# Digital Twins in Industrial IoT: a survey of the state of the art and of relevant standards

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***Abstract*—Industry 4.0 revolution is in full swing and the adoption process is happening in many industries. However, companies have reservations about the transition process, especially ones with older but still functional machines. The key measure for machine Industry 4.0 readiness is their ability to communicate with other machines. This paper presents the design guidelines in the creation of digital twins in Industrial Internet of Things (I-IOT). The relevant scientific works and the most popular I-IOT digital protocols in the industry are collected and presented. Considering this information and data, the list of design guidelines are extracted and presented in the corresponding section.**

## I. Introduction

The term Industry 4.0 was introduced in 2011 by a group of representatives from different fields under an initiative to enhance the German competitiveness in the manufacturing industry [1]. Industry 4.0 is powered by nine technological pillars: Big Data and Analytics, Autonomous robots, Simulation, Horizontal and Vertical system integration, Industrial Internet of Things (I-IOT), Cybersecurity, Cloud, Additive manufacturing and Augmented reality [2]. There are also four design principles: Information Transparency, Decentralized Decisions, Technical Assistance and Interconnection [3]. Information Transparency enables availability of data provided by the interconnectivity of various devices, people and technologies. Decentralized Decisions ensures that Cyber-physical systems can take autonomous decisions when needed, and Technical Assistance means that information collected by various systems can be used for assisting humans in making more efficient and informed decisions. Interconnection is particularly important as it allows various devices, sensors, systems and people to share information. Regarding this principle, we observe how industrial networking is divided into two different domains that have different purposes and standards: **OT** and **IT** [4]. OT (Operations Technology) is traditionally considered as the control network of the machine. It needs to adhere to certain standards and rules for that domain such as reliability and security. OT feeds the IT (Information Technology) part with information that is processed to produce useful inference[5]. Industry 4.0 goals can be achieved by converging IT and OT. However, OT, in addition to receiving all the benefits of the IT, receives also its vulnerabilities [6].

Digital twin is the enabling element of the Industry 4.0 principles, and it is the contact point between OT and IT. A digital twin is a virtual representation of a physical industrial entity [7]: it resides in the IT world but is fed with data collected from the machine through the OT network. This means that to create a digital twin we need a *talking* machine. The concept of digital twins can be broadly applied to many technologies and is thus likely to disrupt industries beyond manufacturing. It is therefore critical to expand its definition. By enabling the seamless transmission of data between the physical and virtual world, digital twins will facilitate the means to monitor, understand, and optimise the functions of all physical entities, living as well as nonliving.

By building the digital twin of a machine, it is possible to get information that will enable various advanced 4.0 services like production analytics and predictive maintenance; but to create it, a sufficient amount of relevant data needs to be collected. To this purpose, the entity that is being duplicated (in this case an industrial machine), must have the means of sharing said data. The digital twin of such a machine can be created easily if it has digital interfaces that can be used to gather such data. As Wei et al. [8] concludes, the machines can be mainly divided into two different types: connection-ready and non-connectable, here called respectively *talking* and *mute*. Machines that may even be connected to the OT network, although via closed or protocols than can not be interfaced with the modern IT standards and technologies can also be considered *mute*.

Even though a machine is nominally connection-ready, there could still be difficulties to access its data because the used protocols can be proprietary and dedicated, and the interconnectivity principle of Industry 4.0 does not apply. Therefore the data can not be accessed without the knowledge of the dedicated protocol. For the purposes of this paper, machines like these are considered as *mute*. Unfortunately, dealing with mute machines is not a remote possibility. The world is currently full of *mute* machines. These machines are typically less than ten years old thus they still work perfectly and they will never be replaced because of their lack of connectivity. According to the 2019 Microsoft Report on I-IOT [9], one of the major limitations in the scale-up of 4.0 proof of concepts is the difficulty of calculating the return of investment. This means that the investment required for connecting *mute* machines to the IT is difficult to evaluate and can be probably considered one of the major bottlenecks in the application of the 4.0 paradigm.

