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Design and Performance Evaluation of Energy-Efficient Routing Protocols for Scalable IoT-Enabled Wireless Sensors Networks in Smart Environments

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Abstract

The high growth rate of the Internet of Things (IoT) system augmented the demand of energy-efficient and scalable routing protocol in Wireless Sensor Networks (WSNs), most notably in smart infrastructures, urban systems, precision agriculture, and industrial automation. In this paper, the authors are to design and test the performance of three commonly known energy-optimized routing protocols commonly cited in the literature namely LEACH, PEGASIS, and RPL modified to be used in IoT-based WSNs. An extensive simulation model based on NS-3 and MATLAB was designed to rate the performances of each of the protocols in our various simulation parameters such as the energy consumption, packet delivery ratio (PDR), network lifetime, and scalability with dynamic node density. The findings reveal that RPL has better network scalability and network stability with more than 95 percent PDR in densely deployed networks and supports increased node uptime. LEACH is not scalable, but applies a cluster-based architecture to achieve competitive energy efficiency in terms of small networks. The PEGASIS has satisfactory performance in moderate-density situation with low transmission overhead. These results give desirable design recommendations in choosing optimum routing protocols that match requirements of the IoT applications. This study has been able to help in the development of sustainable and high-performance WSN architectures to facilitate the further usage of intelligent and energy-aware IoT solutions on real-life smart environments.

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Introduction

Wireless Sensor Networks (WSNs) are a core element of Internet of Things (IoT) systems, which support distributed sensing, data gathering, and real-time communication in smart environments, such as smart cities, precision agriculture, environment conditions supervision, industrial automation and so on. Since the size of the interconnected IoT devices is exponentially increasing, the design of energy-efficient and robust routing protocols now represents a serious problem because of the limited resources of sensor nodes when considering their power, processing, and memory capabilities.[7]

Many routing protocols have been suggested to reduce energy usage and to enhance network performance in WSNs. Nodes are so arranged in groupings or clusters with cluster head roles rotated in cluster based protocols e.g. Low-Energy Adaptive Clustering Hierarchy (LEACH)[1] to lower transmission overhead. Chain-based methods such as Power-Efficient Gathering in Sensor Information Systems (PEGASIS)[2] require little data redundancy transmission since they place the nodes in chains. Very recently, IoT applications have been standardised with the IPv6 Routing Protocol for Low-Power and Lossy Network (RPL) that provides support to scale-able, dynamic topologies that are defined in the Directed Acyclic Graph (DAG) structure.

Although such steps have been made, the current protocols have some significant caveats. LEACH and PEGASIS are mainly applicable in small/homogeneous approaches and in many cases are not flexible to dynamic topology. Although scalable, RPL may become over-head-prone due to the exchanges of control messages, and may need to be fine-tuned to operate efficiently energy wise in a dense network. In addition, there is less evaluation of these protocols on IoT-enabled environments in a comprehensive way.[5]

The current paper is going to fill these gaps by designing performance analysis of LEACH, PEGASIS and RPL across various scenarios of deployment. It is hoped that the scope of trade-offs between energy consumption, packet delivery ratio (PDR), network lifetime, and scalability will be compared to offer realistic idea in selection of protocols in practical cases in Internet of Things (IoT).

Related Work

Many routing protocols have been deployed in the last 20 years to deal with the issue of energy and scalability in Wireless Sensor Networks (WSNs) especially in the confines of IoT applications.

Low-Energy Adaptive Clustering Hierarchy(LEACH), first proposed by Heinzelman et al.[1] is one of the oldest and most influential solutions. LEACH sets up a clustering type mechanism in which nodes become clustered and the cluster head position is randomized in the network. It is through this technique that a lot of energy is saved in small to medium sized networks particularly where nodes are homogenous, and deployment is stationary. Lindsey and Raghavendra[2] furthered the concept of energy conservation to PEGASIS (Power-Efficient Gathering in Sensor Information Systems) in which a chain of sensor nodes is formed as a method of data aggregation and forwarding.[8] PEGASIS reduces the number of transmission by letting in every round only one node on the chain to have communication with the base station. It is effective to minimize transmission overhead, but its practicality is reduced in very dynamic, or large-scale networks by latency and the complexity of chain maintenance. The IETF made a more recent specification of the Routing Protocol for Low-Power and Lossy Networks (RPL)[3] to support the needs of the scalable and heterogeneous IoT implementations. In IPv6 enabled networks, RPL creates a Destination-Oriented Directed Acyclic Graph (DODAG) to effectively route the data.[6] However, RPL is able to support multi-hop, dynamic routing, at the cost of control overhead and losses in energy balancing caused by high-density deployments.[4]

