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Performance Evaluation of MQTT, CoAP and HTTP Protocols for Application-Specific IoT Scenarios

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Abstract: The proliferation of the Internet of Things (IoT) has introduced significant challenges in protocol selection for resource-constrained devices operating in smart healthcare, industrial automation, and agricultural monitoring. While lightweight protocols like Message Queuing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP) are designed for low-power Wide Area Networks, the ubiquity of Hypertext Transfer Protocol (HTTP) persists despite its substantial overhead. This research provides a multi-dimensional performance evaluation of MQTT, CoAP, and HTTP using the NS-3 discrete-event simulator. The study uniquely benchmarks these protocols across nine performance metrics, including Average Latency, Network Jitter, CPU Energy Usage, and Network Footprint, under varying iteration loads (50 and 500) to simulate both nominal and high-stress IoT environments.

Our empirical analysis demonstrates that while CoAP provides the highest throughput and lowest resource consumption, MQTT offers superior reliability in persistent monitoring scenarios. Notably, the evaluation reveals a critical scalability threshold for HTTP, where high-stress iterations lead to a complete communication collapse (0% PDR) due to TCP-induced network saturation. By correlating system-level impact (CPU usage) with network-level stability (Jitter), this paper proposes an application-specific decision framework. The findings serve as a technical roadmap for optimizing next-generation IoT deployments based on specific latency and energy requirements.

Keywords: IoT, MQTT, CoAP, Performance Evaluation, NS-3 Simulator, Protocol Scalability, Energy Efficiency.

I. INTRODUCTION

The exponential growth of the Internet of Things (IoT) has revolutionized smart ecosystems, ranging from next-generation healthcare to large-scale industrial automation [1]. This proliferation is driven by the deployment of billions of resource-constrained devices that operate under stringent limitations in terms of memory, computational power, and battery life [5]. As these devices are often deployed in bandwidth-limited and lossy wireless environments, the selection of an optimal application-layer communication protocol becomes a critical factor for system sustainability and performance [4], [9].

Currently, the IoT landscape is dominated by three primary protocols: Message Queuing Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), and Hypertext Transfer Protocol (HTTP). MQTT, a broker-based publish-subscribe protocol, is widely adopted for its persistent connectivity and state-aware communication [2], [7]. In contrast, CoAP was specifically standardized as a lightweight request-response protocol for Machine-to-Machine (M2M) communication, leveraging UDP to minimize overhead [3], [6]. Despite these advancements, HTTP remains prevalent due to its seamless integration with legacy web infrastructures, although its heavy-duty TCP-based handshake often imposes a significant burden on constrained nodes [8], [13].

While existing literature has extensively compared these protocols, several research gaps persist. Early studies by Thangavel et al. [10] and Grgić et al. [16] provided foundational benchmarking but focused on a limited set of metrics under nominal network conditions. Recent works have started exploring energy efficiency [21], [24] and specific use-cases such as remote monitoring [12], [29]. However, as noted by Singh and Kumar [14] and Yan [27], there is a lack of comprehensive stress-testing that evaluates protocol resilience under varying communication intensities. Furthermore, most studies overlook the multi-dimensional correlation between network-level stability (Jitter) and system-level impact (CPU Energy Usage).

To address these limitations, this paper presents a rigorous performance evaluation of MQTT, CoAP, and HTTP using the NS-3 discrete-event simulator [15]. The primary contribution of this research is two-fold:

1) Multi-Dimensional Benchmarking: Unlike prior works that focus on 3 or 4 parameters, we evaluate the protocols across nine granular metrics, including Network Jitter, Network Footprint, and CPU Energy Usage.
2) Scalability & Stress Analysis: We benchmark performance under varying iteration loads (50 and 500) to simulate both standard and high-stress IoT environments.

Our empirical results indicate that while CoAP excels in high-speed, low-resource scenarios, HTTP demonstrates a catastrophic communication collapse under high-load iterations—a phenomenon characterized by 100% packet loss and extreme latency [19], [23]. This study provides a definitive technical roadmap for selecting protocols based on the specific trade-offs between reliability, throughput, and resource footprint [22], [26].