In this paper, we discuss the problem of the creation of digital twins by revising the main communication standards in Industry 4.0 and a selection of recent scientific works on digital twins. We conclude the survey by highlighting design guidelines concerning digital twins extracted from the literature.

## II. Review of scientific works

In this section, we review the current state of the art in the creation of digital twins and the scientific works that are dealing with the topic.

The digital twin concept contains three main parts: physical product in real space, virtual product in virtual space, and the connections of data and information that ties the virtual and real products together [10]. Therefore, the creation of a digital twin requires data. One of the key enabling technologies of the digital twins is I-IOT because it allows for the collection of the necessary data [11] as well as the abundance, resolution, real-time and safety of that data [12]. Tao and Zhang [13] believed that data is the core driver of digital twin technology, and they expanded on the Grieves' concept [10] by adding the twin data and services to it. Another example of the importance of the data gathering quality to the digital twins is given by Barbie et al. [14]. They state that, due to limitations of low bandwidth in their application, it is not possible to achieve synchronization between the physical and digital twin. Another limitation presented in their work is the emulation of the complex actuators. Because of inadequate emulation, it is necessary to test the actual physical model before implementation. This ensures that safety is one-hundred-per cent guaranteed, which is paramount to the process. Durao et al. [15] in 2018. concluded that the most prominent requirements for digital twin creation are real-time data, integration, and fidelity. They have also shown that industry requirements are close to literature.

Industrial Internet Consortium (IIC) examined the technical aspects of digital twins and defined interoperability, security, deployment, connectivity, and information synchronization as the important ones, where interoperability is defined as the ability of systems to mutually exchange and use the information [16]. In this work, the authors point to key decisions to be made regarding the interoperability of digital twins, while Tao Fei et al. [13] consider interoperability as a key requirement in reaching smart interconnection in smart manufacturing. Platenius-Mohr et al. [17] state that I-IOT systems, which are often provided by different organizations, need to interact with each other to fulfil the requirements of the systems, so the devices and systems need to be interoperable. Therefore, they made a set of requirements to make digital twins of I-IOT devices interoperable. This would help various use cases that require an exchange of information between organizations. Many authors state that openness and flexibility provide a good basis and enable the rapid development of the digital twin.

Kamath et al. [18] promote the use of the open-source software solutions in digital twin creation and utilisation stating that using so promotes collaboration and learning. They also conclude that openness allows for the public inspection, utilisation, and expansion as well as unlocking lower software development costs, reduced time to market, abundant support, and the ability to scale and consolidate. Barbie et al. [14] noticed the benefits of easy prototyping in Reference Architectural Model Industry 4.0 [19]. This is enabled by having a modular embedded system that can be easily upgraded and scaled. In their work, they have used in their work Robot Operating System (ROS) as an example. The fact that ROS is organised in loosely coupled modules and that it is open-source results in a framework that is steadily improved and, even more important, thoroughly tested. Digital twins have been primarily used in engineering and the manufacturing industry. However, in recent years they have been used in healthcare, smart cities, retail, and automotive industry [20], [21].

Da Silva et al.[22] present work that is characterized by heterogeneous edge nodes which provide data to a 3D application. The data is collected and initial processing is performed at the edge. The data is then forwarded to the fog using the ROS publisher-subscriber system. In the fog, more sophisticated processing is performed, with the main idea of the whole concept to divide the workload between the edge and the fog node. In IoTwin project [23], edge computing is cited as one of the cornerstones for the creation of distributed digital twin infrastructures that can be adopted by small and medium enterprises. Edge computing especially makes it possible to close the loop between accurate models and optimal decisions by enabling very responsive on-line local management of operational parameters in the targeted plants and filtered/fused reporting to the cloud side of only significant monitoring data.