Nevertheless, under these improvements, there have been suspicion of constraints to implementing these protocols in a diversified and large scale smart environment. The LEACH and PEGASIS protocols work best in static and homogeneous networks and RPL is tedious to execute to make it perform well in energy limited IoTs. No thorough comparative assessment is also carried out under different densities of networks and circumstances of use of protocols, preventing their optimal choice.

This paper intends to fill this gap by conducting a fair performance analysis of LEACH, PEGASIS, and RPL based on conventional metrics (namely network lifetime, packet delivery ratio (PDR)); energy consumption, and scalability in smart IoT contexts)..

System Architecture

The intended architecture of proposed system represents a heterogeneous IoT-enabled Wireless Sensor Network (WSN) being implemented in a smart environment, e.g., smart campus, precision agriculture, or industrial IoT system. The design of the architecture is aimed at being energy efficient, scaleable and provides low red latency in communicating data with a wide range of monitoring applications in real-time environments.

Network Topology and Components

The system has three major layers, which include:

- Sensor Nodes (Edges Layer): There are static wireless sensor nodes that are distributed in the area of interest to sense the environmental or operating parameters. Such nodes are powered by batteries, they have low-power microcontrollers and communication is done using IEEE 802.15.4 compliant transceivers. Initialisation places all nodes with the same amount of energy, and each node senses and sends data periodically to the closest gateway node.
- IoT Gateway Nodes (Aggregation Layer): These nodes are local aggregators, and routers. It is a set of devices enabled with IoT that is more powerful in terms of processing, and performs the functions of data fusion, initial analytics, and transmitting the processed information to the base station or any cloud facility. They connect to the sensor nodes via low-power wireless connections and to the cloud via Wi-FI, LTE or Ethernet.
- Base Station / Cloud (Application Layer):On top level, a centralized base station / cloud receives

and stores aggregated information and can further process it, visualize and make decisions. This layer can also contain AI powered analytics to detect anomalies, forecast trends, or to control actuations.

Figure 1 shows the interaction between the Edge, Aggregation and Application Layers of the IoT enabled WSN architecture.

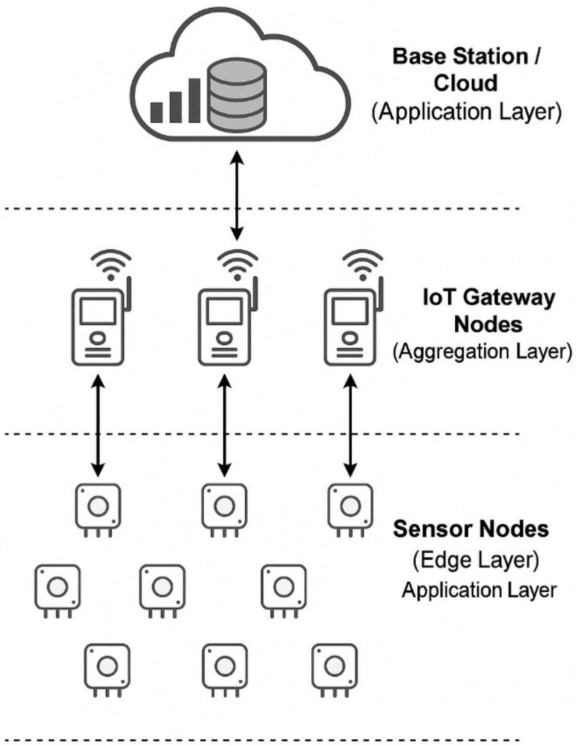

Fig. 1: Three-layer IoT-enabled WSN architecture illustrating sensor nodes, IoT gateway nodes, and the cloud-based application layer.

