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Hybrid-LEAP Protocol: A Hybrid of LEACH and PEGASIS Protocols With TDMA for Healthcare WSNs Enhancement

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Abstract

Wireless Sensor Networks (WSNs) have become an essential component and integral to healthcare monitoring systems, where timely and energy-efficient data transmission is crucial for safeguarding patients and maintain system reliability. However, existing routing protocols face challenges in meeting the stringent energy and latency needs of healthcare environments. LEACH, though its effective in decreasing transmission distances by clustering, it suffers from extreme energy overhead due to its frequent cluster head rotations. In contrast, PEGASIS enhances energy efficiency by organizing nodes into chains, but this approach introduces significant communication delays, rendering it unsuitable for time-sensitive, real-time healthcare monitoring.

This paper introduces **Hybrid-LEAP**, a novel hybrid routing protocol that combines the strengths of both LEACH and PEGASIS while conquering their individual limitations. The protocol incorporates LEACH-based clustering to organize the network, PEGASIS-style intra-cluster chaining to optimize energy consumption, and TDMA-based scheduling to minimize transmission collisions and delays. Designed specifically for healthcare WSNs, Hybrid-LEAP aims to enhance data delivery performance, reduce energy depletion, and support real-time monitoring.

The proposed protocol is implemented using the Python simulation environment with healthcare-specific parameters and evaluated against standard LEACH and PEGASIS protocols. Simulation results show that Hybrid-LEAP achieves significant improvements in network lifetime, end-to-end delay, and packet delivery ratio. To the best of available knowledge, this is the first work to fully integrate clustering, chaining, and scheduling for healthcare applications. The findings highlight Hybrid-LEAP's potential as an effective and practical solution for energy-aware and delay-sensitive healthcare monitoring systems.

I INTRODUCTION

Wireless Sensor Networks (WSNs) have emerged as a critical technology in modern healthcare systems, enabling continuous monitoring of patients, real-time health data acquisition, and intelligent decision-making in remote and critical care settings. These networks consist of spatially distributed sensor nodes that monitor physiological parameters such as heart rate, blood pressure, and glucose levels, and transmit the data to a central base station or medical server. The efficiency of routing protocol is a key determinant of overall system performance, it serves as a critical factor directly affecting energy consumption, latency, and network reliability[1], [2]. In healthcare applications, WSNs face unique and severe challenges, where sensor nodes are typically battery-powered and deployed in environments that recharging or replacing them is impractical. Additionally, healthcare data is highly time-sensitive requiring directed and reliable transmission to prevent delays that could threatens patient safety. Consequently, routing protocols must achieve a delicate balance between minimizing energy consumption and ensuring low-latency communication [2], [3].

To address these challenges, several routing protocols have been developed, LEACH (Low-Energy Adaptive Clustering Hierarchy) and PEGASIS (Power-Efficient Gathering in Sensor Information Systems)

are widely studied. LEACH utilizes clustering to minimize communication distance and distribute energy load among sensor nodes. However, its reliance on random and frequent cluster head (CH) rotation mechanism introduces significant overhead and can lead to unbalanced energy depletion [4]In contrast, PEGASIS reduces energy consumption by organizing nodes into a linear chain, where data is aggregated and forwarded along the chain to the base station. Despite its energy-efficient, PEGASIS suffers from increased communication delay, especially in long chains, making it less suitable for latency-sensitive healthcare applications[5].

To overcome these limitations, recent research has explored hybrid approaches. However, most existing works focus on combining two techniques or restricted to the theoretical models without a comprehensive implementation in realistic simulation environments. Moreover, few studies have specifically meet the requirements of healthcare applications, which include rigid constraints on latency, high reliability, and optimal energy efficiency[6].

This paper aims to introduce **Hybrid-LEAP**, a novel hybrid routing protocol that integrates three key mechanisms: **LEACH-based clustering**, **PEGASIS-style intra-cluster chaining**, and **TDMA-based transmission scheduling**. The objective is to combine the energy-saving advantages of clustering and chaining with scheduled communication mechanisms to minimize collisions and reduce latency. Hybrid-LEAP is implemented and evaluated in the Python simulation environment using healthcare-relevant parameters and scenarios.

II LITERATURE REVIEW

Wireless Sensor Networks have revolutionized healthcare monitoring by enabling continuous, remote, and real-time tracking of physiological data [2]healthcare WSNs face critical challenges due to limited battery life and the need for timely data delivery. Energy efficiency is essential to prolong network lifetime, while low latency is crucial to such systems that necessitate highly optimized routing protocols [3], [7]. So, routing protocols must be specifically designed to minimize energy consumption and reduce communication delays, going beyond the capabilities of conventional WSN protocols [7], [8] .

A. **LEACH and PEGASIS Mechanisms, Advantages, and Limitations**

1) LEACH (Low-Energy Adaptive Clustering Hierarchy)

LEACH is a hierarchical routing protocol aimed to enhance the energy efficiency of WSNs by organizing nodes into clusters. In each operational round, a subset of nodes is randomly selected as cluster heads (CHs), these CHs collect aggregate data from their respective cluster members and transmit it to the base station. this rotation of CH among nodes over time, helps to balance energy consumption across the network and prevent energy depletion of individual nodes [9], [4].

• Advantages:

o Minimizes transmission distance via clustering.

o Balances energy consumption through periodic, randomized selection of cluster heads.

o Supports data aggregation to reduce redundancy [9], [4]

• Limitations: (dup: abstract ?)
o Frequent CH re-selection introduces control overhead.

o Random CH selection may lead to varying cluster distribution.

o Not suitable for delay-sensitive applications like healthcare [4], [8], [9].

2) **PEGASIS (Power-Efficient Gathering in Sensor Information Systems)**

PEGASIS enhances energy efficiency by arranging all nodes into a chain structure, where each node only communicates with its close neighbor. As data passed along the chain, it is aggregated at each node and ultimately transmitted to the base station by a designated leader node [5].

• Advantages:

o Reduce the number of long-distance transmissions by the reliance on local neighbor communication.

o Extends the network lifetime through series data aggregation along the chain.

o Requires less control messages overhead comparing with LEACH [5].

• Limitations:

o Suffers from high latency since data is transmitted sequentially through the entire node chain.

o Chain formation and leader selection are often complex and lack flexibility.

o Offers poor robustness, Less flexibility with long chains, due to its sensitivity to individual node failures [5], [10].

While LEACH and PEGASIS provide complementary advantages in energy efficiency, they individually fail to meet the combined demands of low latency and high reliability required in healthcare applications. This motivates hybrid designs like Hybrid-LEAP, that aim to leverage the advantages of both while addressing their individual limitations [8].

B. LEACH Variants and Enhancements

Although LEACH established the basis for hierarchical routing in WSNs, numerous enhanced versions have been proposed to overcome its limitations, particularly the randomness in cluster head (CH)

selection, energy imbalance, and communication overhead. These enhanced versions introduce mechanisms such as centralized control, energy-aware CH selection, and mobility adaptation to improve network lifetime and overall performance.

1) **LEACH-C (LEACH-Centralized)**

LEACH-C enhances the original LEACH by performing CH selection through a **centralized approach** managed by base station. In this model, each node sends its location and residual energy to the base station, which then calculates the optimal CHs based on this information [4]. This results in **more balanced** cluster formations and minimize energy **consumption** compared to the random CH selection used in standard LEACH.

• **Key Enhancement**: Centralized CH selection based on location and energy.

• **Benefit**: More balanced clusters, enhanced energy balancing, and improved overall network stability.

2) **E-LEACH (Enhanced LEACH)**

E-LEACH addresses the energy imbalance issue by employing a residual energy-based approach to cluster head CH selection. Instead of random selection, nodes with higher remaining energy are prioritized and given a greater probability of becoming CHs. This strategy avoids energy depletion in weaker nodes and extends overall network life[11].

• **Key Enhancement**: Energy-aware CH selection, cluster head selection based on residual energy levels.

• **Benefit**: Minimizes early node failures and promotes balanced energy consumption across the network.

3) **sLEACH (Solar-aware LEACH)**

sLEACH introduces energy-aware routing by prioritizing nodes with solar energy harvesting capabilities for cluster head (CH) roles. By assigning greater communication responsibilities to energy-replenishing nodes, the protocol minimizes the load on battery-powered sensors and extends the overall network lifetime especially for long-term healthcare applications[12].

• **Key Enhancement**: CH selection based on solar energy availability.

• **Benefit**: Maximizes the use of renewable energy and prolongs network life.

4) M-LEACH (Mobile LEACH)

• M-LEACH modifies the original protocol to support mobile sensor environments by introducing mobility-aware cluster head (CH) selection and handover mechanisms. This is particularly relevant Inhealthcare settings where sensors are attached to moving patients, such as in wearable monitoring systems [13].

• **Key Enhancement**: Enables mobility-aware CH selection and seamless handover between nodes.

• **Benefit**: Maintains routing stability in dynamic and mobile healthcare environments.

