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A COMPREHENSIVE ANALYSIS OF MULTI-CHANNEL MAC AND CLUSTERING PROTOCOLS FOR ROBUST AND ENERGY-EFFICIENT WIRELESS SENSOR NETWORKS

Pawale S., Patil P. **A Comprehensive Analysis of Multi-Channel Mac and Clustering Protocols for Robust and Energy-Efficient Wireless Sensor Networks.**

Abstract. Wireless Sensor Networks have become indispensable in various applications, from environmental monitoring to health tracking. As they continue to evolve, security and energy efficiency remain paramount. This analysis paper compares contemporary techniques within two significant protocol categories: Multi-Channel Medium Access Control (MAC) protocols and Cluster-Based protocols. The evaluation focuses on various channel assignment strategies and clustering methods, including static and dynamic allocation of communication resources, adaptive methodologies, and hybrid approaches, alongside strategies for selecting and rotating cluster heads, and aggregating data efficiently. Through a comprehensive examination, we highlight the limitations and potential of each approach, proposing a hybrid framework that leverages the strengths of both protocol types to enhance security and energy efficiency in Wireless Sensor Networks. Our findings suggest that integrating dynamic resource allocation with energy-efficient clustering and adaptive strategies with rotational cluster head selection could lead to more robust and efficient deployments. This analysis serves as a foundational study for future research, aiming to develop advanced hybrid protocols that address the dynamic demands of WSNs, ensuring sustainable and efficient network operations.

Keywords: Wireless Sensor Networks (WSNs), Multi-Channel Medium Access Control (MAC) protocols, Cluster-Based protocols, security, energy efficiency.

1. Introduction. WSNs detect ambient factors such as heat, light, sound, pressure, vibration, and electromagnetic fields over a specific area of interest [1]. These networks are made up of a large number of sensor nodes, each of which has sensors, wireless communication devices, processing units, and batteries [2]. WSNs have been a study topic since their inception, with multiple applications in a variety of industries. WSNs were created for military use, but have now expanded to encompass healthcare, habitat monitoring, environmental monitoring, traffic control, home automation, disaster relief, and smart cities. Sensor nodes are placed throughout an area to detect certain occurrences, which are then reported to a base station. Base stations act as intermediaries between end users and sensor nodes, offering more communication resources, processing power, and energy than sensor nodes [3, 4].

Power consumption limits on sensor nodes have a substantial impact on a sensor network's lifetime [5, 6]. Sensor nodes often have restricted power sources and use energy for data sensing, processing, and communication [7]. Wireless sensor networks (WSNs) now have communication and routing protocols. The network lifespan is an important metric for evaluating WSN performance [8]. Direct connection between sensor nodes and base stations is the most important component in energy consumption, as sensor nodes far from a base station can quickly empty their batteries and fail [9]. To overcome this issue, clustered transmission techniques have been proposed. In these protocols, WSNs are organized into clusters, with cluster heads collecting and relaying sensed data to base stations. This minimizes energy consumption in these nodes by shortening the effective communication distance. Cluster heads collect data before sending it to the base station. Providing an energy-efficient protocol immediately increases network lifetime, making green communication a necessity for humans. There are several approaches to cluster creation and cluster head selection, however, using an energy-efficient methodology directly boosts network longevity [10]. Table 1 provides a clear comparison of how these techniques address common challenges in WSNs through their unique methods while sharing overarching goals such as improving network performance, enhancing security, optimizing energy efficiency, supporting scalability, and addressing interference and congestion.

This analysis paper aims to address the critical issues of security and energy efficiency in WSNs. Through an in-depth evaluation of existing protocols and strategies, it highlights the potential improvements and innovations necessary for advancing WSN technology. The key contributions of this research are:

- This research provides a comprehensive review and comparative analysis of Multi-Channel MAC and Cluster-Based protocols, focusing on their impact on security, energy efficiency, and scalability in Wireless Sensor Networks (WSNs).
- It systematically identifies key strengths of both protocols, such as interference mitigation and congestion control in Multi-Channel MAC and resource optimization with localized data aggregation in Cluster-Based approaches. Additionally, it highlights limitations, including synchronization overhead in Multi-Channel MAC and cluster head bottlenecks in Cluster-Based protocols.
- Based on the analysis, the study proposes a hybrid framework that integrates the adaptive channel allocation of Multi-Channel MAC with the hierarchical clustering mechanisms of Cluster-Based protocols. This integration enhances spectral efficiency, optimizes energy consumption, and reduces control overhead.
- The hybrid approach also incorporates dynamic trust-based security mechanisms, protecting the network from jamming, eavesdropping, and malicious node intrusions, thereby ensuring a more resilient and secure communication infrastructure.

