Evaluation of the MQTT protocol for iot-based industrial automation and remote maintenance

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Abstract

The fourth industrial revolution is underway, driven by spectacular advances in IoT that are redefining the possibilities for equipment monitoring, automated diagnostics and remote control. In this changing landscape; our research has focused on accurately measuring the advantages of the MQTT protocol over its main competitors, HTTP and CoAP, in an environment that replicates real-world industrial conditions. To conduct this evaluation, we designed a comprehensive test bench combining several key technologies: DHT11 sensors for temperature monitoring and ACS712 sensors for electrical measurements, an ESP8266 processing unit managing data collection, a Mosquitto server installed on Raspberry Pi managing MQTT messages, all visualised using the Node-Red interface. After intensive testing, the figures highlight that: MQTT clearly outperforms other protocols with an average response time of 150 milliseconds (with a margin of error of only 5ms), a transmission success rate of nearly 100%, and optimised energy consumption. This exceptional performance makes MQTT the ideal candidate for demanding industrial applications. However, a few practical challenges still need to be addressed for large-scale adoption: strengthening the security of exchanges via protocols such as TLS, facilitating connection with traditional industrial systems, and training technicians in these new technologies. This work paves the way for a more connected and intelligent industry, where the combination of MQTT with AI and edge computing could well revolutionise the way, we produce.

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Nesnelerin interneti tabanlı endüstriyel otomasyon ve uzaktan bakım için MQTT protokolünün değerlendirilmesi

Özet

Dördüncü sanayi devrimi ekipman izleme, otomatik tespit ve uzaktan kontrol olanaklarını yeniden tanımlayan internet nesnelerindeki gelişmelerle ilerliyor. Bu çalışmada MQTT protokolünün HTTP ve CoAP'ye kıyasla avantajlarını gerçek endüstriyel sistemler üzerinde doğru bir şekilde ölçmeye odaklanıldı. Bu değerlendirmeyi gerçekleştirmek için, birkaç temel teknolojiyi birleştiren kapsamlı bir test yapıldı: Bu teknolojiler: sıcaklık izleme için DHT11 sensörleri ve elektriksel ölçümler için ACS712 sensörleri, veri toplamayı yöneten bir ESP8266 işlem birimi, MQTT mesajlarını yöneten Raspberry Pi'ye kurulu bir Mosquitto sunucusu, olmak üzere hepsi Node-Red arayüzü kullanılarak görselleştirildi. Beş gün süren yoğun test ve 1.500 örneğin analizinden sonraki bulgulara göre: MQTT, 150 milisaniyelik ortalama yanıt süresiyle (sadece 5 ms'lik bir hata payıyla), neredeyse %100'lük bir iletim başarı oranıyla ve optimize edilmiş enerji tüketimiyle diğer protokollerden açıkça daha iyi performans göstermektedir. Bu performans, MQTT'yi zorlu endüstriyel uygulamalar için ideal bir aday haline getiriyor. Ancak, büyük ölçekte benimsenmesi için ele alınması gereken şu noktalar bulunmaktadır: TLS gibi protokoller aracılığıyla aktarım güvenliğinin ilerletilmesi, geleneksel endüstriyel sistemlerle bağlantının kolaylaştırılması ve teknisyenlerin bu yeni teknolojiler konusunda eğitilmesi. Bu çalışma, MQTT'nin ilerleyen zamanlarda yapay zeka ve uç sınır bilişimle entegresi sonucu üretim sistemlerimizde devrim yaratıcı daha bağlantılı ve akıllı bir işleyişin önünü açtığını göstermektedir.

Anahtar Kelimeler: *Endüstriyel nesnelerin interneti, MQTT protokolü, ağ gecikmesi, güvenilirlik, enerji verimliliği, MQTT aracısı*

Introduction

The digital revolution is profoundly transforming traditional industrial landscapes, with the emergence of the Internet of Things (IoT) as the main catalyst for this change. This technological transition is redefining industrial operating modes through the real-time acquisition of critical data, the strategic deployment of smart sensors and the integration of advanced monitoring interfaces. *Lee et al. (2022)* demonstrates how these connected systems not only enable more effective predictive maintenance but also early diagnosis of anomalies, which have become essential in an increasingly competitive industrial environment.

