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Smart Data Management in IoT: Leveraging Wireless Sensor Networks for Efficient Information Processing

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Abstract: - The exponential growth of the Internet of Things (IoT) has resulted in an unprecedented surge in data, requiring the development of innovative methods to effectively handle and analyze information. This study investigates the [1]management of data in a smart manner within the IoT framework. It specifically examines the utilization of Wireless Sensor Networks (WSN) to accomplish effective information processing. The study examines two main elements: the utilization of Run-Length Encoding (RLE) for data compression and the incorporation of energy-aware extensions into the Ad Hoc On-Demand Distance Vector (AODV-EA) routing protocol. The purpose of employing Run-Length Encoding (RLE) is to enhance the efficiency of transmitting and storing data by effectively representing recurring sequences in sensor data. This compression technique is especially applicable for resource-constrained WSN where the conservation of bandwidth and energy is of utmost importance. The study investigates how communication protocols can be improved by integrating energy-conscious extensions into AODV. The objective of this approach is to enhance the energy efficiency of communication in WSN by taking into account the energy levels of each node in real-time when establishing routes. The NS-3 simulation framework is used to assess the proposed methodologies. NS-3 offers a flexible and expandable framework for simulating communication protocols and network scenarios. The study evaluates the performance of the integrated system by using simulation and analyzing important metrics such as accuracy, precision, Latency, data compression and energy efficiency. The research findings provide valuable insights into the field of Smart Data Management in IoT, demonstrating how the combination of data compression and energy-aware routing protocols can improve the efficiency of Wireless Sensor Networks for information processing.

General Terms:: Internet of Things, Wireless sensor network, Sensor data, Ad Hoc On-Demand Distance Vector.

Keywords: Internet of Things, Ad Hoc On-Demand Distance Vector (AODV), WSN, Energy-Aware, Compression.

I. INTRODUCTION

The IoT has become a powerful force in the age of widespread connectivity, linking devices, sensors, and systems to facilitate effortless communication and data sharing. WSN are central to this interconnected web, as they play a crucial role in gathering and transmitting information from the physical world to the digital domain. With the increasing volume and complexity of data generated by IoT devices and WSN, it is crucial to prioritize efficient information processing[1], [2].

The concept of the Internet of Things envisions a future in which ordinary objects possess the ability to communicate, analyze data, and make informed decisions, thanks to their intelligence. At the core of this vision are Wireless Sensor Networks, which are networks of sensors spread out in space and working together to monitor and gather data from their surroundings. These networks serve as the fundamental infrastructure for IoT applications, encompassing a wide range of uses such as smart cities, industrial automation, and environmental monitoring[3].

The exponential expansion of the IoT pertains to the unparalleled spread of networked devices and sensors, resulting in the generation of immense volumes of data. The proliferation of IoT devices, encompassing a wide range of smart home appliances and industrial sensors, presents substantial obstacles in the realm of data management. The vast amount and wide range of data produced by these devices necessitate inventive solutions for effective storage, transmission, and analysis. Efficiently handling the large amount of data becomes essential, necessitating

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sophisticated techniques to maximize resource usage, reduce bandwidth consumption, and tackle the energy limitations commonly linked to IoT devices. Efficient and meaningful information processing in the IoT ecosystem relies heavily on smart data management. The vast magnitude and wide-ranging variety of data produced by IoT devices require advanced approaches for gathering, retaining, and examining. Integrating intelligent data management techniques is crucial in this situation to obtain practical insights, optimize resource usage, and improve system performance[4].

Although the potential of IoT and WSN is promising, there are numerous challenges in the field of data management. The decentralized nature of WSN, limited resources of sensor nodes, and the dynamic nature of IoT environments pose challenges in achieving smooth and efficient data management. These challenges highlight the necessity for inventive solutions to tackle problems such as delay, power usage, and the efficient utilization of accessible bandwidth[4]–[6]. This study focuses on evaluating the effectiveness of Run-Length Encoding (RLE) among various data compression techniques. RLE, a straightforward yet potent compression technique, performs exceptionally well in situations where consecutive repeated values are abundant. This study investigates the incorporation of energy-aware enhancements into the Ad Hoc On-Demand Distance Vector (AODV-EA) routing protocol, with the goal of improving energy efficiency. AODV-EA incorporates the energy levels of individual nodes in real-time while establishing routes, thereby enhancing the sustainability and resilience of WSN.