5) **T-LEACH (Threshold LEACH)**

T-LEACH introduces a **threshold-based mechanism** for CH selection, that considers both residual energy and time duration to optimize the rotation interval. This helps reduce frequent re-clustering, which can lead to unnecessary energy waste [14].

• **Key Enhancement**: Threshold-based CH selection incorporating both time and energy criteria.

• **Benefit**: Reduces re-clustering overhead and promotes more consistent communication behavior.

These LEACH variants and enhancements demonstrate a clear trend toward **more** adaptive **and context-aware CH selection**, whether through centralized coordination, energy metrics, mobility awareness, or renewable energy integration. These enhancements significantly improve network stability, greater energy efficiency, and suitability for delay-sensitive applications like healthcare monitoring, where both reliability and extended operational lifetime are critical.

C. PEGASIS-Based Improvements

Although PEGASIS achieves significant energy savings by minimizing long-distance transmissions, it suffers from high latency and low fault tolerance, particularly in extended chains. To overcome these shortcomings several improved versions of PEGASIS have been proposed to improve data delivery speed, robustness, and **s**calability in wireless sensor networks (WSNs), particularly under demanding conditions such as those in healthcare monitoring [5], [8].

1) **Improved PEGASIS**

Improved PEGASIS enhances the original chain-based structure by introducing a multi-chain formation mechanism. Instead of forming a single long chain, the network is segmented into multiple shorter chains, each with a local leader. This approach minimizes the number of hops per transmission and significantly lowers end-to-end delay, making the protocol more suitable for delay-sensitive applications [15].

• **Key Enhancement**: Multiple shorter chains with parallel transmissions. Each with a dedicated leader.

• **Benefit**: Reduces latency and balances energy consumption more evenly across chains.

2) **HEED-PEGASIS**

HEED-PEGASIS combines the residual energy-aware clustering of the HEED protocol with the chain-based communication strategy of PEGASIS. By using energy-based node selection and localized

clustering before chain formation and improves the overall reliability of the transmission chain and load balancing, it also improves fault tolerance, as nodes with low energy are excluded from key roles, reducing the risk of early node failures [16].

• **Key Enhancement**: Energy-aware CH selection before chain formation.

• **Benefit**: Improves robustness and extends network lifetime by minimizing reliance on energy-depleted nodes.

3) **CHIRON (Chain-Based Hierarchical Routing Protocol)**

CHIRON introduces a hierarchical chain-based structure, that integrates chain-based communication within a clustered network structure. Each cluster forms its own intra-chain, and designated cluster leaders are responsible for forwarding aggregated data to the base station. This combination of clustering and chaining reduces both transmission delay and energy consumption while significantly enhancing scalability and robustness [8], [16].

• **Key Enhancement**: Hierarchical design combining clustered intra-chains with centralized data forwarding.

• **Benefit**: Provides low-latency communication and high robustness making it well-suited for large-scale WSN deployments.

Enhancements to the PEGASIS-based highlight a growing focus on reducing the protocol's inherent latency and improving its adaptability in real-world applications. Through the integration of techniques such as energy-aware node selection, multi-chain division, and hybrid hierarchical structures, protocols like Improved PEGASIS, HEED-PEGASIS, and CHIRON offer more reliable and timely communication, these improvements make them more suitable for healthcare scenarios, where low latency and high fault tolerance are essential [8].

D. Hybrid Routing Approaches

To address the individual shortcomings of LEACH and PEGASIS particularly regarding energy imbalance and high transmission delay researchers have proposed hybrid routing protocols that combine the advantages of both clustering and chaining techniques. These hybrid approaches aim to enhance energy efficiency while minimizing end-to-end latency, making them more suitable for performance-critical applications such as in healthcare monitoring.

1) **H-PEGASIS (Hybrid PEGASIS)**

H-PEGASIS enhances the conventional PEGASIS protocol by introducing cluster-based segmentation within the chain. The network is partitioned into multiple local chains (clusters), each managed by a **cluster head (CH)** that aggregates data from member nodes. These CHs then form a secondary chain to

forward the aggregated data to the base station. This hierarchical, two-level architecture shortens the overall chain length, thereby reducing transmission delay while retaining the energy-efficient characteristics of PEGASIS [17].

• **Design Philosophy**: Integrate clustering into PEGASIS to minimize transmission delay and support parallel data aggregation.

• **Energy–Delay Balance**: limiting the number of hops in each chain promotes local data aggregation. H-PEGASIS achieves effectively balancing energy efficiency with lower latency.

2) **HEERP (Hybrid Energy Efficient Routing Protocol)**

HEERP combines energy-aware clustering with chain-based intra-cluster communication. Initially, clusters are formed based on residual energy and node location. Within each cluster, nodes are arranged in a local chain to minimize intra-cluster communication overhead. Once data is aggregated, cluster heads (CHs) transmit it directly to the base station or via multi-hop relays. HEERP focuses on extending network lifetime without compromising delay performance .

• **Design Philosophy**: Utilize energy-based clustering for load balancing and intra-cluster chaining to minimize energy use and communication overhead.

• **Energy–Delay Balance**: HEERP reduces long-distance transmissions while maintaining a fast data flow through structured, short-range links.

Hybrid protocols such as H-PEGASIS and HEERP illustrate a transition toward **multi-level architectures** that intelligently integrate clustering and chaining techniques. These designs aim to achieve a balance between energy efficiency and transmission delay by enabling localized data aggregation, minimizing hop count, and optimizing communication paths. As a result, protocols offer a **scalable and reliable routing solution**, especially for **healthcare-oriented WSNs**, where both energy conservation and timely data delivery are essential [18].

E. Comparative Assessment of Hybrid-LEAP with Existing Hybrid Protocols

While protocols such as H-PEGASIS [17] and HEERP[18] mark significant progress in combining energy efficiency with latency reduction, they still face limitations that restrict their effectiveness in highly constrained environments such as healthcare-focused WSNs. While both adopt hybrid strategies integrating clustering and chaining to lower communication overhead and delay, they often lack essential features such as dynamic scheduling, precise latency control, and evaluation under realistic healthcare-specific conditions [3], [8].

The proposed **Hybrid-LEAP** protocol builds upon these foundational ideas of these hybrid strategies introducing several key innovations specifically designed to meet the stringent demands of healthcare monitoring applications.

1) **Three-Level Integration: Clustering, Chaining, and TDMA**

In contrast to H-PEGASIS and HEERP, which primarily focus on two mechanisms (either clustering and chaining, or clustering and energy awareness), Hybrid-LEAP incorporates a **third** essential component: **TDMA-based scheduling**. This time-slot-based communication strategy significantly reduces **collisions and idle listening**, which are major sources of energy waste in healthcare settings where sensor traffic can be periodic and dense.

2) **Healthcare-Driven Design**

Hybrid-LEAP is specifically to meet the stringent demands of healthcare applications, emphasizing low latency, high reliability, and energy efficiency. While prior protocols provide generalized improvements, Hybrid-LEAP is evaluated using healthcare-relevant traffic patterns and node deployment scenarios that closely reflect real-world healthcare environments, ensuring its practical relevance and effectiveness.

3) **Implementation and Evaluation in Python**

Most hybrid protocols are either evaluated in simplified custom simulators or lack reproducibility. Hybrid-LEAP is fully implemented and tested in the Python simulation environment, enabling realistic performance analysis, including metrics such as network lifetime, end-to-end delay, and packet delivery ratio. This distinguishes it from prior works that is often theoretical or lacks complete system-level validation.

By strategically integrating LEACH-based clustering, PEGASIS-style chaining, and TDMA scheduling, Hybrid-LEAP effectively overcomes key limitations of previous hybrid routing protocols. It offers a more robust, energy-efficient, and delay-aware solution specifically designed for healthcare WSNs, where both timely data transmission and extended network lifetime are essential. This positions Hybrid-LEAP as a significant and meaningful advancement in the evolution of WSN routing protocols for mission-critical wireless sensor network environments.

Table.1 produces a comparative advantage of Hybrid-LEAP with existing hybrid protocols.

Table.1: Comparative Advantages of Hybrid-LEAP

Feature	H-PEGASIS	HEERP	Hybrid-LEAP (Proposed)
Clustering	✗	✗	✓
Chaining	✓	✓ (intra-cluster)	✓ (intra-cluster)
TDMA Scheduling	✗	✗	✓
Energy-Aware CH Selection	✗	✗	✓
Healthcare-Specific Evaluation	✗	✗	✓
Python Implementation	✗	✗	✓
Delay Optimization	Moderate	Moderate	High
Fault Tolerance	Basic	Improved	Enhanced via scheduling and structure

F. TDMA-Based Scheduling in WSNs

Time Division Multiple Access (TDMA) is a widely used medium access control technique in Wireless Sensor Networks (WSNs) where each sensor node is assigned a specific time slot for transmission. This scheduled access eliminates packet collisions and idle listening. Two major sources of energy consumption in contention-based protocols such as CSMA. Consequently, TDMA has become a well-suited for energy-constrained WSN environments that require efficient and reliable communication [19].

