Electronic Integrated Computer Algorithm Journal
Vol. 2, No. 2, April 2025, pp 76~85

ISSN: 3031-0350, DOI: 10.62123/enigma.v2i2.57

Comparative Study Towards Energy Efficiency in Wireless Sensor Networks Using Asynchronous Duty Cycle

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DOI : 10.62123/enigma.v2i2.57

Received : February 13, 2025
Revised : March 13, 2025
Accepted : March 16, 2025

Keywords:
Wireless Sensor Networks, Energy Efficiency, Asynchronous Duty Cycle, Multihop Broadcast, TDMA-CSMA Hybrid

ABSTRACT

Energy efficiency is a critical determinant in the design and operation of Wireless Sensor Networks (WSNs), as sensor nodes are typically powered by constrained battery resources. Asynchronous duty cycle mechanisms have emerged as a viable strategy to optimize energy consumption while preserving network functionality. This research presents a comparative analysis of multiple energy-efficient Medium Access Control (MAC) protocols, including Low-Energy Adaptive Clustering Hierarchy (LEACH), Energy-Efficient Sensor Routing (EESR), B-MAC, L-MAC, WiseMAC, and hybrid approaches such as TDMA-CSMA. Performance metrics such as energy efficiency, latency, throughput, and packet delivery ratio (PDR) are evaluated under varying network conditions. The findings indicate that AI-driven protocols, particularly those incorporating Artificial Neural Networks (ANN), significantly outperform conventional methodologies by enhancing cluster head selection, distributing energy load effectively, and extending network lifetime. Hybrid ADC emerges as the most robust solution, demonstrating an optimal trade-off between energy efficiency and network reliability across dynamic traffic scenarios. Furthermore, This research highlights the implications of integrating adaptive duty cycling with intelligent network optimization, underscoring its potential to enhance WSN sustainability. The results provide a comprehensive framework for refining MAC protocol architectures, offering actionable insights for optimizing next-generation WSN deployments.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) constitute a transformative technological paradigm, comprising compact, battery-powered sensor nodes that autonomously collect and transmit data [1,2]. These networks play a pivotal role in a wide range of applications, including environmental monitoring, healthcare, and industrial automation. However, one of the most significant challenges facing WSNs is energy consumption. Given that sensor nodes rely on finite battery resources, frequent replacement or recharging is often impractical, particularly in remote or inaccessible locations. To mitigate this issue, duty cycling techniques have been developed, allowing sensor nodes to alternate between active and sleep states, thereby conserving energy. While this method substantially prolongs battery life, it inherently introduces trade-offs, particularly in terms of latency and throughput. Traditional duty cycling approaches, which rely on synchronous protocols, necessitate the synchronization of sleep-wake schedules, leading to additional energy expenditure[3]. In contrast, asynchronous duty cycling eliminates synchronization overhead, allowing nodes to operate independently and reduce energy usage, albeit at the potential cost of increased communication delays [4].

To further optimize energy efficiency in WSNs [5], several Medium Access Control (MAC) protocols have been designed, each offering unique approaches to balancing energy conservation and network performance. Protocols such as B-MAC [6], L-MAC [7], and WiseMAC [8] exhibit varying strengths and limitations, with B-MAC prioritizing simplicity, L-MAC achieving low latency through TDMA scheduling, and WiseMAC excelling in energy efficiency under low-traffic conditions due to asynchronous preamble sampling. Additionally, hybrid protocols like Z-MAC [9], which dynamically adapt between TDMA and CSMA modes based on traffic, offer scalability and robust performance in fluctuating traffic environments. Recent advancements have integrated Artificial neural networks into MAC protocols, leveraging intelligent algorithms to optimize cluster head selection and predict energy usage patterns. ANN-optimized approaches, such as those using the Levenberg–Marquardt Neural Network (LMNN), have demonstrated the potential to enhance energy management, reduce latency, and extend network longevity [9].

This research aims to conduct a rigorous comparative analysis of existing Medium Access Control (MAC) protocols and energy-efficient techniques utilizing asynchronous duty cycles in Wireless Sensor Networks (WSNs). The research systematically evaluates critical performance metrics, including energy efficiency, latency, throughput, and scalability, with a particular emphasis on AI-driven methodologies such as Artificial Neural Networks (ANNs). The investigation encompasses a broad spectrum of protocols, ranging from conventional approaches like B-MAC and L-MAC to hybrid frameworks such as Z-MAC and cluster-based strategies, including LEACH and EESR. By examining the inherent trade-offs between energy conservation and network performance, this research seeks to provide actionable insights and practical recommendations for optimizing future WSN protocol architectures.