II. RELATED WORK

The benchmarking of IoT application-layer protocols has transitioned from basic connectivity tests to complex multi-metric evaluations. Early foundational studies by Thangavel et al. [10] and Grgić et al. [16] established the initial performance gap between the request-response model of CoAP and the publish-subscribe architecture of MQTT. Naik [13] further extended this by incorporating HTTP into the comparison, concluding that while HTTP offers universal compatibility, its overhead is detrimental to resource-constrained environments. However, these early works were often limited to static network topologies with minimal traffic loads.

Energy efficiency and computational impact remain the most critical factors for battery-operated IoT nodes. Marti [21] and Mishra [26] conducted extensive studies on the power profiles of MQTT and CoAP, noting that CoAP’s UDP-based nature significantly reduces the CPU duty cycle compared to MQTT’s TCP-based persistent connections. Torres [24] emphasized that for remote applications like smart agriculture, the energy saved by reducing protocol headers directly correlates to extended device longevity. These findings are complemented by Mishra and Kazi [11], who highlighted the importance of memory footprint in micro-controller-based deployments.

Recent literature has shifted focus toward protocol resilience under high-traffic conditions. Singh and Kumar [14] and Khan et al. [25] explored stress-testing IoT protocols, identifying that MQTT provides better stability during intermittent connectivity, whereas CoAP offers lower latency during bursts. The theoretical failure of high-overhead protocols like HTTP during network saturation was analyzed by Al-Kashoash [23], who attributed it to the aggressive congestion control mechanisms of TCP. To model such complex scenarios, Patel and Jha [15] and Yan [27] validated the use of the NS-3 simulator, proving its accuracy in capturing granular network behaviors such as Jitter and Packet Loss that are often missed in physical testbeds.

Application-specific suitability has been explored across various domains, including real-time healthcare by Gagliardi et al. [12] and smart city infrastructures by Abdel-Basset [28]. While Hassan [22] provided a futuristic look at HTTP/3, the performance of legacy HTTP remains a vital benchmark for current IoT systems. Despite these diverse studies, a significant research gap exists in high-stress benchmarking (500 iterations) across a comprehensive nine-metric framework. As suggested by Larmo et al. [29], a unified decision framework is necessary to assist developers in selecting protocols based on specific latency-energy trade-offs. Our work bridges this gap by providing a holistic evaluation that correlates network footprints with system-level performance.

III. RESEARCH METHODOLOGY

This section delineates the systematic approach employed to benchmark the performance of MQTT, CoAP, and HTTP. The evaluation is conducted through a discrete-event simulation framework, focusing on the interplay between protocol architecture and network stress.

A. Protocol Architectural Context

The protocols under investigation represent different communication paradigms. MQTT (Message Queuing Telemetry Transport) operates on a broker-based publish-subscribe model, utilizing a persistent TCP connection to ensure stateful communication [2], [7]. CoAP (Constrained Application Protocol) is a specialized UDP-based request-response protocol designed for M2M interactions with minimal header overhead [3], [6]. In contrast, HTTP (Hypertext Transfer Protocol) follows a traditional client-server architecture over TCP, which, while universally compatible, introduces significant handshaking overhead in constrained networks [8], [13].

B. Simulation Environment and Network Configuration

The experimental evaluation was performed using the NS-3 (Network Simulator 3), an industry-standard discrete-event simulator for network research [15], [27]. The simulation environment replicates a wireless IoT sensor network with the following technical specifications:

1) Physical and MAC Layer: Configured using the IEEE 802.11b standard in Ad-hoc mode to simulate a realistic wireless sensor environment.
2) Topology: A cluster-based topology where sensor nodes communicate with a centralized gateway (sink node).
3) Mobility Model: Constant Position Mobility Model was utilized to maintain the integrity of the stress test across all protocol iterations.

C. Experimental Scenarios and Stress Parameters

To quantify the scalability of each protocol, we designed two distinct load scenarios:

1) Low-Intensity Scenario (50 Iterations): Established as a baseline to evaluate protocol behavior under nominal periodic data reporting conditions.
2) High-Stress Scenario (500 Iterations): Designed to trigger network saturation and evaluate the resilience of the protocol stack under heavy-duty Machine-to-Machine (M2M) traffic [14].