Several studies have integrated TDMA into WSN routing protocols to improve energy efficiency and support timely data transmission. Protocols such as LEACH-TDMA and PEDAP-TDMA utilize scheduled communication to minimize redundant retransmissions and extend network lifetime [20], [21]. These models demonstrate that TDMA can significantly enhance channel utilization and reduce latency, especially when combined with hierarchical topologies that facilitate organized and efficient data flow.

TDMA is particularly suitable for healthcare-oriented WSNs, where sensor nodes often generate periodic, predictable traffic patterns and transmit critical patient data that demands low-latency and reliable delivery. Scheduled access ensures that time-sensitive physiological data (e.g., heart rate, oxygen saturation, or blood pressure) reaches the base station without delay or collision, thereby enabling real-time monitoring and prompt medical response. additionally, by eliminating energy loss from overhearing and contention, TDMA significantly extends the battery life of sensor nodes as crucial requirement for remote and implantable medical devices [3], [8].

G. Healthcare-Oriented WSN Protocols

Wireless Sensor Networks (WSNs) employed in healthcare applications must meet more stricter requirements than general-purpose WSNs, specially in terms of real-time responsiveness, energy efficiency, and overall system reliability. Consequently, numerous routing protocols have been developed specifically to address the demands of healthcare monitoring systems.

A notable example is MEDiSN (Medical Emergency Detection in Sensor Networks), which utilizes a multi-tiered architecture facilitate reliable transmission of patient data to healthcare personnel. It concentrates on minimizing packet loss and latency during critical medical events by maintaining redundant communication paths and prioritizing the delivery of emergency information [22].

Another example is BodyQoS, a Quality-of-Service (QoS)-aware framework developed for Body Area Networks (BANs). It dynamically adjusts transmission rates and prioritizes critical health data, such as abnormal ECG signals. By optimizing latency, throughput, and signal degradation, BodyQoS is suitable for wearable healthcare devices requiring timely and reliable data delivery [23].

Although primarily designed as a wearable platform, HealthGear integrates lightweight routing mechanisms to enable continuous health monitoring. It concentrates on low power consumption, real-time processing, and reliable data delivery making it more suitable for mobile patients in dynamic healthcare environments [24].

H-MAC employs a hybrid routing strategy that combines TDMA-based scheduling with coordinated sleep–wake cycles to reduce energy consumption while preserving low-latency data transmission. H-MAC is specifically tailored to prolong **network lifetime** and efficiently support both periodic monitoring and event-driven alerts capabilities that are vital for reliable healthcare applications [25].

Several studies have also aimed to reduce node death rates and improve packet delivery ratios under healthcare conditions. For example, energy-efficient protocols like EECDA and TEEN-HEALTH employ clustering and threshold-based techniques to minimize unnecessary transmissions and extend the lifespan of sensor nodes particularly in high-demand settings like intensive care units [26], [27].

Collectively, these protocols share a common objective that to ensure reliable and timely transmission of health data while conserving energy to enable long-term deployment. They typically optimize parameters such as end-to-end delay, packet delivery ratio, energy consumption, node death rate, and system responsiveness, all of which are crucial in medical and healthcare applications.

III RELATED WORKS

A wide range of routing protocols have been developed to enhance energy efficiency in healthcare WSNs, LEACH and PEGASIS among the most extensively studied. LEACH leverages clustering, while PEGASIS employs chain-based routing, both face in terms of scalability and balanced energy distribution. To address these challenges, recent studies propose hybrid approaches and TDMA-based techniques. This

section categorizes related works into six thematic groups and highlights how Hybrid-LEAP advances current solutions for reliable and energy-efficient healthcare monitoring.

A. Foundational Protocols (Baseline and Comparison)

The early development of routing protocols in Wireless Sensor Networks (WSNs) was marked by two contributions: LEACH (Low-Energy Adaptive Clustering Hierarchy) [4]and PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [5] LEACH introduced a hierarchical, cluster-based communication model with dynamic cluster-head rotation, it aims to balance energy consumption and extend the overall network lifetime. Conversely, PEGASIS proposed a chain-based routing strategy where nodes communicate with their close neighbors and send the aggregating data along the chain to a designated leader node which then transmits the data to the base station. This approach significantly minimizing long-distance transmissions. Both protocols significantly advanced energy-efficient communication in WSNs but also presented notable trade-offs, such as higher transmission delays, particularly in long chains in PEGASIS and scalability and control overhead issues in LEACH.

To comprehensively understand the performance and applicability of LEACH and PEGASIS, several comparative analyses have been conducted. Studies such as[28], [29] and[30] systematically evaluated LEACH and PEGASIS across critical performance metrics, including energy consumption, network lifetime, and transmission delay. These comparisons consistently reveal that while PEGASIS achieves better energy efficiency, it suffers from higher latency, making protocol selection dependent on application-specific requirements. These foundational works form the benchmark upon which modern hybrid protocols like the proposed Hybrid-LEAP are designed and evaluated.

B. LEACH Modifications and Enhancements

To overcome the limitations of the original LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol such as random cluster-head selection, scalability challenges, and uneven energy distribution, several enhancements have been proposed. These modified versions of LEACH integrate advanced techniques including machine learning, fuzzy logic, optimization algorithms, and game-theoretic models to enhance energy efficiency, stability, and adaptability in Wireless Sensor Networks (WSNs). For example, [31]utilized k-means clustering to optimize cluster formation, while [32]introduced F-LEACH, employing fuzzy logic for intelligent cluster-head decisions by considering residual energy and data urgency. Similarly, [33]proposed NN_ILEACH, which employed supervised neural networks for energy-aware and data-driven routing, leading to notable improvements in network lifetime and delivery rates. MFG-LEACH [34] utilized the Mean Field Game (MFG) theory to model node interactions as a dynamic game to achieve optimal energy consumption across different densities. Other protocols, such as IMP-RES-EL and EEL [35]improve cluster-head selection in both residual energy and node position, whereas T-LEACHSAS [36]combined threshold-based selection with centralized sleep–awake scheduling mechanism to reduce energy waste. Additionally, S-LEACH [37]introduced a sector-based clustering structure to localize energy usage and prolong network lifespan. A comprehensive survey presented in [38]categorized and evaluated these LEACH-based protocols, highlighting their evolution and identifying

key performance trade-offs. Together, these enhancements serve as a robust foundation for hybrid models that build upon LEACH's architecture such as the proposed Hybrid-LEAP protocol by integrating intelligent and adaptive mechanisms into LEACH's core architecture, Hybrid-LEAP aims to address the stringent energy and latency requirements of healthcare monitoring systems.

C. PEGASIS Enhancements

While the PEGASIS (Power-Efficient Gathering in Sensor Information Systems) significantly improves energy efficiency by employing a chain-based data transmission model, it faces notable limitations such as increased transmission delay, limited clustering flexibility, and failures in heterogeneous or dynamic environments. To address these challenges, several enhanced versions of PEGASIS have been proposed. E-PEGASIS [39]improved the chaining mechanism by incorporating parameters such as average inter-node distance and radio range thresholds to optimize data paths and improve extend network lifetime. EPEGASIS [40] introduced a hybrid approach that combines PEGASIS's chain-based routing with k-means-based cluster head selection, this approach effectively reducing transmission delays and balancing energy usage across nodes. In a more specialized application context, [41]applied a PEGASIS-based routing scheme in a smart contact lens system for continuous ocular health monitoring, demonstrating how chain-based energy optimization can support real-time biomedical sensing in wearable healthcare devices. These advancements highlight PEGASIS's adaptability and its growing relevance in both general WSN deployments and domain-specific applications, supporting the rationale for incorporating PEGASIS elements into hybrid protocols like Hybrid-LEAP.

D. Hybrid LEACH-PEGASIS Approaches

To leverage the complementary strengths of LEACH's clustering and PEGASIS's chain-based transmission, several hybrid routing protocols have been developed, aiming to enhance energy efficiency, scalability, and data delivery in Wireless Sensor Networks (WSNs). For example, the hybrid model in [42] combined LEACH's adaptive cluster-head selection with PEGASIS's multi-hop data aggregation for throughput improvements and to extend network lifetime. Similarly, [43]integrated PEGASIS-like chain routing within LEACH-formed clusters to effectively minimize redundant transmissions and balance node energy consumption. Expanding on these foundations, [44]proposed an advanced hybrid framework that merges Firefly-based clustering with PEGASIS-inspired routing and neural network-based distortion control, demonstrating robust energy optimization and resilience in large-scale deployments. Additionally, Q-LEACH [45]introduced a hybrid clustering protocol that incorporates a redesigned TDMA schedule alongside an energy-aware cluster-head selection mechanism, significantly enhancing Quality of Service (QoS) metrics and network stability.

These hybrid solutions collectively underscore the effectiveness of combining LEACH and PEGASIS principles augmented by TDMA and intelligent mechanisms as a promising direction for protocols like Hybrid-LEAP, especially in energy-sensitive healthcare monitoring environments.