Cybersecurity is cited in many works as the area that needs to be specifically monitored as a potential risk. Laak et al. [24] state that the underlying problems of the digital twin creation are authentication of each device and user, safety, and security and data ownership issues. These issues can be particularly dangerous in healthcare digital twins, but the importance of security should not be overlooked in the other areas of digital twin application. Moreover, Mazzei et al. [11] tell us that security, trust, and tampering will become major problems in the fourth and fifth industrial revolutions, and it is not trivial to solve them. Wanasinghe et al. [25] looked at implementing the digital twin in the oil and gas industry and have noted that the lack of standardization and cybersecurity are the key challenges for digital twin deployment. Manglani et al. [26] especially point to the various types of security threats and the possible dangers that ignoring cybersecurity can cause. Many surveys have been conducted with the emphasis on the IOT and I-IOT security [27], [28]

## III. Review of standard digital protocols

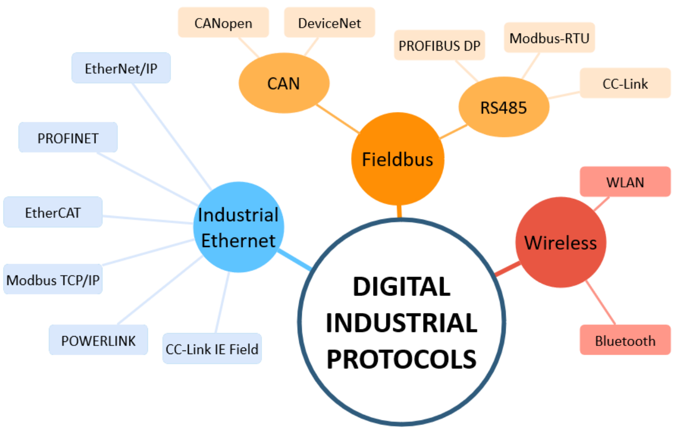


Fig. 1: Industrial Protocol Ontology

Having in mind that we have classified industrial machines as *talking* and *mute* the most important characteristic for those machines is their ability to communicate. In order to measure that ability of the machine and make a set of requirements regarding their connectivity, it is important to get a grasp on the state-of-the-art in industrial communication protocols. The properties that are seen as the most important is the popularity of the protocol in the industrial sphere and openness of the protocol, which is paramount for determining the connectivity of the machine. According to Carlsson [29] the most used digital communication protocols in the industry are industrial Ethernet protocols with a 64% market share in 2020, followed by fieldbus protocols with wireless protocols coming up last. When the results from the previous years are taken into account the steady growth of Ethernet can be perceived with the corresponding decline of fieldbus share while wireless remained at 6 percent.

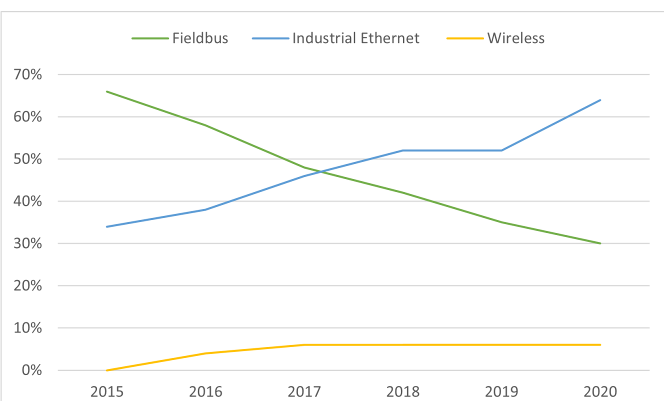


Fig. 2: Industrial Network Market Shares

Looking specifically at the industrial Ethernet family of protocols, two protocols stand out with the share of 17%: EtherNet/IP and PROFINET. As we can see in Figure 3 there has been a significant rise in market share for these two protocols since 2015. Other protocols with significant market share are EtherCat, Modbus TCP/IP, and POWERLINK, which all have a share below 7%. Their share has stagnated in the previous five years. The other Industrial Ethernet protocols have a combined share of 12%.