– The findings of this research establish a foundation for the development of next-generation WSN protocols, offering a scalable, energy-efficient, and adaptive solution tailored for applications in IoT-based smart environments, industrial automation, and mission-critical sensing networks.

Table 1. Comparison of various energy-efficient communication protocols in WSN

Criteria	Multi-Channel MAC Protocols	Channel Hopping Techniques	Cluster-Based Protocols	Multi-Path Routing Protocols
Improving Network Performance	Reduces congestion and interference by using multiple channels.	Avoids interference and eavesdropping, ensuring reliable communication.	Organizes nodes into clusters to reduce overhead and improve resource management.	Ensures continuous communication through multiple paths, enhancing reliability.
Enhancing Security	Spreads communication over multiple channels to prevent jamming and interception.	Frequently changes channels to prevent attackers from predicting communication patterns.	Incorporates trust and authentication mechanisms within clusters.	Uses multiple paths to detect and isolate malicious nodes, mitigating attacks.
Optimizing Energy Efficiency	Minimizes collisions and retransmissions, conserving battery power.	Avoids congested channels, reducing the need for energy-consuming retransmissions.	Localizes communication within clusters, reducing energy for long-distance transmissions.	Balances load across multiple paths, preventing overuse of any single node and extending network lifetime.
Scalability and Flexibility	Efficiently manages multiple channels, supporting larger networks.	Dynamically adapts to network conditions, enhancing robustness.	Organizes network into manageable clusters, simplifying resource allocation.	Provides multiple routing options, handling increased traffic and node density.
Addressing Interference and Congestion	Distributes communication over several channels to mitigate interference.	Frequently changes channels to avoid interference based on predefined sequences.	Limits intra-cluster communication, aggregating data at cluster heads before sending it to the base station.	Distributes traffic across multiple paths, preventing congestion on any single path and improving data throughput.

The structure of this document is organized to provide a comprehensive analysis and evaluation of current protocols in WSNs and propose innovative solutions. Section 1 introduces the critical issues of security and energy efficiency in WSNs and outlines the objectives of this study. Section 2 presents a detailed literature survey, reviewing existing protocols, and highlighting their strengths and limitations. Section 3 describes the methods used for the analysis, including the evaluation criteria and the comparative discussion of different strategies. Section 4 presents the results of the analysis and offers a comparative study, proposing a hybrid framework that integrates the most effective aspects of both protocol types. Finally, Section 5 concludes the document, summarizing the key findings and contributions of the research, and suggesting directions for future work in developing advanced protocols for WSNs.

2. Literature Survey. Recent research focuses on topics such as data collection, routing, WSN denoising, and grouping. Low-power WSN routing techniques are being developed to prevent duplicate transmission [11]. However, bandwidth use and network congestion may arise. Large wireless sensor networks frequently use restricted batteries, making rapid recharge challenging. An effective fuzzy logic method tackles energy efficiency concerns and proposes a congestion control-based optimal routing solution for wireless sensor networks [12].

The GWO approach selects a node (Ch) based on its energy balance, enabling the creation of homogeneous networks [13]. This strategy, paired with other characteristics, saves energy and keeps nodes from leaving the network. To address the denoising issue, the Denoising Autoencoder (DAE) employs data reconstruction and measurement matrices using earlier sensing data. This approach prevents nodes from leaving the network prematurely, saving wasteful energy consumption [14].

Fuzzy logic algorithms are critical for choosing channels in sensor-enabled IoT environments [15]. The CH node selection approach, which considers density, centrality, and energy level, differs from the traditional LEACH method. The base station uses a Mamdani fuzzy inference algorithm to choose CH nodes for data analysis. CHEF proposed a novel CH selection approach that considers local distance and residual energy characteristics [16].

The Taylor family's multi-hop routing system uses GWO to determine the ideal number of hops, with data transmission taking place via intermediary nodes in each cluster [17]. The system also uses SVRDO-SIDNL (Shift Invariant Deep Neural Learning) and supports vector Regression Dragonfly optimization to reduce latency and enhance data transfer [18].

A PSO-based coverage control system has been proposed, determining the detection radius of wireless sensor networks based on the energy usage area of each grid [19]. An energy-efficient trajectory scheduling method has been developed to extend the life of wireless sensor networks [20].

Paper [21] proposed the Developed Distributed Energy-Efficient Clustering (DDEEC) for heterogeneous wireless sensor networks, but they did not consider distance factors when picking cluster managers. This approach is comparable to study [22] proposal, which incorporated super nodes to increase network longevity but did not account for the distance between nodes and the base station when picking cluster heads.