Fig. 1 Layered architecture of an IoT-enabled Wireless Sensor Network (WSN) where there is the edge layer being the sensor nodes that is fixed, the aggregation layer consisting of IoT gateway nodes that provides figure to data fusion and the application layer as the analytics and decision-making facility of a cloud or base station.

Operational Assumptions

The design of the system is under pinned with the following assumptions:

- Sensor nodes are stationary and evenly distributed on the area of monitoring.
- The nodes are provided with an initial energy budget which is fixed, thereby stressing the relevance of energy-aware routing strategies.
- The network is based on a fixed topology, and sensor nodes transmit the information at a common frequency, which points to the general application of WSN in infrastructure and environmental monitoring.
- The MAC protocol is IEEE 802.15.4 that provides low-power communication, as well as CSMA/CA channel access mechanisms. This MAC protocol is often applied in a wireless personal area network (WPAN) with use of low-rate (LR-WPAN) wireless protocols such as ZigBee and 6LoWPAN stacks.

The kernel of the system model is illustrated in Fig. 2 that visually shows the network constraints and protocol standards that are implemented in this study.

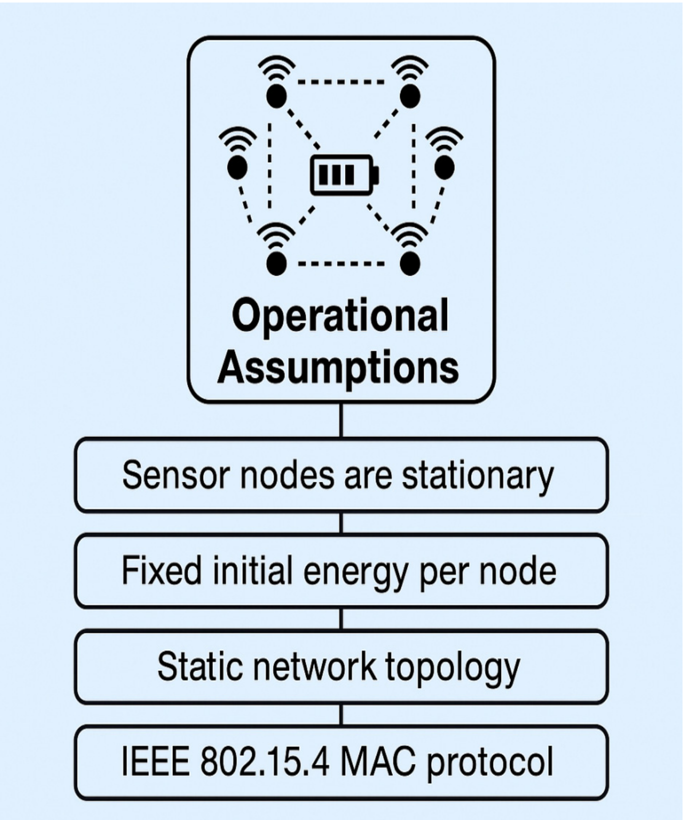

Fig.2: Operational Assumptions for IoT-Enabled WSN Deployment

Fig. 2. Operational assumptions of the IOT-enabled wireless sensor network model such as stationary sensor nodes, fixed initial energy assignment, no changes in the network topology, use of the IEEE 802.15.4 MAC protocol that supports low-power communications are summarized.

Communication Flow

In the course of work, sensor nodes are sent to scan the environmental data periodically and send it to the closest gateway node by multi-hop communication or single-hop, depending on the routing protocol used (LEACH, PEGASIS, or RPL). In-network aggregation of data is done through the gateway nodes that transmit the compressed data to the cloud server or base station to be processed on an application layer. As shown in Fig. 3, the data transmission between the sensor nodes and the gateway as well as to cloud is carried out step-by-step.

