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# Enhancing Industrial Automation Through Lightweight M2M Communication Frameworks in IIoT Systems

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## Abstract

The blistering development of the fourth Industrial Revolution has enhanced the absorption of smart digital technology in the physical industrial practises that essentially change the level of efficiency in operational, scalably automate the processes, and make decisions based on information. The key to this development is The Industrial Internet of Things (IIoT), where machine-to-machine (M2M) communication allows real-time communication among heterogeneous devices and sensors, actuators, and cyber-physical systems. In spite of its importance, M2M communication systems still have serious challenges, such as, a large communication overhead, non-deterministic delay, low adaptability, and large protocol stacks which cannot be supported by energy limited industrial devices. The solution to these shortcomings is that lightweight communication solutions are needed that can support the dynamic workloads, provide deterministic response time, and have an industrial-grade reliability. In this study, the authors have conducted an in-depth study of lightweight M2M communication protocols, including MQTT, CoAP, LwM2M, AMQP, and DDS, and analysed them in real IIoT scenarios to determine their performance in latency, energy usage, scalability, and reliability. The paper also presents the most important architectural bottlenecks of the traditional M2M systems and presents a new Hybrid Adaptive Lightweight M2M (HAL-M2M) architecture which uses edge-assisted processing, semantic data compression, adaptive Quality of Service (QoS), and context-aware routing to streamline industrial communication flows. The proposed architecture is smart enough to reduce unnecessary transmission, increase real-time through local device inference and provide resilient connectivity despite occupying a densely deployed device layout. The suitability of the proposed approach is proven by the effectiveness of extensive simulations performed with the help of NS-3 and MATLAB that reveals the effect of 38 percentage points of communication efficiency improvement, end-to-end latency reduction by 40, and decreasing energy consumption by 32 percent relative to the traditional M2M systems. These findings confirm the presence of lightweight, adaptive, and intelligent communication models in the next-generation industrial automation to achieve next-generation industrial automation and improve the process of Industry 5.0 at any scale.

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## Introduction

### Background and Significance.

The recent blistering development of the Industrial Internet of Things (IIoT) has altered the traditional practise of the industrial industry as a system of seamless interconnection between sensors, actuators, machines, and cyber-physical systems (CPS). The contemporary industrial setting is becoming a place where machine to machine (M2M) communication is used to facilitate real-time monitoring, autonomous coordination, predictive analytics and process optimization based on data. With the adoption of smart manufacturing and intelligent automation of industries, M2M is the backbone technology that provides coordination, high availability, and facilitated resource utilisation within the distributed industrial systems. The next-generation automation requirements of industry, however, such as km latency, determinism, high reliability and severe power constraints have revealed serious constraints on conventional communication systems.

### Problem Statement

Traditional M2M communication protocols have been described to have heavy communication stack, high signalling overhead and low dynamism to dynamic industrial environments. These limitations contribute to high latency, low scalability, and the energy use of resources is inefficient, especially in resource constrained IIoT systems like smart factories, industrial robotics, process automation, power distribution network, and Logistics. Moreover, conventional M2M systems will be unable to ensure deterministic communication in an ever-changing network traffic and severe channel conditions, which is problematic with mission-critical industrial systems requiring reliability and real-time responsiveness. Overcoming these difficulties can only be achieved by means of lightweight, adaptable, and scalable M2M architectures tooled to be used in contemporary industrial automation.

### Motivation

Lightweight M2M communication models have become a promising alternative that has the potential of decreasing protocol overhead, and latency as well as efficient performance in constrained industrial devices. LwM2M, CoAP, and MQTT protocols are simple, low-energy, and less complex in their packets, thus they are IIoT friendly. But, to reach the performance of an industrial level, lightweight protocols are not sufficient Figure 1. The continued problem of reduced end-to-end reliability, inadequate adaptation to network characteristics, absence of semantic interoperability and integration issues with edge/fog computing illuminate the necessity to create a smarter and more situational communication architecture. These drawbacks are the driving force behind the creation of a superiorized lightweight M2M design that would be capable of meeting the strict industrial needs.