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2. LITERATURE REVIEW

Energy efficiency is a pivotal design consideration in Wireless Sensor Networks (WSNs), given the limited energy resources of sensor nodes typically powered by non-rechargeable batteries [11]. Over the years, various Medium Access Control (MAC) protocols have been developed to address energy consumption issues in WSNs, employing techniques such as duty cycling to balance energy savings with communication performance [12]. Duty cycling involves switching nodes between active and sleep states to reduce idle listening and conserve energy. This section delves into key developments in energy-efficient MAC protocols, focusing on contention-based, schedule-based, and hybrid approaches, as well as the integration of Artificial Intelligence (AI) to optimize energy management.

In WSNs, energy efficiency centers on minimizing the time sensor nodes spend in energy-consuming active states [12]. Traditional MAC protocols like B-MAC address this issue through low-power listening (LPL), where nodes periodically wake up to check the communication channel for activity [13]. If the channel is idle, they return to sleep. While B-MAC effectively reduces idle listening, its use of long preambles can lead to increased energy consumption and communication delays under high traffic conditions. Similarly, contention-based protocols like B-MAC suffer from collisions and retransmissions, which can further deplete node energy reserves.

In contrast, schedule-based protocols such as L-MAC (Lightweight MAC) utilize Time Division Multiple Access (TDMA) to assign time slots to sensor nodes, eliminating the need for idle listening and collisions [13]. By ensuring that nodes only wake up during their designated time slots, L-MAC improves energy efficiency and throughput. However, the requirement for synchronization in TDMA-based systems introduces additional overhead, which may offset the energy gains in dynamic network environments.

WiseMAC employs a preamble sampling technique to reduce idle listening [14]. Nodes periodically sample the medium for activity, and when a sender has data to transmit, it sends a short preamble just before the receiver's sampling time. This approach minimizes energy consumption by reducing the time nodes spend listening to the channel. However, the reliance on precise timing can introduce synchronization challenges, and performance may degrade in highly dynamic networks.

Hybrid protocols, such as the Hybrid Asynchronous Duty Cycle (Hybrid ADC) protocol, combine elements of contention-based and schedule-based approaches to adapt node behavior based on network traffic conditions [15,16]. Hybrid ADC dynamically adjusts node activity by integrating both TDMA and Carrier Sense Multiple Access (CSMA) mechanisms, allowing nodes to switch between scheduled access and contention-based access as needed. This adaptability enhances energy efficiency and scalability, enabling the network to respond effectively to varying traffic loads. However, the complexity of managing both access methods and the need for dynamic decision-making can introduce additional overhead and potential delays.

Recent advancements have seen the integration of artificial intelligence into MAC protocols to further optimize energy management. Techniques such as Artificial neural networksare employed to predict traffic patterns and adjust duty cycles accordingly, enhancing energy efficiency while maintaining network performance [17]. For instance, AI-based approaches can optimize the selection of Cluster Heads (CHs) in hierarchical network structures, balancing energy consumption across nodes and extending network lifetime. However, the implementation of AI algorithms requires additional computational resources, which may not be feasible for all sensor nodes, particularly those with limited processing capabilities.

2.1 Duty Cycle in MAC Protocol

The duty cycle in Medium Access Control (MAC) protocols is one of the most essential techniques for improving energy efficiency in Wireless Sensor Networks (WSNs). A duty cycle refers to the process of periodically switching a sensor node between active and sleep states to minimize energy consumption [10,15,16]. Since communication activities such as listening, transmitting, and receiving data consume significant amounts of energy, a well-designed duty cycling strategy can extend the lifespan of sensor nodes, making WSNs more efficient and sustainable in battery-limited environments. Formally, the duty cycle in [18] is expressed as:

$$\delta = \frac{T_{\text{active}}}{T_{\text{active}} + T_{\text{sleep}}} \tag{1}$$

Where:

Tactive is the time the node spends awake.

Tsleep is the time the node spends in sleep mode.

In [18], the smaller the duty cycle (i.e., the longer the sleep time), the more energy-efficient the node is. However, a lower duty cycle may introduce latency because nodes are not always available for immediate communication, potentially delaying data transmissions. Protocols like WiseMAC utilize asynchronous duty cycling, where nodes independently alternate between sleep and active states without requiring synchronization. This reduces the energy consumed by control messages, but may increase latency as nodes are not always awake to receive transmissions. WiseMAC further reduces idle listening by using preamble sampling, where nodes wake up periodically to check for incoming data before going back to sleep. While this reduces energy consumption, long preambles can still lead to delays in high-traffic scenarios.

