

Industry 4.0 Machine-to-Machine Communication Protocols and Architectures on the Shop Floor

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Abstract. The concept of Industry 4.0 and the introduction of the Internet of Things (IoT) on industrial applications, known as Industrial Internet of Things (IIoT), have been changing the scenario of industrial automation. This new paradigm is expected to optimize industrial processes, increase productivity, lower costs and improve operations integration. For that, structured Machine-to-Machine (M2M) communication is key to ensure agility, interoperability and reliability, with several solutions currently available in the literature and in industry. This paper reviews the state of the art on industrial communication protocols and architectures, providing a classification and comparison of these different solutions based on their most relevant features in the context of Industry 4.0.

Keywords: Industry 4.0, Industrial Internet of Things (IIoT), Machine-to-Machine (M2M) communication, Industrial automation

1 Introduction

Industry 4.0 is a concept introduced by the German government with the goal to transform industrial manufacturing systems through digitalization and the use of new technologies. Also referred to as the Fourth Industrial Revolution, this new paradigm focuses on creating smart products, smart production systems, and smart services, aiming for the optimization of industrial processes, while increasing productivity and lowering costs.

In an Industry 4.0 environment, some elements need to be guaranteed, such as security, reliability, agility, interoperability and connectivity. For that, structured, manufacturer independent, and real time capable machine-to-machine (M2M) communications should be established.

From the first successful attempt on structured industrial communication in the 1980s with fieldbuses, to most recent concepts like the implementation of the Industrial Internet of Things (IIoT), there have always been many heterogeneous solutions for M2M communication, each optimized to fulfill different requirements. The purpose of this work is to review the state of the art on industrial communication protocols and architectures, providing a classification and

comparison of these different solutions, based on their most relevant features in the context of Industry 4.0.

This paper is structured as follows. Section II presents some concepts about industrial communication systems. Section III discusses the state of the art on industrial M2M communication, reviews recent works in the area and compares different solutions. Section IV presents promising future solutions for industrial communication, and Section V details the conclusions of this work.

2 Industrial Communication Systems

Also referred to as “Industrial Networks”, industrial communication systems are networks typically adopted in factory automation, manufacturing and process control, to implement data exchange between controllers, sensors, actuators, input/output devices and industrial equipment in general [27]. These networks are also responsible for the data flow and information sharing to higher levels of automation in factories, such as Supervisory Control and Data Acquisition (SCADA) systems, Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP).

In the 1980s, dedicated automation networks, called fieldbus systems, were initially developed and implemented as a replacement for point-to-point links between industrial devices, using serial digital communication. This change allowed more flexibility in the shop floor, enabling remote configuration and diagnostics to be carried out more easily. Moreover, noticeable savings were made in both cabling and deployment costs, because of the shared communication support [29].

The downside of fieldbuses was, though, the lack of standardization. Over the years, many proprietary solutions were developed, such as PROFIBUS, INTERBUS and MODBUS, as well as CAN-based implementations, such as DeviceNet and CANopen. Some of these protocols are still often used in industry, typically in shop floors, between PLCs, I/O-modules, sensors or actuators. In the end of the 1990s, Ethernet-based networks were introduced in the industrial environment, due to the growing use of Internet technologies and Information Technology (IT). At first, the lack of genuine real-time capabilities in standard Ethernet prevented the development of one single Ethernet solution for automation purposes [31], and more dedicated proprietary ones were created.

Over the years, modifications were made to meet these time constraints and several solutions emerged, such as EtherCAT and PROFINET IRT, which are two of the most used Real-Time Ethernet (RTE) protocols. Ethernet protocols are most commonly being used in industry for communication between process control entities and support systems, such as SCADA [29].

Most recently, aiming for the same practicality of the increasing use of wireless technology in daily life, industrial wireless networks (IWNs) have emerged. Starting from the wireless sensor networks (WSNs), such as WirelessHART, these solutions were initially implemented along with wired networks to increase flexibility, mobility and easiness of deployment. Some examples used in industry are Zigbee, Bluetooth and WLAN [29].

The main disadvantages of IWNs can be security issues and the power consumption, particularly for battery powered equipment, but its advantages match most of the requirements for Industry 4.0, so more of these solutions are been adopted within factories [18]. For non-battery operated devices, a physical wired connection must exist for power, thus the advantage of having a complete wireless device is lower, when compared to a battery-operated device.