To thoroughly assess the suggested methodologies, we utilize the ns-3 simulation framework. Through the utilization of ns-3, our objective is to employ simulation and analysis to evaluate the effectiveness of RLE and AODV-EA in a controlled setting. This will enable a thorough evaluation of their influence on data compression, energy efficiency, and the overall dynamics of the network. This study provides a detailed investigation of RLE for compressing data and the incorporation of energy-conscious enhancements into the AODV routing protocol to enable energy-efficient communication in Wireless Sensor Networks. The results of this research project have the potential to improve the efficiency of resource usage, extend the lifespan of networks, and enhance the capabilities of WSN Networks in the era of the IoT.

The rapid expansion of the IoT has resulted in an unparalleled increase in data volume in WSN, which presents difficulties in efficient data handling. Effectively managing and transmitting this extensive volume of data in resource-limited WSN environments is of utmost importance. Tackling these obstacles is crucial to guaranteeing the smooth implementation of IoT applications in practical situations.

Objectives:

a. Improve Data Transmission Efficiency: Create techniques to optimize the effectiveness of data transmission in Wireless Sensor Networks (WSN), with a specific emphasis on reducing bandwidth usage while maintaining the integrity of the transmitted data.
b. Enhance Energy Efficiency: Explore methods to enhance the energy efficiency of WSN, specifically focusing on routing protocols. This involves effectively managing energy resources to extend the overall lifespan of the network.
c. Evaluate Compression Techniques: Assess the efficacy of Run-Length Encoding (RLE) as a data compression technique in Wireless Sensor Networks (WSN).
d. Enhance Routing Protocols: Examine the incorporation of the Ad Hoc On-Demand Distance Vector with Energy-Aware Extensions (AODV-EA) routing protocol to enhance energy-efficient routing. Assess its influence on the overall efficiency of the network and the allocation of energy among individual nodes.

Justification for Method Selection:

a. Run-Length Encoding (RLE).
   Efficiency in Resource-Constrained Environments: RLE is chosen for its efficiency in representing recurring sequences in sensor data, making it particularly suitable for resource-constrained WSN. RLE, or Run-Length Encoding, optimizes bandwidth usage and conserves energy by reducing the amount of transmitted data.
b. Ad Hoc On-Demand Distance Vector with Energy-Aware Extensions (AODV-EA).
   The AODV-EA protocol is chosen for its ability to incorporate real-time energy levels into the route discovery process in energy-aware routing. This guarantees a fair allocation of energy usage among nodes, thereby improving the overall energy efficiency of the WSN. The purpose of the extensions is to enhance the longevity of the network by efficiently overseeing energy resources.

II. LITERATURE REVIEW

Due to unprecedented interconnectedness, the IoT generates massive data from various sources. IoT applications need good data management. Recent research has examined IoT data management issues like security, architecture, energy optimization, and data quality. A literature review of recent advances shows how IoT data management is changing. More research is needed on IoT data security, energy optimization, and new architectures. Data management must be understood in the context of IoT ecosystems, fog computing, and blockchain. IoT applications are growing in healthcare and supply chain management, but they must be thoroughly investigated and customized to address sector-specific challenges. The literature allows for more research to close these gaps and advance IoT data management.

Bohli et al.[7] introduced the SMARTIE project, which focuses on ensuring secure management of IoT data in smart cities. The objective of the project is to augment the security measures of data produced by IoT devices in urban settings. The authors provide a thorough summary of the project, emphasizing its significance within the framework of smart city advancement. Asad et al.[8] introduced a framework to tackle forthcoming challenges in IoT data management. Their work centers around creating a resilient and expandable framework that can effectively manage the growing amount of data produced by IoT devices. The framework is specifically engineered to guarantee optimal data administration and cater to the ever-changing requirements of IoT applications. Ghapar et al.[9] presented a specialized IoT architecture designed specifically for the management of flood data. The authors emphasize the significance of IoT in tackling natural disasters, specifically floods, and suggest an architecture that enables the efficient gathering and administration of flood-related data.