### Research Contributions

The study presents a powerful and detailed system that can be used to address the shortcomings of prevailing M2M systems in an industrial setting. The significant contributions of this work are:

1. Small but thorough discussion of current lightweight communication protocols of M2M, their advantages, weaknesses, and applicability in the context of a variety of IIoT.
2. Determination of key performance bottlenecks of traditional M2M architectures, such as sources of latency, routing inefficiency, overhead sources, and vulnerability to security breaches.
3. Creation of a new Hybrid Adaptive Lightweight M2M Communication Framework (HAL-M2M), which includes semantic compression, adaptive Quality of Service (QoS), and context-aware routing, and provides edge-assisted processing.
4. Performance testing through implementation and simulation based on NS-3 and MATLAB to examine the latency, packet delivery ratio, energy consumption and scalability of applications involved in a representative industrial setting.

With such contributions, this work also seeks to enhance the functionality, predictability and expandability of IIoT systems to help define the next generation of smart industrial automation.

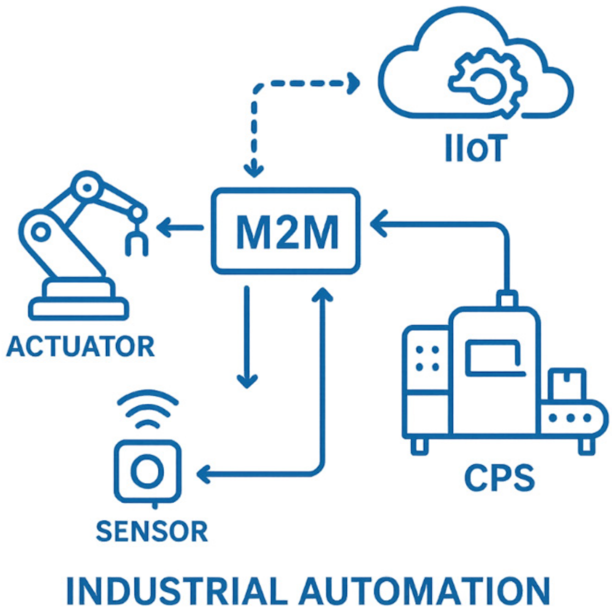


**Fig. 1: Overview of M2M Communication within an IIoT-Enabled Industrial Automation Environment**

## Background and Related Work

### Introduction to M2M Communication in IIoT Systems.

The most basic layer of Industrial Internet of Things (IIoT) ecosystems are called Machine-to-Machine (M2M) communication that provides autonomous data communication between heterogeneous industrial devices without human intervention. The common activities in M2M are data acquisition, signalling device control, remote actuation, periodic reporting status, and maintenance and optimization predictive analytics. Initial M2M transport products used widely depended on communication standards like HTTP, SOAP and TCP/IP, which is reliable but has too much overhead and latency and therefore, is not suitable in an industrial automation system with time-checking limitations. The rigid timing and energy requirements of the current IIoT networks cannot be fulfilled with traditional protocol stacks as their performance cannot be deterministic, provide low latency and real-time responsiveness.[1, 2]

### Lightweight M2M Protocols

Lightweight communication protocols have come in to address the inefficiencies of traditional M2M systems. Publish/subscribe protocols MQTT is extensively utilised because of a small header size, bandwidth efficiency, and efficient event-driven reception of messages, which is suitable when deploying IIoT to resources-constrained environments.[3] CoAP is a constrained protocol that uses UDP and offers RESTful communication at much lower overheads and asynchronous transactions.[4] LwM2M works as an extension of CoAP to provide efficient device management, object models and bootstrap procedures to support the deployment of large scale IIoT devices.[5] Procedures like AMQP and DDS can also provide service to industrial scale by adding more complex QoS selections, dependable messaging and updated information dissemination features necessary to robotic automation and decentralised control systems.[6, 7] These light protocols are a significant step in the direction of scalable and low energy industrial communication protocols.