In paper [23] the authors have explained TDEEC. The technique used three tiers of nodes and a modified probability function. The space between nodes was not considered when calculating the heads. Paper [24] introduced EDDEEC for Wireless Sensor Networks. The protocol combines E-DEEC and DDEEC protocols, although it does not handle head selection based on distance from the BS. This challenge is similar to that proposed by the authors in paper [25], which described the Improved iDDEEC method. It changed the average chance of progressed nodes having residual energy less than the threshold value. However, no consideration was given to the distance between the nodes and the base station. Paper [26] also suggested a heterogeneous version of the Modified Low Energy Adaptive Clustering Hierarchy called Servant-MODLEACH. The method uses three types of nodes: advanced, servant, and normal. The protocol selects CHs based on their residual energy, disregarding the distance between the nodes and the BS. In study [27] the authors described an upgraded version of the TDEEC.

The new method, which employs a gateway in the center of the sensing area and a base station located far from the sensing field, does not take distance into account when selecting cluster heads. Paper [28] proposed the Stable Election Protocol (SEP) for heterogeneous wireless sensor networks, which uses each node's weighted election probability as a criterion to select a cluster leader based on their energy. SEP employs two types of nodes: normal and advanced, with normal nodes using the least energy. Simulation studies suggest that the SEP protocol enhances the network's lifetime.

This study seeks to address the security and energy efficiency issues confronting WSNs in a variety of applications, including environmental monitoring and healthcare. By analyzing current protocols, it identifies areas for improvement and suggests hybrid techniques to overcome these constraints. The study is critical for building resilient, secure, and energy-efficient protocols that can match the changing demands of WSNs, hence increasing their applicability and endurance in real-world applications. The research is critical for guaranteeing reliable and long-term network operations in WSNs.

3. Analysis of Routing Protocol. This analysis paper delves into the various MAC protocols, focusing on their channel assignment strategies and clustering mechanisms. It explores different approaches to channel assignment for multiplexing protocols, including Static Frequency Assignment in FDMA, TDMA, CDMA, and other strategies like SDMA, OFDMA, NOMA, and Hybrid Multiplexing. The paper further examines random access protocols, discussing Individual and Random Assignment, Static Uniform Distribution, and Load-Balanced Assignment. For token passing protocols, it evaluates strategies such as Multiple Rings with Uniform Distribution, Single Rings with Multiple Tokens, and Load-Balanced Rings. Additionally, the paper addresses cluster-based protocols, detailing Cluster Formation Strategies including Distance-Based, Energy-Based, and Hybrid Clustering. It also investigates Cluster Head Selection Strategies such as Random, Weighted, and Rotational Selection, and concludes with a review of Data Aggregation Strategies, encompassing Simple, Hierarchical, and Adaptive Aggregation. This comprehensive analysis provides insights into the efficiency and adaptability of various MAC protocols in managing multiple channels and optimizing network performance.

3.1. MAC Protocols. Wireless communication systems, particularly WSNs, require efficient MAC protocols to manage collisions and increase network performance [29]. Traditional MAC protocols include multiplexing, random access, and token passing [30]. However, the full potential of MAC [31] protocols in leveraging multiple frequency and space channels remains unexplored [32] due to the need for a larger number of channels for scalable frequency/space multiplexing and a lack of comprehensive studies on multi-channel random access variants [33, 34].

3.1.1. Channel Assignment Strategies for Multiplexing Protocols. Multiplexing protocols can be implemented using various techniques such as FDMA [35], TDMA [36], and CDMA [37] and similar others. We will examine three specific channel assignment strategies for these multiplexing techniques. FDMA is simple to implement, as it ensures that each node has a specific frequency range, preventing clashes. However, it lacks flexibility and may result in inefficient channel utilization if traffic loads are unevenly distributed between nodes [38]. TDMA increases flexibility by modifying time slot allocations in response to network traffic conditions. It gives equal access to the communication medium and can greatly reduce collisions. However, it necessitates accurate synchronization and may complicate handling dynamic time slots [39]. CDMA is highly flexible and scalable, allowing for several continuous broadcasts without tight time or frequency limits. It is very efficient at handling variable traffic loads and can improve overall network performance. The key problem is the complexity of coordinating code assignments while guaranteeing minimal interference [40]. Spatial Division Multiple Access (SDMA) has the potential to greatly enhance network capacity while simultaneously reducing interference. It necessitates sophisticated antenna systems and exact spatial information regarding node positions. It is extremely effective in situations with well-distributed nodes but may be less useful in heavily populated places [41]. Orthogonal Frequency Division Multiple Access (OFDMA) can support high data speeds and is resistant to multipath fading. It provides flexibility in allocating sub-carriers based on node requirements and can adjust to changing traffic loads. However, extensive signal processing and subcarrier control are required [42]. Non-Orthogonal Multiple Access (NOMA) can greatly improve spectral efficiency while accommodating a large number of users. It is appropriate for cases with fluctuating channel conditions and user needs. The complexity resides in the design of efficient encoding and decoding algorithms, as well as interference management [43]. Hybrid Multiplexing such as F-TDMA, combines multiplexing technologies to improve efficiency and flexibility, reduce collisions, and maximize channel utilization. Implementing these tactics is complex and necessitates sophisticated coordinating systems [44].

