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Markov Chain-based Optimization for Efficient and Reliable Wireless Sensor Networks: A Comprehensive Analysis and Enhanced TDMA-CSMA Hybrid Protocol

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ABSTRACT

This paper presents a comprehensive analysis of various protocols using Markov chain-based optimization techniques for wireless sensor networks (WSNs). Markov chain models have been used to address the challenges faced by WSNs, including limited resources, QoS requirements, energy consumption, network reliability, adaptability, and real-time decision-making. An Enhanced TDMA-CSMA Hybrid protocol is proposed to overcome existing protocol limitations. It combines the advantages of TDMA and CSMA, dynamically allocating time slots based on traffic patterns. The protocol incorporates collision avoidance mechanisms, synchronization techniques, and energy-saving mechanisms to reduce delay, improve network throughput, and enhance reliability in wireless networks. Through performance analysis and comparison with existing protocols, the proposed Enhanced TDMA-CSMA Hybrid protocol demonstrates its superiority in terms of throughput, delay, channel utilization, and energy consumption. This research contributes to efficient and reliable communication in wireless networks, benefiting IoT, smart cities, and industrial automation applications.

General Terms

Markov-Chain, Quality of Service, Delay

Keywords

Markov chain, optimization, wireless sensor networks, efficient, reliable, comprehensive analysis, TDMA-CSMA hybrid protocol

1. INTRODUCTION

Researchers have explored various advanced techniques to accurately model and analyze the performance of heterogeneous networks using Markov chains. This includes considering different network characteristics such as varying channel conditions, traffic patterns, and device heterogeneity in the modeling process. There is ongoing research on developing efficient and scalable optimization algorithms specifically tailored for heterogeneous networks. These algorithms aim to find the optimal network configurations considering various performance metrics, such as throughput, latency, energy efficiency, and fairness. Genetic algorithms, reinforcement learning, and game theory-based approaches are being explored in this context. Researchers are also investigating dynamic resource allocation schemes based on Markov chain models to adaptively allocate resources, such as transmission power, channel bandwidth, and modulation schemes, in real time. This allows for the efficient utilization of available resources based on changing network conditions and traffic demands [1].

Cross-layer optimization approaches are being explored to leverage the interdependencies between different layers of the network protocol stack. Markov chain models are used to capture these interdependencies and optimize the performance by jointly considering parameters and decisions across multiple layers, such as the physical layer, MAC layer, and routing layer. Markov chain- based optimization techniques are being applied to address performance challenges in IoT applications [2]. This includes optimizing resource allocation and scheduling strategies in IoT networks, improving energy efficiency in IoT sensor deployments, and enhancing QoS in IoT communication systems. Researchers are investigating the integration of machine learning techniques with Markov chain-based optimization to enhance the performance of heterogeneous networks. This includes using machine learning algorithms for intelligent decision-making, prediction of network states, and optimization of network parameters based on historical data and real-time observations [3-4].

WSNs typically operate with limited resources, including energy, bandwidth, and processing power. Markov chain-based optimization allows for efficient allocation and management of these resources based on the dynamic behavior of the network. It helps in maximizing the utilization of limited resources and extending the network's operational lifetime. Wireless sensor networks often have specific QoS requirements, such as reliability, latency, and throughput, depending on the application. Markov chain-based optimization enables the analysis and improvement of network performance metrics to meet these QoS requirements. It allows for intelligent decision-making in selecting appropriate network configurations and policies to enhance QoS in WSNs [5-7].

Energy consumption is a critical factor in WSNs due to the resource-constrained nature of sensor nodes. Markov chain-based optimization can help minimize energy consumption by optimizing transmission power levels, duty cycles, and sleep/wake scheduling of sensor nodes. By intelligently managing energy resources, it extends the network's lifetime and reduces the need for frequent battery replacements or recharging. Wireless sensor networks are often deployed in challenging environments where nodes may be prone to failures or disruptions. Markov chain- based optimization allows for the analysis of network reliability and robustness by considering factors such as node failures, interference, and channel conditions. It aids in identifying vulnerabilities, optimizing routing protocols, and improving the overall resilience of the network [8-9].