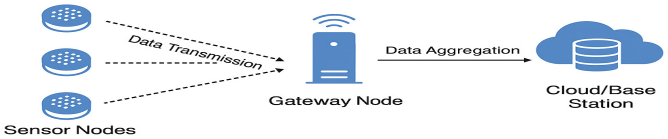

Fig. 3. Communication Flow in an IoT-Enabled Wireless Sensor Network

Fig. 3. Illustration of the data flow transmission in an IoT-enabled WSN: the sensor nodes communicate data periodically to the gateway node through single-hop or multi-hop communication; the gateway acts as the data aggregator and sends the data to cloud or base-station where it will be processed by the application.

Routing Protocol Design

Robust data delivery, extended network life and scalable communication of IoT-enabled Wireless Sensor Networks (WSNs) is important as a way of efficiently achieving routing. Three well-known energy-aware routing protocols, LEACH, PEGASIS and RPL are introduced in this section, with each one of them corresponding to a different routing paradigm and being appropriate to different deployment levels and traffic patterns. The chosen protocols are compared concerning architecture, the way they work, and their usability in smart environment settings.

LEACH: Low-Energy Adaptive Clustering Hierarchy

LEACH is a hierarchical clustering routing protocol operating in WSNs that aims at reducing overall energy consumed in serving static and homogeneous WSN.[1] The protocol also groups sensor nodes in compact clusters whereby each cluster of nodes has a special node known as Cluster Head (CH). The head of cluster changes after some period of time so as to equalise energy dissipation throughout the network.

- Clustering Mechanism: Nodes are self-organized into clusters with reference to their proximity. Individual CHs compile the data of the cluster people and send it to the base station.
- Random CH Rotation: The rotational possibility of cluster heads is performed in a probabilistic method that avoids energy hotspots and makes the network lifetime longer.
- Use Case Suitability: LEACH is best suitable in low-mobility, compact network e.g. where topology is stationary and reasonably high uniform power consumption is feasible.

PEGASIS: Power-Efficient Gathering in Sensor Information Systems

PEGASIS uses a chain-like system of collecting data in order to lessen the energy used in transmission and cut out on redundant communications.[2] PEGASIS creates a linear chain of sensor nodes rather than the multiple cluster heads.

- Chain Formation: It is composed of nodes that are linked in a chain such that only one node is allowed to communicate with a neighbor which is at a close distance.
- Leader Node Transmission: There is a specific leader node setup for every round transmission to provide aggregated information to the base station hence adding less cost in total transmission.
- Energy Efficiency: PEGASIS remarkably reduces the number of long-distance transmissions yet it might cause more delay in large or irregularly distributed networks.
- Deployment Scenario: It will work best on medium-density WSNs where the topology changes are fewer.

RPL: Routing Protocol for Low-Power and Lossy Networks

RPL is an IPv6 protocol, a distance-vector routing protocol, and standardized by IETF, to operate in low power and lossy networks (LLNs).[3] It is the one which is specifically used to support a variety of IoT applications that demand high scalability and multi-hop communicative solutions.

- Topology Building: RPL uses a Destination-Oriented Direct Acyclic Graph (DODAG) having the sink node or base station as the root. Nodes choose preferred parents using some metric on the links, either ETX (Expected Transmission Count) or residual energy.
- Multi-Hop and Loop-Free: RPL is multi-hop and IPv6 routing protocol, and it can support a loop-free path using the rank-based mechanisms.
- Adaptability: RPL is flexible as it allows configurable Objective Functions (OFs) to use an energy-aware, latency-sensitive, or load-balanced routing algorithm to work in large

scale heterogeneous and dynamically changing IoT deployments.

The different routing dimensions covered in each of the above protocols are different. Their performance under different situational scenarios is later compared in subsequent sections (Section VI) so as to determine which protocol gives the best guidance to be followed depending on application requirements in a specific scenario. An illustrative comparative description of the operational attributes of the LEACH, PEGASIS and RPL routing protocols is presented as shown in Fig. 4.