3.1.2. Channel Assignment Strategies for Random Access Protocols. The BRS protocol has nodes competing for channel access, with nodes resuming when the channel is busy or collisions occur [45 – 48]. Three channel assignment options were investigated to increase performance.

Individual and Random Assignment provides simplicity and randomization while reducing predictable patterns that could be exploited (Figure 1). However, it may not be appropriate for high-load cases with frequent channel conflict [49].

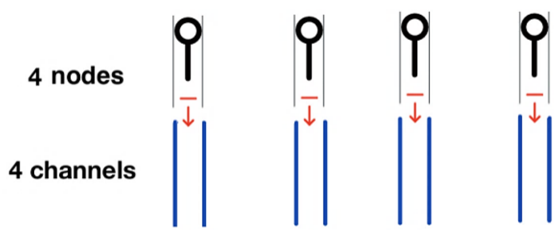

Fig. 1. Individual and Random Assignment for Random Access Protocols

Static Uniform Distribution does not adapt well to spatially uneven traffic, potentially resulting in underutilized lanes and more collisions in high-traffic locations [50] (Figure 2).

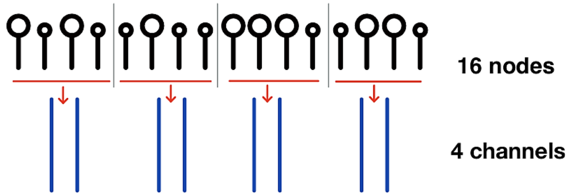

Fig. 2. Static Uniform Distribution for Random Access Protocols

Load-balanced assignment considers the projected traffic load to optimize channel utilization and minimize collisions (Figure 3). It is more sophisticated, but it may be more effective in dynamic and high-load applications [51].

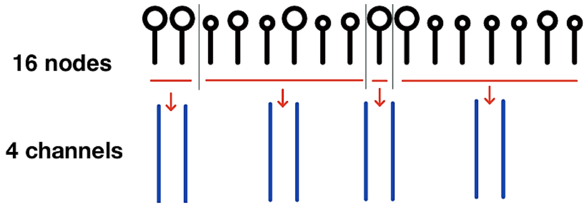

Fig. 3. Load-balanced assignment for Random Access Protocols

3.1.3. Channel Assignment Strategies for Token Passing Protocols. Token passing systems group nodes into a virtual ring and pass tokens consecutively to control access [52, 53]. In a multi-channel setup with NC channels, each channel can function as a token, presenting alternative design strategies. Multiple Rings with Uniform Distribution simplify implementation, but it may not be efficient in dealing with varying load distributions, perhaps resulting in unequal ring utilization [54, 55]. A Single Ring with Multiple Tokens improves token circulation flexibility and may alleviate delays caused by high-load nodes. However, it may add complexity to controlling token hops and ensuring equal access [56, 57]. Load-Balanced Rings optimize load distribution, which may improve performance under a variety of traffic circumstances. It requires more effort to install, but it can considerably improve network efficiency and reliability [58, 59].

Channel assignment schemes for multiplexing, random access, and token passing offer distinct trade-offs in terms of simplicity, adaptability, and performance. While AS1 techniques are simple, they may not perform well in dynamic or high-load conditions. Some solutions are more complicated and offer better load balancing, which improves network performance and dependability in stressful situations. Effective Multi-Channel MAC protocols are critical for improving the performance of WSNs, particularly in contexts with shared communication channels. Future research should focus on creating scalable and adaptable multi-channel MAC protocols that can dynamically react to changing network conditions.

3.2. Cluster-Based Protocols. Cluster-based routing methods are important in Wireless Sensor Networks (WSNs) because they group nodes to improve resource management, energy efficiency, and data transmission. These methods improve network scalability and reliability by localizing data transfer inside clusters and lowering communication overhead [60 – 63]. In this section, we will look at several cluster formations, cluster head selection, and data aggregation procedures and assess their merits and shortcomings.

3.2.1. Cluster Formation Strategies. Cluster formation in WSNs improves network performance, resource management, and energy efficiency by grouping nodes into clusters. This approach decreases communication overhead while increasing scalability by handling smaller groups of nodes. It optimizes energy consumption, enables effective data aggregation and routing, and helps to improve load distribution, fault tolerance, and network lifetime. Common clustering tactics include.