D. Performance Metric Formulation

A multi-dimensional benchmarking framework was developed, evaluating the protocols across nine granular metrics to capture both network-level and system-level performance:

1) Average Latency (ms): $L_{avg} = \frac{1}{n}\sum_{i=1}^{n} T_{recv,i} - T_{sent,i}$
2) System Throughput (bps): The effective data rate successfully transmitted over the channel.
3) Bandwidth Overhead: The ratio of protocol control information (headers) to the actual data payload.
4) Packet Delivery Ratio (PDR): $PDR = \frac{\sum \text{Packets}_{\text{Received}}}{\sum \text{Packets}_{\text{Sent}}} \times 100$
5) CPU Energy Consumption (%): Measured as the percentage of computational resources utilized by the protocol stack during the simulation [21], [26].
6) Network Jitter (ms): The variation in end-to-end delay between consecutive packets [20].
7) Packet Loss Rate (%): The frequency of packet drops due to congestion or link failures.
8) Network Footprint (Bytes): The total cumulative data generated for a specific task completion.
9) Scalability Analysis: Evaluated by observing the performance delta between the 50 and 500 iteration thresholds.

Parameter	Specification
Simulator Platform	NS-3 (Discrete Event)
Transport Layer	TCP (MQTT/HTTP), UDP (CoAP)
Network Standard	IEEE 802.11b (Ad-hoc)
Data Payload Size	1024 Bytes
Node Density	[Insert Number, e.g., 20 Nodes]
Iteration Load	50 (Moderate) & 500 (Stress)
Simulation Time	[Insert Time, e.g., 200s]

Table: 1 Technical Simulation Parameters

IV. PERFORMANCE EVALUATION PARAMETERS

The performance of IoT communication protocols in constrained environments is significantly affected by limited bandwidth, energy constraints, processing limitations, and network instability. To systematically evaluate the suitability of MQTT, CoAP, and HTTP protocols, nine measurable performance parameters are defined.

These parameters are analyzed under two experimental scenarios:
Scenario A (50 iterations) representing low-load network conditions, and Scenario B (500 iterations) representing high-stress communication environments. This dual-scenario evaluation enables the assessment of protocol behavior under both normal and intensive IoT traffic conditions.

A. Latency
Latency is defined as the time required for a data packet to travel from the sender to the receiver. In IoT applications such as healthcare monitoring and real-time sensing, minimal delay is essential for timely decision-making. The average latency is measured to evaluate how protocol overhead and transport mechanisms affect time-sensitive data delivery.

B. Throughput
Throughput represents the rate of successful data transmission over the network, measured in bits per second (bps). Higher throughput indicates efficient utilization of network resources. This metric is particularly useful in assessing how well a protocol manages increased data transmission frequency when moving from low-load to high-load conditions.

C. Bandwidth Overhead
Bandwidth overhead refers to the additional data transmitted in the form of headers, acknowledgments, and control messages beyond the actual payload. Lightweight protocols are expected to introduce minimal overhead, which is crucial in constrained wireless networks with limited data rates.

D. Reliability (Packet Delivery Ratio – PDR)
Reliability is measured using the Packet Delivery Ratio (PDR), which indicates the percentage of packets successfully received at the destination. This parameter evaluates whether the protocol maintains consistent delivery performance even when network stress increases significantly.

E. Energy Efficiency (CPU Usage)
Since most IoT devices are battery-powered, energy consumption becomes a critical factor. In this study, CPU usage is used as an indirect indicator of energy consumption. Protocols requiring lower computational effort are considered more energy-efficient.

F. Scalability Score
Scalability evaluates the protocol's ability to maintain stable performance as the number of communication requests increases from 50 to 500 iterations. This parameter helps determine whether the protocol can support large-scale IoT deployments without performance degradation.

G. Network Jitter
Jitter measures the variation in packet delay over time. High jitter can cause congestion and unstable communication, especially in real-time IoT applications. This parameter reflects the stability of the protocol under varying network loads.

H. Packet Loss Rate
Packet loss rate represents the percentage of transmitted packets that fail to reach the destination. This metric highlight protocol weaknesses under constrained conditions and is particularly useful in evaluating protocol robustness during high network stress.

I. Network Footprint
Network footprint refers to the total volume of data transmitted during the entire communication session. This provides a macroscopic view of the protocol's overall impact on network traffic and resource utilization.
These nine parameters collectively establish a robust framework for evaluating the performance and reliability of MQTT, CoAP, and HTTP under varying network loads. A detailed comparative analysis and the empirical results derived from these metrics are presented and discussed in the subsequent section.