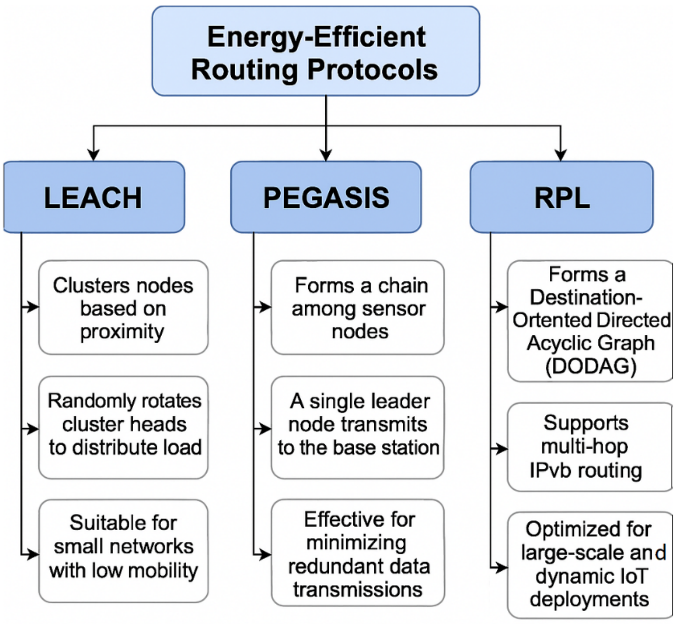

Fig. 4: Flowchart comparison of LEACH, PEGASIS, and RPL routing protocols in IoT-enabled Wireless Sensor Networks, highlighting their structural models, energy strategies, and application suitability.

Simulation Setup

A sophisticated simulation environment was created in order to determine the capability of the identified routing protocols in the IoT-enabled Wireless Sensor Networks (WSNs), which include LEACH, PEGASIS, and RPL. Simulations were carried out with unified parameters to make them be comparable with all protocols.

Simulation Tools

The two platforms employed on the simulation framework were industry standard:

- NS-3: Used in simulation and analysis of the RPL protocol because it natively simulates IPv6 networking, low-power lossy networks (LLNs) and real world MAC/PHY layers.
- MATLAB: To implement and test LEACH and PEGASIS protocols, this software has the advantage of enabling fine control over clustering and chain-oriented routing protocols behavior in specified scenarios.

Deployment Environment

The studies were simulated in a square area of 500 m on a side, which would be a realistic area of deployment of a smart environment: an agricultural field, industrial area or a monitoring grid in the city. To test the protocol responsiveness and scalability, the range of deploying sensor nodes varied by keeping a control of 100 to 500 sensor nodes.

We assumed that each node is stationary, that is uniformly distributed and each node has one-time energy to simulate energy-constrained WSN deployments.

Performance Metrics

Evaluation of each routing protocol was estimated using the following key performance indicators (KPIs):

- Network Lifetime: The duration that passes before a certain percentage (e.g. 50%, 100%) of sensor nodes runs out of energy.
- Average Energy Consumption: Represents the overall consumption of energy on the network which shows efficiency of the protocol.
- Packet Delivery Ratio (PDR): Packet delivery Successful packet reception by sink/ sum of packets generated by sensor nodes.
- Latency: This is defined as an average end-to-end delay in a packet after it has left its source and arrived at its destination.

All these metrics form the energy sustainability, reliability, as well as responsiveness of the network at varied protocol setups.

Simulation Parameters

Table 1 is a description of the baseline simulation parameters used in every protocol.

Table 1: Simulation Parameters

Parameter	Value
Transmission Range	50 meters
Initial Energy	2 Joules
Packet Size	64 bytes
Simulation Time	500 seconds
Deployment Area	500 × 500 m^2
Number of Nodes	100-500

This configuration allows objective and reproducible analysis of routing protocols performance under different WSN sizes and energy constraints so that the results could be applicable to practice in IoT. Fig. 5 presents the simulation scenario such as node distribution, transmission area and the area of deployment.

