OPC-UA in interoperability – a performance comparative testing

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Abstract: Interoperability is considered one of the main obstacles to the fully adoption of Industry4.0. Reference Architectures, like RAMI4.0, considering normal operation and maintenance of industrial equipment, paved the way to break that interoperability barrier and OPC-UA, in this context, is the reference communication protocol. This paper explores findings when performing a performance comparative study between OPC-UA and MQTT in an industrial application. The results shows that a lighter protocol brings advantages to direct applications when the data needs to be delivered fast and without a specific focus on the data structure.

Keywords: *Cyber-Physical production systems, control architectures, interoperability, communication protocols, OPC-UA, Industrial internet of things.*

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1. INTRODUCTION

Although Industry 4.0 (I4.0) was announced several years ago, in 2011 and officially incorporated in the strategic plan of the German Government in 2013 (KAGERMANN et al., 2012), the adoption of Industry 4.0 technologies is slower than expected, mainly in small and medium enterprises. After important methodologies regarding some analysis techniques of industrial controllers (Machado et al., 2011) (Campos et al., 2008) the most recent evolutions are related with achieving and implementing one of the key challenges in research is achieving interoperability (both vertically and horizontally) of Cyber-Physical Systems (CPS) within Internet of Things (IoT) domain. Considering recent advances in science and technology, the primary focus of investigation lies in exploring the interoperability and distributed control of networked CPS in industrial manufacturing environments.

It is of utmost importance to examine the key benefits and constraints associated with using Open Platform Communications – Unified Architecture (OPC-UA) as a possible answer to the mentioned issues. Moreover, it is vital to explore solutions that are comparable in order to facilitate the digital transformation of procedures and machinery in future intelligent factories.

This paper will focus on examining the adoption of OPC-UA for achieving horizontal integration of Cyber- Physical Production System (CPPS) as suggested by the Reference Architectural Model Industrie 4.0 (RAMI4.0) architecture. The comparative base is the widespread lightweight MQTT communication protocol. After introducing the background and works related with Interoperability, Reference Architectures and OPC-UA in Chapter 2, the experimental methodology, namely configurations and system measurements, is presented in Chapter 3. The experimental results and its discussion are referred in Chapter 4 and 5, followed by the main conclusions of the developed work.

2. BACKGROUND AND RELATED WORK

2.1 Cyber-Physical Systems in Industry 4.0

CPS are complex, interconnected systems that integrate physical and digital components to operate in a coordinated and optimized manner. The National Science Foundation defines CPS as engineered systems that are built from, and depend upon, the seamless integration of computation and physical components. In a CPS, it is combined the computing, storage and communication properties of the cyberspace in order to monitor and control the physical features (Javaid et al., 2023). The cyber component is viewed not as an add-on but as an integrated part of the system. In I4.0 concept, CPS goes from smart machines to entire production facilities that can communicate and control itself (Hermann et al., 2015). These systems are becoming increasingly prevalent in various domains such as transportation, manufacturing, energy, and healthcare. A typical system architecture of CPS is presented in Figure 1.

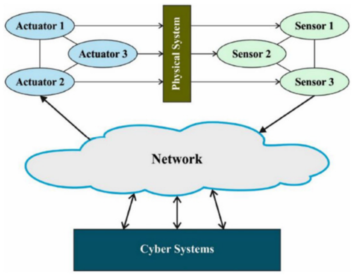

Figure 1 - Possible illustration of a CPS (Mansour, n.d.)

2.2 Interoperability

CPS integration is extremely dependent of interoperability between different hardware and software. Interoperability can be described, by ISO16100 ("Industrial automation systems and integration — Manufacturing software capability profiling for interoperability — Part 1: Framework," 2009) as "the ability to share and exchange information using a common syntax and semantics to meet an application specific functional relationship across a common interface". In control engineering, it is possible to describe interoperability in two ways: as vertical and horizontal integration. Vertical integration refers to the interoperability between different equipment or between shop-floor departments, and horizontal refers to the interoperability between machines, equipment or systems and the cloud (Zeid et al., 2019). As consequence of evolution from Industry 3.0 (I3.0) to I4.0, the number of connection devices and its ability to communicate is completely increased and the necessity of guaranteeing systems' interoperability is a central issue, as illustrated in Figure 2.