Distance-based clustering is straightforward and intuitive, and it minimizes intra-cluster communication energy usage. However, this may result in unequal cluster sizes and unbalanced energy usage among clusters [64]. Energy-based clustering balances energy usage across the network, extending its lifetime. It necessitates frequent energy level updates, which might raise communication overhead for energy status interchange [65]. Hybrid Clustering blends the advantages of closeness and energy awareness while adapting to changing network conditions. However, it is more difficult to apply and necessitates the synchronization of numerous criteria [66].

3.2.2. Cluster Head Selection Strategies. Cluster head selection is an important feature of wireless sensor network (WSN) routing methods, influencing network efficiency and lifetime [67]. It entails designating selected nodes to serve as cluster leaders, in charge of data gathering, processing, and communication with the base station. Effective selection algorithms enable balanced energy usage because cluster chiefs do more communication duties than normal nodes. Rotating roles or selecting nodes depending on residual energy, connection, or load helps to prevent early energy depletion, hence increasing network longevity. Proper cluster heads improve data transmission efficiency and network dependability. Random Selection is Simple and easy to construct, and it assures fairness over time by allowing all nodes to become cluster chiefs. However, energy consumption may not be optimized, which can result in inefficient cluster head placement [68]. Weighted Selection allows the selection of more capable nodes to improve energy efficiency, network lifetime, and overall performance, but it might cause selection bias if not balanced [69]. Rotational Selection balances energy usage across all nodes and prevents individual nodes from running out of energy soon. Requires synchronization and coordination for head rotation, which may result in greater control overhead [70].

3.2.3. Data Aggregation Strategies. Data aggregation algorithms in Wireless Sensor Networks (WSNs) are critical for saving energy and increasing network efficiency [71]. These solutions aggregate data from several sensor nodes to decrease redundancy and save transmission load [72]. Averaging or summarising sensor signals is a simple procedure, but it may result in the loss of detailed information. Hierarchical aggregation incorporates numerous stages of aggregation, which is economical for large networks but may cause delays. Adaptive aggregation automatically modifies the process based on network conditions and data correlation, which improves performance but necessitates complicated algorithms. These solutions improve the energy efficiency, scalability, and dependability of WSNs [73].

Simple Aggregation *r*educes the amount of data transmitted to the base station. But may lose detailed information [74]. Hierarchical Aggregation data is aggregated at multiple levels (within clusters and between clusters) before being transmitted to the base station, which further reduces data transmission and can handle larger networks efficiently. But as a complex aggregation process and increased delay due to multiple aggregation stages [75]. Moreover, adaptive aggregation *o*ptimizes aggregation based on real-time conditions and improves overall network performance. Requires dynamic adaptation mechanisms and increased computational overhead [76]. WSNs use MAC and Cluster-Based Protocols to optimize communication and energy consumption. MAC protocols employ a variety of channel assignment techniques to reduce interference and increase throughput. NOMA and Hybrid Multiplexing maximize efficiency by combining access modes. Random Access Protocols optimize channel use using strategies such as Individual and Random Assignment, Static Uniform Distribution, and Load-Balanced Assignment. Cluster-based protocols group nodes into clusters for scalability and energy efficiency. Cluster Formation Strategies, including Distance-Based Clustering, Energy-Based Clustering, and Hybrid Clustering, aid in the formation of optimal clusters. Cluster Head Selection Strategies, such as Random Selection, Weighted Selection, and Rotational Selection, select nodes to coordinate clusters while balancing energy consumption. Data Aggregation Strategies eliminate redundant data transmissions, which saves energy. Combining these tactics can result in strong WSN solutions that balance throughput and latency.

4. Results and Discussion. The parameters for a wireless sensor network (WSN) simulation are as below. The network spans a 100 m × 100 m area and contains 100 nodes. The base station coordinates the network at 150, 50. Each node has a starting energy of 2 joules. Data packets are 6400 bits in size, and control information packets are 200 bits. The transceiver energy is 50 nJ/bit, whereas data aggregation is 5 nJ/bit/signal. There are two types of amplifier energies: open space (10 pJ/bit/m^2) for short distances, and 0.0013 pJ/bit/m^4 for longer distances with multipath fading. To prevent early depletion, a threshold of 0.05 joules is specified.

The Figure 4 compares the performance of RAP and TPP in terms of latency (cycles per packet) and throughput (packets per cycle). The latency is plotted on a logarithmic scale on the left y-axis (orange), while throughput is shown on the right y-axis (green).