E. Other Hybrid or Advanced Routing Protocols

Beyond LEACH- and PEGASIS-based frameworks, a diverse range of advanced routing protocols has emerged to address the evolving demands of Wireless Sensor Networks (WSNs), particularly in complex and energy-constrained environments. These protocols employ innovative strategies such as metaheuristic optimization, machine learning, mobility-awareness, and centralized control strategies to improve routing efficiency, network adaptability, and fault tolerance. For instance, PEEHSRA [46]and MIMO-HC [47] incorporate intelligent search and clustering mechanisms to optimize routing paths based on residual energy and network conditions. Others, such as EEHCHR [48] and IK-MACHES[49], introduce fuzzy clustering and mobility-aware cluster-head selection enabling node heterogeneity and mobility challenges. In a more scalable context, the EEMCR protocol [50] adopted a mega-cluster-based structure with dynamic CH selection and data mules for scalable energy management in large-scale WSNs. Although these approaches do not directly extend LEACH or PEGASIS, they provide valuable insights into designing hybrid architectures such as the proposed Hybrid-LEAP that demand real-time adaptability, fault tolerance, and long-term energy sustainability for critical applications like healthcare monitoring and IoT systems.

F. Most Relevant Related Works

The proposed Hybrid-LEAP protocol which integrates LEACH and PEGASIS topologies with TDMA-based scheduling draws its conceptual and structural foundation from a body of influential research aimed for enhancing energy efficiency and communication reliability in healthcare-oriented Wireless Sensor Networks (WSNs).

At its core, Hybrid-LEAP builds upon the foundational routing models introduced by LEACH[4] and PEGASIS [5]LEACH pioneered a clustering-based approach to reduce communication overhead through localized clustering, while PEGASIS introduced a chain-based model to minimize long-distance transmissions via sequential data forwarding. These protocols laid the groundwork for numerous hybrid designs seeking to harness the strengths of both.

Notably, Studies such as [42]and [43]demonstrated how merging LEACH's adaptive clustering with PEGASIS's efficient multi-hop data forwarding can significantly improves network lifetime and balance energy distribution. Further enhancements, including EPEGASIS [40], Q-LEACH [45], and hybrid frameworks utilizing TDMA and intelligent clustering methods [44]illustrate the effectiveness of synchronizing cluster-based and chain-based models with time-scheduled communication to reduce latency and prevent collisions. Complementing these architectural innovations, energy-efficient routing strategies specifically designed for healthcare and IoT environments have emerged. Protocols like F-LEACH [32], EEHCHR[48] and NN_ILEACH[33] incorporate fuzzy logic and machine learning to enhance responsiveness, reliability, and adaptability in critical medical monitoring applications.

Together, these related works offer a comprehensive and validated basis for the development of the Hybrid-LEAP protocol, demonstrating the feasibility and value of combining clustering, chaining, and scheduled transmission to deliver energy-aware, scalable, and healthcare-sensitive routing solutions.

Particularly in scenarios demanding energy-aware, scalable, and application-sensitive routing mechanisms.

Table.2 presents a comparative summary of previous research works that have explored the key routing protocols, including foundational models (LEACH, PEGASIS), their enhanced variants, and hybrid approaches. The comparison focuses on core routing mechanisms, energy efficiency, latency management, scalability, and relevance to healthcare applications. The presence of the proposed Hybrid-LEAP highlights how it addresses existing limitations through a unified clustering, chaining, and TDMA-based scheduling framework, optimized for the stringent requirements of healthcare Wireless Sensor Networks (WSNs) to balance energy consumption and communication delay under realistic healthcare constraints.

Table.2: Comparative Summary of Routing Protocols

Protocol	**Routing Strategy**	**Energy Optimization**	**Latency Performance**	**Scalability**	**Healthcare Suitability**
LEACH	Clustering	Moderate	Low	Limited	Basic
PEGASIS	Chaining	High	Poor	Moderate	Low
F-LEACH	Fuzzy Logic + Clustering	High	Moderate	Improved	Targeted
NN_ILEACH	ML + Clustering	High	Moderate	Improved	Targeted
E-PEGASIS	Improved Chaining	High	Moderate	Improved	General
EPEGASIS	Hybrid (Chain + Clustering)	High	Improved	Improved	Targeted
Q-LEACH	Hybrid (Clustering + TDMA)	High	Improved	Improved	Targeted
Hybrid [21]	Hybrid (LEACH + PEGASIS)	High	Improved	Good	Potential
Hybrid [22]	Hybrid (LEACH + PEGASIS)	High	Improved	Good	Potential
Hybrid [23]	Firefly + PEGASIS + NN	High	Improved	High	High
Hybrid-LEAP	Clustering + Chaining + TDMA	Very High	High (with TDMA)	High	Designed for Healthcare

In conclusion, the previous studies demonstrate the evolution of routing strategies in Wire-less Sensor Networks, from foundation-al models like LEACH and PEGASIS to advanced hybrid and healthcare-specific solutions. While many approaches offer enhancements in energy efficiency, latency, or

adaptability, they often fall short in addressing the rigid demands of healthcare scenarios. These gaps highlight the need for integrated frameworks like Hybrid-LEAP, which tactically combines clustering, chaining, and scheduled communication to achieve reliable, energy-aware, and timely data transmission making it as a viable solution for high-priority healthcare WSN applications and monitoring scenarios.

IV THE METHODOLOGY

This section presents the design, development, and evaluation of the Hybrid-LEAP protocol, it is a hybrid routing model that combines essential elements from three well-known models LEACH (clustering), PEGASIS (intra-cluster chaining), and TDMA (scheduled communication) into a unified framework to optimize energy efficiency and reduce latency in healthcare-focused Wireless Sensor Networks (WSNs). The protocol is specifically designed for real-time patient monitoring scenarios where both timely data delivery and extended network lifetime are critical.
In contrast to existing approaches that typically optimize either energy consumption or communication delay in isolation, Hybrid-LEAP implements an approach that dynamically selects cluster heads based on residual energy and distance, forms an effective intra-cluster chains for data forwarding, and utilizes TDMA-based slot allocation to minimize collisions and idle listening.

The protocol is evaluated within a custom Python-based simulation environment designed to reflect realistic healthcare scenarios including heterogeneous node energy levels and periodic traffic patterns.

A. Protocol Architecture

The Hybrid-LEAP protocol combines three key routing components, each responsible for addressing a specific aspect of WSN performance:

1) **Cluster Formation (LEACH-Based)**:

The network is divided into clusters where Cluster Heads (CHs) are selected based on a composite metric including residual energy and distance to the Base Station (BS). This strategic selection relieves the limits of purely randomized CH selection and improves load distribution across the network.

2) **Intra-Cluster Chain Formation (PEGASIS-Inspired)**:

Within each cluster, member nodes are organized into a chain topology that supports energy-efficient, multi-hop data forwarding toward the CH. This reduces long-distance transmissions and balances energy use among nodes.

3) **TDMA Scheduling**:

Time Division Multiple Access is applied to assign exclusive time slots for node transmissions within the chain. This minimizes data collisions and idle listening, significantly improving energy conservation.

B. Energy- and Distance-Aware Logic

To improve protocol flexibility, Hybrid-LEAP continuously monitors each node's residual energy and distance to the base station. These metrics effect both CH selection and chain formation, ensuring that overloaded or energy-depleted nodes are avoided in key roles. This adaptive logic improves fault tolerance and extends the network's operational life.

The energy consumption model used follows the first-order radio model:

• Transmitting:
$E_{tx}(k,d) = E_{elec}. k + \varepsilon_{amp}. k .d^2$

• **Receiving**:

$E_{rx}(k) = E_{elec}. k$

Where

E_{elec}=50 nJ/bit ,E_{amp}=100 pJ/bit/m^2 ,k is the number of bits, and d is the distance

The model reflects realistic energy usage during communication, accounting for the distance-based path loss during transmission.

C. Evaluation Metrics

The performance of Hybrid-LEAP is evaluated using a set of metrics designed to healthcare WSN requirements, focusing on energy efficiency, network longevity, and communication reliability. The following metrics are evaluated over multiple simulation rounds:

1) **Total Residual Energy per Round**:

It measures the sum of remaining energy across all alive nodes after each round, reflecting the protocol's ability to protect energy and extend network life.

2) **Number of Active Nodes per Round**:

Paths the count of nodes with non-zero energy, indicating network stability and the rate of node failures due to energy depletion.

3) **Average Energy per Chain**:

Calculates the average residual energy of nodes within each PEGASIS chain, measuring the energy balance within clusters and the effectiveness of chain formation, providing scalability and efficiency of intra-cluster communication.

4) **Overall Network Lifetime**:

Defined as the number of rounds until all nodes reduce their energy, providing a comprehensive measure of the protocol's longevity under healthcare constraints.

These metrics allow for a comparative analysis of Hybrid-LEAP against traditional protocols like LEACH and PEGASIS under healthcare-specific constraints.

