasets, UCI repositories, and Kaggle datasets are publicly available under their respective licenses.

All NS-3 simulation scripts and configuration files used to generate WBAN workloads will be released in an open repository upon publication (link to be activated in final version).

No proprietary or restricted data were generated in this study.

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