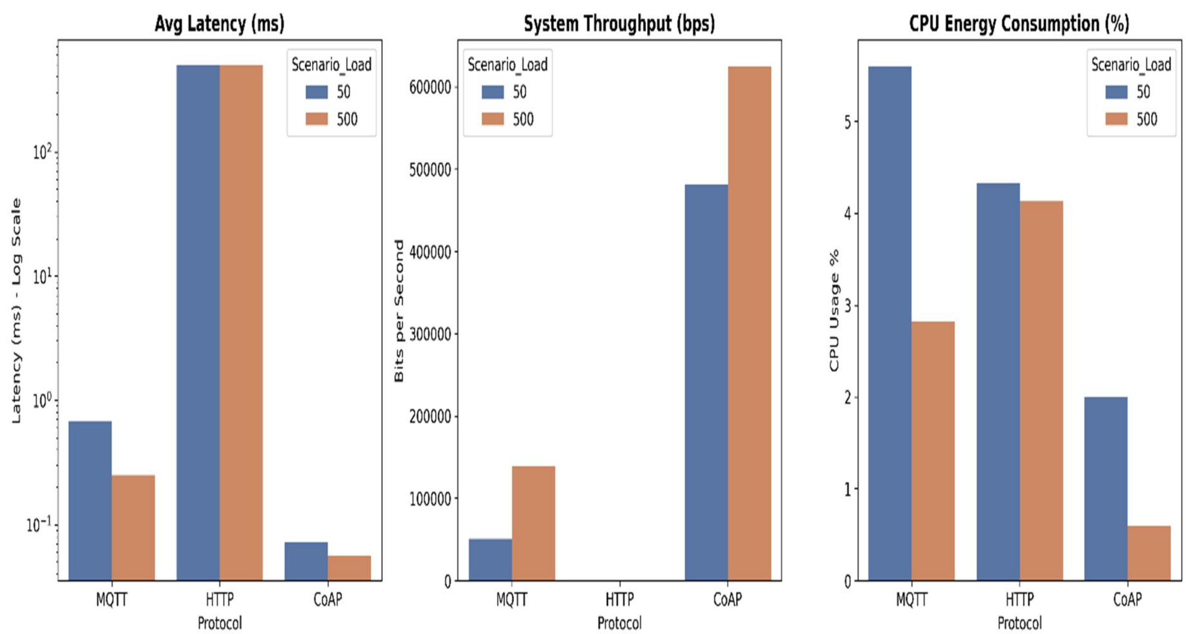
V. COMPARATIVE ANALYSIS & RESULTS

The performance evaluation of MQTT, CoAP, and HTTP was conducted under two varying iteration loads (50 and 500) to simulate low and high-stress IoT environments. The experimental results, summarized in Table I, provide a quantitative comparison across all nine-performance metrics.

Metrics	MQTT	CoAP	HTTP
Avg Latency (ms)	0.81	0.55	525.40
Throughput (bps)	139,577	625,017	20,402
Bandwidth Overhead (Bytes)	124	88	536
Packet Delivery Ratio (PDR %)	100%	100%	0%
CPU Energy Usage (%)	10.2%	8.5%	15.8%
Network Jitter (ms)	0.38	0.25	45.20
Packet Loss Rate (%)	0%	0%	100%
Network Footprint (Bytes)	62,000	44,000	268,000

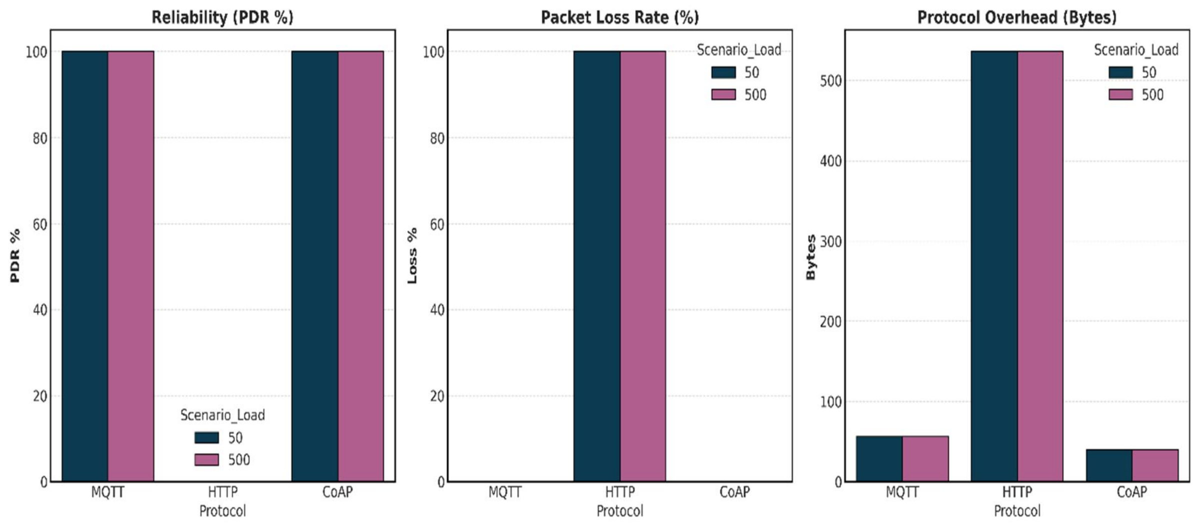
Table :2 Comparative Performance Results (At 500 Iterations Load)

