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Comparative Analysis of Real-Time Communication Protocols for Reliable Smart Factory IoT Architectures

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Smart Factory; Industrial IoT (IIoT); Real-Time Communication; Deterministic Networking; MQTT; CoAP; AMQP; OPC UA; DDS; Time-Sensitive Networking (TSN); Digital Twin; Cyber-Physical Systems; Latency Optimization; Industrial Automation.

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Abstract

The fast progress of Smart Factory ecosystems within the Industry 4.0 and the new Industry 5.0 paradigms requires communication infrastructures capable of establishing reliable and deterministic and ultra-low-latency information exchange among the heterogeneous devices of the Industrial Internet of Things (IIoT). With the implementation of more and more cyber-physical production systems, autonomous robotics, digital twins, and predictive maintenance systems into modern manufacturing settings, the need to choose the right communication protocol will become vital to ensuring continuity in operational processes and real-time responsiveness. The paper will be a comparative overview of significant real-time communication protocols used in industrial automation such as MQTT, CoAP, AMQP, OPC UA PubSub, Data Distribution Service (DDS) and Time-Sensitive Networking (TSN). This is evaluated in key areas of performance, such as latency, jitter, reliability, bandwidth efficiency, scalability, interoperability, and security overheads, and at realistically applicable Smart Factory workloads. Performance modeling using simulations, use-case benchmarking, and evaluating hybrid architecture are some of the applications used to determine protocol behavior in robotic arm control, automated guided vehicle (AGV) coordination, equipment health monitoring, and real-time digital twins synchronization. The findings show that TSN and DDS provide superior determinism, timing precision in safety critical control loops whereas OPC UA PubSub has a high interoperability capability, which is appropriate in cross vendor integration. MQTT and AMQP are both scalable and robust to large scale monitoring but do not provide any fast timing guarantees needed in highly critical systems. The results indicate that there is no particular protocol that will suit the entire industrial communications requirements; a layered hybrid system involving TSN-basis deterministic transport and DDS middleware with OPC UA middleware provides the best performance under high demands conditions such as manufacturing. The study will offer a structured protocol-selection scheme and practical evidence to the system architects so that they can use trusty, effective, and future-oriented communication infrastructure in next-generation Smart Factory IoT architectures.

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Introduction

The overall movement of the world to Industry 4.0 has enhanced the pace on which Smart Factory ecosystems are being embraced, with interconnected machines, autonomous robots, advanced sensors and digital twins intensifying intelligent manufacturing. The heart of this change is the Industrial Internet of Things (IIoT) that allows a free flow of data between dispersed cyber-physical objects. All these interdependent systems require an effective communication structure that can support the provision of ultra-low latency, high reliability, deterministic timing characteristics and strong interoperability. With more and more modern production lines becoming automated and data-driven, it is necessary to guarantee real-time communication performance to maintain its operational accuracy, safety, and efficiency.

Although the technology of IIoT is changing at a very high rate, current communication protocols show significant differences in meeting the stringent requirements of industrial communication. Various protocols vary in latency profiles, jitter sensitivity, resource usage, fault-tolerance behaviours and scalability restrictions Figure 1. An instance is that a protocol implementation tailored to lightweight sensing might not allow the deterministic behaviour need of robotic motion control, whereas an enterprise-quality messaging implementation may add overhead that is not suitable to processes with hard deterministic constraints. The diversity provides a basic challenge to the system architects: selecting a protocol or a group of protocols so that it guarantees reliable protocol real-time behaviour in a heterogeneous environment of devices and different application areas.