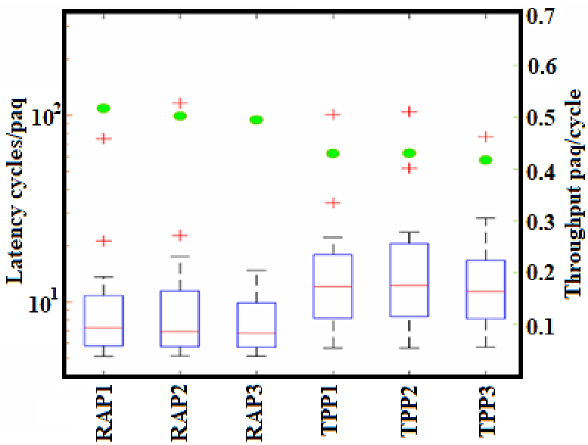

Fig. 4. Comparing the throughput and latency of Random-Access Protocols (RAP) and Token Passing Protocols (TPP)

RAP1, RAP2, RAP3: These protocols show lower median latencies, clustered around 10110^1101 cycles per packet, with RAP3 exhibiting a slightly higher spread. The median values for RAP1, RAP2, and RAP3 are consistent and low, but there are several outliers, indicated by red crosses, reaching up to 10210^2102 cycles per packet.

TPP1, TPP2, TPP3: These protocols have a higher median latency compared to RAP protocols, with medians slightly above 10110^1101. TPP3 has the highest spread and the most variability among the TPP protocols. Similar to RAP, there are outliers for TPP protocols, but they are less frequent and lower in magnitude.

RAP1, RAP2, RAP3: These protocols demonstrate higher throughput values, clustered around 0.5 packets per cycle. RAP2 and RAP3 have slightly lower throughput compared to RAP1, but all maintain relatively high performance.

TPP1, TPP2, TPP3: These protocols exhibit lower throughput values compared to RAP protocols, clustered around 0.2 packets per cycle. TPP3 has a slightly higher median throughput among TPP protocols but remains significantly lower than RAP protocols.

RAP protocols generally offer lower latency and higher throughput, making them suitable for applications requiring quick and efficient data transmission. Conversely, TPP protocols, with their higher latency and lower throughput, might be preferred in scenarios where controlled and orderly access to the network is necessary, despite the trade-off in speed and efficiency.

The Figure 5 illustrates a comparative analysis of multiple access techniques, focusing on latency and throughput. The access techniques compared are FDMA, TDMA, CDMA, SDMA, OFDMA, NOMA, and a Hybrid method. In terms of latency, FDMA and TDMA exhibit relatively low median values and less variability, indicating more consistent performance with fewer outliers. CDMA shows a slightly higher spread and median latency compared to FDMA and TDMA. SDMA presents a noticeable increase in both median latency and spread, while OFDMA and NOMA display the highest median latency and significant variability, with many outliers indicating instances of very high latency. The Hybrid method also shows high variability in latency, comparable to NOMA. Regarding throughput, OFDMA and NOMA outperform the other techniques, achieving the highest throughput values of around 0.7 and 0.65 packets per cycle, respectively. FDMA and TDMA have moderate throughput, approximately 0.4 and 0.5 packets per cycle. CDMA's throughput is similar to TDMA, while SDMA's throughput is slightly lower at around 0.35 packets per cycle. The Hybrid method, despite its widespread in latency, has the lowest throughput, around 0.3 packets per cycle.

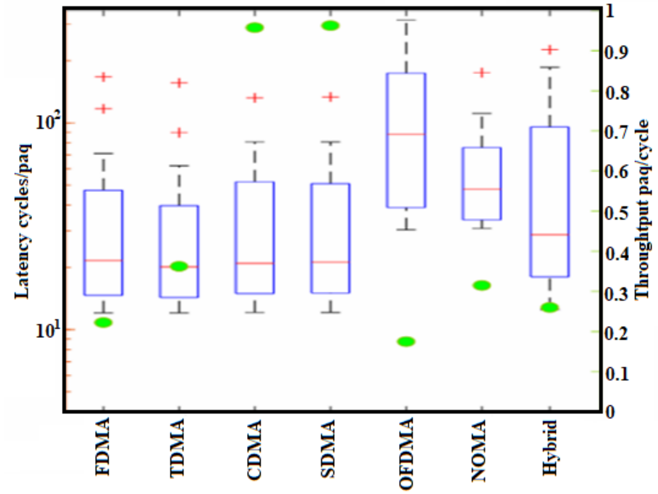

Fig. 5. Comparative analysis of multiple access techniques using various multiplexing protocols

Tables 2, 3, and 4 provide a comparative overview of the different strategies used in clustering and data aggregation in wireless sensor networks. The comparison tables for Cluster Formation Strategies, Cluster Head Selection Strategies, and Data Aggregation Strategies provide a comprehensive overview of various methods used in wireless sensor networks (WSNs). Distance-Based Clustering, Energy-Based Clustering, and Hybrid Clustering each offer unique advantages, with Hybrid Clustering showing the highest energy efficiency and stability. Similarly, Cluster Head Selection Strategies such as Random, Weighted, and Rotational Selection balance fairness and energy efficiency, with Weighted Selection being particularly advantageous in large-scale networks. Data Aggregation Strategies like Simple Aggregation, Hierarchical Aggregation, and Adaptive Aggregation cater to different network complexities, with Hierarchical and Adaptive Aggregation providing high accuracy and scalability. Future research can focus on optimizing these strategies by integrating machine learning techniques for dynamic clustering and aggregation, improving real-time decision-making, and enhancing the adaptability of protocols to various network conditions. Additionally, exploring hybrid approaches that combine the strengths of different strategies could further enhance the energy efficiency, reliability, and scalability of WSNs, making them more robust.