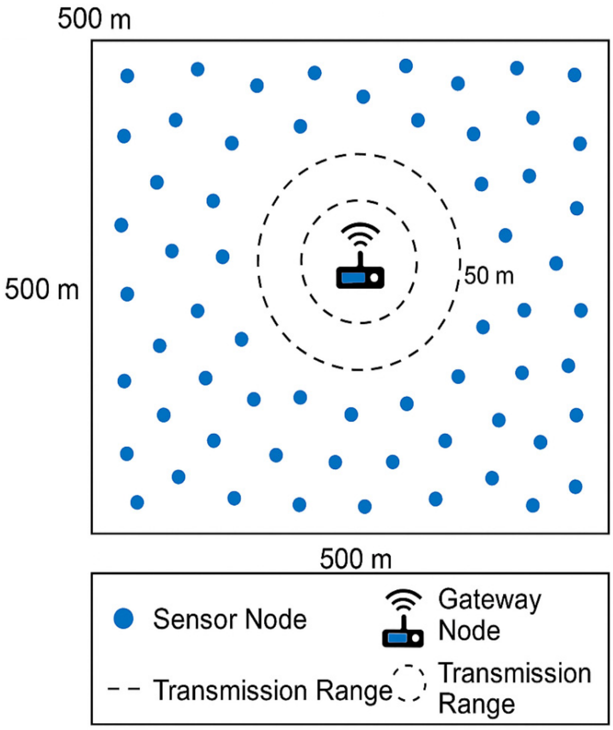

Fig. 5: Simulation setup of the IoT-enabled WSN showing uniformly distributed sensor nodes within a 500 × 500 m² area, a centrally positioned gateway node, and a 50-meter transmission range.

Results and Discussion

In this part, a detailed analysis of the energy-efficient routing protocols as LEACH, PEGASIS, and RPL, on the basis of the simulation framework outlined in Section V was carried out. Its performance metrics are energy efficiency, network lifetime, packet delivery ratio (PDR), and scalability. To be able to check its compatibility to level of deployment of a specific node in an IoT-based WSN, each of the two protocols were subjected to different ranges of node densities (100-500 nodes).

Energy Consumption

Energy is a key factor in WSN, and nodes are normally battery-powered and have limited energy profiles. At probably sparse network (<=200 nodes) configurations, LEACH had the least average energy consumption as shown in Fig. 6 because its periodic cluster head rotation makes the transmission load characteristics distribute. PegasIS used less energy by creating linear chain and reducing base to base transmissions. In low-density environments, RPL was a little bit more energy consuming in terms of control overhead, but it was otherwise equally energy efficient with all node densities whereas CoAP suffered energy inefficiency when the node density increased, and it was not a promising protocol to use in large-scale dynamically configured IoT systems.

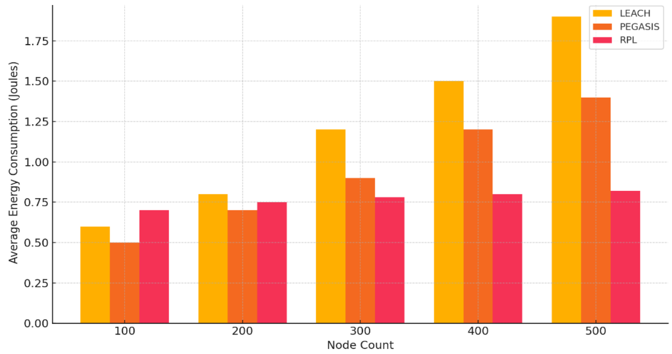

Fig. 6. Average energy consumption vs. node count for LEACH, PEGASIS, and RPL protocols.

Network Lifetime

The lifespan of the network was quantified as the time taken before a vast number of nodes (50 percent and 80 percent) got exhausted. RPL maintained more than 80 percent node survivability till the end of the simulation (500 seconds), as Table 2 shows due to its adaptive selection of parent nodes, and the balanced multi-hop forwarding. LEACH showed a sharp performance deterioration after the energy in the nodes fell below the 60 percent mark because overhead of cluster reformation was too frequent. PEGASIS performed moderately well and has the advantage of diminished inter-node transmissions and the drawback of possible chain bottle necks in high density.