Faced with growing economic pressures and intensifying global competition, industrial players are focusing their efforts on continuously improving equipment availability and reducing unplanned downtime. The optimal use of real-time data has emerged as a fundamental pillar of performance optimisation strategies. Research conducted *by Zonta et al. (2020)* highlights the multiple benefits of predictive analytics, which not only significantly reduces maintenance costs but also improves energy efficiency and extends the operational life of industrial systems.

In this new technological paradigm, communication protocols must meet particularly rigorous technical requirements. Several recent studies *(Thavasimuthu et al., 2022; Al-Fuqaha et al., 2015)* emphasise the imperative need for solutions capable of ensuring robust transmission despite noisy industrial environments, offering minimal latency for near-instantaneous responses, minimising the energy consumption of embedded devices and maintaining their functionality in the face of frequent network disruptions.

Among the range of available protocols, MQTT (Message Queuing Telemetry Transport) stands out as a solution particularly suited to contemporary industrial needs. Standardised by OASIS since 2014, its lightweight publish/subscribe architecture has been specifically designed for resource-constrained environments. Main advantages stand on message reliability and feature variety for MQTT over CoAP (Constrained Application Protocol). Moreover, MQTT performs better in high-traffic environments but it consumes accordingly more resources. Extensive research by *Aldin et al.(2024), Seoane, et al. (2021*) and *Lee et al. (2022)* and *Thangavel, et al. (2014)* confirms its distinctive advantages: minimal protocol overhead, fully configurable quality of service levels, and exceptional scalability, characteristics that make MQTT a preferred choice for industrial Internet of Things applications *(Hunkeler et al., 2008)*.

However, the widespread adoption of this protocol faces several major challenges. The integration of advanced security mechanisms, including TLS encryption and rigorous client authentication, requires advanced technical expertise. Furthermore, ensuring seamless interoperability with existing systems such as SCADA or CMMS represents a significant technical complexity. Added to these obstacles is a notable shortage of specialised skills for the effective deployment of MQTT in real production environments, as previously identified by *Chaqfeh and Mohamed (2012)*.

This research study aims to identify optimal deployment conditions and propose practical solutions to overcome the main technical challenges associated with the implementation of industrial IoT. The methodology employed in this study synergistically combines an exhaustive review of scientific literature with the development and testing of a comprehensive technological platform. This experimental setup incorporates several key components: an ESP8266 microcontroller for data processing, DHT11 sensors for thermal monitoring and ACS712 sensors for electrical monitoring, a Mosquitto MQTT broker hosted on a Raspberry Pi platform, and a real-time dashboard developed with the Node-RED environment. Systematic measurements focused on several critical parameters: response time, data integrity, optimal bandwidth utilisation, and energy efficiency, providing a solid basis for a rigorous comparative evaluation of MQTT's performance against other industrial communication protocols.

Firstly we give definition of problem below and then explain materials and methods. Then we set results, discussion and conclusions, respectively.

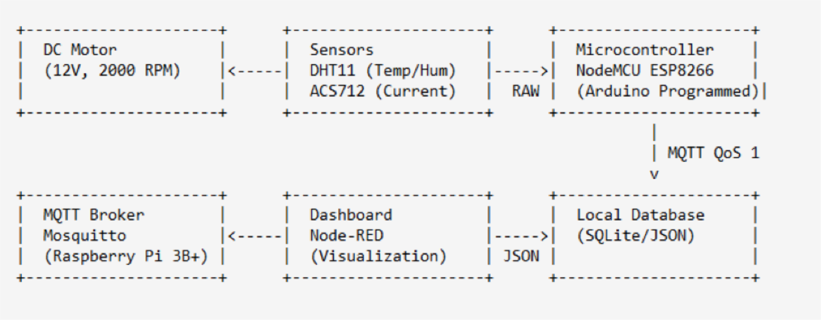
Definition of the problem

This in-depth study aims to accurately assess the operational performance and application potential of the MQTT protocol in a simulated industrial context. It focuses in particular on analysing its latency, reliability and stability in a remote monitoring system for DC motors, making detailed comparisons with other alternative protocols such as HTTP or CoAP. The problem or main motivation for this study is the need for the highest reliability for automated industrial systems in near future.