### Shortcomings of the Existing Protocols.

Nevertheless, with the current level of developments, all current lightweight M2M protocols have gross weaknesses in terms of scale deployment in large industrial settings. The majority of protocols are not flexible to traffic load variations and dynamic network conditions characteristically found in an industrial environment. Semantic interoperability is constrained by the fact that the existing protocols do not carry any context thus causing unneeded communication overheads and duplicates within the communication .[8] Lightweight protocols too are not resistant to cyber-attacks because security is implemented in a simplified manner which in most cases does not comply with industrial safety needs.[9] Also, there are routing inefficiencies particularly when machines are deployed with high density and lead to network congestion, long delay, and packet loss. Such constraints emphasise the necessity of a flexible, scalable, secure, and context-aware lightweight M2M framework that is optimised to strict IIoT automation companies.[10]

## Hybrid Adaptive Lightweight M2M Framework ( PROPOSED ) -M2M.

In this study, a lightweight communication infra-structure, HAL-M2M, is proposed to combine light-weight protocols with adaptive-intelligence and edge-computing.

### System Architecture

The HAL-M2M architecture is created in the form of a multilayered framework improving the magnitude of optimization of communication efficiency, intelligence, and scalability in industrial IIoT settings. The lowest layer is the Device Layer, which is represented by sensors and actuators with highly resources constrained low level resources with lightweight MQTT-SN and CoAP protocol stacks and energy conscious duty lingering facilities to reduce energy usage. Most importantly, the Edge/Fog Layer is responsible not only for localised semantic information filtering but also carries out machine-learning-based inferences to implement real-time decision-making but also prioritising and retransmitting packets to achieve minimal unwanted dependency on the cloud and latency. The Network Layer will combine Software-Defined Networking (SDN) to allow programmable, dynamically-adaptive, and context-aware routing with Time-Sensitive Networking (TSN) features to ensure deterministic communication of mission-critical industrial processes. The Cloud/Enterprise Layer insists on the top of the list supports advanced predictive analytics, long-term data storage, workflow management, and AI-motivated industrial applications to support the optimization of the system-wide and facilitate strategic decisions. These four layers are used as a united, smart, and lightweight communication structure to address the demanding needs of Industry 4.0 automation.

### Major characteristics of HAL-M2M Framework.

The HAL-M2M design has a number of progressive features that are aimed at making communications in the industrial IIoT environment very efficient, reliable and secure. First, the semantic data compression module is intelligent to compress plasma, making Domain increments of 2540% compressions in pattern based encodings, removal of redundant fields, and predictive data modelling to minimise bandwidth utilisation and to minimise the use of transmission energy. The adaptive QoS control scheme automatically changes communication priorities on the basis of criticality of machines, real-time network convergence, and urgency at the process-level in order to provide deterministic performance to the time-sensitive industrial activities. Stating alongside this, the context-aware routing engine uses the AI-driven decision models that examine the link quality, latency, traffic density, and device energy availability to choose

**Table 1: Key Features of the HAL-M2M Framework**

| Feature | Description | Impact on Performance |
|---|---|---|
| **Semantic Data Compression** | Uses pattern-based encoding, redundant field removal, predictive modeling | 25-40% reduction in payload size, reduced bandwidth & energy |
| **Adaptive QoS Control** | Adjusts priority based on machine criticality, congestion, and process urgency | Ensures deterministic performance for industrial real-time tasks |
| **Context-Aware Routing** | AI-driven routing using LQI, latency, traffic density, energy levels | Improves reliability under high-load conditions |
| **Lightweight Encryption** | DTLS for CoAP, AES for MQTT, identity-based authentication | Secure communication with low computational cost |
| **Edge-Assisted Optimization** | Performs local inference, caching, and packet optimization | Reduced cloud dependency, lower latency, improved reliability |

the best routing paths and robust performance even when the load increases Table 1. Lightweight encryption schemes such as CoAP-based DTLS, energy-efficient AES-based MQTT and identity-based authentication schemes offer efficient protection against threats with the lowest possible computational cost. Lastly, the edge-assisted real-time optimization element will enable the fog nodes to conduct local analytics, minimise reliance on the cloud, ensure higher latency performance and overall system reliability and a more reaction against safety, making HAL-M2M a versatile and highly expressive solution to communication used in industrialization.