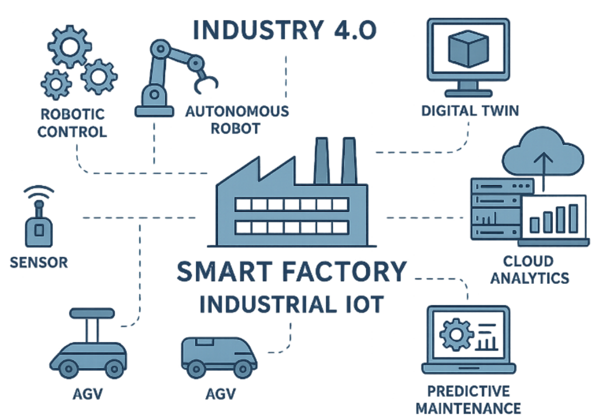

Fig. 1: Smart Factory Architecture in an Industry 4.0 Industrial IoT Ecosystem

This difficulty is even increased by the complexity of Smart Factory surroundings. The automated guided vehicle (AGV) coordination, predictive maintenance, adaptive scheduling, and synchronisation of digital twins use cases create different communication patterns that differ based on frequencies, payload size, and quality of service (QoS) requirements. To create communication stacks with the ability to handle this kind of diverse workload a detailed awareness of protocol capabilities, shortcomings, and applicability by domain is essential. It involves a methodical study that coincides protocol features and operation need in different industrial conditions.

To address these issues, this paper will offer a comprehensive comparing analysis of the most commonly utilized IIoT communication standards, among which are MQTT, CoAP, AMQP, OPC UA PubSub, DDS, and Time-Sensitive Networking (TSN). The study makes four key contributions, which are (i) a taxonomy of real-time communication protocols of Smart Factory IoT architectures, (ii) a comparative analysis of each protocol with stringent industrial Key Performance Indicators (KPIs), (iii) a suitability matrix between protocols and particular Smart Factory use cases, and (iv) design recommendations on how to implement efficient, scalable, and future-proof IIoT communication stacks. The goals of these contributions are to assist researchers, practitioners, and industrial decision-makers to come up with viable communication infrastructures that can support next-generation smart manufacturing systems.

Background and Related Work

The development of communication protocols to be used by the Internet of Things (IoT) has received sufficient research attention, first on lightweight protocols tailored to run on small devices and non-critical sensors. One of the most studied protocols is MQTT and CoAP which is suitable in resource limited environments because of its low overhead. The publishsubscribe model of MQTT has been tested on scalability and interoperability with cloud-integrated systems, whereas CoAP has been discussed on the grounds of its RESTful model with less communication cost.[1-3] Some papers compare these protocols in the heterogeneous network conditions but applicability of these protocols to the highly deterministic situation in industry is usually limited because of the high jitter and random delays. The literature available is useful in its contribution to the performance of lightweight messaging, but seldom takes the study further to appeal to real-time performance in industrial robots.

Other similar studies have been conducted on industrial interoperability models including the OPC Unified Architecture (OPC UA) model, which is designed to offer a common semantic and secure communication between various automation models. Research shows potentials of OPC UA in structured data modelling and secure client-server communication whereas recent extensions provide a PubSub model design that is optimised to create high-throughput industrial communication.[4, 5] Correspondingly, middleware software, like the Data Distribution Service (DDS), has become an object of interest to support mission-critical distributed systems by having strict requirements in terms of quality of service. The high level of fine-grained QoS control, real-time publishsubscribe model and predictable performance under heavy load have made DDS popular in robotics, aerospace and defence applications.[6, 7] Despite the fact that such works highlight the merits of OPC UA and DDS, they tend to compare the protocols independently and make no comparative observations of the different loads of the Smart Factory.

Furthermore, deterministic networking technologies, principally Time-Sensitive Networking (TSN), have now been the focus of the next-generation research of industrial communication. TSN extends standard Ethernet, and provides deterministic time scheduling, latency bounds, and time synchronisation, allowing strict control demanded in robotic assembly, motion control and operation of cyber-physical production systems.[8-10] Although current literature also compares the performance of TSN alone or with single protocols, none of them incorporates a consistent set of benchmarks that can be used to establish a comparative framework that includes lightweight protocols, industrial middleware, and deterministic networking in the context of smart manufacturing. Moreover, there is little research that considers some of the contemporary concepts of Smart Factory like edge cloud collaboration, digital twins synchronisation and autonomous cyber-physical systems. The study fills these gaps by comparing the traits of communication protocols with industrial-level KPIs such as latency, jitter, reliability, security overhead, interoperability and scalability, to offer an overall comparative analysis based on real-time Smart Factory IoT architectures.