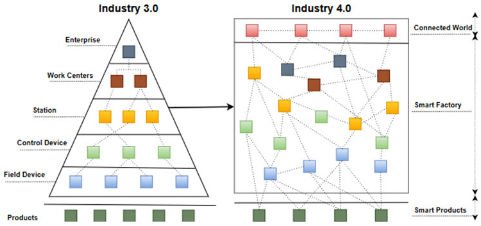

Figure 2 – Industry 3.0 vs Industry 4.0 (Mirani et al., 2022)

Hazra et al (Hazra et al., 2021) define two key properties for dealing with interoperability issues:

- Extreme heterogeneity – the devices are connected using networking, middleware, application-based protocols with different types of data. The abundance of technologies complicates the understanding between devices during the transmission and processing of data.
- Dynamic and spontaneous communication - there is no connection between IIoT devices until runtime.

Each organization has started to develop/create infrastructures, proprietary protocols, standards, Application Programming Interfaces (API) and data formats (Hazra et al., 2021).

Mirani et al (Mirani et al., 2022) define Interoperability, via literature analysis, as one of the six key requirements for implementation of IIoT. In addition, the smart connection level is considered by Wu et al. (Wu et al., 2020) as one possible research direction for future works, since the diversity of systems and communication technologies increases the complexity and makes it more difficult to integrate CPS. They suggest that standardization and semantic interoperability is important, mainly above the plant level.

As a result, several architectures emerge as a potential fix, or at least a guide, to overcome the interoperability issue. Having a robust architecture allows better integration, even more so in an environment of constant conceptual and technological development (Pivoto et al., 2021).

2.3 Reference Architectures

A reference architecture (RA) serves as a comprehensive and foundational understanding of various scenarios, aiding in the identification of problems and challenges. The primary objective of designing an RA, such as a service-oriented architecture (SOA), is to emphasize modularity, scalability, adaptability, and interoperability among diverse devices connected in a real-time environment. In the past few decades, numerous RA have been developed to establish an interoperable IoT/IIoT ecosystem (Hazra et al., 2021).

RAMI4.0 ("Reference Architecture Model Industrie 4.0 (RAMI4.0)," 2016) and IIRA (Industry IoT Consortium, 2022) are considered the most important and mentioned architectures for interoperability issues management when implementing I4.0 concept. For this paper, the focus is RAMI4.0.

RAMI4.0 is proposed as a reference model for the alignment of several standards that can be used in I4.0 (Nazarenko et al., 2021). It is an Architecture Reference Model in Industry 4.0 developed by several industry partners based on Germany (Platform Industrie 4.0). The main goal was to define communication structures and a common language for industry in all its different areas of expertise. It takes its form as a three-dimensional representation with three axes: Hierarchy Levels, Product Life-cycles value stream and Architecture Layers (Figure 3). ("Reference Architecture Model Industrie 4.0 (RAMI4.0)," 2016)

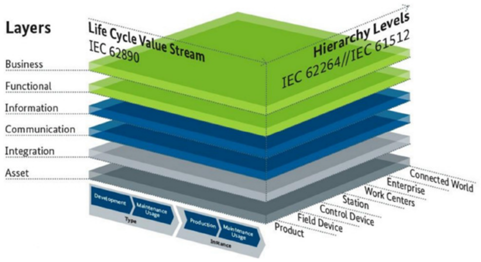

Figure 3 – RAMI4.0 representation ("Reference Architecture Model Industrie 4.0 (RAMI4.0)," 2016)

Axis 1, hierarchy levels, describes the relation between all the elements within and that are related with a factory – vertical integration. It serves as the base of the idea that I4.0 does not follow the traditional hierarchy of I3.0 but every system, every machine is connected and the interaction and communication between them is the core of I4.0 (Figure 2).

Axis 2, life cycle value stream, describes all the steps that an asset may take in an industrial environment from the "first idea to the scrapyard" (Melzer, n.d.). It allows a standardised approach to describe and track Industry 4.0 components.

Finally, the third axis, the architecture layers, addresses interoperability as it proposes a set of interoperability layers. These layers are used to provide a clear view of the abilities of a component – that can be a physical machine, a software or other.