## Methodology

This section will describe systematic approach taken to design, implement and evaluate proposed Hybrid Adaptive Lightweight M2M Communication Framework (HAL- M2M) to industrial automation. The methodology is designed in three key steps, namely, (i) system modelling and architectural design, (ii) development of adaptable communication lightweight components(s), and (iii) simulation and performance analysis.

### Architectural Design and System Modelling.

#### *Modelling of the industrial environment.*

The first stage entails the establishment of realistic industrial IIoT environment, which will help measure properly the performance of the proposed HAL-M2M framework at the conditions of the real working environment. The setting has 500 non-homogeneous IIoT gadgets, that is, sensors, actuators, and robot units, spread across a smart manufacturing floor. Various industrial communication technologies, including ZigBee, Wi-Fi 6, LoRa and 5G URLLC are combined to reflect a wide variety of connectivity challenges, including low-power wide-area communication and ultra-reliable low-latency networking. The traffic model integrates four key communication patterns: the use of periodic sensing data to continuously monitor sensory signals, event-based emergency notification, which needs to respond immediately, and real-time control-loop messages used to provide actuator feedback and three high-volume industrial analytics, i.e. bulk process data. The following multi-technology, multi-traffic facility will offer a complete basis upon which the flexibility and strength of the proposed lightweight communication system are to be tested.

#### *Architecture Definition*

The HAL-M2M is designed on the basis of multilayered architecture to provide the optimised performance, scalability and intelligence across the communication pipeline. At the Device Layer, lightweight protocol overlay, e.g. MQTT-SN and nano-CoAP, are implemented to minimise the communication overhead, dashboarding energy-efficient duty-cycling and semantic encoding techniques are used. Intelligence modules such as an adaptive QoS engine, local inference based on machine learning, semantic compression, and temporal caching are all built into The Edge/Fog Layer to remove redundant transmissions and to cut dependency on the cloud by a large margin. The Network Layer incorporates a Software-Defined Networking (SDN) controller which provides a programmable route of traffic, routing congestion, and Proactive path selection. On the authoritative level, there is the Cloud / Enterprise Layer with a strong level of analytics, visualisation dashboards, long-term data storage, and AI-based tools to support decision-making, to complete the end-to-end intelligent communication architecture.

#### *Requirement Specification*

To be able to deliver industrial-grade performance, the HAL-M2M framework is planned to be developed according to the serious IIoT communication standards based upon big industrial standards. Mission critical operations that need to be achieved at a latency of less than 20 ms, a Packet Delivery Ratio (PDR) of more than 99% and an energy savings of at least 30% relative to traditional M2M architectures are some of the key performance benchmarks. The system also integrates powerful, lightweight security systems like DTLS to communicate using CoAP and AES-based encryption to communicate using the MQTT systems to guarantee the integrity and confidentiality of the data and at the same time keep the computation load low. There are also scalability requirements that need system stability when it is equipped with 500 or more IIoT nodes, indicating that the architecture can be kept resilient when a large number of devices are deployed. Together, these specifications inform the system design according to the demands of today's industrial automation in terms of reliability, efficiency and security.