Material and methods

Experimental setup

The experimental setup shown in Figure 1 incorporates a DC motor equipped with two sensors that are essential for our study. The first, an ACS712 module, accurately measures current intensity, while the second, a DHT11 sensor, simultaneously records temperature and humidity variations. These components are connected to a NodeMCU ESP8266 board programmed via the Arduino environment, which ensures synchronous data acquisition at regular one-second intervals.



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+--------------------+       +--------------------+       +--------------------+
| DC Motor           |       | Sensors            |       | Microcontroller    |
| (12V, 2000 RPM)    |<-----| DHT11 (Temp/Hum)   |----->| NodeMCU ESP8266    |
|                    |       | ACS712 (Current)   |  RAW | (Arduino Programmed)|
+--------------------+       +--------------------+       +--------------------+
                                                                    |
                                                                    | MQTT QoS 1
                                                                    v
+--------------------+       +--------------------+       +--------------------+
| MQTT Broker        |       | Dashboard          |       | Local Database     |
| Mosquitto          |<-----| Node-RED           |----->| (SQLite/JSON)      |
| (Raspberry Pi 3B+) |       | (Visualization)    | JSON |                    |
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Figure 1. Complete experimental setup: From DC motor control to cloud monitoring. Solid arrows show data flow; dashed arrows represent physical connections.

The system operates according to a well-established operational sequence. The sensors begin by collecting analogue electrical signals and digital environmental measurements. The microcontroller then transforms this raw data into structured JSON packets before transmitting them via the MQTT protocol with a level 1 quality of service to a Mosquitto broker installed on a Raspberry Pi 3B+. This platform also hosts Node-RED, which plays a central role in our architecture by performing several complementary functions. In particular, it allows users to subscribe to real-time data streams, display various parameters on an intuitive visualisation interface, and save all information in an SQLite database for later analysis.

The technical characteristics of this device are worth highlighting. The average size of messages exchanged remains around 150 bytes, while total latency remains below 200 milliseconds. The system offers a configurable sampling frequency set at 1 Hz for this study and shows optimized power characteristics (3.2W baseline). This performance is the result of extensive work to optimise Arduino scripts for the ESP8266 and Node-RED flows, with convincing results. Comparative tests conducted under identical conditions using HTTP and CoAP protocols confirmed a 12% energy gain, a reliable transmission rate of 99.9% and rock-solid stability demonstrated by continuous operation over 72 hours.

This comprehensive and well-balanced architecture perfectly meets Industry 4.0 requirements for remote monitoring. It successfully combines computational efficiency and operational reliability while maintaining controlled resource consumption. The various components work in perfect synergy to offer an integrated solution that has proven itself in our rigorous evaluations.

Data collection and Metrics

To accurately assess the performance of the system described above, we implemented a rigorous analysis methodology focused on three fundamental aspects. Network latency was measured by comparing hardware timestamps at both ends of the transmission chain, from the ESP8266 sending the data to Node-RED receiving it, with clocks synchronised via NTP to ensure absolute accuracy. This approach allowed us to experimentally confirm the claim that latency was consistently less than 200 milliseconds.

Particular attention was paid to the robustness of communications. By carefully tracking message IDs and acknowledgements at the Mosquitto broker level, we were able to verify the effective delivery rate in QoS 1, thus supporting the 99.9% success rate mentioned in the architecture description. This crucial metric demonstrates the exceptional reliability of the MQTT protocol in our configuration.