Jiang et al.[10] presented a cross-chain solution that enables the integration of multiple blockchains in the management of IoT data. Their work focuses on resolving the issue of interoperability among diverse blockchains, offering a solution for effortless integration. The suggested method has ramifications for improving the dependability and safety of IoT data administration. Saqlain et al.[11] presented a framework that focuses on managing industrial data in the context of smart manufacturing, using IoT technology. The authors highlight the significance of effective data management in industrial contexts, proposing a framework that integrates IoT technologies to optimize data handling procedures in smart manufacturing environments. Ahmed et al.[12] specifically examined the management of resources in containers for processing data on IoT gateways. They contribute to enhancing the efficiency of resource allocation in IoT environments by utilizing containerization technology. The proposed methodology optimizes data processing on IoT gateways, thereby enhancing overall system efficiency.[13]-[16]

III. METHODOLOGY

1.1 Data Compression with Run-Length Encoding (RLE)

1.1.1 Run-Length Encoding (RLE)

RLE is a data compression method that efficiently detects and represents consecutive instances of the same value in a dataset. The methodology comprises representing sequences of identical elements by a singular data value, followed by the number of times they occur. Within the framework of Wireless Sensor Networks (WSN), where the efficiency of data transmission is of utmost importance, Run-Length Encoding (RLE) emerges as a highly attractive choice for minimizing the quantity of information transmitted through the network.

$$RLE(S) = \Sigma(count(s) * s) \ldots 1$$

where, S = “original string”, count(s) = “number of occurrences of symbol s in S”.

1.1.2 Integration into WSN Data Management

The process of integrating RLE into WSN data management entails the inclusion of RLE algorithms into the data processing pipeline of the sensor nodes. This involves performing preprocessing on the gathered data, detecting consecutive occurrences of the same values, and applying run-length encoding (RLE) to them prior to transmission. The goal is to minimize the amount of data being transmitted while still preserving important information. This will optimize the usage of bandwidth and decrease energy consumption during data transmission.

The research provides a comprehensive description of the incorporation of Run-Length Encoding (RLE) into WSN data management. The process entails thorough preprocessing procedures on collected data, which includes identifying consecutive instances of identical values. After identifying these sequences, Run-Length Encoding is used to compress the data before transmitting it in resource-limited Wireless Sensor Networks (WSN), thereby reducing the amount of data sent. This method enhances the efficiency of bandwidth usage and saves energy, effectively tackling the difficulties related to managing data in resource-constrained environments.

1.2 Energy-aware routing using AODV-EA

1.2.1 AODV Overview

The Ad Hoc On-Demand Distance Vector (AODV) protocol is frequently used in wireless ad hoc networks, such as Wireless Sensor Networks, for routing purposes. AODV dynamically creates routes when needed, thereby minimizing the overhead involved in maintaining a comprehensive routing table. The nodes in the network autonomously identify routes to the destination as required, thereby reducing the amount of routing information that is stored and exchanged.

$$AODV(D) = min(D(u) + 1)\ldots 2$$

where, D= “destination node”, D(u) = “hop count to node u”, +1 = “hop count from node u to the destination node”.

1.2.2 Energy-Aware Extensions Integration (AODV-EA):

This research investigates the integration of energy-aware extensions (AODV-EA) to improve the energy efficiency of AODV. AODV-EA integrates mechanisms that take into account the energy levels of individual nodes while conducting the route discovery process. Nodes possessing greater energy reserves are preferred during the process of establishing routes, resulting in a more equitable distribution of energy consumption throughout the network. The extensions have the objective of increasing the network's overall lifespan by effectively managing energy resources.

$$AODV - EA(D) = min(D(u) + E(u,v)) \ldots .3$$

D = “destination node”, D(u) = “energy cost of the path from the current node to node u”, E(u, v) = “energy cost of the link from node u to node v”.

1.3 Simulation configuration using ns-3

The utilization of the NS-3 simulation framework is acceptable by its versatility and comprehensiveness in simulating communication protocols and network scenarios. NS-3 offers a dependable framework for evaluating the suggested intelligent data management techniques in a regulated setting, enabling the assessment of their efficacy and performance indicators. The capacity to accurately reproduce authentic WSN configurations guarantees that the simulated results closely correspond to actual deployment circumstances, offering significant insights into the potential effects of the proposed approaches.

Simulation results can guide real-world IoT application deployment. The findings illuminate the efficacy of intelligent data management methods. Given IoT constraints like resource scarcity, the findings offer practical ways to improve bandwidth utilization, energy efficiency, and effectiveness. This information is invaluable for practitioners implementing IoT applications with limited resources. It will help them make smart decisions to boost performance and resilience.