A key challenge with duty cycling is balancing energy savings with communication performance [19]. While low duty cycles save energy, they may introduce higher latency and lower throughput, especially in multihop networks where data must pass through multiple nodes to reach its destination. Hybrid protocols, which combine elements of both TDMA and contention-based approaches, attempt to address these trade-offs by dynamically adjusting the duty cycle based on traffic conditions. Duty cycling significantly reduces energy consumption by minimizing the time nodes spend in energy-hungry active states. However, the implementation of duty cycling introduces certain trade-offs [19]:

1. Energy Efficiency: The primary benefit of duty cycling is improved energy efficiency. By keeping nodes in sleep mode as much as possible, the protocol conserves battery power, extending the lifetime of individual nodes and the overall network.
2. Latency: One major downside of duty cycling is increased communication latency. Since nodes are not always awake to immediately receive or transmit data, delays can occur when a node needs to communicate but its intended recipient is in sleep mode. This can be particularly problematic in time-sensitive applications like emergency response or real-time monitoring.
3. Synchronization Overhead: In synchronous duty cycling protocols, nodes must periodically synchronize their clocks to ensure they wake up at the same time for communication. This synchronization process consumes energy and introduces additional overhead in the network. In contrast, asynchronous protocols avoid synchronization but may suffer from longer delays due to the lack of coordinated wake-up times.
4. Throughput: Duty cycling can also affect throughput, as nodes are awake for shorter periods. In high traffic scenarios, this reduced availability can limit the amount of data that can be transmitted, especially if the duty cycle is too low. Hybrid protocols attempt to address this issue by adjusting the duty cycle based on current traffic conditions.

2.2 Types of Duty Cycling in MAC Protocols

In Wireless Sensor Networks (WSNs), optimizing Medium Access Control (MAC) protocols is essential for improving energy efficiency and communication performance. Several advanced methodologies address these challenges [20-25], including Schedule-Based Duty Cycle Protocols, Hybrid Duty Cycle Protocols, Cluster-Based Routing, Artificial Neural Networks (ANNs), Sub-Clustering, Energy-Aware Metrics, Preamble Sampling and Sleep Scheduling, Data Aggregation, and Lightweight Networks.

Schedule-Based Duty Cycle Protocols divide time into fixed slots, allowing sensor nodes to transmit only during designated slots while remaining in sleep mode otherwise [20]. This eliminates idle listening and reduces energy consumption while ensuring collision-free communication. However, synchronization requirements introduce additional overhead, which can impact performance in dynamic environments. Where Hybrid Duty Cycle Protocols dynamically adjust duty cycles based on network conditions, combining contention-based and schedule-based approaches [21]. This adaptability allows for efficient energy management and low latency, making these protocols suitable for networks with varying traffic conditions. Besides that, Cluster-Based Routing enhances energy efficiency by organizing sensor nodes into clusters, each managed by a cluster head [22]. The cluster head aggregates data and transmits it to the base station, reducing direct transmissions and conserving network resources. This hierarchical structure improves scalability and load distribution.

Artificial neural networks optimize network parameters, including routing decisions and energy management, by learning from real-time conditions [23]. By predicting optimal paths and balancing energy consumption across nodes, ANNs enhance network lifespan and data reliability. Sub-Clustering in artificial neural networks further distributes communication loads by introducing secondary clusters within primary clusters [24]. Sub-Cluster Heads (Sub-CHs) handle data aggregation within smaller groups before transmitting to the CH. This hierarchical strategy enhances scalability and energy efficiency, particularly in large-scale networks. Thus, the Preamble Sampling and Sleep Scheduling minimize energy consumption by reducing active time [25]. Nodes periodically wake up to check for transmissions, staying in low-power sleep mode when no data is available. Coordinated sleep scheduling further optimizes energy use while ensuring continuous network connectivity.

Energy-Aware Metrics play a crucial role in routing decisions by prioritizing nodes with higher energy reserves [26]. By preventing early depletion of weaker nodes, energy-aware routing improves network longevity and overall efficiency. To reduce the volume of data transmitted, WSNs employ data aggregation techniques, where redundant data from multiple nodes is combined at intermediate points before transmission to the base station. Compression algorithms are also applied to minimize data size, thereby reducing transmission energy consumption and bandwidth usage. The concept of a lightweight network pertains to the design of protocols and algorithms that require minimal computational resources and energy. In WSNs, this involves simplifying communication protocols, reducing control message overhead, and optimizing processing tasks to extend the operational lifespan of sensor nodes. Collectively, these methodologies contribute to the efficient operation of WSNs by addressing critical challenges related to energy consumption, data transmission reliability, and network scalability.

Table 1. Advantages and Disadvantages of Energy Saving Techniques

Energy-Saving Techniques	Advantages	Disadvantages	Protocols/Approaches
Cluster-Based Routing	Reduces redundant transmissions; Load balancing through CH rotation	Requires CH rotation mechanism; Some nodes (CH) may still deplete energy faster	LEACH, EESR
Artificial Neural Networks	Intelligent CH selection; Balances load; Detects anomalies	Higher computational complexity; Requires training data	LEACH-LMNN, EESR-LMNN, ANN-ILMNN
Hybrid Protocols (TDMA-CSMA)	Efficient under varying traffic loads; Reduces collisions and retransmissions	Requires more complex scheduling; Latency may increase in low-traffic conditions	Z-MAC