WSNs are typically deployed in dynamic environments where network conditions and requirements can change over time. Markov chain-based optimization provides a framework for adaptability and scalability, allowing the network to dynamically adjust its parameters and configurations based on the current state. This adaptability ensures optimal network performance even in changing conditions and facilitates the scalability of the network as it grows. Many applications of WSNs require real-time decision making based on the sensed data. Markov chain- based optimization enables the analysis of network performance in real-time, allowing for intelligent decision-making algorithms to be implemented. It supports timely and accurate decisions based on the current network state, facilitating applications such as environmental monitoring, surveillance, and industrial automation [10-11].

In summary, the topic of Markov chain-based performance optimization holds great importance for wireless sensor networks. It addresses key challenges related to resource management, QoS, energy efficiency, network reliability, adaptability, and real-time decision-making. By leveraging Markov chain modeling and optimization techniques, WSNs can achieve enhanced performance, efficient resource utilization, and improved overall functionality, making it a crucial topic for researchers and practitioners in the field. The present work analyzes the performance of the various protocols using Markov chain model and proposed enhanced model which includes the features of both TDMA and CSMA protocols. The novelty and contribution of the proposed work is explained below:

- The proposed work combines the advantages of TDMA and CSMA protocols to achieve higher channel efficiency and reduced delay.
- The Enhanced TDMA-CSMA Hybrid protocol dynamically allocates time slots to nodes based on their traffic patterns, further improving channel utilization and reducing delay.
- The protocol is designed to work well in wireless networks with a large number of nodes and high traffic rates.
- The protocol employs collision avoidance mechanisms, reducing the likelihood of packet loss and retransmissions, leading to improved reliability and reduced energy consumption.
- The proposed work is a significant step forward in optimizing communication in wireless networks, enabling more efficient and reliable communication in a range of applications, including the Internet of Things, smart cities, and industrial automation.

2. LITERATURE STUDY

Jainali et al. proposed an algorithm for optimizing the selection of heterogeneous networks based on a Markov model. The algorithm takes into account various factors such as network quality, user preferences, and energy consumption. The Markov model is used to predict the future network conditions and to make decisions accordingly. The proposed algorithm has been tested and compared with other existing algorithms, and the results show that it outperforms them in terms of network selection accuracy and energy efficiency. Overall, the paper offers a solution for improving the performance of heterogeneous networks and enhancing the user experience [12].

Wei et al. proposed a Markov chain-based algorithm for optimizing the vertical handoff process in heterogeneous wireless networks. The proposed algorithm takes into account the network dynamics and user preferences to make optimal handoff decisions [13]. Jiajia et al. proposed a Markov chain-based optimization framework for heterogeneous wireless networks. The proposed framework considers network dynamics and user requirements to optimize the network performance [14].

Shuangquan et al. proposed a Markov chain-based mobility prediction scheme for optimizing handover decisions in heterogeneous wireless networks. The proposed scheme takes into account user mobility patterns and network dynamics to predict the future location of a mobile user [15].

Y. Zhang et al. apply a Markov decision process (MDP) model to optimize network selection in a heterogeneous wireless network. However, their focus is on dynamic resource management, which involves allocating resources (such as bandwidth) among different networks in real-time based on the changing network conditions and user demands. The authors propose a novel MDP-based algorithm that takes into account both the network quality and the resource availability when making network selection decisions. They also introduce a new state representation that captures the temporal dynamics of the network conditions and the resource usage. The simulation results show that their proposed algorithm outperforms several existing methods in terms of both network performance and resource utilization. They also demonstrate the effectiveness of their approach under various network scenarios and user mobility patterns [16].

Rehman et al. proposed a performance analysis of a heterogeneous wireless sensor network using a Markov model. The authors investigate the effect of channel fading, interference, and collision on the network's performance [17]. Djenouri et al. proposed a Markov chain model to analyze the performance of a heterogeneous wireless sensor network. The authors consider the impact of different traffic patterns, network topologies, and channel conditions on the network's performance [18]. Djenouri et al. proposed a performance analysis of a heterogeneous wireless sensor network using Markov chain models. The authors investigate the impact of different parameters such as traffic patterns, network topologies, and channel conditions on the network's performance [19].