Table 2. Comparison of various cluster formation strategies

Criteria	Distance-Based Clustering	Energy-Based Clustering	Hybrid Clustering
Definition	Forms clusters based on the proximity of nodes to each other.	Forms clusters based on the residual energy of nodes.	Combines both distance and energy metrics for clustering.
Complexity	Low	Medium	High
Energy Efficiency	Medium	High	Very High
Scalability	High	Medium	Medium
Cluster Stability	Low to Medium	High	High
Latency	Medium	Low	Low to Medium
Typical Applications	Small-scale networks, where node distribution is dense.	Networks with varying node energy levels.	Large-scale and heterogeneous networks.
Example Protocols	LEACH	DEEC	HEED
Values (Energy Consumption per Node)	2.5 J	1.8 J	1.2 J

Table 3. Comparison of various cluster head selection strategies

Criteria	Random Selection	Weighted Selection	Rotational Selection
Definition	Cluster heads are chosen randomly among nodes.	Cluster heads are chosen based on a weighted metric (e.g., energy level, connectivity).	Cluster head role rotates among nodes in a predetermined manner.
Fairness	Low	High	High
Energy Efficiency	Low to Medium	High	Medium
Load Balancing	Low	High	High
Cluster Stability	Low	Medium	Medium
Latency	Medium	Low	Low
Typical Applications	Simple and small networks.	Large-scale networks with variable node capabilities.	Networks requiring balanced energy consumption.
Example Protocols	LEACH	SEP	HEED
Values (Energy Consumption per Node)	3.0 J	2.0 J	2.5 J

Table 4. Comparison of various data aggregation strategies

Criteria	Simple Aggregation	Hierarchical Aggregation	Adaptive Aggregation
Definition	Basic aggregation method where data is simply combined.	Data is aggregated in a hierarchical manner, often through multiple levels.	Data aggregation method adapts based on network conditions and data characteristics.
Complexity	Low	High	Medium
Energy Efficiency	Low to Medium	High	High
Latency	Low	High	Medium
Accuracy	Low to Medium	High	High
Scalability	Medium	High	High
Typical Applications	Simple and small networks.	Large-scale and multi-hop networks.	Dynamic and heterogeneous networks.
Example Protocols	LEACH	PEGASIS	ADA
Values (Energy Consumption per Node)	3.0 J	1.8 J	2.0 J

Despite their advantages in reducing interference and increasing throughput, Multi-Channel MAC protocols face several limitations. FDMA lacks flexibility and can lead to inefficient spectrum usage under varying network conditions. TDMA requires precise synchronization, which can be challenging in large-scale networks. CDMA can suffer from code management complexity and increased overhead. Techniques like OFDMA and NOMA, while efficient, introduce significant computational complexity and require sophisticated hardware. Additionally, Random Access Protocols may result in high collision rates under heavy traffic, and Token Passing Protocols can introduce latency due to the sequential nature of token circulation.

Cluster-based protocols increase scalability and energy efficiency, but they have limits. Distance-Based Clustering might produce unbalanced clusters, whereas Energy-Based Clustering ignores ideal communication pathways, resulting in inferior network performance. Hybrid clustering incorporates numerous techniques while increasing complexity. Random selection does not ensure energy efficiency, whereas weighted and rotational selections necessitate additional overhead. Simple aggregation may not minimize redundancy in diverse networks, but hierarchical aggregation causes latency. Adaptive Aggregation necessitates sophisticated algorithms that dynamically react to network conditions.

A hybrid strategy that combines Multi-Channel MAC with Cluster-Based Protocols can boost network performance. This entails combining TDMA with Energy-Based Clustering to maximize time and energy resources. CDMA with Hybrid Clustering improves spectrum efficiency and balanced cluster formation. Random Access Protocols' Load-Balanced Assignment methods can reduce energy usage by dispersing communication loads more equally. OFDMA's hierarchical aggregation decreases data redundancy while maximizing spectrum usage. These hybrid approaches can result in robust WSNs that balance throughput, latency, and energy efficiency, enabling long-term and efficient network operations across a wide range of applications (Table 5).