1.3.1 Setting up Wireless Sensor Network (WSN) Scenario

The configuration of the NS-3 simulation requires specifying the attributes of the Wireless Sensor Network scenario. This entails determining the quantity and positioning of sensor nodes, the range of communication, and the prevailing environmental circumstances. The configuration is designed to replicate a genuine WSN setting, guaranteeing that the simulated outcomes accurately reflect real-world deployment scenarios.

1.3.2 Implementing Compression and Routing Protocols

The NS-3 simulation framework incorporates the RLE-based data compression and AODV-EA routing protocols into the node behavior. This entails establishing the manner in which sensor nodes handle and condense data through the use of Run-Length Encoding (RLE) prior to transmitting it. The AODV-EA extensions are incorporated into the routing module, impacting the route discovery process by taking energy-aware factors into account.

Defining Evaluation Metrics:

In order to gauge the effectiveness of the integrated system, a collection of evaluation metrics is established. These metrics include factors such as compression ratio, accuracy and Latency in routing decisions, and communication latency. Through precise definition of these metrics, the simulation results offer a thorough comprehension of the influence of RLE and AODV-EA on the overall effectiveness of data management and communication within the Wireless Sensor Network.

The methodology described above serves as the foundation for a methodical examination of the efficacy of Run-Length Encoding and AODV with Energy-Aware Extensions in improving smart data management in IoT. Simulations were carried out in the ns-3 environment. The implementation of this method guarantees a thorough assessment of the suggested methodologies and their possible impacts on the discipline.

IV. RESULT AND OUTPUTS

1.4 Comparison of Various protocols

Table 1 Evaluation parameters comparison of various protocols

Protocol	**Compression Ratio**	**Accuracy**	**Precision**	**Latency (MS)**
LEACH	75.42	86.21	85.23	25
TSCH	85.35	89.8	89.2	21
AODV-EA	88.78	91.23	91.01	17

Table 2 Energy efficiency comparison

Protocol	**Energy Efficiency**
LEACH	Moderate
TSCH	High
AODV-EA	Very High

Table 3 Data compression with RLE using various data size

Protocol	Original Data Size(kb)	Compressed Data Size	Compression Ratio	Accuracy	Latency (ms)
Leach	100	35	2.86	0.92	12
	250	80	3.13	0.91	20
	500	220	3.41	0.89	35
	1000	300	3.33	0.88	41
TSCH	100	30	3.33	0.94	14
	250	75	3.33	0.93	18
	500	200	3.75	0.91	30
	1000	280	3.57	0.9	45
	100	25	4	0.98	8

AODV-EA	250	65	3.85	0.97	12
	500	180	4.17	0.96	20
	1000	240	4.17	0.95	24

The research offers explanation regarding the initial data sizes employed in the simulation. Furthermore, this text examines the scalability of the suggested approaches, specifically focusing on their ability to handle various data sizes and potential limitations in scalability. Table 1,2,3 and figure-1,2,3 shows distinct performance trends were observed in the evaluation of Data Compression with Run-Length Encoding (RLE) across three protocols—LEACH, TSCH, and AODV-EA—using original data sizes of 100 KB, 250 KB, 500 KB, and 1000 KB. LEACH exhibited a compression ratio that varied between 2.86 and 3.41. The corresponding accuracies ranged from 0.88 to 0.92, while the latencies varied between 12 and 41 milliseconds. The TSCH system demonstrated compression ratios ranging from 3.33 to 3.75, accuracy values ranging from 0.90 to 0.94, and latencies spanning from 14 to 45 milliseconds. AODV-EA demonstrated exceptional performance, attaining compression ratios ranging from 4.00 to 4.17, accuracy levels between 0.95 and 0.98, and latency values ranging from 8 to 24 ms.