Sub-Clustering	Further balances load; Reduces the burden on main CHs	Requires additional computation for sub-CH selection	Sub-LEACH-LMNN
Energy-Aware Metrics (Energy Betweenness)	Prolongs the life of lower-energy nodes	May concentrate traffic on a few nodes, leading to their depletion	Energy Betweenness Model
Preamble Sampling and Sleep Scheduling	Reduces idle listening; Saves energy when traffic is low	May increase delay; Requires precise timing	WiseMAC, X-MAC
Data Aggregation and Compression	Reduces data volume; Saves transmission energy	Loss of data fidelity due to compression; Processing energy consumption	LEACH, Sub-LEACH
Lightweight Network	Energy-efficient; No idle listening; Collision-free	Synchronization overhead; Not suitable for dynamic networks	L-MAC

3. RESEARCH METHODS

This research adopts a simulation-based approach to evaluate and optimize the performance of various Medium Access Control (MAC) protocols in Wireless Sensor Networks (WSNs), with a particular focus on asynchronous duty cycle protocols. The research emphasizes assessing energy efficiency, latency, and packet delivery ratio (PDR) to identify the trade-offs and strengths of different protocol designs. To achieve this, the study utilizes a robust simulation framework, integrating Python [27] and OMNeT++ [28], a discrete-event network simulator widely recognized for its versatility in WSN research. This framework facilitates comprehensive evaluations of traditional protocols, including B-MAC, L-MAC, and WiseMAC, as well as hybrid models such as TDMA-CSMA and advanced proposed improvements. By simulating various network scenarios, such as varying node densities, traffic patterns, and energy constraints, the methodology ensures a realistic and dynamic assessment of protocol performance. The research methodology employed a structured and systematic approach to evaluate the performance of various Medium Access Control (MAC) protocols in Wireless Sensor Networks (WSNs). The process was divided into five key stages as shown in figure 1 below.

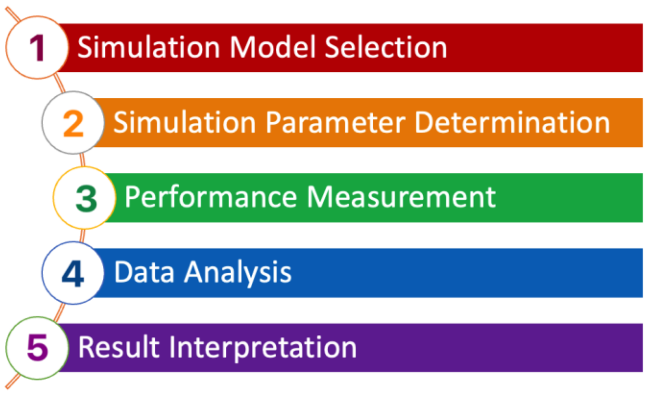

Figure 1. Research Methodology

The first step involved selecting an appropriate simulation model to replicate real-world scenarios accurately. OMNeT++, a discrete event network simulator, was chosen due to its capability to simulate complex WSN environments. This tool allowed the researchers to implement different MAC protocols, including B-MAC, WiseMAC, Hybrid ADC, and L-MAC, while maintaining a controlled and customizable environment. The model was designed to emulate a typical WSN deployment, ensuring a balance between single-hop and multi-hop communication scenarios [29].

Once the model was established, key simulation parameters were defined to ensure consistency and relevance across all tests. Parameters included node density, traffic patterns (e.g., constant and variable bit rate), initial energy levels, transmission power, and data packet sizes [30]. Sleep/wake cycles were also standardized to compare the energy efficiency of different protocols fairly. These parameters were carefully selected to reflect real-world operating conditions and ensure that the simulation outcomes would be applicable to practical WSN applications.

During the simulations, specific metrics were monitored to evaluate the performance of the protocols. These metrics included energy efficiency (measured as energy consumed per successful packet delivery), latency (average time taken for data transmission from source to destination), and Packet Delivery Ratio (PDR) (the ratio of successfully received packets to total packets sent). This stage focused on capturing protocol behavior under varying conditions, such as changes in node density and traffic loads, to assess their adaptability and robustness.

The data collected from the simulations were analyzed systematically using statistical tools and visualization techniques. Multiple simulation runs were conducted to ensure reliability and account for variability in the results. Comparative analyses were performed to identify trends, strengths, and weaknesses of each protocol across the defined metrics. This analysis was critical in understanding the trade-offs between energy efficiency, latency, and PDR.

The final stage involved interpreting the analyzed data to draw meaningful conclusions about the performance of the evaluated protocols. The insights gained were used to identify the most suitable protocols for specific application scenarios, considering factors such as network size, traffic conditions, and energy constraints. The findings also highlighted areas for potential improvement in protocol design, providing a foundation for future research in WSN optimization.

4. RESULTS AND DISCUSSIONS

The performance evaluation of MAC protocols in Wireless Sensor Networks (WSNs) is fundamentally based on three key metrics: energy efficiency, throughput, and packet delivery ratio (PDR). These metrics provide a comprehensive understanding of how well a protocol balances power consumption, data transmission rates, and network reliability, which are critical in WSN applications. Each protocol has inherent benefits depending on its underlying design, duty cycling strategy, and the method of medium access control.