D. **Implementation of Hybrid-LEAP Protocol**

1) Simulation Framework
A custom simulation framework was developed in Python, utilizing libraries such as NumPy and Matplotlib. The simulation is designed to replicate realistic WSN behaviors under healthcare-relevant conditions, capturing energy dynamics, node failures, and data communication across 75 operational rounds.

2) **Network Model**

The simulated network consists of 75 static sensor nodes randomly distributed within a 400m × 400m field, for represent a typical healthcare deployment area (e.g., a hospital or remote monitoring zone). A base station (BS) is positioned at coordinates (200, 200) to serve as the central data sink. To model node heterogeneity common in healthcare WSNs due to varying battery capacities initial energies are randomly assigned between 0.1J and 1.0J. Nodes are considered "alive" if their energy exceeds 0J; otherwise, they are marked as "dead" and excluded from further operations.

3) Simulation Process:

• Prerequisites

o **Python: Version 3.6+**

o **Required Libraries: matplotlib**: For plotting the network visualization and metrics, numpy: For numerical computations and averaging metrics.

o Install via pip:
pip install matplotli numpy [51].

o Clone the repository:
git clone https://github.com/Mona-Sbakhi/hybrid-leap-.gitcd hybrid-leap-

o Run the simulation:
• python hybrid_leap_simulation.py

o Simulation Parameters

Nodes: 75, static, random positions.

Field Size: 400m × 400m.

BS Location: (200, 200).

Initial Energy: Uniform random [0.1J, 1.0J].

CH Probability: 0.1.

Packet Size: 4000 bits.

Packet Loss Probability: 0.1.

Rounds: 120 (or until network death).

Reproducibility: Optional random seed for consistent node placement and selections.

Output: Network plots per round/protocol, overall metrics plots, and CSV export of results [51] .

V EXPERIMENTAL RESULTS AND EVALUATION

This section presents the experimental results obtained from simulating the Hybrid-LEAP protocol and comparing its performance against two baseline routing protocols: LEACH and PEGASIS. The evaluation focuses on key performance metrics relevant to healthcare Wireless Sensor Networks (WSNs), including network lifetime, residual energy, number of alive nodes, end-to-end latency, and packet delivery ratio (PDR). The simulations were conducted using a custom-built Python-based simulator under consistent environmental parameters across all protocols. Results were recorded over 120 rounds and analyzed using the data exported to a structured CSV file.

After applying the installation process, this command was used:

python hybrid_leap_simulation.py --num_nodes 75 --field_size 400 400 --ch_probability 0.1 --bs_location 200 200 --seed 10 --save_plot simulation --num_rounds 120 --min_energy 0.1 --max_energy 1.0 --packet_size 4000

1) **Network Lifetime**

Network lifetime is typically assessed by measuring the residual energy of the sensor nodes across simulation rounds. As shown in Fig. 5, the proposed Hybrid-LEAP protocol consistently maintains higher residual energy compared to conventional routing strategies. This behavior emphasizes the effectiveness of Hybrid-LEAP's integrated mechanisms namely energy-aware cluster head selection, chain-based transmission, and TDMA scheduling in reducing energy dissipation. The gradually declined of residual energy also indicates balanced energy usage across nodes, so extending the overall operational lifetime of the network.

2) **Alive Nodes per Round**

Figure 6 shows the number of alive sensor nodes throughout the simulation rounds. Hybrid-LEAP illustrates superior node survivability, with all 75 nodes remaining operational for a more extended duration compared to competing protocols. This flexibility is attributed to its adaptive clustering and balanced load distribution, which collectively reduce prematurely node failures. Maintaining a higher number of active nodes not only enhances network coverage but also eimproves data reliability critical for healthcare monitoring applications where data loss could compromise patient safety.

3) **Average Latency per Round**

Latency is a critical parameter in healthcare Wireless Sensor Networks (WSNs), where timely delivery of data is essential for patient safety and system responsiveness. Figure 7 illustrates the average latency per round across the evaluated protocols. The results show that Hybrid-LEAP consistently achieves lower latency compared to LEACH and PEGASIS, particularly in the early and mid-lifecycle of the network. This improvement can be attributed to the protocol's TDMA-based scheduling and intra-cluster chaining, which minimize transmission delays and avoid channel contention. The predictable time slot customization in Hybrid-LEAP allows for smoother communication and better support for real-time monitoring scenarios.

4) **Packet Delivery Ratio per Round**

Figure 8 presents the packet delivery ratio, which reflects the reliability of the protocol in transmitting sensed data to the base station. Hybrid-LEAP outperforms both LEACH and PEGASIS across most rounds. It maintains a higher delivery ratio, especially during the initial 50 rounds, ensuring that critical data reaches the base station with minimal loss. This superior performance is largely due to Hybrid-LEAP's structured routing and fault-tolerant chain formation, which prevents congestion and retransmissions. The use of energy-aware cluster head selection also helps sustain reliable communication by avoiding overburdened or low-energy nodes.

5) **Residual Energy per Round**

Residual energy is a key indicator of energy efficiency in WSNs. As shown in Fig. 5 before, Hybrid-LEAP retains higher average residual energy compared to LEACH and PEGASIS throughout the simulation. This reflects its ability to distribute the communication load more evenly across nodes and reduce redundant transmissions. By leveraging both clustering and chaining strategies along with scheduled communication, Hybrid-LEAP conserves energy at each node, contributing to extended network lifetime and stable performance over time.

Table.3 presents a comparative summary of LEACH, PEGASIS, and the Proposed Hybrid-LEAP Protocol

Table.3: Comparative Summary of LEACH, PEGASIS, and the Proposed Hybrid-LEAP Protocol

Feature / Protocol	LEACH	PEGASIS	Hybrid-LEAP
Architecture Type	Cluster-based	Chain-based	Hybrid (Clustering + Chain-based + TDMA)
Cluster Head (CH) Selection	Random, rotated periodically	Sequential leader rotation	Dynamic selection based on residual energy and distance
Energy Efficiency	Moderate	High (due to reduced long-range communication)	Very High (scheduled communication + efficient chaining + energy-aware clustering)
Latency	Low	High (due to long chains and multiple hops)	Low (due to intra-cluster chains and TDMA scheduling)
Energy Load Balancing	Limited (some nodes deplete faster)	Better but may overload the chain leader	Balanced (adaptive CH rotation and efficient chain construction)
Communication Scheduling	Not defined (uses CSMA or random access)	Not defined	TDMA-based, reduces collisions and idle listening
Suitability for Healthcare	Not ideal for critical, real-time applications	Poor suitability for delay-sensitive scenarios	Designed specifically for healthcare monitoring and time-critical data
Packet Delivery Ratio (PDR)	Moderate	High	Very High (improved reliability through TDMA and structured paths)
Scalability	Moderate (performance drops with node count)	Good but affected by chain length	High (leverages clustering and chaining adaptively)
Best Use Case	General-purpose WSNs with low time sensitivity	Long-term energy-efficient monitoring	Healthcare WSNs, emergency monitoring, real-time biomedical data collection

VI CONCLUSIONS AND FUTURE WORK

A. Conclusion

This study introduced **Hybrid-LEAP**, a hybrid routing protocol that integrates LEACH-based clustering, PEGASIS-inspired intra-cluster chaining, and TDMA-based scheduling to meet the specific demands of healthcare Wireless Sensor Networks (WSNs). By leveraging the complementary strengths of these three models, Hybrid-LEAP achieves a balance between energy efficiency, low latency, and reliable data delivery parameters that are vital for continuous patient monitoring and key requirements in medical monitoring applications.

Extensive simulation results demonstrated that Hybrid-LEAP outperforms traditional LEACH and PEGASIS protocols in terms of **network lifetime**, **end-to-end delay**, and **packet delivery ratio**. The use of TDMA scheduling not only reduced packet collisions but also minimized idle energy consumption, while dynamic cluster head selection ensured balanced energy utilization across nodes.

B. Future Work:

Although Hybrid-LEAP demonstrates promising improvements, several enhancements can be implemented in future research:

• **Mobility Support**: Adapting protocol to support mobile sensor nodes, which are common in wearable and implantable healthcare technologies.

• **Security and Privacy**: Integrate lightweight encryption and authentication mechanisms protect sensitive medical data during wireless transmission. ensuring confidentiality and integrity without significantly increasing energy consumption.

• **Real-World Deployment**: Employ the protocol on physical hardware (e.g., TelosB or Arduino sensor nodes) or healthcare-oriented IoT systems to validate its practicality and robustness.

• **Adaptive Scheduling**: Explore dynamic TDMA slot allocation strategies in which transmission schedules are adjusted in real time based on the urgency of sensed physiological data or the criticality of the patient's health status. For instance, sensors detecting abnormal vital signs or monitoring high-risk patients (e.g., in intensive care) can be prioritized for more frequent or immediate transmission slots. This approach aims to reduce communication delays for critical data and improve the overall efficiency and responsiveness of the network.

• **Machine Learning Integration**: Investigate the use of machine learning methods to improve decision-making in the network, such as selecting the most suitable cluster heads based on real-time conditions (e.g., energy levels and node locations) and predicting data traffic patterns to manage communication more efficiently, even as network conditions change.These directions aim to strengthen Hybrid-LEAP's potential for broader deployment in mission-critical healthcare applications.