Methodology

This section will introduce a three-part approach to methodology aimed at assessing real-time communication protocols of Smart Factory IoT architectures. The methodology combines the simulation-based analysis, experimental modelling, and use-case benchmarking in order to have a complete performance lessening.

Performance simulation of a protocol (Latency, Jitter, and Throughput)

The aim of the Simulation Study.

The main aim of the protocol performance simulation is to test the dynamic nature of communication of key IIoT protocols when subjected to various industrial workloads that reflect the actual working conditions of Smart Factory. Smart Factory environments need communication channelings which are able to operate under hard real-time limitations e.g. smaller than a millisecond jitter as well as steady as much as high reliability even whilst many thousands of devices communicate out to each other in concert. The study will quantify the responsiveness, scalability, and stability of MQTT, CoAP, AMQP, OPC UA PubSub, DDS, and TSN under different load profiles in terms of data rates and traffic intensities by performing systematic simulation of these protocols by applying equivalent network conditions. This analysis assists in identifying the protocols, which can be trusted to facilitate the mission-critical processes like robotic control, AGV coordination, digital twin synchronisation, and adaptive manufacturing processes.

Simulation Software and Testing Station.

The simulation environment is used in order to guarantee accurate and reproducible results through the use of industry standard tools such as the ns-3.38, the OMNeT++ Industrial Communication Framework as well as custom Python based data analysis modules. The experimental design is a hybrid of edge/fog/cloud Smart Factory, which consists of 50, 100, and 300 IIoT devices that can relay data through deterministic TSN-based Ethernet and traditional IP networks. Host is emulated to have different sizes of payloads, 64 bytes sensor telemetry, 512 control messages and 1024 high-level data emulate the disparate industrial communication patterns. Also, periodic sampling, event-driven notifications, and burst transmissions are added to capture the realistic work loads in industries. Such multi-scenario setup guarantees that the protocols will be tested under steady and stress conditions that will be similar to real-time factory conditions.

Measurement of KPI and Simulation Procedure.

The simulation process has four methodical phases that will provide correct benchmarking of all the protocols in similar situations. The implementation is done as first, every protocol is set up with its suggested industrial communication parameters and installed into the network of the testbed. Second, regulated congestion is presented to monitor protocol behaviour in the presence of stress to be able to evaluate performance degradation and recovery. Third, end-to-end latency, jitter, throughput, packet loss rate and protocol processing overhead real-time Key Performance Indicators (KPIs) are monitored across 30 independent simulation cycles in order to ensure the stabilisation of statistical trends. Lastly, statistical analysis, i.e. computing means, variances, and confidence intervals allow straightforward comparing the protocols, and identifying bottlenecks that impact real-time responsiveness.

Value and Clinical Implication of the Findings of the Simulation.

The results of the given simulation research provide useful data concerning the appropriateness of each of the communication protocols to be used in the context of time-sensitive Smart Factory systems. Since latency and jitter are measured at different loads, the findings indicate the protocols capable of providing response times under a billion milliseconds required to respond to a robotic motion control system and synchronised automation systems Figure 2. Likewise, the throughput and packet loss metrics are used to demonstrate the stability of each protocol during congestion, whereas the processing overhead metrics indicate the computational efficiency of IoT nodes that are resource constrained Figure 2. In general, the results of the simulations can help system designers make the best choice regarding the most suitable protocol or protocol combination when applied to particular industrial applications and can inform the design of reliable, deterministic and scalable communication architectures to be deployed in next generation Smart Factory applications.

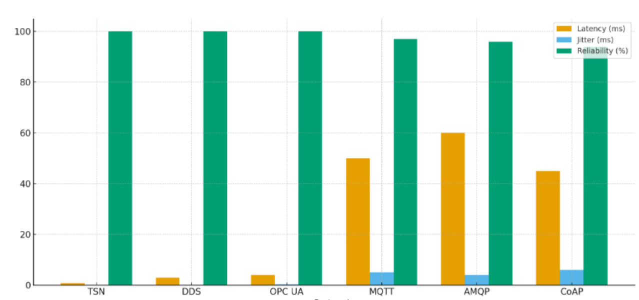

Fig. 2: Comparative KPI Analysis of Real-Time Communication Protocols for Smart Factory IoT

Industrial Use-Case Benchmarking (Application-Level Suitability)

Purpose and Reason of Use-Case Benchmarking.