The communication layer outlines the compliant access to information and functionalities of a networked asset within the context of I4.0. It employs a standardized communication protocol and a uniform data format to ensure seamless communication. This layer facilitates communication along various dimensions, including the entire life cycle of an asset (from development to production to service) and across different functional hierarchical levels, spanning from individual products to the interconnected world. To achieve modularity and granularity, the communication layer is subdivided into distinct blocks within the RAMI 4.0 cube model, Figure 4, allowing for independent descriptions of each block. The services descriptions and data model are specified in the information layer.

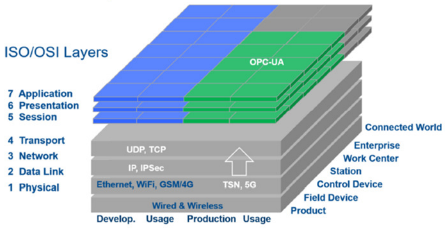

Figure 4 – RAMI4.0 Communication layer mapped to the OSI model (Joshi et al., 2022)

It gives preference to a TCP/UDP/IP communication (wired and wireless). Features likes Time Sensitive Networking (TSN) and 5G can be introduced in the future. Within the ISO/OSI layers 5-7, I4.0 prioritizes the production/service area (usage) and extends its focus on the product up to the work center, specifically for OPC-UA (highlighted as the green area in Figure 4).

An important previous distinction to make is the difference between CLIENT/SERVER and publish/subscribe (PUB/SUB) architecture. In a client/server architecture, the communication is structured around a central server that manages resources and services, responding to requests from clients. This model is characterized by a point-to-point communication pattern, where clients request information or services from the server.

In the other hand, a PUB/SUB architecture, publishers disseminate messages without explicit knowledge of subscribers, who express interest in specific topics or events. For the purpose of this paper, only broker-based pub/sub architectures are mentioned. In this case, a broker is a server that receives all messages from the clients and then routes the messages to the appropriate destination clients

2.4 Open Platform Communications – Unified Architecture

OPC-UA is a communication protocol responsible for exchanging data among industrial control systems and the enterprise level. It is an open standardized software based in the Client/Server, and more recently Publish/Subscribe (PUB/SUB), architectures (Figure 5). It is an evolution of the original OPC, named Object Linking and Embedding (OLE) for process control. It is formalized as an IEC international standard - IEC 62541.

OPC-UA provides an integral information model that serves as the fundamental model for the required infrastructure to integrate information. It allows vendors and organizations to structure their complex data within an OPC-UA namespace, benefiting from the robust SOA provided by OPC-UA (Zezulka et al., 2018).

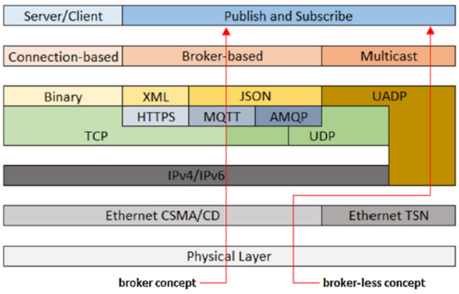

Figure 5 - Broker and broker-less concepts for OPC-UA (Pivoto et al., 2021)

An important distinction is made between the Address Space Model, the Information Model and the Address Space. The Address Space Model defines the building blocks for creating Information Models, which are essential for constructing the Address Space of an OPC-UA server. Ultimately, the Information Model serves as the base for generating the specific data of a server.(Damm et al., 2009)

The OPC-UA specification itself consists of fourteen different specifications going from security model to the information model and the recent Pub/Sub specification and Time Sensitive Networking (TSN). Current efforts are focused on implementing a real-time protocol based on TSN (Denzler et al., 2022). The Publish-Subscribe extension adds the capability of many-to-many communication based on the Publish-Subscribe paradigm. In conjunction with upcoming TSN extensions for Ethernet, OPC-UA Publish-Subscribe aims to also cover deterministic time connectivity. TSN introduces a variety of real-time functions to the IEEE 802 Ethernet standard (Li et al., 2020).