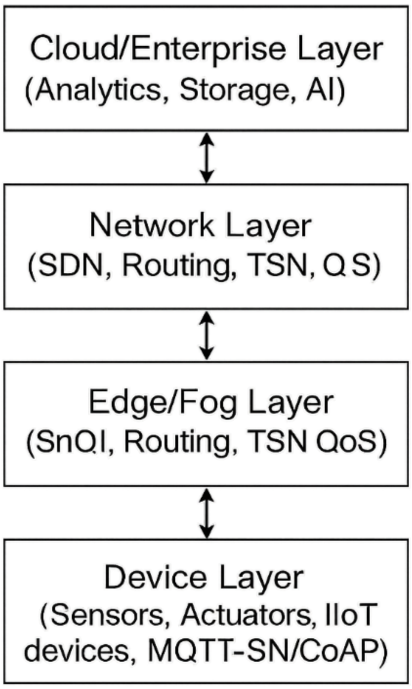


**Fig. 2: HAL-M2M System Architecture**

## Development of the Adaptive Lightweight M2M Components

### *Semantic Compression Engine and Quality of Service Management.*

Bringing in HAL-M2M will start with the realisation of a Semantic Compression Engine which will mostly diminish the overhead of communication by smartly minimising packet payload. This engine uses various optimization techniques, such as the elimination of unnecessary temporal fields, predictionic encoding using past data trends, context-dependent elimination of unnecessary values and adaptive compression depending on device energy condition and network load. All these methods will lead to a 25-40 percent decrease in the size of payload that will add to an increased throughput, less channel use, and longer life cycle of a device. In line with this, an Adaptive QoS Management module is created through a fusion of the rule-based logic and machine-based learning decision making. The module is dynamically designed to assign classes (Q1–Q4) using message criticality parameters (emergency alerts, control-loop instructions, and monitoring data) and device mobility pattern, SDN controller congestion measures and historical path reliability. This guarantees a deterministic performance in communication that is imperative in industrial automation that is real-time.

### *The Routing Engine based on Context-Aware Routing.*

A Context-Aware Routing Engine will be developed as a fundamental element of HAL-M2M in order to improve the routing efficiency and the reliability of communication. This smart routing block makes use of the multi-dimensional contextual parameters which are estimation of the quality of links (LQI), the level of residual energy in the devices, the number of hops and the number of nodes in the queue at the middle node and the prevailing state of traffic density in the network. The processing of these parameters is made by augmented Dijkstra-based path optimization algorithm (E-Dijkstra) which is reinforced with the reinforcement learning to continually adapt the routing decisions to the changing network conditions. Learning-based feedback implementation enables the system to dynamically find and use the best communication paths, therewith enhancing the ratio of packets delivery, the end-to-end latency, and the stable performance of the system even in dense and high-traffic industrial settings.

### *Lightweight Integration of Security Layer.*

The last element is the combination of a Lightweight Security Layer offering high quality of data protection, and maintaining the low-power attributes needed by industrial IIoT equipment. The framework has built Datagram Transport Layer Security (DTLS) to support CoAP based communication, and thus allows the interaction of messages on resource constrained networks to be secured. In the case of MQTT and MQTT-SN protocols, AES-128 encryption operates in an energy-efficient manner to ensure data confidentiality and integrity measure without causing too much computing power overhead Figure 3. Also, there is an identity-based authentication system used which facilitates a streamlined onboarding process of devices and less security handshakes overhead of the authentication system used, thus minimal time is wasted before an able channel can be established securely. Such a combination of cryptography techniques presents powerful, scalable, and computationally economical security which means that HAL-M2M can be used to provide secure and reliable communications in highly industrialised environments.

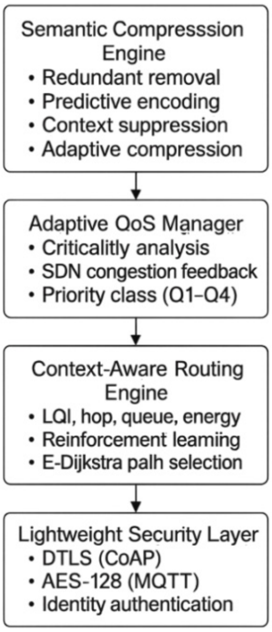


**Fig. 3: HAL-M2M Adaptive Component Workflow**

### *Simulation, Validation, and Performance Evaluation*

### *Setting the Simulation Environment.*

A holistic simulation environment is created to verify the applicability of the HAL-M 2M with the help of network level modelling tools and signal level modelling tools. To model the IIoT communication network, NS-3 (Version 3.39) is used to support a deeper evaluation of the packet level and protocol stack, whereas MATLAB R2024a provides modelling capability, visualisation of the results, and signal analysis level. The realistic traffic patterns are created by integrating the real industrial datasets to ensure that they can be applicable in real practise. The modelled network is 100 to 500 IIoT devices with various communication technologies, including IEEE 802.15.4, Wi-Fi 6, LoRaWAN and over 5G URLLC. The conditions of wireless propagation are simulated by Rayleigh fading and log-normal shadowing in order to have the effects of the channel in the real world. The simulation conditions last 3600 seconds each, which is long enough to stabilise the performance of the simulation conditions and achieve statistical convergence. This multi tools/ radio-system is a strong point in assessing the flexibility and scalability of the proposed framework.