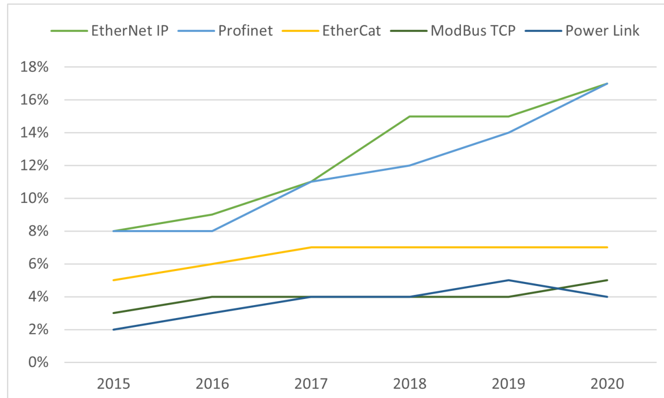


Fig. 3: Industrial Ethernet Protocol Market Shares

The rise of the industrial Ethernet protocols has come at the expense of the fieldbus protocols. In Figure 4 we can see the decline of the fieldbus protocol popularity over a period of five years. All fieldbus protocols have declined in popularity but PROFIBUS DP has seen the largest decline from 18 to 8%. The others from the list Modbus-RTU, CC-Link, CANopen, and DeviceNet have declined less but the decline is constant.

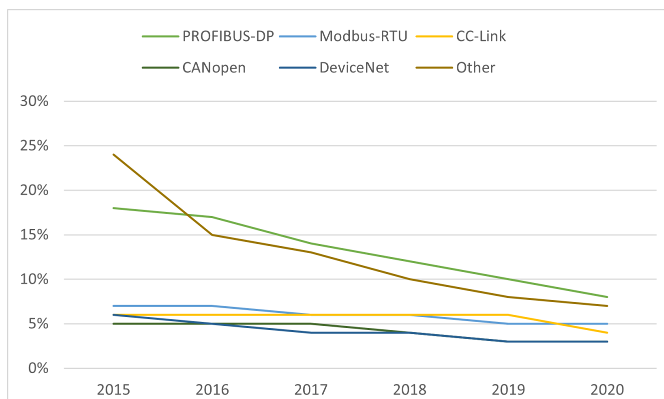


Fig. 4: Fieldbus Protocol Market Shares

Digital industrial network protocols can be classified by type as fieldbus, industrial Ethernet protocols and wireless protocols. Industrial protocols are real-time communication protocols designed to connect sensors and actuators with control devices.

### A. Fieldbus

The oldest type is of industrial digital protocol is fieldbus which has been in use since the 1980s. The most common fieldbus protocols used in industry today are:

- *PROFIBUS DP* is a fieldbus-based automation standard, a master-slave protocol that supports multiple master nodes. PROFIBUS uses tokens to enable the master to communicate with its slaves, this allows for multiple masters. The original PROFIBUS has several variants, where PROFIBUS DP is the most commonly used. PROFIBUS DP supports several different physical layer deployments with RS-485 as the most common. PROFIBUS DP is the most common fieldbus protocol in the industry with the 8 percent share[29].
- *Modbus-RTU*, a variant of the original Modbus protocol that was created in 1979 by Modicon (now Schneider Electric). It is an application layer protocol that uses various physical layer communication standards such as RS-485, RS-232, fiber optics, and Ethernet. It is an open master/slave protocol where master initiates all communication, and it is the most common fieldbus variant with a market share of 5%.
- *CC-Link* is an open RS-485-based field network developed by Mitsubishi Electrical Corporation. CC-Link is the high-speed field network able to simultaneously handle both control and information data [30]. CC-Link is the third most popular fieldbus protocol with a 4% share in 2020.[29].
- *CANopen* is an open fieldbus protocol based on the Controller Area Network (CAN) data link layer. CANopen has been developed as a standardized embedded network with highly flexible configuration capabilities [31]. The CANopen protocol stack handles the communication via the CAN network. It is represented with the 3% share in the Carlsson report [29] as of 2020.
- *DeviceNet* uses CAN hardware to define an application layer protocol that structures the task of configuring, accessing, and controlling industrial automation devices. Similar to CANopen, it uses CAN physical layer. DeviceNet uses a Communications and Information Protocol (CIP) for transferring automation data between two devices. It has a market share of 3%.