Packet Delivery Ratio (PDR)

The reliability of communication and the robustness of its routing are reflected by packet delivery ratio. As shown in Fig. 7, RPL persistently supported a PDR higher than 95 percent in any case, which can be put at the mercy of its DODAG-representative topology and embedded formalities of route maintenance. Conversely, LEACH and PEGASIS suffered significant packet loss with an increase in the number of nodes because of overloading in cluster heads and chain heads respectively. These results validate the need of having proper protocol structure when maintaining data integrity in dense deployments.

Scalability Analysis

WSNs that are supposed to perform monitoring in large areas should be scalable. The results of simulations

Table 2: Performance Comparison of Routing Protocols

Metric	LEACH	PEGASIS	RPL
Avg. Energy Consumption	Low (sparse networks)	Moderate	Low-Moderate (stable)
Network Lifetime	Short-Medium	Medium	Long
Packet Delivery Ratio	85-90%	88-92%	>95%
Scalability	Poor beyond 200 nodes	Moderate	High (up to 500 nodes)

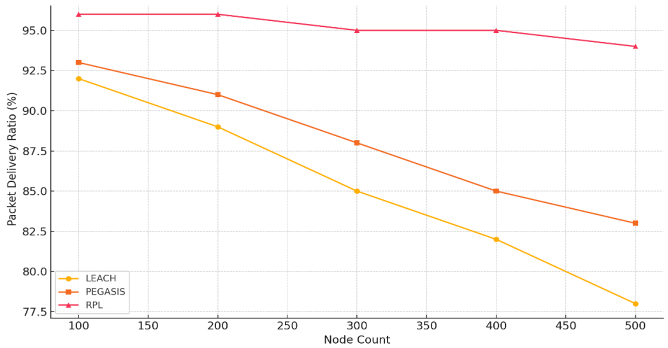

Fig. 7: Packet delivery ratio for various routing protocols across increasing node densities.

revealed that RPL is able to scale to 500 nodes effectively with no loss of PDR or energy efficiency. The hierarchical routing topology and flexibility to topological changes are factors that made it resilient. LEACH however faced massive performance failure after 200 nodes as the cluster heads got saturated, and more inter-cluster interference occurred. The less affected PEGASIS was prone to delays because of chain length and minimal parallel data paths.

The comparative review indicates that RPL outperforms in all the key metrics across the board, especially when it comes to large-scale deploying of IoT. Nevertheless, LEACH is a low-powered scheme to use in small and stationary settings, and PEGASIS is a way to save energy in the medium-dense environment. Such observations can lead the selection of protocols using according to the deployment large, energy limitations, and application priorities.

Conclusion and Future Work

This paper showed extensive design as well as performance analysis of three outstanding energy-efficient routing protocols namely LEACH, PEGASIS, and RPL protocols in IoT-enabled Wireless Sensor Networks (WSNs) implemented in smart environment. With a common simulation model in NS-3 and MATLAB, each protocol was evaluated on several performance factors along the line of energy consumption, network lifetime, packet delivery ratio (PDR) and scalable performance in terms of node density. The results indicate that RPL is more scalable, more reliable and provides more consistent performance in dense and dynamic network environments, which is appropriate in large scale intelligent applications/infrastructures like monitoring infrastructures in cities and industrial automation. LEACH was demonstrated to be competitive in terms of energy efficiency in sparse networks owing to its cluster-based architecture and hence can be adopted where energy efficiency is limited and deployment levels are low. PEGASIS showed moderate performance, as the energy consumption is lower when compared to chain-based aggregation strategy. The strategy however causes latency in high density settings.

The major contribution of the presented work in this area is a comparative analysis framework providing the ground of pragmatic understanding of protocol choice with references to the requirements of IoT application and limits of its deployment. What is more, the use of realistic simulation tools and multi-metric analysis increases the applicability and repeatability of the outcomes.

Future directions will set to the realization of hybrid routing schemes intermarrying the virtues of clustering (such as in LEACH) and graph-based routing (as in RPL), coupled with adaptive machine learning techniques to realize dynamic topology maintenance, energy forecasts and smart routing decisions. The option of integrating reinforcement learning and federated intelligence in the edge is going to be explored so that next-generation WSN-IoT ecosystems with increased autonomy and resiliency can be created.

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