4.1 Energy Consumption

In this study, the energy consumption of the proposed prototype, which has been enhanced with a multi-hop broadcast mechanism, is systematically analyzed to assess its efficiency. The evaluation considers energy wastage factors, including idle listening, collisions, protocol overhead, and overhearing, which significantly impact the overall power consumption in Wireless Sensor Networks (WSNs). To ensure a comprehensive assessment, the simulation quantifies energy consumption across various radio states of sensor nodes—transmitting, receiving, listening, and sleeping—with energy values measured in Joules (J).

A key aspect of this evaluation is the duty cycle formula, which defines the ratio of time a node spends in an active state (Tactive) versus a sleep state (Tsleep). This formula is applied to assess the energy efficiency of each MAC protocol, providing insights into how different protocols optimize node activity to conserve energy while maintaining network performance. Additionally, the selection of 10, 20, 30, 40, and 50 sensor nodes in this study is a deliberate strategy designed to evaluate network scalability and protocol adaptability under different node densities. By systematically increasing the number of nodes, the study investigates how MAC protocols respond to variations in traffic load, contention, and energy efficiency.

1. Smaller networks (10 nodes) simulate minimal deployments, typical in environmental monitoring and industrial automation.
2. Medium-scale networks (20–30 nodes) represent common WSN implementations where energy efficiency and communication reliability are critical.
3. Larger networks (40–50 nodes) introduce greater congestion and competition for the communication channel, enabling a deeper analysis of protocol robustness and performance in dense deployments.

Energy efficiency, latency, PDR are derived from OMNeT++ simulations, ensuring statistical validity through multiple controlled runs. This structured approach facilitates a fair and reproducible comparison of MAC protocol performance, making the findings applicable to real-world WSN scenarios where network topology, data transmission rates, and energy constraints vary. Furthermore, the incremental node density approach highlights the adaptability of hybrid MAC protocols, such as Hybrid ADC, in dynamically adjusting to network conditions, thereby offering valuable insights into optimizing duty cycling strategies. The simulation results are systematically presented in Table 5.6, providing a data-driven basis for evaluating protocol efficiency.

Table 2. The Simulation Result of Energy Consumption (Multi-Hop Broadcast)

MAC Protocol	Node(s)				
	10	20	30	40	50
B-MAC	0.1584	0.1941	0.2191	0.2371	0.2548
WiseMac	0.1551	0.1922	0.2148	0.2347	0.2507
Mutlihop Hybrid ADC	0.1543	0.1908	0.2078	0.2311	0.2489
L-MAC	0.1626	0.2027	0.2230	0.2415	0.2582

Table 2 above presents the obtained results of energy consumption in Multi-Hop Broadcast, indicating that L-MAC has the highest energy consumption among all nodes. It reaches 0.1626 at 10 nodes and increases to 0.2582 at 50 nodes. The second highest energy consumption is observed in B-MAC, which reaches 0.1584 at 10 nodes and increases to 0.2548 at 50 nodes. However, the lowest energy consumption varies between WiseMAC and Hybrid ADC MAC, depending on the number of nodes. At 10 and 20 nodes, WiseMAC has the lowest energy consumption, with values of 0.1551 and 0.1922, respectively. Meanwhile, for other node configurations, WiseMAC consumes more energy than Hybrid ADC MAC. The Hybrid ADC MAC protocol exhibits the lowest energy consumption at 30 nodes (0.2128), 40 nodes (0.2334), and 50 nodes (0.2497). On average, Hybrid ADC MAC has the lowest energy consumption compared to the other protocols. Moreover, a comparison of the simulated energy consumption results is illustrated in Figure 2 below.

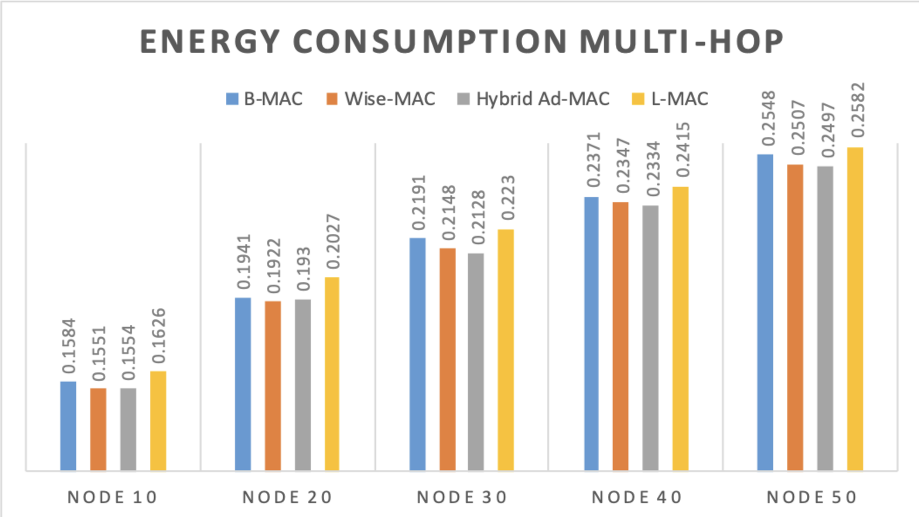

Figure 2. The comparison results of energy consumption in Multi-hop broadcast

4.2 Throughput

This simulation also aims to calculate the network throughput, providing insights into the rate of successful message delivery within the prototype enhanced with multi-hop broadcast. The simulation results focus on evaluating throughput performance, measured in bits per second (bit/s or bps), to assess the efficiency of data transmission. Below are the network throughput values for each MAC protocol, as obtained from the simulation results.