Therefore, the field of industrial communication networks is very heterogeneous, with many different, non-interoperable, solutions being used. Table 1 shows some network examples and applications, while Fig. 1 shows the industrial networks market share of new nodes installed in 2020, according to HMS Networks⁴. The graph shows Industrial Ethernet continues to take market share from fieldbuses, which went from 35% of new nodes installed in 2019, down to 30% in 2020. Meanwhile, wireless solutions' share stayed stable compared to past years. The most used Industrial Ethernet protocol was Ethernet/IP, whereas PROFIBUS was still the number one in fieldbus usage.

Table 1. Classification of Industrial Networks

Networks	Features	
	<i>Solutions</i>	<i>Level of use</i>
Fieldbuses	PROFIBUS, INTERBUS, Modbus, CANopen, DeviceNET	Device communication in shop floors
Industrial Ethernet	PROFINET IRT, EtherCAT, Ethernet/IP, Modbus TCP	Communication between control units and SCADA systems
Wireless Networks	Zigbee, WirelessHART, Bluetooth, WLAN	Sensor networks, parameter monitoring and automation control

As a consequence of this heterogeneous landscape, automation practitioners resort to the use of middleware software to interconnect systems. In this context, a middleware can be seen as a digital interface used to establish communication between physical(OT-Operations Technology) and digital environments(IT-Information Technologies). By connecting hardware and applications with the necessary level of abstraction from heterogeneous systems, it provides a common infrastructure to support communication [6]. The use of this kind of strategy is also compatible with the idea of IIoT, where every node is connected and data flows not only horizontally, at the device control level, but also vertically, between control, production and planning systems [25]. Fig. 2 shows both aspects

⁴ <https://www.hms-networks.com/news-and-insights/news-from-hms/2020/05/29/industrial-network-market-shares-2020-according-to-hms-networks>, accessed in 13/04/2020.

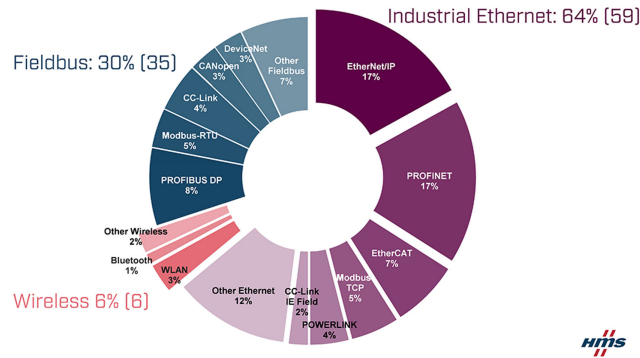


Fig. 1. Industrial Networks market share in 2020⁴.

in the company pyramid. Examples of communication middleware for industrial applications are MQTT, DDS, AMQP, CoAP and OPC UA.

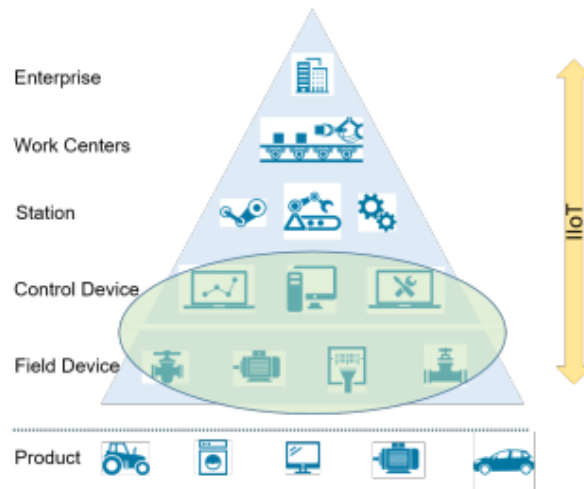


Fig. 2. The company pyramid [25].

The Message Queue Telemetry Protocol (MQTT) is a standard developed by the OASIS consortium. It is described as “an extremely lightweight publish/subscribe messaging transport that is ideal for connecting remote devices with a small code footprint and minimal network bandwidth”⁵. It uses the concept of an MQTT-server, also known as a broker, which holds all the data from

⁵ <https://mqtt.org/>

the connected nodes. Therefore, devices must simply report data to the broker, not storing any data themselves. Such devices can also be controlled by the broker [22]. MQTT also provides 3 levels of Quality of Service (QoS).

As MQTT is an open communication protocol, some companies in the automation sector saw it as an opportunity to develop IIoT solutions using this standard. That is the case of Sparkplug, which is a specification for MQTT created with the purpose of better defining its infrastructure and semantics to improve interoperability and make data easily available and standardized for SCADA, MES and HMI (Human-Machine Interface) solutions in industry [7].