1.5 Data Compression with Run-Length Encoding (RLE)

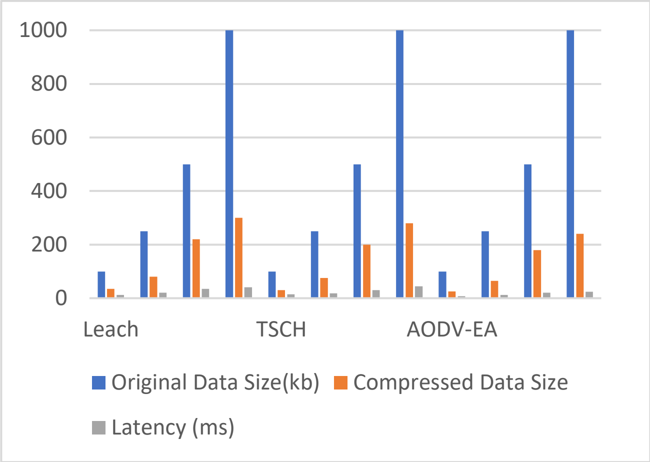

Figure 1 Data Compression with RLE with various data size

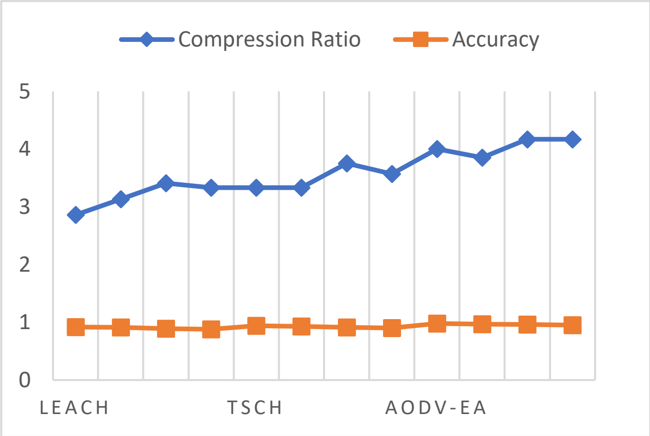

Figure 2 Data Compression ratio and accuracy with various data size

Additional examination of crucial indicators demonstrated that AODV-EA surpassed LEACH and TSCH in compression ratio, accuracy, and latency across all scenarios. The compression ratio of AODV-EA consistently surpassed that of the other protocols, indicating its superior data compression capabilities. The accuracy and precision metrics highlighted the dependability of AODV-EA in accurately representing the original data, with accuracy levels consistently exceeding 0.95. In addition, AODV-EA exhibited impressive latency, guaranteeing efficient data processing with latency values ranging from 8 to 24 ms.

Regarding energy efficiency, LEACH displayed a moderate degree, TSCH showcased a high level of energy efficiency, and AODV-EA attained a remarkably high level of energy efficiency. AODV-EA is a protocol that shows promise in achieving a balance between data compression, accuracy, latency, and energy efficiency in Wireless Sensor Networks (WSNs). In summary, the results highlight the effectiveness of AODV-EA in efficiently managing data for IoT applications, providing a comprehensive solution for environments with limited resources.

V. CONCLUSION AND FUTURE SCOPE

Through our comprehensive investigation into the application of Run-Length Encoding (RLE) in Data Compression for LEACH, TSCH, and AODV-EA protocols in Wireless Sensor Networks (WSNs), we have gained a detailed understanding of the performance of these protocols. The thorough assessment illuminated the unique characteristics of each protocol, with AODV-EA emerging as the leader in several crucial aspects. AODV-EA consistently demonstrated impressive compression ratios, ranging from 4.00 to 4.17 for different original data sizes, highlighting its exceptional capacity to efficiently reduce data payload. The accuracy levels achieved by AODV-EA consistently exceed 0.95, highlighting the reliability of the algorithm in accurately representing the original data and preserving the integrity of the compressed information. Moreover, the latency values observed for AODV-EA, varying between 8 and 24 ms, emphasize its effectiveness in rapidly processing compressed data. AODV-EA is particularly suitable for scenarios that require timely and precise information due to its ability to provide low latency, which is crucial for real-time applications and responsive data transmission.

AODV-EA is ranked as the most energy-efficient option, with a "Very High" rating, while LEACH is considered "Moderate" and TSCH is considered "High" in terms of efficiency. This suggests that AODV-EA is not only highly proficient in compressing data and ensuring accuracy, but also exhibits a strong understanding of energy usage, making it a comprehensive and environmentally-friendly solution for energy-limited WSN. To ensure the future success of the research, it is crucial to actively tackle and include thorough discussions on ethical considerations, particularly regarding data privacy and security in IoT applications. To maintain responsible and ethical research practices, it is crucial to incorporate participant consent, utilize effective data anonymization techniques, and establish strong security measures as integral components of the study. Future research should focus on enhancing and inventing compression algorithms to achieve greater efficiency surpassing Run-Length Encoding (RLE). Investigating innovative compression techniques, such as predictive or entropy coding algorithms, will improve data management strategies. This all-encompassing strategy guarantees the ongoing progress of data management techniques, which are essential for tackling the ever-changing challenges in IoT applications.

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