Kumar et al. proposed a Markov chain model to analyze the performance of a heterogeneous wireless sensor network. The authors consider the effect of different node types, traffic patterns, and network topologies on the network's performance [20]. Yang et al. proposed a Markov chain model to analyze the performance of a heterogeneous wireless sensor network. The authors consider the effect of different node types, traffic patterns, and network topologies on the network's performance [21]. Liu et al. proposed a Markov chain model to analyze the performance of a heterogeneous wireless sensor network. The authors consider the effect of different node types, traffic patterns, and network topologies on the network's performance [22].

Sun et al. proposed a Markov chain model to analyze the performance of a heterogeneous wireless sensor network. The authors consider the effect of different node types, traffic patterns, and network topologies on the network's performance [23]. Wang et al. proposed a Markov chain model to analyze the performance of a heterogeneous wireless sensor network. The authors consider the effect of different node types, traffic patterns, and network topologies on the network's performance [24].

From the literature study, it is evidently found that the wireless networks face challenges in achieving efficient and reliable communication due to limited bandwidth, high noise, and interference. The existing protocols such as IEEE 802.15.4, CSMA, ALOHA, and TDMA-CSMA Hybrid have limitations in addressing these issues, leading to increased delays and reduced network throughput.

To address the above challenges, an Enhanced TDMA-CSMA hybrid protocol is proposed. The protocol combines the advantages of TDMA and CSMA to allocate time slots dynamically based on traffic patterns. The proposed protocol also includes enhanced collision avoidance mechanisms and synchronization techniques to reduce delay and improve network throughput. The key contributions of the proposed protocol are:

- **Dynamic Slot Assignment:** The protocol allocates time slots based on traffic patterns, allowing nodes with higher traffic demands to be allocated more slots, thereby improving network throughput.
- **Adaptive Collision Avoidance:** The protocol employs a dynamic backoff mechanism to adjust the backoff window size based on the network traffic, reducing collisions and improving channel utilization.
- **Synchronization Mechanisms:** The protocol uses a synchronization mechanism that synchronizes the nodes' clocks to improve network synchronization, reducing delays and improving network throughput.
- **Enhanced Energy Efficiency:** The protocol incorporates energy-saving mechanisms such as sleep mode, reducing energy consumption and improving network lifetime.
- **Reduced Delay and Improved Network Throughput:** The proposed protocol reduces delay and improves network throughput by optimizing channel utilization, collision avoidance, and synchronization, resulting in efficient and reliable communication in wireless networks.

3. ENHANCED TDMA-CSMA PROTOCOL

The Enhanced TDMA-CSMA Hybrid protocol is bandwidth efficient protocol that combines the advantages of Time-Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) techniques to improve network performance and efficiency. This protocol dynamically allocates time slots to nodes based on their traffic patterns, allowing nodes with higher traffic demands to be assigned more slots, thereby optimizing channel utilization and improving network throughput. Additionally, the Enhanced TDMA-CSMA Hybrid protocol incorporates adaptive collision avoidance mechanisms, such as dynamic backoff algorithms, to minimize collisions and enhance the overall network performance. It also employs synchronization mechanisms to synchronize the nodes' clocks, reducing delays and improving network synchronization. With its focus on dynamic slot assignment, collision avoidance, synchronization, and energy efficiency, the Enhanced TDMA-CSMA Hybrid protocol offers a robust solution for efficient and reliable communication in wireless networks.

A mathematical model of the Enhanced TDMA-CSMA Hybrid protocol can be formulated to describe the key parameters and their relationships. To develop a mathematical model, a network is considered. Let N be the total number of nodes in the network, n_i denote the ID of node i, where i = 1, 2, ..., N. Si be the set of time slots assigned to node i. T_i represent the transmission time of node i during its assigned time slots. C_i denote the collision probability of node i during its transmission. The traffic model is developed with λi represent the arrival rate of packets at node i. Let pi be the probability of a successful transmission for node i. Li be the average packet length for node i. R_i be the average data rate of node i. Similarly, a delay model is developed. Let D_i be the average delay experienced by node i and D_{total} be the total delay in the network.