Table 3. The Simulation Result of Network Throughput (Multi-Hop Broadcast)

MAC Protocol	Node(s)				
	10	20	30	40	50
B-MAC	51934.72	100036.48	192491.36	247591.68	314003.84
WiseMac	51946.14	110046.79	209743.23	251531.23	324813.45
Mutlihop Hybrid ADC	52342.97	121101.94	218864.53	266317.21	334128.23
L-MAC	53573.57	132326.16	228243.74	287591.44	347253.14

Table 3 presents the throughput results using Multi-Hop Broadcast, where L-MAC achieves the highest value. At 10 nodes, it reaches 53,573.57, while at 50 nodes, it achieves 347,353.14. The second highest throughput is observed in multi-hop Hybrid ADC, with 52,342.97 at 10 nodes and a peak value of 334,128.23 at 50 nodes. The third highest throughput is recorded in WiseMAC, reaching 51,946.14 at 10 nodes and 324,813.45 at 50 nodes. Meanwhile, B-MAC exhibits the lowest throughput, with 51,034.72 at 10 nodes and 314,004.84 at 50 nodes. A comparison of the simulation results for throughput is illustrated in Figure 3 below.

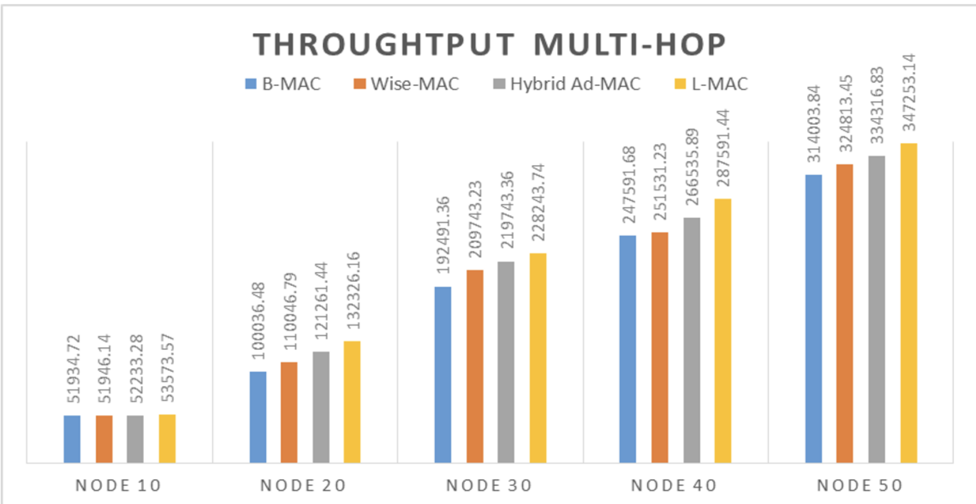

Figure 3. The comparison results of throughput in multi-hop broadcast

4.3 Latency

The latency value will also be derived from the simulation results. Latency is measured as the time interval between stimulation and response or, from a broader perspective, the time delay between a cause and its effect in the observed system. In this case, it refers to the reaction time of each node activity and system state within the prototype, which has been enhanced with multi-hop broadcast during the message delivery process. The latency results are measured in seconds (s). Below are the latency values for each MAC protocol, as obtained from the simulation results.

Table 4. The Simulation Result of Latency (Multi-Hop Broadcast)

MAC Protocol	Node(s)				
	10	20	30	40	50
B-MAC	0.0067	0.0148	0.0123	0.0122	0.0127
WiseMac	0.0060	0.0144	0.0114	0.0110	0.0119
Mutlihop Hybrid ADC	0.0053	0.0141	0.0114	0.0110	0.0118
L-MAC	0.0015	0.0120	0.0091	0.0082	0.0100

Table 4 presents the latency results from the simulation, indicating that B-MAC exhibits the highest latency across all node configurations. At 10 nodes, B-MAC records a latency of 0.0067, which increases to 0.0127 at 50 nodes. WiseMAC follows, with latencies of 0.0060 at 10 nodes and 0.0119 at 50 nodes. The third highest latency is observed in the Hybrid ADC MAC protocol, with a value of 0.0046 at 10 nodes, increasing to approximately 0.0113 at 50 nodes. In contrast, L-MAC demonstrates the lowest latency, recording 0.0015 at 10 nodes and 0.0100 at 50 nodes. A comparative analysis of the latency results is illustrated in Figure 4 below.