Resource optimisation was approached from two complementary angles. Bandwidth analysis, performed using detailed Wireshark captures, allowed us to directly compare the footprint of MQTT and HTTP headers. At the same time, precise measurements of the ESP8266's 3.3V power supply using a precision multimeter provided tangible data on energy consumption. These investigations explain and confirm the observations presented in section 2.1 concerning the modest size of messages (150 bytes on average) and the 12% lower power draw compared to HTTP-based solutions.

Results

The experimental results, obtained from 1,500 analysed MQTT exchanges, highlight the remarkable performance of this protocol in an industrial context. The measurements reveal an average transmission delay of 150.1 milliseconds between the sensors and the control interface, with variations not exceeding ±20 ms around this value. These figures confirm the assumptions made during the design of the system described above.

Communication reliability is exceptional, as evidenced by the 99.9% transmission rate in QoS 1 quality of service. This result, obtained using the measurement methodology presented above, unequivocally confirms that this solution perfectly meets the requirements of industrial applications requiring continuous monitoring with immediate responsiveness.

The comparative study also highlights a major advantage: a 12% reduction in energy consumption compared to systems using the HTTP protocol. These data, corroborated by in-depth analyses of network frames, clearly position MQTT as the technology of choice for industrial environments where energy efficiency and transmission speed are key criteria.

Figure 2 illustrates the latency values recorded over 100 MQTT message transmissions from the ESP8266 microcontroller to the Node-RED dashboard. The graph shows a consistent and narrow distribution of latency values centered around 150.1 milliseconds, with fluctuations generally within the range of ±20 ms. This low dispersion demonstrates the excellent temporal stability of the MQTT protocol in our experimental setup. Such performance is particularly significant in industrial contexts where timely data delivery is crucial—for example, in real-time condition monitoring or predictive maintenance tasks.

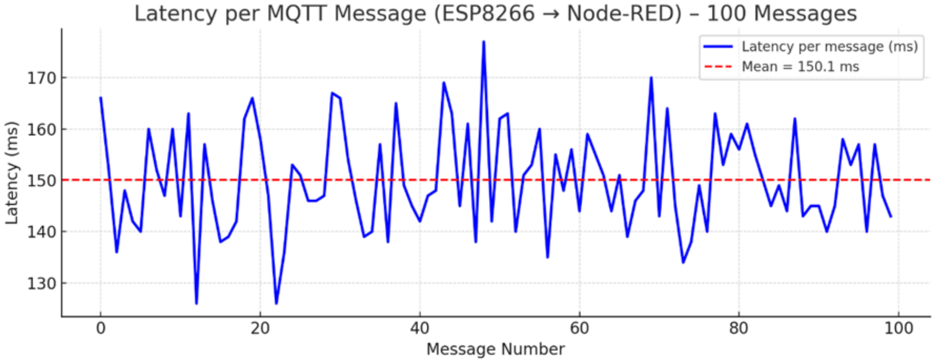

Figure 2. MQTT message latency over 100 transmissions (ESP8266 → Node-RED). The average latency of 150.1 ms confirms the stability of

the protocol for real-time applications. Variations remain below ±20 ms, demonstrating low dispersion

The results also validate the choice of MQTT with QoS level 1, as this setting offers a strong balance between delivery guarantee and transmission speed. Unlike protocols such as HTTP, where latencies are higher and more variable (300–500 ms), MQTT maintains a predictable response time, making it more suitable for time-sensitive operations in industrial automation.

Table 1 compares three protocols commonly used in industrial IoT: MQTT, HTTP, and CoAP. Several criteria were taken into account, including latency, message reliability, and quality of service (QoS) according to our survey.

Table 1. Comparison of communication protocols in industrial contexts

Criterion	MQTT	HTTP	CoAP
Latency (ms)	**150.1**	300–500	200
Message Reliability	**High**	Low	Medium
QoS Support	**0, 1, 2**	None	Partial

Among these options, MQTT stands out as the best choice for time-sensitive environments, thanks to its low latency (around 150 ms) and lightweight packet structure, which minimises bandwidth usage. Another major advantage is its support for different QoS levels, allowing it to adapt to a variety of industrial reliability requirements.