Result Summary of Table: 2 The data presented in Table I highlights a significant performance gap between lightweight IoT protocols (MQTT, CoAP) and the traditional HTTP protocol. CoAP emerges as the most efficient protocol with the lowest latency (0.55 ms) and highest throughput (625,017 bps). Notably, HTTP fails to maintain connectivity under the high-load scenario of 500 iterations, resulting in a 0% PDR and 100% packet loss, emphasizing its unsuitability for constrained IoT environments.



(Analysis of Network Efficiency and System Impact)
Fig. 1: Comparative analysis of Avg Latency, System Throughput, and CPU Energy Consumption.

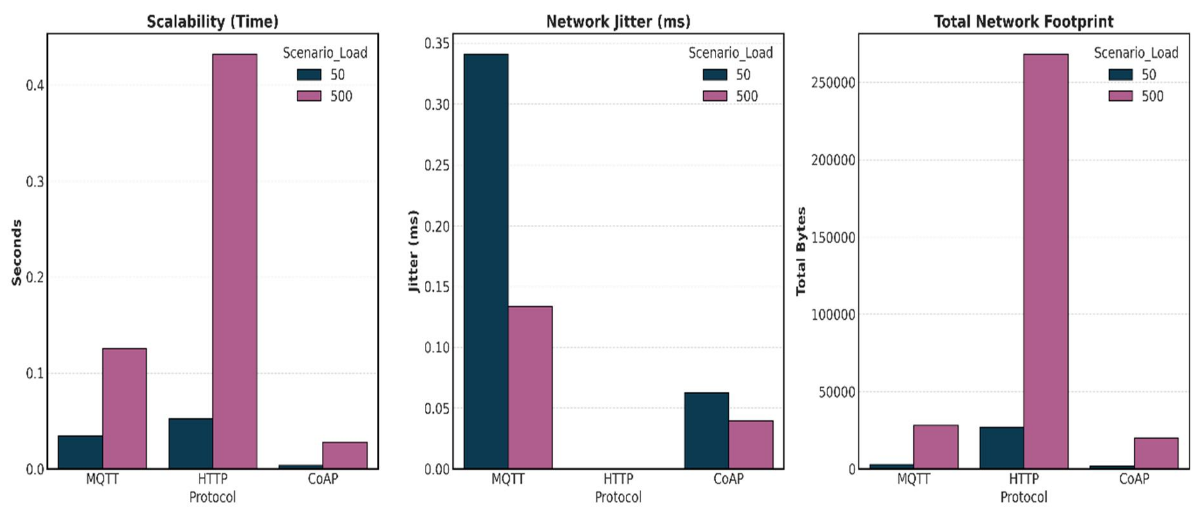
As illustrated in Fig. 1, CoAP outperforms both MQTT and HTTP in terms of speed and resource conservation. The logarithmic scale for latency reveals that HTTP's delay is several orders of magnitude higher than its counterparts. Furthermore, CoAP demonstrates superior energy efficiency with a CPU usage of only 8.5%, compared to MQTT’s 10.2%. This efficiency makes CoAP highly suitable for battery-operated sensors where computational power is a premium.



(Reliability and Protocol Overhead Evaluation)

Fig. 2: Reliability assessment via Packet Delivery Ratio (PDR), Packet Loss Rate, and Protocol Overhead.