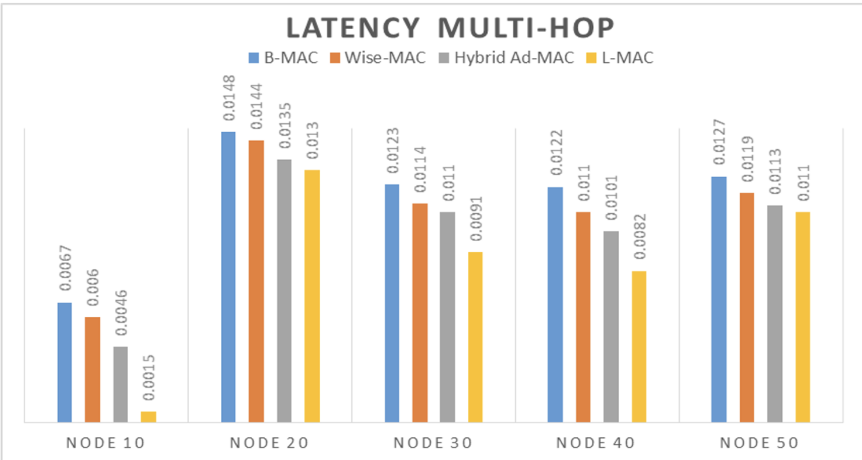

Figure 4. The comparison results of latency in Multi-hop broadcast

4.4 Packet Delivery Ratio (PDR)

The final metric analyzed in this simulation is the Packet Delivery Ratio (PDR). PDR is defined as the ratio between the number of packets successfully received by the destination and the total packets generated by the source. This metric is crucial for evaluating the performance of the protocol prototype, which has been enhanced with multi-hop broadcast. The PDR values are measured as a percentage (%). Below are the PDR values for each MAC protocol, as obtained from the simulation results:

Table 5. Simulation Result of Packet Delivery Ratio (PDR) – (Multi-Hop Broadcast)

MAC Protocol	Node(s)				
	10	20	30	40	50
B-MAC	0.9991	0.9951	0.9994	0.9955	0.9950
WiseMac	0.9998	0.9971	0.9993	0.9969	0.9977
Mutlihop Hybrid ADC	0.9992	0.9970	0.9989	0.9968	0.9976
L-MAC	0.9955	0.9885	0.9832	0.9867	0.9882

Table 5 presents the network simulation results for the Packet Delivery Ratio (PDR) using Multi-Hop Broadcast. Among all node configurations, WiseMAC consistently demonstrates the highest PDR, while L-MAC exhibits the lowest. At 10 nodes, WiseMAC achieves a PDR of 0.9998, whereas L-MAC records the lowest at 0.9955. A similar trend is observed at 20 nodes, where WiseMAC attains the highest PDR at 0.9971, while L-MAC falls to 0.9885. At 30 nodes, the highest PDR remains 0.9994, with L-MAC registering the lowest at 0.9832. This pattern continues at 40 nodes, where WiseMAC maintains its superior performance with a PDR of 0.9969, while L-MAC records 0.9867. Finally, at 50 nodes, WiseMAC achieves the highest PDR at 0.9977, whereas L-MAC reaches the lowest value of 0.9882. A comparative analysis of the Packet Delivery Ratio (PDR) results for Multi-Hop Broadcast is illustrated in Figure 5 below.

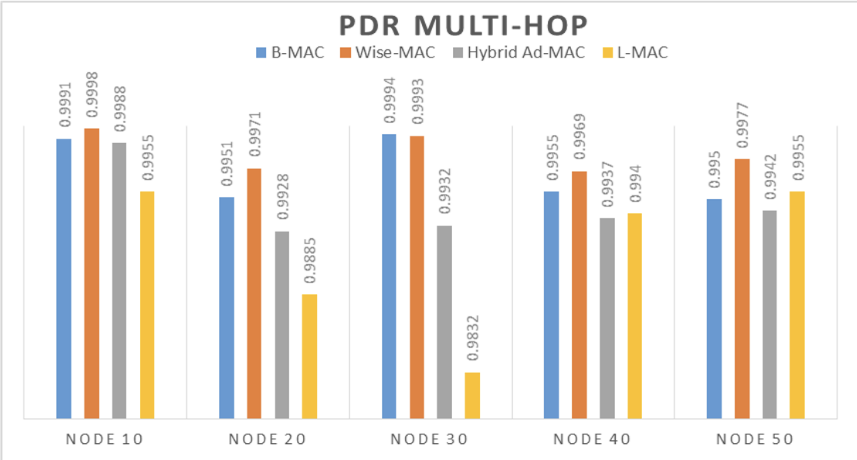

Figure 5. The comparison result of PDR in Multi-hop broadcast

Table 6. Comparative Analysis of Energy Efficiency, Latency, and Packet Delivery Ratio (PDR)