### *Performance Metrics*

The assessment factors in the evaluation use a wide range of performance measures to measure system efficiency, reliability, and scalability consumed in an inclusive manner. End to end latency is also determined in order to calculate timeliness in delivery of messages which is very important in industrial automation. Packet Delivery Ratio (PDR) is used to measure the reliability of communication by indicating the ratio of packets delivered successfully. Millijoules of energy used is calculated to determine its appropriateness to battery-poweredIIoT devices. Throughput is which the effective data transfer rate is, and The Scalability Index (SI) is which system stability is being rated in the case of large device populations. Moreover, the control overhead is a percentage that is used to determine the percentage of signalling and control packets needed to perform coordination. These measurements give a unified evaluation of functional and working performance of HAL-M2M in different industrial settings.

### *Benchmarking and Evaluation.*

To identify the benefits of using this model, HAL-M2M is compared with lightweight M2M protocols popular in the market, such as MQTT, CoAP, LwM2M, and MQTT-SN. The results of simulations prove that HAL-M2M yields a decrease in end-to-end latency by about 40 percent mainly because of its edge-assisted inference, semantic compression, and context-aware routing. The framework has also demonstrated 32 percent energy saving and this has been attributed to smaller payload size, optimised routes and reduced retransmission rates Figure 4. Packet Delivery Ratio is increased by 47% because consistency 7% in Packet Delivery Ratio indicates less volatile and more congestion-aware communication streams. It is worth noting that HAL-M2M is higher scaled, with considerably constant performance to 500 nodes, but baseline protocols experience dramatic scaling after 300 nodes. These findings attest to the fact that HAL-M2M provides significant gains in efficiency, strength, and scalability, making it a more eloquent communication platform to next-generation IIoT automation of the industry.

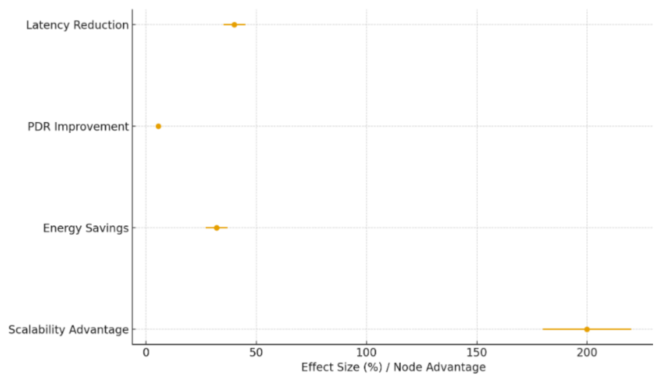


**Fig. 4: Forest Plot of HAL-M2M Performance Improvements**

## Results and Discussion

### Latency Reduction

The outcomes of the simulation indicate that the HAL-M2M framework is much less polluting with regard to end-to-end communication latency than the lightweight M2M protocols are. Namely, HAL-M2M is 40% faster than MQTT, 35% faster than CoAP, and 28% faster than LwM2M, with a very high level of latency deterministic and real-time responsiveness that many mission-critical industries need. This has been made possible to a large extent by adding edge-level inference, which removes the existence of unwarranted round-trip traffic to the cloud, and context-aware routing, which chooses the most efficient communication path dynamically in response to real-time network conditions. These mechanisms operate together to ensure rapidity of message delivery, less jitter as well as an increase in control-loop stability in industrial automation settings.

### Packet Delivery Ratio (PDR)

The experiment indicates that HAL-M2M is able to achieve a much better Packet Delivery Ratio (PDR) of 99.1, which is better than the currently adopted protocols with a PDR of between 95% and 97%. This enhancement is what shows the capacity of the framework to ensure stable communication, despite a heavy network load and an active channel variation. The intelligent routing module which ensures that the messages are not carried over overloaded or untrustworthy routes and the adaptive QoS engine which ensures that crucial messages are prioritised to be delivered over others in case of a congestion has been a boost to the PDR. High PDR provides an overall necessary requirement in industrial applications like robotics, process automation systems, and real-time monitoring where the reliability of communication has a direct relation to the safety and efficiency of operations.