The Data Distribution Service (DDS) is an open middleware standard developed by the Object Management Group (OMG). It works by introducing a virtual Global Data Space where applications are able to share information by reading and writing data-objects addressed by means of an application-defined name and a key⁶. It supports QoS parameters, such as reliability, bandwidth, delivery deadlines and resource limits. It is also real-time capable, with its nodes being able to do peer-to-peer communication using UDP multicast, thus removing the need of a centralized network management system [3].

The Advanced Message Queuing Protocol (AMQP) is referred to as a reliable protocol for business messaging. It allows different systems to interact, as long as they can create and interpret this data format. Using AMQP, the network will be organized in nodes, which can deliver messages or provide them storage. Data is directly transferred between nodes, so any network model can be implemented, the most used being the centralized model, where data is transmitted via the server [2]. It also supports QoS.

CoAP stands for Constrained Application Protocol and it is a specialized web transfer protocol for use with constrained nodes and constrained networks in IoT⁷. It was developed as an Internet Standards Document and it uses the Representational State Transfer (REST) mechanism [16]. On top of CoAP, the Open Mobile Alliance (OMA) has defined the LightweightM2M (LwM2M), which is a client-server protocol with several management functionalities for resource-constrained devices and remote applications [15]. The LwM2M specification also implements a data model, which is organized as a three-level tree, and the levels are Object, Object Instance, and Resource⁸. The OMA also holds the LwM2M Object and Resource Registry, where new objects and resources can be submitted for registration.

The Open Platform Communication is “the interoperability standard for the secure and reliable exchange of data in the industrial automation space and in other industries”⁹ developed and maintained by the OPC Foundation. The standard brings a series of specifications to define the interface between servers and clients, real-time and historical data access, alarm and events monitoring, and other applications. The OPC UA (Unified Architecture) is a platform indepen-

⁶ <https://www.omg.org/omg-dds-portal/>

⁷ <https://coap.technology>

⁸ <https://avsystem.github.io/Anjay-doc/LwM2M.html#data-model>

⁹ <https://opcfoundation.org/about/what-is-opc/>

dent service-oriented architecture that integrated all OPC Classic functionalities in one extensible framework¹⁰. This architecture has two main components: transport, which defines the protocols to serialize or deserialize data sent over the network, and a data model, which defines rules on how to expose an information model [3]. The semantic description of this model (the address space) is one of the major strengths of OPC UA [22].

Additionally, since 2012 there is the oneM2M initiative, which comprises multiple Standards Developer Organizations (SDOs) worldwide with the objective of providing a standard interface where incompatible devices can exchange data, manage information, and interact [30]. There are currently 200 active members in oneM2M, developing the specifications for a common service layer, which can exist between applications and networks, exposing functions needed by IoT across different industry segments. This standard might work as an interoperability hub across industries and industry-specific protocols¹¹.

3 Related work

Both Industrial Communication Networks and Industrial Communication Middleware studies were reviewed in this work. This section presents the most recent and relevant ones, in the context of Industry 4.0 and IIoT, as well as some related results. Table 2 shows a comparison of the middleware solutions reviewed, regarding their most important features, and some observed disadvantages.

Classical fieldbuses cannot be directly integrated in IIoT systems [27], however, [8] proposes dual fieldbus communication for IIoT using an edge server. The redundant fieldbus is used to prevent bus faults and increase the system's availability, while the edge server implements a long short-term memory (LSTM) to predict future values of sensors and prevent undesirable conditions. The work concluded the proposed system outperformed conventional Modbus in terms of data error detection and success rate. Meanwhile, [19] demonstrated the use of a Profibus sniffer to collect data without interfering with the system. It concludes that it is a simple task to connect legacy systems to the Internet, but this solution does not map the semantics of the information, making it difficult to understand the meaning of what is being collected.

A performance evaluation of the three most used Ethernet based protocols is done in [32]. It is shown that Ethernet/IP has the advantage of lower hardware costs when compared to EtherCAT and PROFINET IRT, but the last two provide not only fast but deterministic communication. When comparing EtherCAT and PROFINET IRT, the paper concludes EtherCAT is more suited for real-time control applications, due to offering better closed-loop control performance than PROFINET IRT.

In [18] there is a review on industrial wireless networks, describing and analyzing QoS and Quality of Data (QoD) based architectures from different aspects, like real-time, reliability, longevity, security and privacy. The work also provides

¹⁰ <https://opcfoundation.org/about/opc-technologies/opc-ua/>

¹¹ <https://www.onem2m.org/resources/white-papers>

a survey and taxonomy of IWNs applications, outlines the main challenges regarding the use of these networks, and comments some research trends, stating how promising this technology is in the context of the Industry 4.0.