2.5 Related Works

Several studies have been conducted on the performance comparison of communications protocols in IIoT. Bayılmıs et al. (Bayılmış et al., 2022) performed a literature review where they studied and compared 22 research papers in terms of performance metrics,

IoT technology, experimental evaluations and simulation environments. The main metrics evaluated can be divided into two categories: related to hardware and related to protocol execution.

Relating to the hardware:

- Bandwidth Usage;
- Latency;
- CPU Usage;
- Energy and Power Consumption;

Protocol Execution:

- Number Of Transmitted Messages;
- Data and Packets Loss;
- Payload;
- Round Trip Time;
- Security Issues;

Regarding OPC-UA, its CPU usage, RAM usage and network traffic was evaluated in (Ladegourdie and Kua, 2022) using two Raspberry Pi as hardware. They increased the number of nodes used in the OPC-UA and evaluated the impact on the Raspberry.

Cavalieri and Chiacchio (Cavalieri and Chiacchio, 2013) used the software OMNeT++ to evaluate OPC-UA security options, the transport protocol and Subscription and Monitored Items. The metrics used was round trip time, delay time and bandwidth utilization. Main conclusion were that in terms of security, using remote certification authorities to verify client and server certificates introduces huge delays and should be avoided. For the transport layer, the time needed to activate a session may be reduced if TCP is adopted instead of SOAP and the TCP protocol options allowed the best performances in terms of roundtrip times, mainly with small size of data exchanged. Finally, in the subscription mechanisms, the publish interval influence both delay time and bandwidth utilization.

Other relevant study was made by Profanter et al. (Profanter et al., 2019) were they compare OPC-UA with ROS, DDS, and MQTT. To achieve that, they performed measurements on an experimental setup to evaluate the round trip time when changing the system states: idle, high CPU load, and high network load. In the same reasoning, in (Silveira Rocha et al., 2018), the software Wireshark was used to measure the ratio between packet and payload length, and time stamps were gathered through the deployment software to measure the loopback time per telegram length, loopback time for different regions of the world and response time for multiple clients participating in publish/subscribe.

None of these works measures real world application with the most common hardware used in industry – the PLC. Therefore, to bridge the gap between these studies and industry practises, this paper explores the same type of performance evaluations but in an industrial environment.

3. EXPERIMENTAL METHODOLOGY

To evaluate the performance of an OPC-UA application, the team used a machine that possesses several sensors and actuators and needs to provide data from these devices to a PC-Based application. The communication protocol chosen to move that data was OPC-UA and, therefore, an excellent case study to evaluate its performance.

Since one of the most pointed disadvantages of OPC-UA is its heavy structure, the team decided to compare it with one of the most lightweight protocols – the MQTT. Since MQTT follows a PUB/SUB architecture, it will also allow the team to conclude about PUB/SUB versus CLIENT/SERVER architectures.

The focus was on measuring the time for the communication protocol to transmit the data (more detail in chapter 3.3). This decision comes from the team's perspective that, in the context of industrial applications, the impact of this setup in hardware performance is neglected in comparison to its processing capabilities.

3.1 System Configuration

The machine uses a PLC (Omron NX1P2) to control its sensor and actuators and it is connected to an IoT device (Ewon Flexy 205), via Ethernet I/P, that sends the data to a PC-Based interface (built in Windows Forms C# application) via OPC-UA. The next figure (Figure 6) presents a diagram of the above-mentioned configuration.

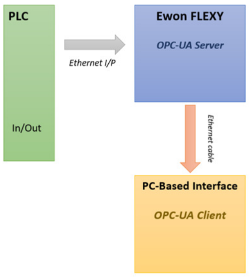

Figure 6 - System configuration with OPC-UA

For the MQTT connection it will follow the below represented configuration (Figure 7).

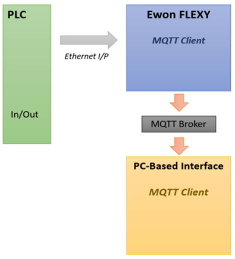

Figure 7 - System configuration with MQTT

3.2 OPC-UA & MQTT configuration

There is a variety of possibilities regarding OPC-UA configurations for this type of applications, but the main questions are the choice of the transport layer, the security policies and the CLIENT/SERVER vs PUB/SUB architecture. Through the years, and has supported with related works like the ones presented in the previous chapter (see 2.5), the transport layer that was better suited for most applications is the UA TCP in opposition of the HTTPS for example. Because of hardware restrictions, the chosen architecture was the CLIENT/SERVER over the PUB/SUB. Since this application will run on a private network, the team choose the no sign&encryption option.