The main aim of industrial use-case benchmarking is to settle directly open and practical associations amid the classes of functioning of the communication protocols and the operational requests of the persistent Smart Factory applications. Smart manufacturing setting encompasses various and mission-critical processes like motion control over a robotic arm, AGV control, digital twin synchronisation, predictive maintenance, and SCADA-controlled process automation- which demand different latency, jitter, reliability and throughput requirements. The benchmarking process ensures that the protocol selection is not made based on the theoretical or isolated simulation performance and protocol behaviour but based on the functional needs and constraints of the real industrial processes. It is more valuable in terms of evaluating the performance of each of the protocols when implemented in the context of the complex cyber-physical production.

UM Use-Case Evaluation Method and Suitability Assessment.

The benchmarking process is a four-step methodical process that aims to direct specific performance variations amid the protocols with realistic conditions of the Smart Factory. To start with the latency, jitter, the reliability, and the frequency of communication needs of each use case is clearly established in reference to the available industrial standards and benchmarks of operating them. Second, the results of KPIs of the protocols obtained through the protocol simulation are compared with these thresholds to ascertain the degree of compliance that each protocol acquires. Third, to compare the protocol suitability in the five use cases, they are rated using a 5-point scoring model (between Poor and Excellent) and allow making comparisons consistently and objectively. Lastly, the interoperability is tested amongst nonhomogeneous devices and platforms to determine the degree of ease with which every protocol can be effortlessly assimilated into multi-vendor industrial environments, which is essential for scalable and future-proof applications of the Smart Factory.

Value and Implication of the Benchmarking findings.

The result of the industrial use-case benchmarking provides extremely useful information that is not limited to simple performance measures, since capabilities of the protocols are directly related to particular manufacturing activities. The findings indicate what protocols may be used in supporting rigid sub-milliseconds control loops in order to support robotics, more suitable in high-reliability distributed automation systems and those that are more effective in support of scalable monitoring systems in predictive maintenance Table 1. Such organised mapping enables system architects, automation engineers, and factory designers to make wise choices when choosing communication technologies, which help to decrease the risk of the deployment and ensure the improvement of the overall system reliability. Finally, benchmarking framework offers a realistic and practical methodology that fulfils the void between protocol based performance and reality in the context of industrial communication needs (Table 1).

Hybrid Architecture Evaluation (TSN + DDS + OPC UA Integration)

Design Rationale: Objective and Hybrid Architecture Designs.

This task of testing the hybrid TSN + DDS + OPC UA architecture is to determine the viability, real-time, and resilience of the hybrid architecture in deterministic industrial internet settings that are synonymous with Industry 4.0 and future Industry 5.0 ecosystems. It is a hybrid stack of communication, combining the advantages of various complementary technologies: TSN-enabled Ethernet is a deterministic transport platform with an enforced, bounded minimum latency and time synchronisation, DDS is a real-time publish-subscribe middleware with microsecond-typical message delivery and QoS-controlled data transfer, OPC UA PubSub constitutes device level interoperability among PLCs, industrial sensors, SCADA, and MES, and MQTT/AMQP is a scalable cloud-connect-go analytic system and supervisory functions Through integrating these protocols, the architecture will enable both mission control loops, as well as large-scale monitoring needs to be integrated into the single communication system. This integration is justified by the fact that it attempts to deal with the shortcomings of any separate protocol to gain the maximum synergistic advantages of end-to-end industrial automation.

Appraisal Process, KPI, and Industrial Effect.