Comparative studies of industrial communication middleware can be seen in [2, 3, 13, 14, 16, 20, 22, 25], while [23] and [24] exclusively compare OPC UA and MQTT on their performance for data exchange. The conclusion in [22] is that OPC UA has its strength on the semantic modeling of the information, MQTT has the advantage of being a lightweight protocol, and DDS has the advantage of having extensive QoS settings. [2] states that OPC UA is designed for larger systems that require more functionality, reliability and security, while AMQP is their recommended standard for less complex systems. It also considers MQTT server as a single point of failure and that its implementations are less reliable. [13] proves that, under network traffic and latency strict requirements, CoAP is lighter and faster than MQTT.

[23] performs four different tests to compare OPC UA and MQTT: ratio between packet and payload length, loopback time per telegram length, loopback time from different regions of the world, and response time for multiple clients participating in publish/subscribe transactions. It concludes that MQTT has the advantage of using less data to transmit the same payload, so, when transmitting the same message to a large number of clients, it is much faster than OPC UA. However, OPC UA has other services besides data exchange, such as data modeling, address space, alarm and event management, variable history, access control, among many others, so the magnitude of this middleware cannot be ignored. [24] achieves the same conclusion regarding pure data exchange and adds that MQTT is unstructured, which implies the use of additional tools to develop such services, such as, for instance, the Sparkplug specification [7].

In [5, 15], the authors research about the interoperability between OPC UA and other protocols. The first work proposes an integration between OPC UA and LwM2M, stating that this connectivity would be beneficial for both domains, due to OPC UA's lack of support for constrained devices, applications and protocols, like CoAP. The interoperability system consists in the development of a virtualization server, which will contain both OPC UA and LwM2M servers and clients that can exchange data from one network to the other. Even though OPC UA does not support CoAP, the open62541 implementation is a quite complete option for use in resource-constrained embedded devices¹². The second work proposes an inter-working solution between OPC UA and oneM2M, including a mapping of data elements of the on2M2M resource model towards OPC UA's Address Space.

Finally, other works focus on the features of a single middleware. [28] researches about security issues within the DDS protocol such as, for example, the possibility of a non-authenticated client enumerating devices, and denial of service (DoS) attacks. Meanwhile, [6] proposes an open middleware solution for IIoT based on MQTT. In [26] an industrial device monitoring and control system is proposed using the oneM2M protocol. [1, 4, 9, 12, 21, 33, 34] relate the use of

¹² <https://www.kalycito.com/opc-ua-sdk/>

OPC UA and Time Sensitive Networking (TSN) for real-time applications in the context of IIoT (this concept will be discussed in more detail the next section).

4 Future of Industrial Networks

Some of the reviewed works for this article also focus on future perspectives and challenges for industrial communication systems. [27] states that the existing IWNs only achieve soft real-time performances, which prevents their deployment in most demanding environments, unless new protocols are defined. [31] brings up the concept of TSN as the future of Industrial Ethernet.

Time Sensitive Networking (TSN) is an Ethernet standardization initiative that aims to evolve standard Ethernet to equip it with native deterministic real-time capabilities, and there are about 60 individual IEEE standards included in its scope. TSN can achieve determinism by using time synchronization and sharing a schedule between the network components. Therefore, all participants of the network must be time synchronized and configured to transmit data according to the shared schedule [9].

TSN is expected to form the technical basis for the effective real-time implementation of OPC UA [33], since OPC UA, by itself, is not capable of guaranteeing deterministic real-time data transfer. Both [21] and [1] propose open-source solutions for industrial communication with OPC UA over TSN, presenting performance evaluations of their implementations. [4] states that OPC UA TSN will replace today's Ethernet-based fieldbuses in a number of applications, due to vendor independence, larger and more flexible topologies, full IIoT capabilities, integrated security, modern data modeling, among others improvements. In [10], the authors propose a combination of communication over TSN and OPC UA Programs, which are used to model a long-running service as a predefined sequence of states they execute, represented by a finite state machine. The integration of TSN-enabled OPC UA and field devices is addressed in [12].

Additionally, [17] analyses 5G-TSN integration to support Industry 4.0. 5G is the next generation of mobile communication networks, but it is the first cellular standard to target industrial use cases. The potential of 5G networks in industrial communication relies on high bandwidth and strict determinism, to allow synchronized monitoring of processes and actions execution. Even though [27] highlights that these networks will be operated by telecom providers, and factory owners may not be inclined to leave this communication operation in the hands of a third-party provider, it is shown in [17] that the industrial applications of 5G can be done within private networks. [11] discusses some requirements and challenges for 5G networks in communication for industrial automation, concluding that the 5G standard is able to attend the needed isochronous deterministic communication involved in closed-loop control with high availability and reliability.