### B. Industrial Ethernet

Industrial Ethernet is a type of communication protocol type that is becoming widely adopted. It uses the Ethernet network in an industrial setting with the added real-time capabilities and determinism. The use of industrial Ethernet over the fieldbus protocols can be explained by the superior speed and scalability of these networks. Traditionally, Ethernet had a limited acceptance in industrial automation. This was attributed to several factors: the lack of sophisticated switches and routers, high cost of implementation, and the domination of large vendors with proprietary protocols. In the last few years, all of these technological difficulties have been solved and the rise of industrial Ethernet protocols followed. The most popular industrial Ethernet protocols are:

- *EtherNet/IP*, an open protocol that adapts the CIP to standard Ethernet. It is managed by ODVA Inc., a global trade and standards development organization. Ethernet/IP operates at the session, presentation, and application levels of OSI model. It uses all the transport and control protocols used in traditional Ethernet including the Transport Control Protocol (TCP) and the Internet Protocol (IP)[32]. Having in mind that DeviceNet also implements CIP, EtherNet/IP can be considered the Ethernet "brother" of DeviceNet. This is, along with PROFINET, the most popular digital protocol with 17% global market share [29].
- *PROFINET* is very similar to PROFIBUS on Ethernet. It is an open standard maintained by the same organization as PROFIBUS, PROFIBUS & PROFINET International. PROFINET IO exchanges data at a much higher rate over Ethernet compared to PROFIBUS. PROFINET IO uses three different communication channels to exchange data with programmable controllers and other devices. The standard TCP/IP channel is used for parameterization, configuration, and acyclic read/write operations. The real-time channel is used for standard cyclic data transfer and alarms. Real-time communications bypass the standard TCP/IP interface to expedite the data exchange with programmable controllers. The third channel, isochronous real-time is the very high-speed channel used for motion control applications.
- *EtherCAT* is an open real-time industrial Ethernet technology originally developed by Beckhoff Automation [33]. This protocol, which is disclosed in the IEC standard IEC61158, is suitable for hard and soft real-time requirements in automation technology. The main focus of EtherCAT is on short cycle times, low jitter for accurate synchronization, and low hardware costs. The principle of EtherCAT is that the master node sends a telegram that passes through each node. Each EtherCAT slave device reads the data addressed to it "on the fly", and inserts its data in the frame as the frame is moving downstream. The EtherCAT has a 7% share of the industrial Ethernet protocol market in 2020.
- *Modbus TCP/IP* is a variant of the MODBUS family of simple, vendor-neutral communication protocols intended for supervision and control of automation equipment. The Modbus commands and user data are themselves encapsulated into the data container of a TCP/IP telegram without being modified in any way. However, the Modbus error checking field (checksum) is not used, as the standard Ethernet TCP/IP link layer checksum methods are instead used to guarantee data integrity. Modbus TCP/IP is an open protocol.
- *POWERLINK* is a completely software-based solution that is fully compliant with the IEEE 802.3 Ethernet standard. Such close conformity with the standard and the absence of proprietary hardware allows POWERLINK to ensure that all of the benefits and flexibility of Ethernet technology have carried over to this real-time protocol as well. To achieve its real-time capabilities, POWERLINK relies on a mixed polling and time-slot procedure that

allows only one node at a time to transmit data.

- *CC-Link IE Field* is a 1-Gigabit Ethernet-based integrated network. It is an Ethernet variation of the CC-Link fieldbus protocol, similarly to PROFINET and MODBUS TCP/IP. It is supported and promoted by the CC-Link Partner Association (CLPA). CC-Link IE Field reserves dedicated bandwidth for both cyclic and transient communication. This realizes stable high speed of up to 1Gbps and deterministic communication [30].

### C. Wireless

Wireless industrial protocols have seen limited use in the previous years, remaining at 6% market share. However, there are definite advantages over wired protocols and in some applications wireless protocols provide the most optimal solution. The main advantages of wireless protocols over wired ones are better scalability and mobility, followed by lower costs and a more straight-forward installation process. Furthermore, security and reliability, paired with lesser range and speed, are the main drawbacks of using wireless protocols. Most popular wireless protocols are:

- *WLAN* or Wireless Local Area Network is based on WiFi technology and IEEE 802.11 standard. IEEE 802.11 defines the physical layer (PHY) and MAC (Media Access Control) layers based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). There are several differences to the non-industrial WLAN mostly regarding reliability. This is predominately manifested in the reduced roaming times when the device is being moved from one Access Point to the other. Furthermore, WLAN is the most commonly used wireless industrial protocol, with 4% share of the market.
- *Bluetooth* is a wireless network based n the IEEE 801.15.1 standard. Bluetooth technology is a robust, easy-to-use wireless solution for industrial wireless applications. Operating in the same 2.4 GHz ISM band as other standard wireless technologies, Bluetooth offers optimal features to satisfy industrial requirements of robustness, reliability, and seamless coexistence and co-located operation with Wireless LAN networks. In addition to low power consumption, Bluetooth allows for multiple wireless links, offers fast connections, and has easier configuration and setup than many other wireless technologies.

Regarding wireless protocols, it is important to note that 5G technology is emerging as an important factor in the digital protocol market. The target performance features of 5G like high reliability, low latency and power requirement satisfy the shortcomings of the previous 4G technology [34].

There is one interesting ontology of the digital industrial protocols. Most of the protocols differentiate in the application layer of the OSI model, but some of the protocols can share the physical layer. This is best manifested in the industrial Ethernet protocols where all of them have the same physical layer, the one corresponding to IEEE 802.3 Ethernet standard. If we take a look at fieldbus protocols, we can see that there are two physical layers that are shared, RS-485 and CAN. And finally, the wireless protocols all have their own physical layer.

## IV. Design Guidelines

In order to create a digital twin, certain guidelines need to be followed. As has been shown in the Section II, availability of data is one of the most important prerequisites of the digital twin creation. Therefore, if we were to formulate this into the guideline that would be **G1: Data Gathering**. The authors feel this is the most important guideline, having in mind that it is one of the three basic principles [10] and the means of connecting the virtual and physical product. Moreover, the fact that the data is being collected in real-time is the key attribute of the data gathering process.

The data gathered for the creation of the digital twin needs to be transferred and shared between the physical and virtual product. To be able to complete this task both twins need to be able to speak to each other, therefore **G2: Connectivity (Interoperability)** is the next guideline to be respected to ensure digital twin creation. In the Section III we presented the most widely used protocols in today's market. Industrial Ethernet is the most used protocol at the moment, and this speaks volumes about the "data hunger" of digital twins. Wireless protocols with the emerging 5G can satisfy that need and we predict that, for this reason, they will be used more in the future.

As the physical systems evolve, following the development and advancement of the industry, their digital twins must evolve with it. Therefore, another important aspect of the digital twin is its ease of development and maintenance. We can formulate this into guideline **G3: Scalability**. Many works emphasize the need for fast development of the digital twin. Some of them advise using open source solutions that have good support and are thoroughly tested and maintained. The prevalence of trusted solutions allows developers to focus on creating the best digital twin for their needs.

It is a fact that I-IOT edge devices are having more and more computational power. The authors feel that this power can be used in digital twin creation and have formulated it as **G4: Edge Node Balancing**. Moreover, I-IOT edge devices are capable of processing some of the data without burdening the cloud. Processing the data on the edge will also reduce the latency thus improving the real-time property of the system. This will also have the added benefit of reducing the bandwidth needed in edge-cloud communication.

During the digital twin design process, **G5: Security** is often one of the last considered steps, even though it should be looked into at an earlier stage. But it is fast becoming indispensable, not only in the digital twin creation, but in all aspects of the industry. With the rise of I-IOT, many authors offered their opinion on its security aspects. In the current state of the industrial IoT the number of possible system vulnerabilities are too many to count.

## V. Conclusion

The need for advancing and embracing the Industry 4.0 paradigms has been recognized in the industry. However, as we have previously shown, there are still difficulties in digitalizing older machines, especially if they are *mute*. According to the analysis of the state-of-the-art and market trends a set of guidelines has been presented in the appropriate section and we have the solution in sight. The solution needs to promote the industry 4.0 advancement and assure the industrial customers that updating and augmenting the machines does not have to be an arduous endeavour. By providing an adaptable, scalable, and interoperable system capable of real-time operations we ensure the seamless transition into the Industry 4.0 and all the benefits it can bring to industries that are a step behind.

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