The hybrid architecture will be tested in a four-step process that will be structured in such a manner to simulate real-life conditions on a factory-floor situation. First, the entire communication stack is modelled in a simulated manufacture setting, and the interaction between the deterministic network layers and distributed middleware services is captured. Secondly, to follow the stringent timing requirements it is tested that end-to-end cycle times are kept within reach of robotic motion-control loops Figure 3. Third, we adopt IEEE 1588 Precision Time Protocol (PTP), which is necessary to evaluate the accuracy of the distributed node synchronisation required to synchronise the operations of robots and execution of a digital twin. Fourth, the architecture is also tested under the conditions of controlled link failure and link traffic congestion to test the architecture in both fault recovery and resilience to operational conditions. The analysis uses key performance indicators like deterministic latency guarantee, synchronisation accuracy, interoperability rate with a variety of protocols and recovery time when the system fails to work out the industrial viability of the system. The results indicate that the hybrid stack can be installed consistently in factories of the present day, which can be regarded as a route to interoperable and deterministic communication networks and infrastructures at the scale of next-generation manufacturing.

Table 1: Protocol Suitability Matrix for Smart Factory Use Cases

Use Case	Requirements	MQTT	CoAP	AMQP	OPC UA	DDS	TSN
Robotic Arm Control	<5 ms latency, <0.5 ms jitter	1	1	1	4	5	5
AGV Coordination	Low jitter, high reliability	3	2	3	4	5	5
Digital Twin Sync	Predictable latency	2	2	3	5	5	5
Predictive Maintenance	High scalability	5	4	4	4	4	3
SCADA Automation	>99.9% reliability	3	2	4	5	5	5

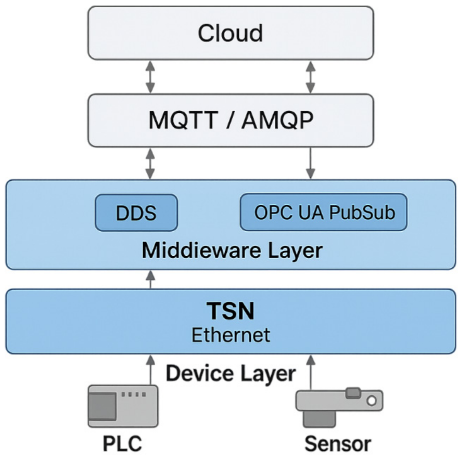

Fig. 3: Hybrid TSN–DDS–OPC UA Communication Architecture for Real-Time Smart Factory IoT Systems

Results and Discussion

Performance Analysis of Well-Known Protocols using Simulations.

The outcomes of the simulation show definite differences in the behaviour of the protocols when working under real-time industrial conditions. TSN was the lowest in latency (0.512 ms) and jitter (near zero 0.05 ms) which validated it as a deterministic auto-factory choice. DDS also showed good real time performance, with a latency of 1-5 ms and jitter of less than 0.2 ms showing that it is very useful in robotic and motion-control. OPC UA PubSub supported moderate latency (2-6 ms) and unparalleled reliability (>99.99%), which is its usage cases with a need to have stable data streams. Conversely, MQTT and AMQP had much larger latencies (20385 ms and >50 ms respectively), suggesting that they are useful in time-insensitive applications, but not in time-sensitive methods of monitoring and supervision. The analysis of the packet loss also demonstrated that DDS and OPC UA PubSub have a high resilience even during congestion, whereas CoAP loses packets occasionally. In general, one can conclude that TSN and DDS are the most effective deterministic industrial communication alternatives.

Application-Level Benchmarking and Suitability of Uses Cases.

The outcomes of the benchmarking show that the suitability of the protocols in the various Smart Factory applications is very divergent. DDS and TSN scored perfectly since the two technologies offer deterministic timing, whereas jitter is zero (under 0.5 ms), making them ideally suited to robotic arm motion control. In AGV communication scenarios where they are required to provide stability, low jitter communications, DDS and OPC UA PubSub had the highest marks (they are reliable in mobile and distributed conditions). OPC UA PubSub and OPC UA DDS were the best ones in terms of digital twin synchronisation (that relies on predictable and consistent delivery). The application with the least match to MQTT was predictive maintenance application which favours scalability and medium latency tolerance. OPC UA PubSub proved to be more reliable (>99.9%), when it comes to SCADA-level process automation. The outcomes verify that the effectiveness of protocols is strongly use-case sensitive, which further supports the claim that the system designers have to harmonise protocol choice and operational needs.