A utilization model has been developed to analyze bandwidth utilization. The model is used for throughput analysis. Let U_i represent the channel utilization of node i and U_{total} denote the overall channel utilization in the network. The energy consumption is also an important factor therefore energy consumption model is also developed. Let E_i represent the energy consumed by node i during its transmission and reception and E_{total} denote the total energy consumption in the network.

The number of time slots assigned to each node should satisfy the constraint:

$$\sum |S_i| \leq S_{\text{total}} \tag{1}$$

where Stotal is the total number of available time slots in the system. The number of assigned time slots determines the transmission time of each node:

$$T_i = \left|\frac{S_i}{R_i}\right| \tag{2}$$

The collision probability of each node depends on the number of contending nodes and the backoff algorithm used. The average delay experienced by each node can be calculated using the delay model specific to the protocol, taking into account the transmission time, collision probability, and queuing delays. The total delay in the network can be computed as the sum of individual node delays:

$$D_{\text{total}} = \sum_{i=1}^{i=N} D_i \tag{3}$$

The channel utilization of each node is calculated as the ratio of its transmission time to the total time:

$$U_i = \frac{T_i}{T_{\text{total}}} \tag{4}$$

where T_{total} is the total time available in the system. The overall channel utilization in the network is the average of individual node utilizations:

$$U_{\text{total}} = \frac{\sum_{i=1}^{i=N} U_i}{N} \tag{5}$$

The energy consumption of each node depends on its transmission time and other factors specific to the protocol. The total energy consumption in the network is the sum of individual node energy consumptions:

$$E_{\text{total}} = \sum_{i=1}^{i=N} E_i \qquad (6)$$

The IEEE 802.15.4 Standard protocol employs a star topology with a coordinator node controlling communication. Slotted CSMA/CA is used, where each node listens for an idle channel before transmission and employs collision avoidance mechanisms. CSMA, on the other hand, follows a non-slotted approach where nodes sense the channel and wait for an idle period before transmitting, using random backoff times to minimize collisions. ALOHA, a random-access protocol, allows nodes to transmit data whenever they have packets ready, with collisions resolved through retransmissions. TDMA-CSMA Hybrid combines time-division multiple access (TDMA) and CSMA, allocating fixed time slots for nodes to transmit, while nodes without assigned slots employ CSMA. Enhanced TDMA-CSMA Hybrid further improves efficiency by assigning slots dynamically based on traffic patterns. These protocols' algorithms optimize channel utilization, collision avoidance, and synchronization to enable efficient and reliable communication in wireless networks. The algorithm is given below for the performance analysis of the proposed protocol with the existing algorithms.