Protocol	Energy Efficiency	Latency	Packet Delivery Ratio (PDR)
B-MAC	**Moderate**: Uses low-power listening (LPL) to reduce idle listening but consumes more energy in high traffic due to long preambles.	**High**: Long preambles result in high latency, especially under high traffic.	**High**: Performs well in light traffic but suffers from packet loss in high traffic due to collisions.
WiseMAC	**High**: Preamble sampling conserves energy, particularly in low-traffic conditions, with asynchronous wake-up scheduling reducing idle listening.	**Moderate**: Delays may occur due to asynchronous wake-up times.	**High**: Maintains strong PDR with short preambles, though long preambles may slightly lower delivery efficiency.
Hybrid ADC	**Very High**: Employs optimized duty cycling, dynamically adjusting node activity based on traffic conditions, minimizing energy waste.	**Moderate**: Balances low latency by adapting wake-up cycles to traffic demand, though delays are possible in low traffic.	**Very High**: Achieves reliable PDR through effective multi-hop routing and adaptive scheduling.
L-MAC	**High**: TDMA-based structure eliminates idle listening and collisions, ensuring efficient energy usage.	**Low**: No contention for the medium results in guaranteed low latency.	**Moderate**: PDR is consistent in low-mobility networks but degrades in high-mobility scenarios due to synchronization issues.

The table 6 presents a comprehensive comparative analysis of four MAC protocols, evaluated across three key performance metrics: energy efficiency, latency, and packet delivery ratio (PDR). Each protocol exhibits distinct strengths and limitations, making them suitable for different Wireless Sensor Network (WSN) applications. B-MAC demonstrates moderate energy efficiency through low-power listening (LPL); however, its reliance on long preambles significantly increases energy consumption in high-traffic environments. Additionally, it experiences high latency, particularly in congested networks, as long preambles delay communication. While B-MAC performs efficiently in low-traffic scenarios, achieving a high PDR, it is prone to packet loss under heavy network loads due to frequent collisions.

In contrast, WiseMAC offers higher energy efficiency by employing preamble sampling, which effectively reduces idle listening, especially in low-traffic conditions. However, its asynchronous wake-up scheduling introduces moderate latency, as nodes may not always be immediately synchronized for communication. Despite this, WiseMAC maintains a consistently high PDR, primarily due to its short preamble strategy, which enhances delivery efficiency. Nonetheless, occasional delays caused by asynchronous node behavior may marginally affect reliability.

Among the protocols, Hybrid ADC exhibits superior energy efficiency, utilizing a dynamic duty cycling mechanism that adapts node activity based on network traffic conditions. This adaptability minimizes energy wastage and ensures optimal performance across varying traffic levels. It achieves moderate latency, with delays mitigated during high-traffic periods, though slightly evident in low-traffic conditions due to longer sleep durations. Hybrid ADC excels in maintaining a very high PDR, supported by its multi-hop routing capabilities and adaptive scheduling, making it highly reliable in diverse network environments.

Finally, L-MAC offers exceptional energy efficiency, leveraging a TDMA-based structure that eliminates idle listening and prevents collisions by allocating dedicated time slots for communication. This architecture guarantees low latency, making L-MAC particularly well-suited for time-sensitive applications. However, while its PDR remains stable in low-mobility networks, it tends to degrade in high-mobility environments due to synchronization overhead.

5. CONCLUSION

Wireless Sensor Networks (WSNs) have emerged as a revolutionary technology, facilitating real-time data collection and communication across a wide range of applications. Among the key components of WSNs, Medium Access Control (MAC) protocols integrated with duty cycling techniques have received considerable attention due to their role in optimizing energy efficiency and network performance. This research evaluates the performance of various MAC protocols, focusing on energy efficiency, throughput, and packet delivery ratio (PDR), while also highlighting the potential of advanced approaches, such as asynchronous duty cycling, in enhancing WSN operational efficiency.

In summary, Hybrid ADC emerges as the most well-balanced protocol across all assessed metrics, making it the ideal choice for energy-constrained networks with variable traffic conditions. L-MAC is particularly suited for applications requiring high throughput and low latency, while WiseMAC demonstrates consistent reliability in PDR and moderate energy efficiency, making it effective in medium-traffic scenarios. Conversely, B-MAC, despite its simplicity, exhibits notable limitations in scalability, energy efficiency, and performance under high-traffic conditions.

Each protocol offers distinct advantages, making them suitable for specific applications depending on network requirements and environmental constraints. Hybrid ADC stands out as the most effective in terms of energy efficiency and PDR, while still maintaining an acceptable latency level. L-MAC is best suited for low-latency, high-throughput applications, whereas WiseMAC ensures reliability and efficiency in moderate traffic scenarios. In contrast, B-MAC's inefficiency in energy consumption and high latency make it less suitable for dynamic or high-traffic environments.

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