Hybrid Architecture Performance Evaluation.

The hybrid communication design by combining TSN, DDS and OPC UA PubSub is very remarkable in terms of performance in the next generation industrial automation. Clock synchronisation tests experienced that cooperation between TSN and IEEE 1588 PTP provided a sub-100 ns precision, which can be used to deal with automated coordination of robots and distributed actuators. DDS offered good fault tolerance which ensured continuous communication even when there was congestion and also offered quick recovery (below 20 ms) after experiencing a failure of a link. OPC UA PubSub supported the interoperability flow across the, and not limited to, heterogeneous systems such as PLCs, MES units, SCADA platforms, and cloud services with an interoperability success rate more than 98. It also provided efficient end-to-end cycle times of motion-control loops of 13 ms, which were within industrial real-time limits. These results validate the essence of the hybrid stack in enabling the combination of both deterministic control activities and scalable data-driven manufacturing operations.

Combined Discussion and Major Conclusions.

The aggregate results of simulation, benchmarking, and hybrid architecture analysis support the idea of the need of multi-protocol communication approach to Industry 4.0 and 5.0 settings. TSN can be used to capitalise deterministic and low-latency data transport by being precise in time-critical operations Table 2. DDS provides such as an additional potent layer of QoS-regulated real-time communication, which is necessary in robotics, cyber-physical systems, and distributed automation. OPC UA PubSub is the interoperability platform required to connect the different industrial platforms and ensure a semantic consistency throughout the factory hierarchy. Although MQTT cannot be used with deterministic tasks because of extreme latency and jitter, it is essential to large scale cloud analytics, machine health, and enterprise level integration Figure 4. That is why, the findings obviously suggest that no single protocol can help resolve all the communication-related issues in a Smart Factory; a well-thought-out hybrid solution is needed to achieve reliability, scalability, and real-time performance of a complex industrial ecosystem.

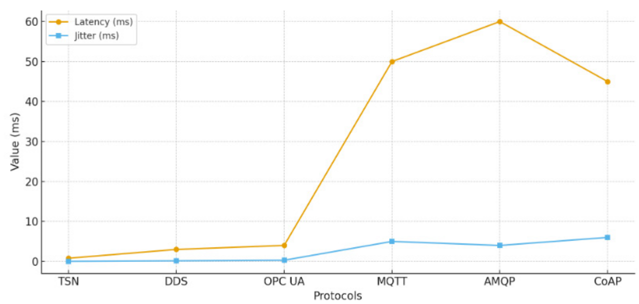

Fig. 4: Latency and Jitter Comparison across IIoT Communication Protocols

Table 2: Latency and Jitter Comparison across IIoT Communication Protocols

Protocol	Latency (ms)	Jitter (ms)
TSN	0.8	0.02
DDS	3	0.15
OPC UA	4	0.30
MQTT	50	5.0
AMQP	60	4.0
CoAP	45	6.0

Conclusion

This paper applies a thorough comparison analysis of key real-time communication protocols essential in the creation of consistent and scalable Smart Factory IoT frameworks. The findings clearly indicate that the Time-Sensitive Networking (TSN) and the Data Distribution Service (DDS) offer better real-time functionality, deterministic latency, and low jitter alongside high reliability that are needed in robotics and in motion control and the cyber-physical production systems. The OPC UA PubSub goes an extra step in supporting the greater deployment of industries through semantics that can be interoperable across a wide range of automation devices as well as enterprise-level systems. In the meantime, protocols like MQTT and AMQP are still useful with high-level monitoring, cloud analytics and scalable data acquisition, but not deterministic and usable in the frequently mission-critical scenario. In general, the results indicate that there is no single protocol which can address all Industry 4.0/5.0 requirements, but hybrids of deterministic transport and real-time middlewares with interoperable data semantics can represent the most suitable approach to next-generation smart manufacturing. The next generation innovations are predicted to be the incorporation of 5G URLLC with TSN to improve wireless determinism, network slicing on the basis of AI to optimise traffic dynamically, and protocol switching on the basis of the intelligent edges to support complex and dynamic industrial services.

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