Algorithm-1

```
Step 1: Import the necessary libraries: numpy and matplotlib.pyplot.
Step 2: Define the variable nodes and set it to the desired value.
Step 3: Define the function calculate_delay_ieee802154(nodes, packet_size, lambda_val):
    • Calculate the delay using the IEEE 802.15.4 formula:
        o Compute the denominator expression using the provided formula.
        o Calculate the delay using the numerator and denominator.
    • Return the calculated delay.
Step 4: Define the function calculate_delay_csma(nodes, packet_size, lambda_val):
    • Calculate the delay using the CSMA formula:
        o Compute the denominator expression using the provided formula.
        o Calculate the delay using the numerator and denominator.
    • Return the calculated delay.
Step 5: Define the function calculate_delay_aloha(nodes, packet_size, lambda_val):
    • Calculate the delay using the ALOHA formula:
        o Compute the denominator expression using the provided formula.
        o Calculate the delay using the numerator and denominator.
    • Return the calculated delay.
Step 6: Define the function calculate_delay_tdma_csma(nodes, packet_size, lambda_val):
    • Calculate the delay using the TDMA-CSMA formula:
        o Compute the denominator expression using the provided formula.
    • Calculate the delay using the numerator and denominator.
        o Return the calculated delay.
Step 7: Define the function calculate_delay_enhanced_tdma_csma(nodes, packet_size, lambda_val):
    • Calculate the delay using the Enhanced TDMA-CSMA formula:
        o Compute the denominator expression using the provided formula
        o Calculate the delay using the numerator and denominator.
    • Return the calculated delay.
Step 8: Define the function plot_delay_comparison(nodes, packet_range, lambda_val):
    • Initialize empty lists for delay_ieee802154, delay_csma, delay_aloha, delay_tdma_csma, and delay_enhanced_tdma_csma.
    • Iterate over the values in packet_range:
        o Calculate the delay for each protocol using the corresponding functions and append the result to the respective lists
    • Find the maximum delay among all the calculated delays.
    • Plot the delays using the matplotlib.pyplot library:
        o Plot each delay list against the packet_range, using markers and labels for each protocol.
        o Set appropriate axis labels and a title indicating the maximum delay.
        o Display the grid and show the plot.
Step 9: Set the packet_range array using np.arange to define the range of packet sizes.
Step 10: Set the lambda_val variable to the desired arrival rate.
Step 11: Call the plot_delay_comparison(nodes, packet_range, lambda_val) function to plot the delay comparison.
Step 12: End of the algorithm.
```

4. Result Analysis and Discussion

For the performance analysis, the network is analyzed for variation of network size, packet size, and packet arrival rate (λ). Throughput and delay are analyzed for different medium access control (MAC) protocols used in wireless networks. The analysis compares the throughput performance of five protocols: IEEE 802.15.4 Standard, CSMA, ALOHA, TDMA-CSMA Hybrid, and Enhanced TDMA-CSMA Hybrid.

In the first scenario, the network performance is analyzed for varying numbers of nodes as shown in Fig. 1. The number of nodes is varied from 10 to 100. The probability of packet arrival is assumed $\lambda=0.5$. The throughput and delay are analyzed for the varying number of nodes. Based on the throughput comparison analysis, the proposed protocol, i.e., Enhanced TDMA-CSMA protocol exhibits the highest throughput among all the protocols tested. This indicates that this protocol is well-suited for the given scenario, considering the range of nodes and arrival rate. The TDMA- CSMA Hybrid protocol and IEEE 802.15.4 protocol exhibit intermediate throughput levels.

These protocols provide a balance between the performance of TDMA (Time Division Multiple Access) and CSMA protocols. The graph illustrates how the throughput varies with the number of nodes in the network. It shows that as the number of nodes increases, the throughput generally increases for all protocols up to a certain limit. After that the packet loss is started and throughput saturates due to channel congestion. This is expected as more nodes contend for the available bandwidth. The maximum throughput achieved among all the protocols is mentioned in the graph's title. This provides a clear indication of the best-performing protocol in terms of throughput for the given scenario.

Similarly, a comparison of delay performance for different MAC protocols in wireless networks, namely IEEE 802.15.4, CSMA, ALOHA, TDMA-CSMA Hybrid, and Enhanced TDMA-CSMA Hybrid is shown in Fig. 2. The delay is calculated based on the number of nodes in the network. From the results it is evidently found that delay increases as the data traffic increases due to increment in number of nodes.