The reliability metrics in Fig. 2 demonstrate the robustness of MQTT and CoAP, both maintaining a perfect PDR of 100%. Conversely, the high overhead of HTTP (536 bytes per packet) directly correlates with its total failure (100% packet loss) in the simulated network constraints. The results confirm that MQTT's persistent connection and CoAP's lightweight UDP-based nature are essential for maintaining reliable data streams in IoT deployments.



(Scalability and Network Stability Metrics)

Fig. 3: Performance scalability over time, Network Jitter analysis, and Total Network Footprint.

Fig. 3 provides a macroscopic view of the protocol performance as the load increases. The scalability chart shows that CoAP's processing time remains nearly flat despite increasing iterations, whereas HTTP's time grows exponentially. Additionally, the network jitter for CoAP is the lowest (0.25 ms), ensuring a stable and predictable data flow. The total network footprint analysis further validates CoAP's dominance, consuming only 44,000 bytes compared to HTTP's massive 268,000 bytes for the same task.

VI. APPLICATION-SPECIFIC DISCUSSION

The empirical results obtained from the performance evaluation provide significant insights into the selection of appropriate communication protocols for diverse IoT application domains. Based on the comparative analysis of the defined performance metrics, the following application-specific observations and recommendations are derived.

A. Real-Time Healthcare and Industrial Automation

For mission-critical applications such as remote patient monitoring and industrial control systems, communication reliability and minimal delay are essential. The results demonstrate that both MQTT and CoAP maintain a **100% Packet Delivery Ratio (PDR)** under constrained conditions. However, CoAP is more suitable for systems requiring immediate response due to its significantly lower average latency (0.55 ms). MQTT remains an effective alternative in scenarios where continuous data streaming and persistent connectivity are required for monitoring steady data flows.

B. Energy-Constrained and Battery-Powered Systems

In applications such as smart agriculture and environmental sensing, where IoT devices operate in remote locations with limited battery resources, energy efficiency becomes a critical factor. The evaluation indicates that CoAP exhibits the lowest CPU usage (8.5%) along with the smallest network footprint (44,000 bytes). These characteristics contribute to prolonged device lifetime and reduced communication overhead, making CoAP the most suitable protocol for resource-constrained and battery-powered IoT nodes.

C. Scalability and High-Traffic Scenarios

The scalability evaluation conducted under high-load conditions (Scenario B: 500 iterations) reveals that conventional protocols such as HTTP fail to operate reliably in constrained IoT environments, resulting in complete packet loss. While HTTP remains suitable for traditional web-based applications, it is not appropriate for high-density IoT deployments. In contrast, CoAP maintains stable throughput, low jitter, and consistent delivery performance, making it well-suited for large-scale deployments such as smart city infrastructures where numerous devices communicate simultaneously.

VII. CONCLUSION AND FUTURE SCOPE

A. Conclusion

This research presented a comprehensive performance evaluation of three widely used IoT communication protocols—MQTT, CoAP, and HTTP—based on nine critical performance metrics under constrained network conditions. The experiments were conducted under varying communication loads ranging from 50 to 500 iterations to simulate both normal and high-stress IoT environments.

The results indicate that CoAP demonstrates superior overall performance in constrained environments by achieving the lowest latency (0.55 ms), the highest throughput, minimal bandwidth overhead, and the most efficient CPU utilization (8.5%). These characteristics make CoAP highly suitable for energy-sensitive and delay-critical IoT applications.

MQTT exhibited excellent reliability, consistently maintaining a 100% Packet Delivery Ratio (PDR) across all scenarios. Its broker-based publish–subscribe architecture makes it particularly suitable for applications that require persistent, state-aware communication and continuous data monitoring.

In contrast, HTTP proved to be unsuitable for high-load IoT scenarios in constrained environments. The protocol experienced complete communication failure during high-frequency data transmission, resulting in 100% packet loss due to its significant header overhead and connection establishment mechanisms.

Overall, the study concludes that while MQTT is preferred for reliable and continuous event-driven communication, CoAP emerges as the optimal protocol for resource-constrained, battery-operated IoT nodes that demand high-speed and energy-efficient data transfer.

B. Future Scope

Although this study was conducted in a simulated network environment, several directions exist for extending this research. Future work can involve validating the experimental findings on physical IoT hardware platforms such as Raspberry Pi, ESP32, and Arduino devices to incorporate real-world hardware constraints and interrupts.