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Figures

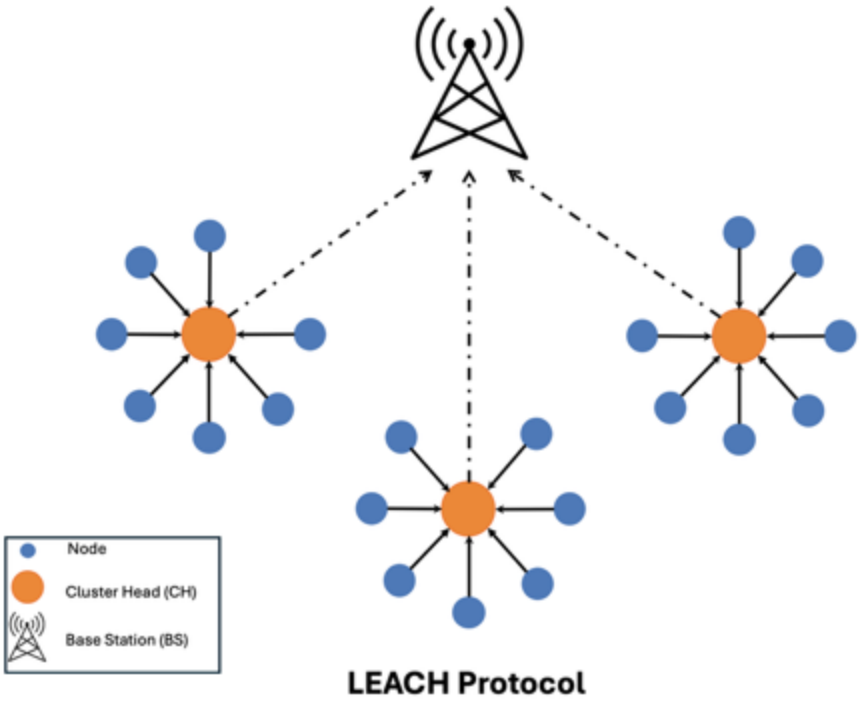


Figure 1

LEACH Protocol

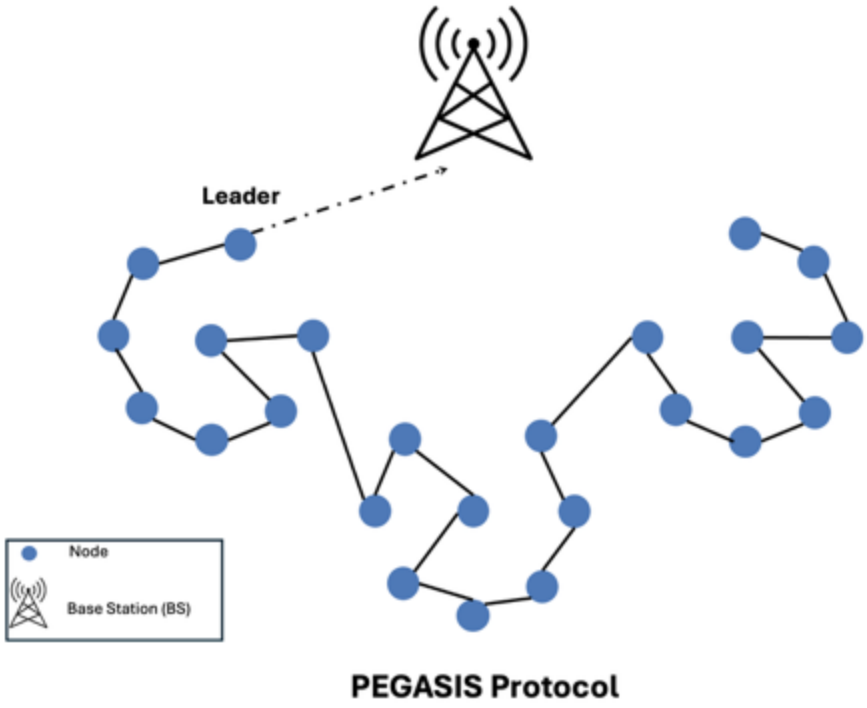


Figure 2

PEGASIS Protocol

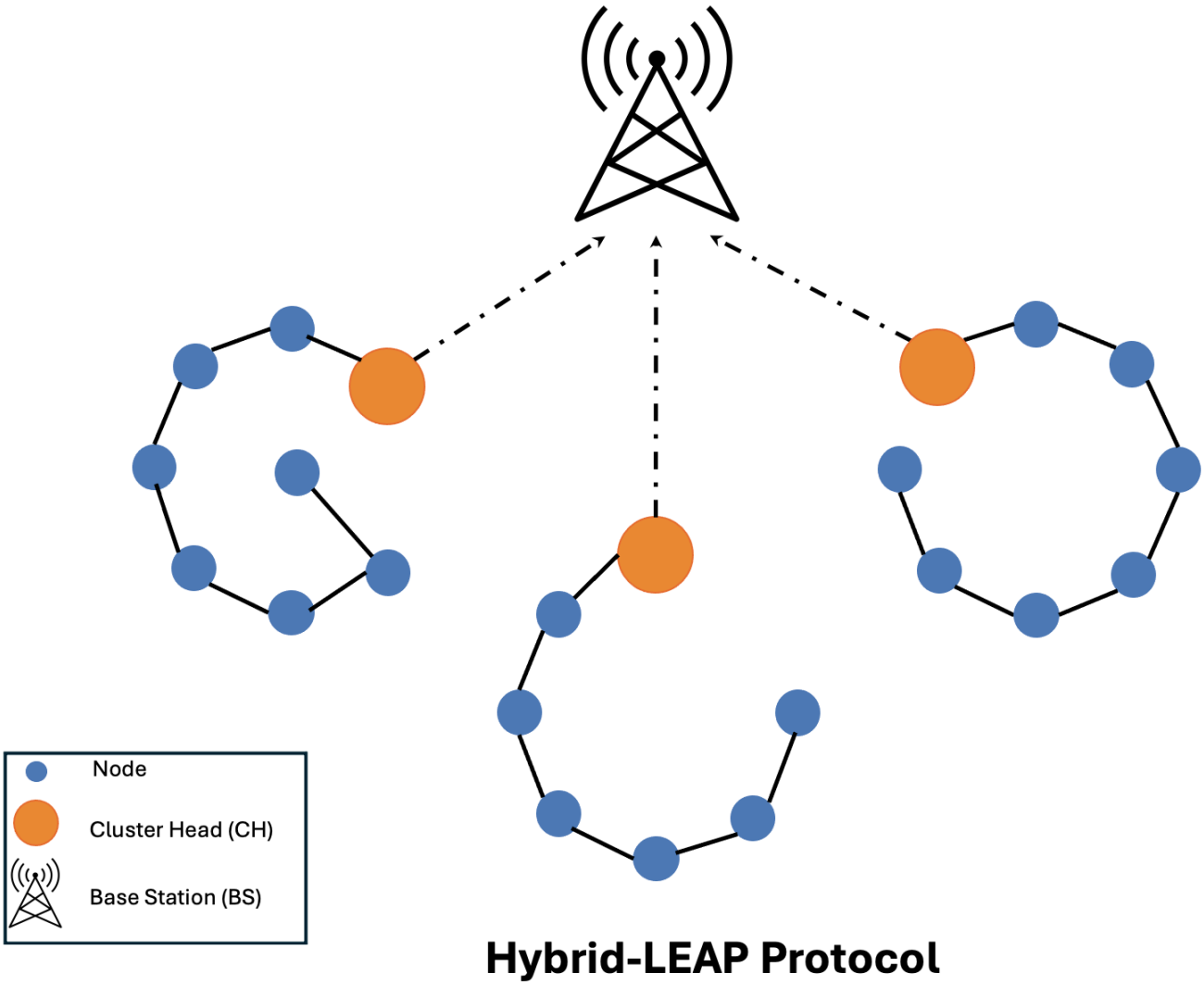