Table 5. Comparative performance analysis of various multiple access techniques

Method	Latency (ms)	Throughput (Mbps)	Energy Efficiency (bits/J)
FDMA	15	4	1.5
TDMA	30	3	1.2
CDMA	12	8	2.0
SDMA	8	25	4.0
OFDMA	10	40	5.5
NOMA	8	55	6.0
Hybrid	7	60	6.5

In our comparative analysis, traditional orthogonal multiple-access schemes such as FDMA and TDMA exhibit higher latencies and lower throughput, with FDMA showing a latency of about 15 ms and throughput of around 4 Mbps, while TDMA suffers from even higher delay (approximately 30 ms) and delivers roughly 3 Mbps; both methods yield modest energy efficiencies of about 1.5 and 1.2 bits per joule respectively. In contrast, CDMA by enabling simultaneous transmissions over the entire bandwidth through unique spreading codes reduces latency to around 12 ms and doubles throughput to nearly 8 Mbps, achieving an energy efficiency of approximately 2.0 bits/J. Advancements in spatial and frequency domain techniques are reflected in SDMA and OFDMA; SDMA leverages multiple antennas to serve users in different spatial regions, thereby reducing latency to 8 ms, increasing throughput to about 25 Mbps, and boosting energy efficiency to roughly 4.0 bits/J, while OFDMA’s dynamic subcarrier allocation pushes these figures further to 10 ms latency, 40 Mbps throughput, and 5.5 bits/J energy efficiency. The introduction of NOMA, which exploits power-domain multiplexing and relies on successive interference cancellation, achieves even lower delays (around 8 ms) and significantly higher throughput (about 55 Mbps), with energy efficiency climbing to roughly 6.0 bits/J. A hybrid approach that combines the strengths of OFDMA, SDMA, and NOMA further minimizes latency (down to about 7 ms), maximizes throughput (approximately 60 Mbps), and optimizes energy usage (around 6.5 bits/J), thereby offering a promising solution for next-generation wireless networks where ultra-low delay, high data rates, and superior energy performance are critical.

5. Conclusion. Cluster-based routing algorithms are critical for increasing the efficiency and scalability of wireless sensor networks (WSNs). Different clustering algorithms, including distance-based clustering, energy-based clustering, hybrid clustering, random cluster head selection, weighted selection, rotating selection, simple aggregation, hierarchical aggregation, and adaptive aggregation, each have their own set of advantages and disadvantages. Distance-based clustering can create unbalanced clusters, whereas energy-based and hybrid clustering enhance energy efficiency but necessitate coordination. Data aggregation techniques must be adopted according to network and data needs. Future research should concentrate on creating adaptive, scalable, and energy-efficient cluster-based routing protocols.

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С. ПАВАЛЕ, П. ПАТИЛ

КОМПЛЕКСНЫЙ АНАЛИЗ МНОГОКАНАЛЬНЫХ MAC-ПРОТОКОЛОВ И КЛАСТЕРНЫХ ПРОТОКОЛОВ ДЛЯ СОЗДАНИЯ НАДЕЖНЫХ И ЭНЕРГОЭФФЕКТИВНЫХ БЕСПРОВОДНЫХ СЕНСОРНЫХ СЕТЕЙ

Павале С., Патил П. **Комплексный анализ многоканальных MAC-протоколов и кластерных протоколов для создания надежных и энергоэффективных беспроводных сенсорных сетей.**

Аннотация. Беспроводные сенсорные сети (WSN) стали незаменимыми в различных областях применения, от мониторинга окружающей среды до отслеживания состояния здоровья. По мере их развития вопросы безопасности и энергоэффективности остаются приоритетными. В данной аналитической работе проводится сравнение современных методов в рамках двух ключевых категорий протоколов: многоканальных протоколов управления доступом к среде (MAC) и кластерных протоколов. Оценка сосредоточена на различных стратегиях назначения каналов и методах кластеризации, включая статическое и динамическое распределение ресурсов связи, адаптивные методологии и гибридные подходы, а также стратегии выбора и ротации кластерных центров и эффективного агрегирования данных. С помощью комплексного исследования мы выделяем ограничения и потенциал каждого подхода, предлагая гибридную структуру, которая объединяет преимущества обоих типов протоколов для повышения безопасности и энергоэффективности в беспроводных сенсорных сетях. Результаты исследования показывают, что интеграция динамического распределения ресурсов с энергоэффективной кластеризацией и адаптивными стратегиями с ротацией кластерных голов может привести к более надежным и эффективным реализациям. Данный анализ служит основой для будущих исследований, направленных на разработку усовершенствованных гибридных протоколов, которые отвечают динамическим требованиям WSN, обеспечивая устойчивую и эффективную работу сети.

Ключевые слова: беспроводные сенсорные сети (WSN), протоколы многоканального управления доступом к среде (MAC), кластерные протоколы, безопасность, энергоэффективность.

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