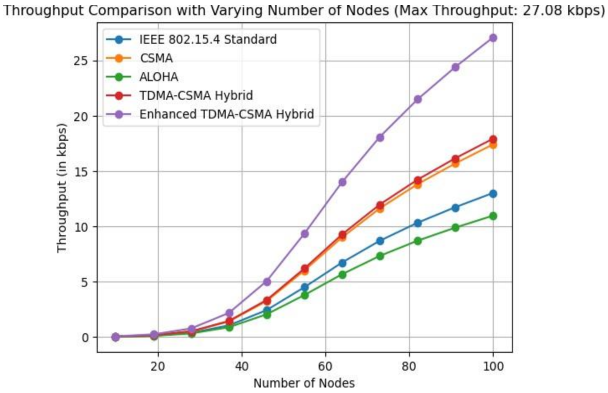

Fig. 1. Throughput comparison of varying number of nodes

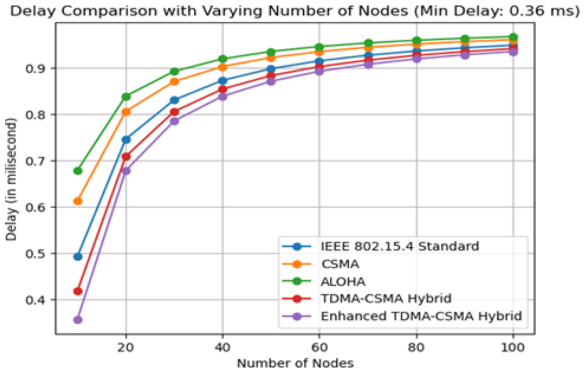

Fig. 2. Delay comparison of a varying number of nodes

The result shows that the delay of the proposed protocol is lower than the other protocols. The Enhanced TDMA-CSMA Hybrid protocol further enhances the delay performance compared to the basic TDMA-CSMA Hybrid. It achieves lower delays by improving the coordination and scheduling of node transmissions, reducing collisions and contention.

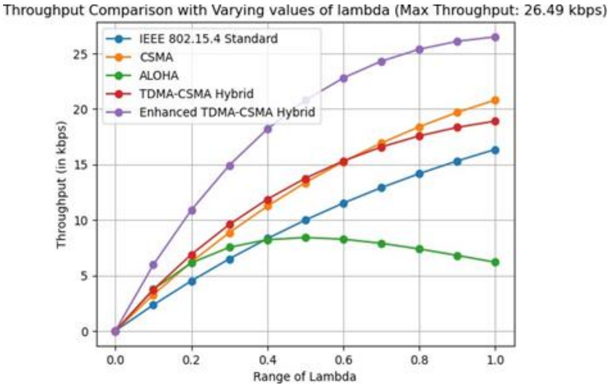

Fig. 3. Throughput comparison of varying packet arrival probability (λ)

The second scenario analyzes the performance for varying traffic arrival rates (λ). The traffic arrival probability is varied from 0.1 to 1 with 80 nodes in the network. The throughput analysis result is shown in Fig. 3. The results show that the throughput increases with data traffic upto a certain level by maximal utilization of the channel. However, after certain traffic, the collision probability increases, channel congestion starts, and throughput saturates after some traffic. In the case of ALOHA, the throughput started decreasing after λ=0.5. However, the proposed Enhanced TDMA-CSMA Hybrid protocol enhances the throughput and outperforms all other existing protocols.

The delay is also analyzed for the proposed protocol and performance is compared with the other existing protocols as shown in Fig. 4. The results show that the ALOHA has highest delay. The performance of CSMA, IEEE 802.15.4, TDMA is moderate. However, the hybrid TDMA-CSMA have better performance. Moreover, the proposed protocol, i.e., Enhanced TDMA-CSMA Hybrid protocol performs better than all other existing protocols.

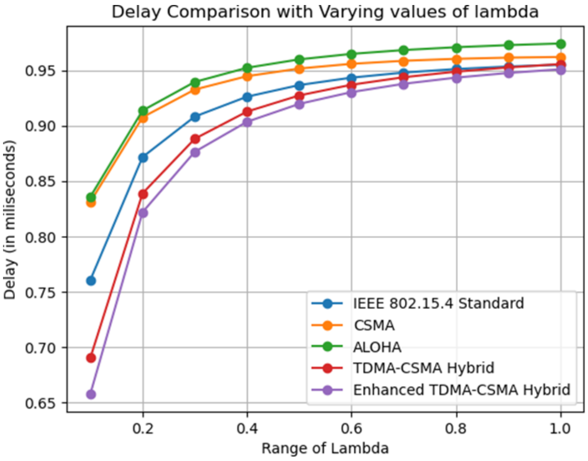

Fig. 4. Delay comparison of varying packet arrival probability (λ)