Figure 3

Hybrid LEAP Protocol

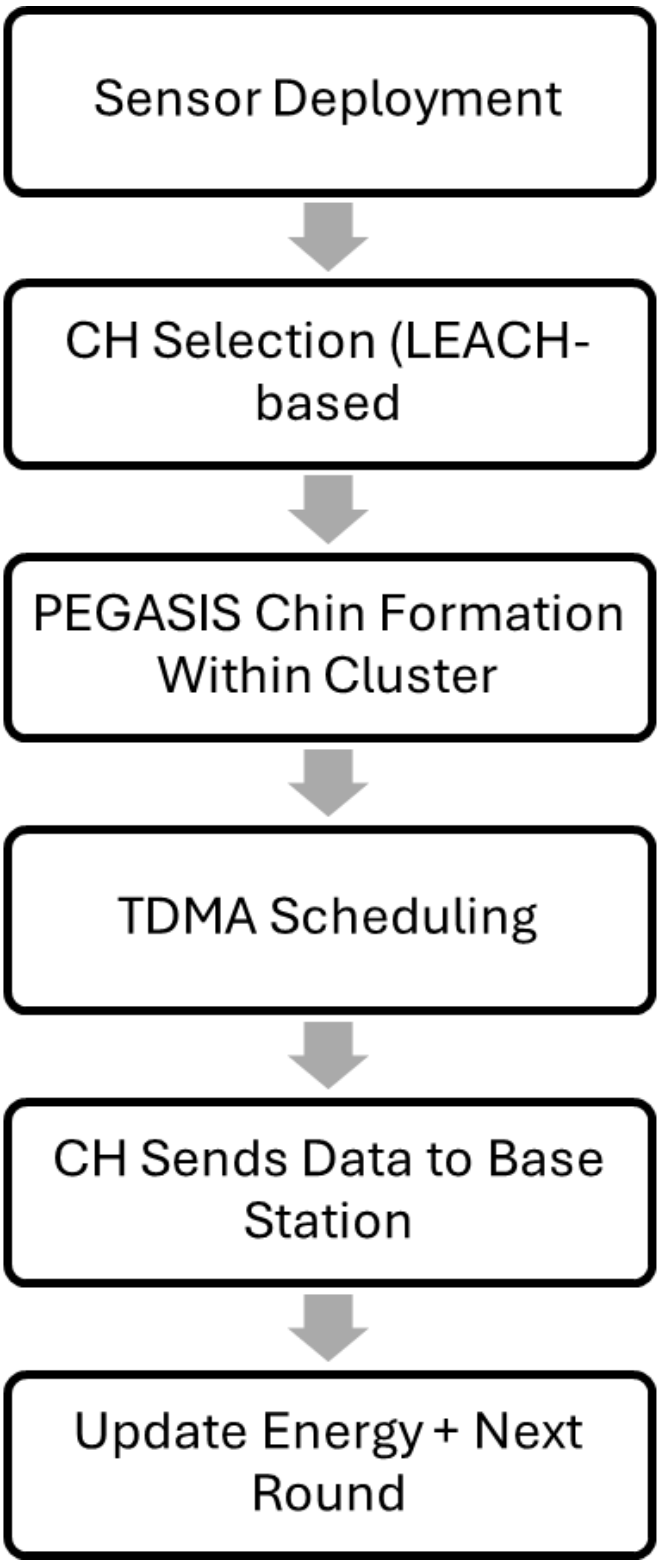


Figure 4

Methodology Diagram

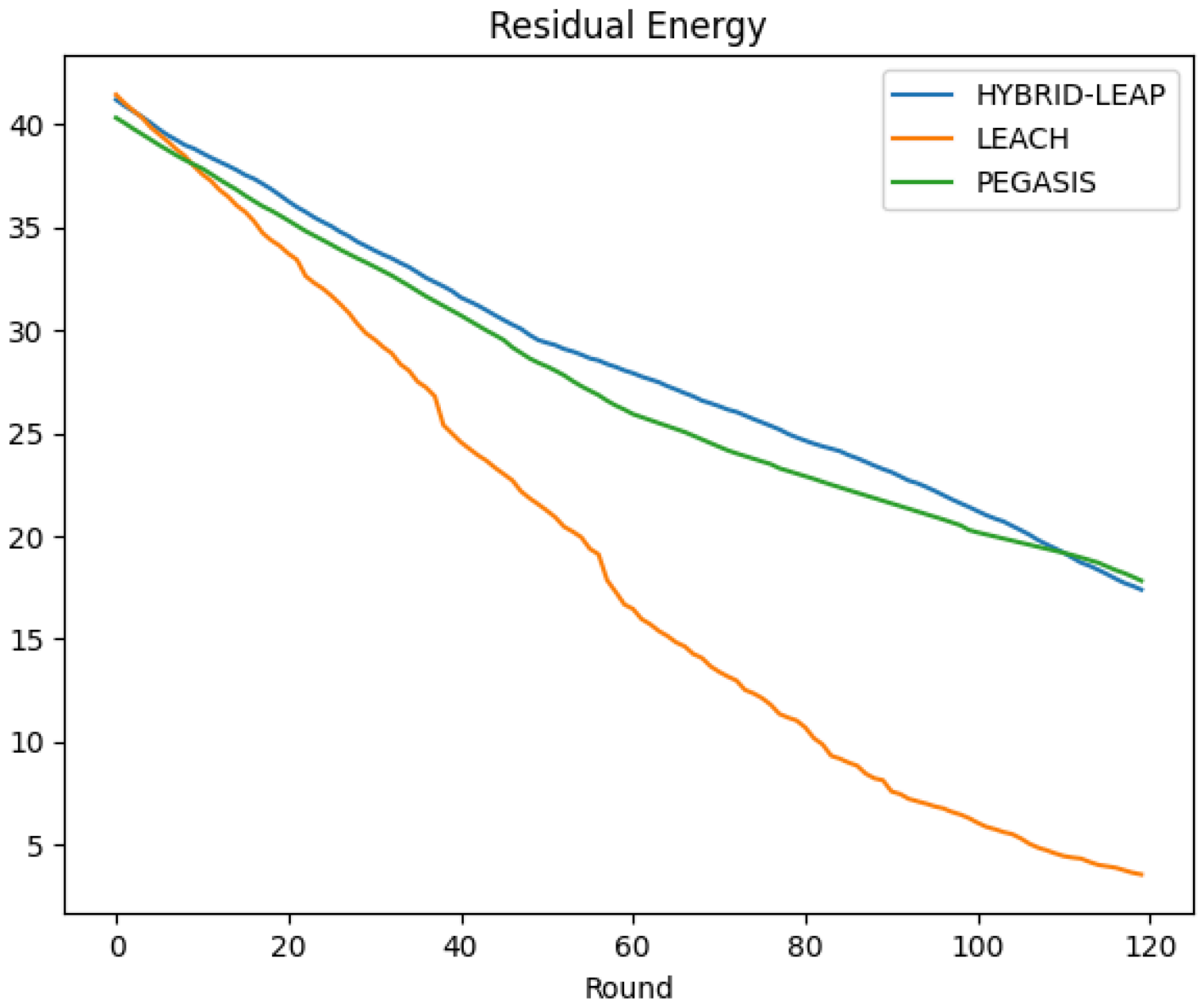


Figure 5

Network Lifetime: Residual Energy per Round