Following the same logic for MQTT, the team choose port 1883 for nonencrypted communication and a QoS 0 (“at most once”) wherein the sender does not anticipate acknowledgment or assurance of message delivery. In this mode, recipients do not confirm the receipt of the message and senders neither store nor retransmit it. Often referred to as "fire and forget," QoS 0 operates similarly to the underlying TCP protocol, allowing messages to be sent without subsequent follow-up or confirmation.

3.3 System measurement

To measure this OPC-UA application, it was introduced a new client to the system with the tool UaExpert client[1]. This tool was a plugin that allowed the team to measure the performance of OPC-UA service calls to a UA server. In this case, a read call is performed for a defined number of nodes in a defined number of cycles, where the time between the server and the client response is measured.

For the MQTT, the team used a Python script[2] that outputs the time between a MQTT client message sent and another client receive.

Both of this metrics gives us the time that the PC-Based Interface can retrieve data from the PLC, via EWON Flexy.

4. RESULTS

For OPC-UA application, the team measure the time for a read call of two nodes. The team recorded 30 samples and the full dataset results are presented in Figure 8.

Figure 8 - OPC-UA time per read call

Table 1 presents the summary for the OPC-UA performance test.

Table 1 - Results summary

Maximum Time (*ms*)	Minimum time (*ms*)	Average Time (*ms*)
4.22	2.61	3.65

For the MQTT performance test, the time between a client publish message and a client subscribed to a topic was measured and the full dataset is presented in the figure below (Figure 9).

Figure 9 – MQTT time per message publish and read

Table 2 presents the summary for the MQTT performance test.

Table 2 - Results summary

Maximum Time (*ms*)	Minimum time (*ms*)	Average Time (*ms*)
4.77	2.55	3.14

5. DISCUSSION

As presented in the tables above the difference between the average times for a single message is 0.5 ms. The fact that MQTT performance test gives lowest values when comparing to OPC-UA is in compliance with most of the literature. The difference in the measurements can be assigned to the lightweight of the MQTT protocol over the UA-TCP and its server/client architecture.

Despite this distinction, the absolute value of the 0.5 ms cannot serve as grounds for discarding or favouring one communication protocol over another. This delay may be neglected for certain applications, especially those present solely on a monitoring or interface layer. In the case of direct control of actuators, for instance, this 0.5 ms delay can be considered as a barrier for the adoption of a specific protocol.

It is important to mention that a study with industrial hardware, which lacks open-source accessibility, introduces a barrier to fully understand the implementation of the chosen protocols and, therefore, be dependent of the proprietary development. However, this limitation is precisely what makes the study pertinent, mirroring real-world scenarios in industrial applications.

For industrial professionals, these results highlights the benefits of using a lightweight protocol as MQTT for direct applications, such as retrieving data from sensors and actuators. What is not explored on this paper but needs to be taken into account is that MQTT does not provide an integrated data structure like OPC-UA, which, depending on the application, may be crucial.

6. CONCLUSIONS and Future Work

The appearance of a large range of protocols is the way to solve the interoperability issue. OPC-UA emerges as one of the most suitable communication protocols for most Industry4.0 applications, as is proven by the favoritism in RAMI4.0. However, as most of the technologies in industrial scenarios, the application particularities will define what is the best protocol to implement. This paper tried to understand, in a real-world application, how OPC-UA compares with a more lightweight protocol like MQTT. As supported by most literature, OPC-UA as some performance disadvantages when applying this type of direct comparisons, but it is somewhat unfair as OPC-UA gives developers important tools, such as its Information Model, which plays such a crucial role when developing applications for Iy4.0 that deals with large and diverse amounts of data. For future work, the team will expand the study to other OPC-UA configurations, focusing on adding the sign&encrypt option and using the OPC-UA PUB/SUB specification. This extended study will allow the team to conclude on the benefits in obstacles on using the OPC-UA communication protocol.

7. Aknowledgements

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