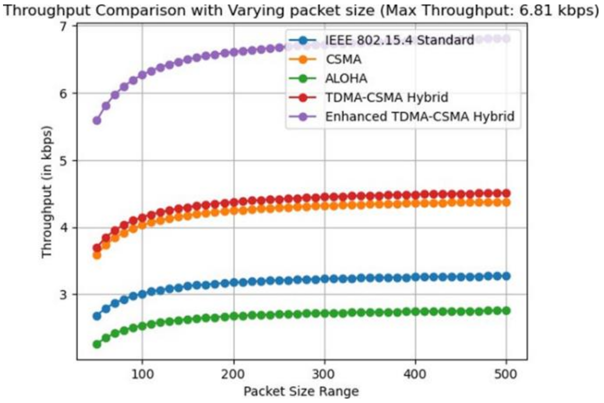

Fig. 5. Throughput comparison of varying packet sizes

In the third scenario, the network performance is analyzed for varying packet size as shown in Fig. 5 and Fig. 6. The packet size is varied from 50 Bytes to 500 Bytes. The probability of packet arrival is assumed λ=0.5. The throughput and delay are analyzed for the varying number of nodes. Based on the throughput comparison analysis, the proposed protocol, i.e., Enhanced TDMA-CSMA protocol exhibits the highest throughput among all the protocols tested. This indicates that this protocol is well-suited for the given scenario, considering the packet size and arrival rate. The TDMA-CSMA Hybrid protocol and IEEE 802.15.4 protocol exhibit intermediate throughput levels. These protocols provide a balance between the performance of TDMA (Time Division Multiple Access) and CSMA protocols. The graph illustrates how the throughput varies with the packet in the network. It shows that as the packet size increases, the throughput generally increases. For the lower packet size, the overhead traffic dominates the data traffic. The maximum throughput achieved among all the protocols is mentioned in the graph's title. This provides a clear indication of the best-performing protocol in terms of throughput for the given scenario.

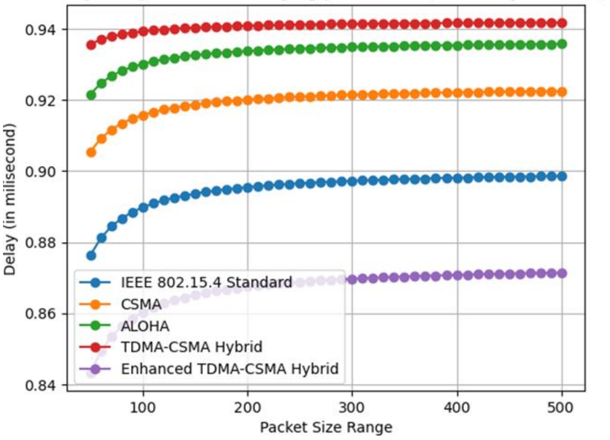

Fig. 6. Delay comparison of varying packet sizes

The delay is also analyzed for the varying packet size. A comparison of delay performance for different MAC protocols in wireless networks, namely IEEE 802.15.4, CSMA, ALOHA, TDMA- CSMA Hybrid, and Enhanced TDMA-CSMA Hybrid is shown in Fig. 6. The delay is calculated based on the varying packet size in the network. From the results it is evidently found that delay increases as the data traffic increases due to increment in packet size. The result shows that the delay of the proposed protocol is lower than the other protocols. The Enhanced TDMA-CSMA Hybrid protocol enhances the delay performance compared to the basic TDMA-CSMA Hybrid.

5. CONCLUSION

In conclusion, the performance analysis of different MAC protocols in wireless networks was conducted for varying network sizes, packet sizes, and packet arrival rates. The proposed Enhanced TDMA-CSMA Hybrid protocol demonstrated the best performance in terms of throughput and delay compared to other existing protocols. The protocol achieved better coordination and scheduling of node transmissions, reducing collisions and contention and improving channel utilization. The analysis showed that as the number of nodes and packet size increased, the performance of the protocols decreased due to channel congestion and packet loss. The results provide useful insights for designing and optimizing MAC protocols in wireless networks to achieve better performance and efficiency. own material.

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