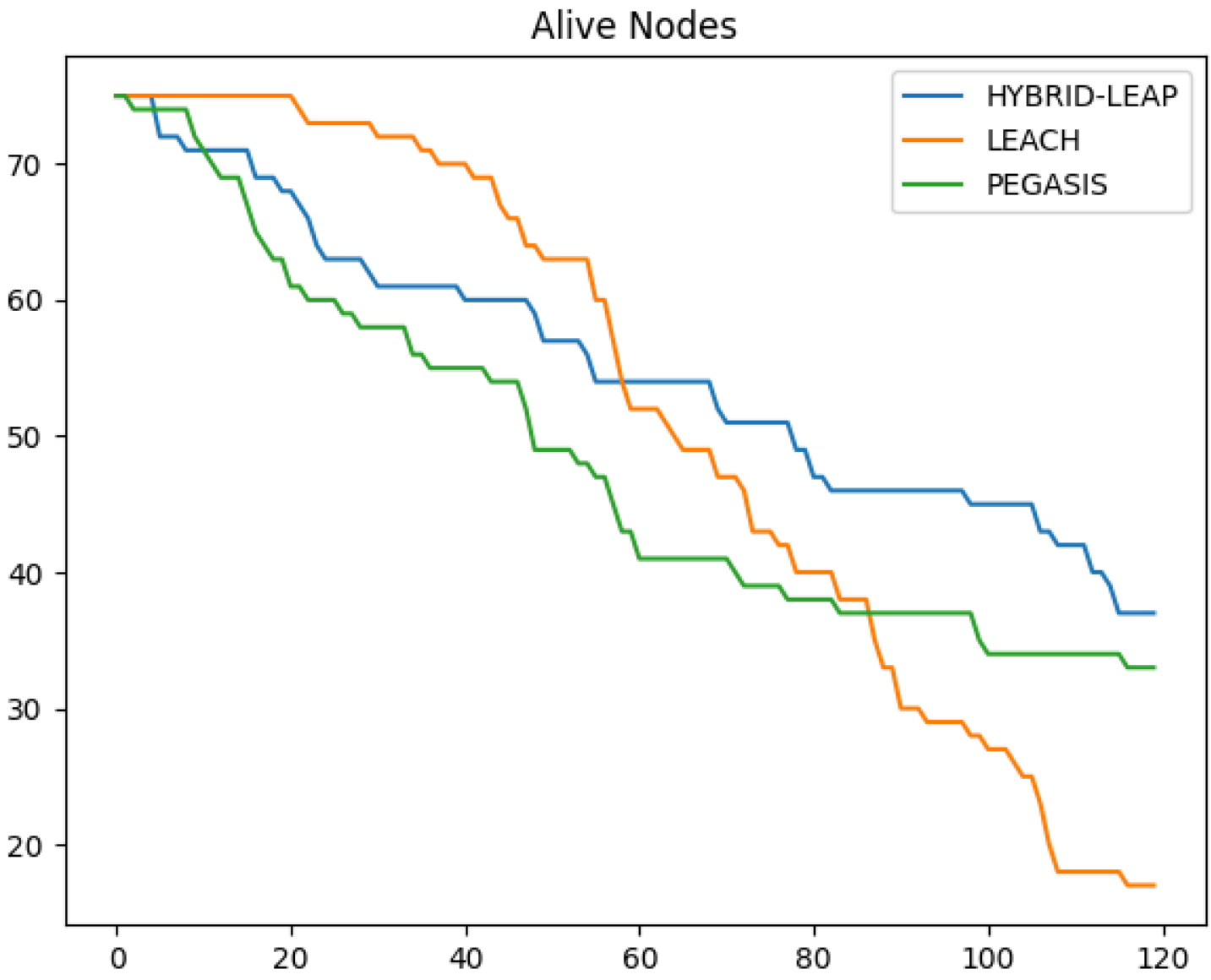


Figure 6

Alive Nodes per Round

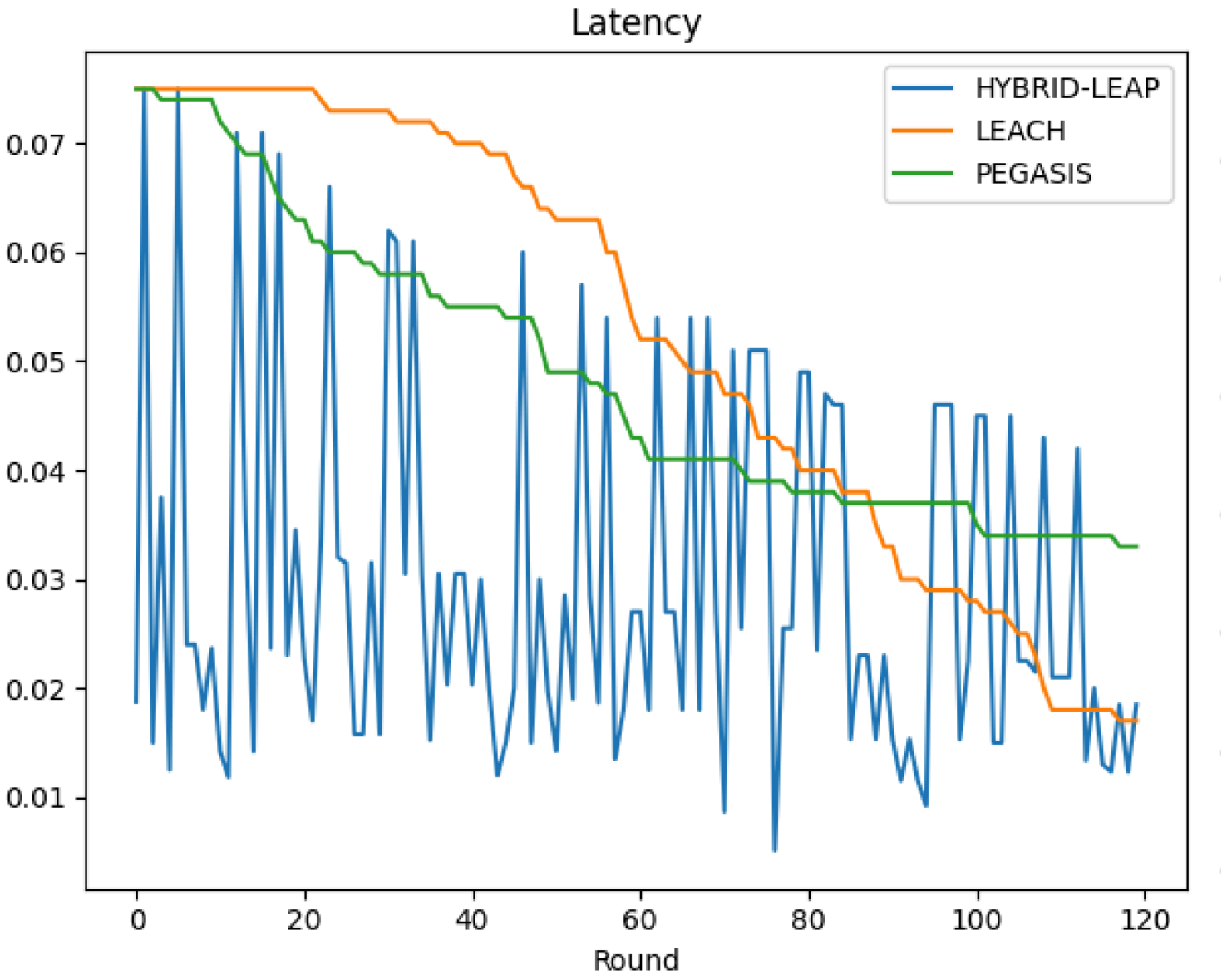


Figure 7

Average Latency per Round

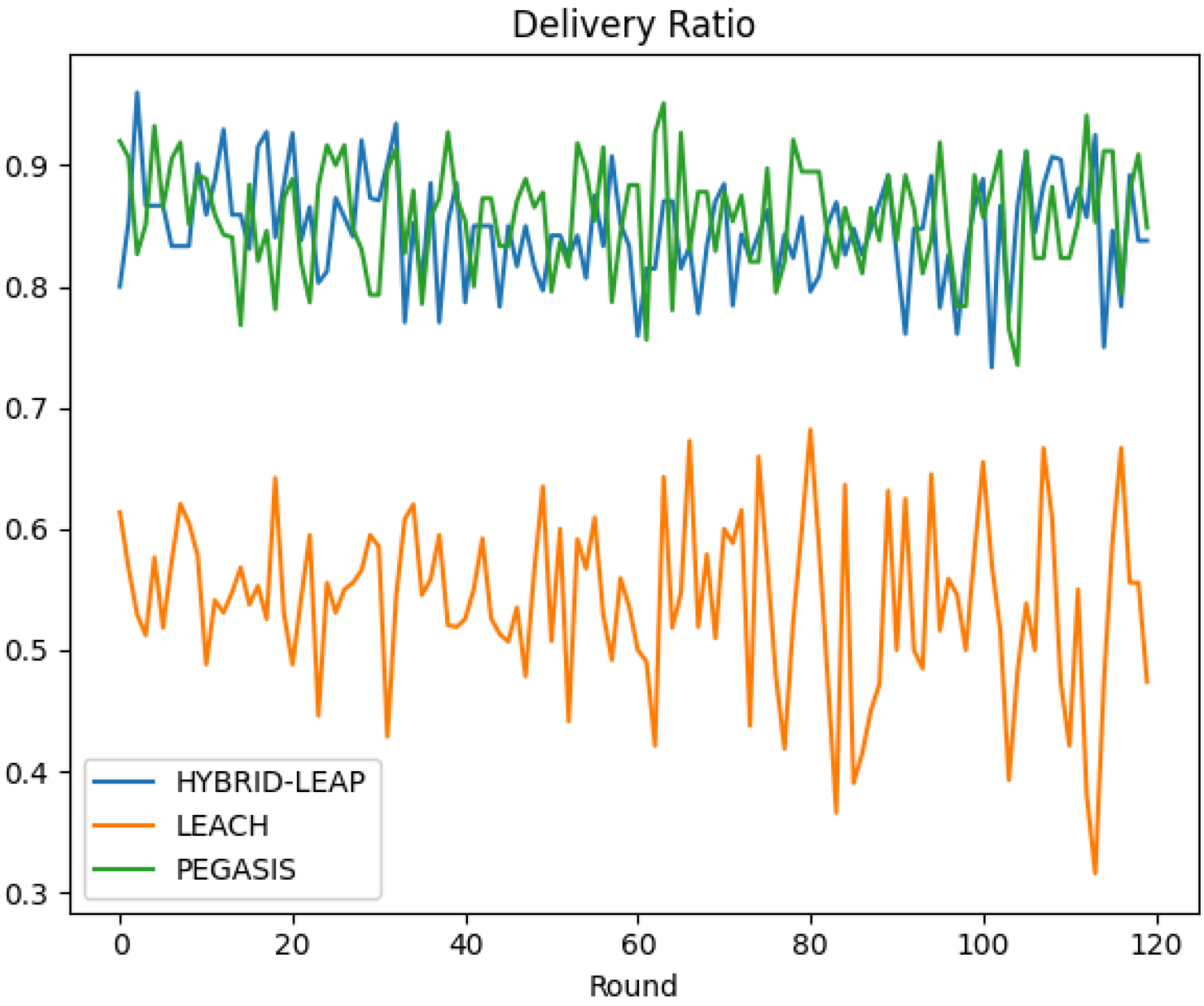


Figure 8

Packet Delivery Ratio per Round