Table 2: Communication middleware solutions comparison

Protocols	Semantic data	Pattern	QoS	OSI layer	Main characteristics	Observed disadvantages
OPC UA	Yes	RPC/PS	No	Application	It is the most used in industry regarding Industry 4.0, according to the number of results found during the search. There are many articles about interworking OPC UA with other protocols, so it shows its interoperability capability. It provides many services besides data exchange, such as data modeling, alarms, event management, historical data, etc. The development of OPC UA's Companion Specifications is oriented to the industrial demands for M2M semantic interoperability	It is not real-time capable. The complexity of the specification and data models can increase the development time
OPC UA TSN	Yes	PS	Yes	Application	It allows OPC UA to be real-time capable, ensuring determinism.	Still in development.
MQTT	No	PS	Yes	Application	It focuses on being simple, fast, and lightweight, so it presents lower transmission times when compared to other protocols. It can also interwork with OPC UA and oneM2M as a transport protocol.	It is unstructured, so it needs third-party solutions to implement services, such as semantics, historical data, alarms, etc.
Sparkplug (MQTT)	Yes	PS	Yes	Application	It defines and structures the MQTT payload to increase M2M interoperability and a better understanding of the transferred data.	Only one result found of its application in the industry.

oneM2M	Yes	RPC/PS	Yes	Application	It aims to be an interoperability hub across different segments, even supporting non-oneM2M devices. It provides many services, including semantics, notifications, as well as device, data, application, and services management. It accepts RDF graphs to introduce semantics to the applications.	It focus on global interoperability across many IoT segments, with few industrial applications being found. Most results were regarding interworking oneM2M with other protocols. Additionally, there were not examples found of the semantics services applied to industrial environments.
CoAP	No	RPC/PS	No	Application	It focuses on data transfer between constrained devices.	Mostly found in the context of IoT rather than in IIoT.
LwM2M (CoAP)	Yes	RPC/PS	No	Application	Introduces semantics to the CoAP protocol and directs its use to industry. The Object and Resource Registry is an attempt of standardizing semantic models for industrial use. Some vendor-specific objects and resources are registered.	The data model is simpler, so it can be limited in complex systems.
DDS	No	RPC/PS	Yes	Transport	It is data-centric, and it has extensive QoS parameters. It is mainly used in transportation, smart energy, medical devices, military, and aerospace segments.	Some performance tests showed DDS uses too much CPU resources compared to other protocols. Some security issues were found in another work.
AMQP	No	RPC/PS	Yes	Application	It is a simple standard to be used in less complex systems. Centralized and decentralized network models can be implemented. It is not focused on industrial applications.	It is unstructured, so it might be more difficult to implement in more complex systems.

5 Conclusion

This paper reviewed the state of the art on industrial communication systems in the context of the Industry 4.0 paradigm. The heterogeneity of such systems was one of the focuses of the work, and many different networks and communication solutions still in use in the industry of today were presented.

Considering the various aspects of Industry 4.0 and IIoT, middleware solutions are the best options to guarantee interoperability and connectivity. However, some of these solutions are mostly used in a more general scope of IoT, rather than in industrial applications, such as DDS, AMQP and CoAP.

oneM2M's objective is to be an interoperability hub, working in a slightly higher level than the other solutions presented. There are many research results relating the interworking capability of oneM2M with OPC UA, LwM2M and MQTT. Not many examples were found of its use as an M2M communication solution in the shop floor level. Meanwhile, LwM2M directs the use of CoAP for industrial applications. The Object and Resources Registry, and the attempt of standardizing semantics in an industrial environment are its strengths, but as it was focused on constrained devices as applications, LwM2M's information model is considered limited.

The two most compared solutions were MQTT and OPC UA, specially regarding data transfer. MQTT is faster than OPC UA on that regard, but its disadvantage is to be unstructured, while OPC UA natively implements services such as semantics, historical data, alarms, events, etc. Sparkplug is an attempt of structuring MQTT and making it more interoperable in a semantic level, but there were not found many results of this specification being researched or used in the industry. Therefore, OPC UA is presented as the most complete and applicable middleware solution for industrial communication systems.

Regarding future solutions for industrial communication systems, TSN is shown as the most promising underlying layer, while there are still many open questions and lack of implementations on 5G networks for industrial communication.

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