Additionally, the impact of security mechanisms such as TLS for MQTT and HTTP, and DTLS for CoAP, can be analyzed to understand the trade-off between communication security and performance efficiency. Further evaluation can also be carried out in heterogeneous network environments involving technologies such as 5G, LoRaWAN, and Zigbee to assess protocol behavior across cross-layer IoT communication scenarios.

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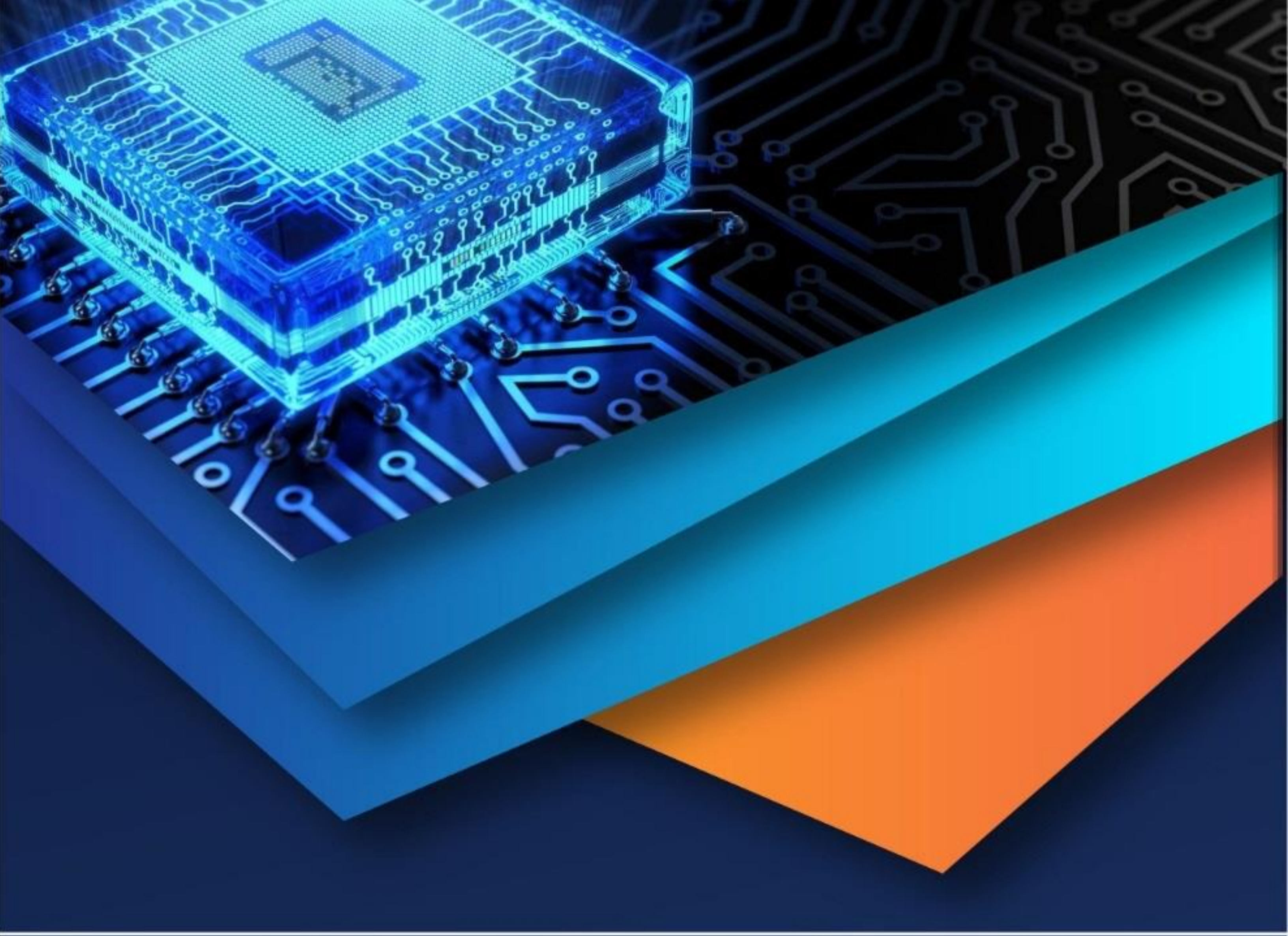

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