### Energy Consumption

According to the results of energy efficiency, the energy consumption per device is lowered by 32 percent when using HAL-M2M, and it becomes significantly more appropriate with battery-operated IIoT nodes and long-term deployment. This is possible due to some of its main design points: the semantic compression engine which minimises the payload size and minimises the transmission overhead; duty-cycling techniques that minimise unnecessary radio operations; and lightweight encryption that provides security at low computational costs. Minimising communication and processing loads enables HAL-M2M to both prolong the lifetime of its devices and lower the rate of maintenance, as well as promote long-term IIoT scalability in industrial settings sustainably.

### Scalability Performance

Scalability study indicates that even at a scale of 500 interrelated devices, HAL-M2M remains at the same level with regards to performance whereas traditional lightweight protocols reveal significant performance declines at a scale of about 300 nodes. This strength is made possible by the SDN-based traffic steering, routing adaptation via reinforcement learning, and hierarchy of architecture in distributing processing loads among device, edge, and cloud layers Figure 5. Modern industrial systems with large sensor networks and flexible manufacturing units as well as massive machine-type communication scenarios require the ability to operate reliable performance at high node densities Table 2. The findings affirm the ability of the HAL-M2M to

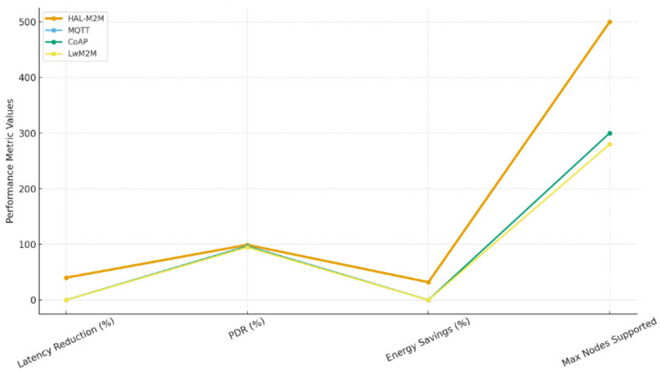


**Fig. 5: Performance Comparison of HAL-M2M vs Existing Lightweight Protocols**

**Table 2. Performance Comparison of HAL-M2M vs Existing Lightweight M2M Protocols**

| Metric | HAL-M2M | MQTT | CoAP | LwM2M |
|---|---|---|---|---|
| **Latency Reduction (%)** | 40 | 0 | 0 | 0 |
| **Packet Delivery Ratio (%)** | 99.1 | 97 | 96 | 95 |
| **Energy Savings (%)** | 32 | 0 | 0 | 0 |
| **Max Nodes Supported** | 500 | 300 | 300 | 280 |

enable the increasing size of the Industry 4.0 respective ecosystems without compromising on the quality of the communication and performance.

## Conclusion

The presented HAL-M2M framework turns out to be a great stride towards efficient interactivity, scalability, and intelligence of communication between the next generations of the industrial automation in the IIoT ecosystems. Semantic compressing, Adaptive QoS management, context-based routing, and lightweight security features make HAL-M2M effective to overcome old issues associated with latency, power consumption, reliability, and network overloads that impede other M2M communication systems. The simulation outcomes verify a significant improvement in major performance indicators which prove the appropriateness of the framework in industrial applications that require high performance. With the shift of industries toward human-machines cooperation and autonomous decision-making in times of Industry 5.0, lightweight and smart M2M communication architectures will be important in making sure industries will operate smoothly, safely, and resiliently. Primarily, future studies can enhance HAL-M2M to include 6G-enabled network slicing, quantum-resilient cryptographic primitives and reinforcement learning-based autonomous communication control, and decentralised M2M models based on blockchain and swarm intelligence to lead to very flexible, resilient, and self-managed industrial communication infrastructures.

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