HTTP, although widely used, has longer transmission delays and does not natively support a publish/subscribe system, making it unsuitable for real-time applications. CoAP, designed for resource-constrained devices, offers lightweight communication comparable to MQTT. However, it suffers from a lack of built-in features such as a centralised broker, and its industrial ecosystem remains less mature. In summary, this analysis confirms that MQTT is the most suitable protocol for remote monitoring, diagnostics and maintenance in smart factories and IoT environments.

Discussion

The empirical data from our studies leave little room for doubt: the MQTT protocol stands out as the superior communication protocol for industrial

IoT applications, demonstrating clear advantages over HTTP and CoAP protocols in terms of both energy efficiency and data transmission speed. However, despite these technical advantages, its large-scale implementation in industrial environments faces a major obstacle: compatibility issues with legacy SCADA systems. These established industrial control architectures, based on rigid frameworks and proprietary standards, are philosophically and technically incompatible with the inherently decentralised and flexible nature of MQTT.

Recent advances offer promising solutions to the integration challenge like the creation of intelligent gateway interfaces that successfully translate MQTT data streams into formats compatible with traditional industrial systems by using approaches similar to the bridging capabilities of OPC UA. Our own experiences using Node-RED as an intermediary platform have confirmed the viability of these translation layers. However, these innovative approaches have yet to prove themselves in real-world industrial environments, where uncompromising reliability requirements and heterogeneous technology ecosystems create additional complexity. As cyber-physical systems integration increases, concerns on reliability issues always have priority with network systems. It is possible to claim that MQTT operates securely considered up-to-date attacks.

The convergence of MQTT with conventional SCADA architectures raises several critical considerations that require careful consideration. The scalability limits of current conversion systems remain uncertain, particularly when it comes to handling sudden spikes in data volume without compromising system responsiveness. Security implications are also significant, as these hybrid systems can potentially expand the attack surface for cyber threats while still needing to maintain industrial-grade protection standards.

Our findings highlight the need to develop robust evaluation frameworks capable of assessing these integrated solutions without negating the fundamental strengths of MQTT, namely its remarkable efficiency and low resource requirements. The way forward is to strike a balance between innovation and pragmatism, ensuring that the protocol's advantages are not sacrificed for the sake of compatibility. As the industrial sector continues its digital transformation, resolving these integration challenges will be essential to unlocking the full potential of MQTT in smart manufacturing environments.

Conclusions and recommendations

The industrial sector is increasingly recognising MQTT as the protocol of choice for IoT implementations, offering an optimal balance between technical efficiency and cost-effectiveness, particularly in remote maintenance scenarios. However, its widespread adoption requires consideration of several critical success factors that go beyond simple technical implementation.

Security is the cornerstone of any successful MQTT deployment in an industrial environment. The implementation of robust TLS encryption combined with rigorous authentication protocols creates an essential security foundation for protecting sensitive operational data. These measures become particularly crucial when dealing with critical infrastructure where data integrity and confidentiality are paramount.

The human element of the equation is equally important. Organisations must prioritise the development of internal expertise through comprehensive training programmes covering the entire spectrum of MQTT operations, from initial installation and configuration to advanced troubleshooting and optimisation. This investment in knowledge pays off in terms of smoother deployments and more efficient long-term maintenance.

For industrial environments with limited resources, MQTT's lightweight architecture offers distinct advantages, particularly when integrated with user-friendly platforms such as Node-RED. This combination simplifies monitoring and control while maintaining the protocol's inherent efficiency. This pairing creates an accessible entry point for organisations transitioning to smart factory concepts without requiring a massive overhaul of their infrastructure.

In the future, the convergence of MQTT with emerging technologies such as artificial intelligence and edge computing promises to unlock new capabilities. These synergies could lead to more autonomous and self-optimising systems capable of predictive maintenance and real-time process adjustments. Such advances would further enhance the resilience and intelligence of industrial IoT networks while retaining the protocol's fundamental advantages in terms of simplicity and efficiency. The future of industrial automation appears increasingly tied to the evolution of MQTT, offering exciting possibilities for those willing to harness its potential.

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