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An Overview of Time-Sensitive Communications for the Factory Floor

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Abstract: The state of the art for real-time factory-floor communications consists of a variety of protocols and technologies that aid in timely data exchange through the network. The majority of these are of a fieldbus type, running on a wired link like Ethernet. The choice of medium widely reflects the desire for high reliability. This attribute, reliability, is an indispensable condition for any industrial communications. Many industrial communication technologies exist, of which the most prominent are: PROFINET, EtherNet/IP, Sercos III, EtherCAT, and OPC UA. Time Sensitive Networking (TSN) is a relative newcomer in this arena, known for the strict synchronisation it maintains between communicating entities, among other things. This work presents and distinguishes between these various technologies, showing how they compare to one another, and also looking into how they may possibly co-exist. The assessment can be used by African industries as they take the first steps in defining the factory-floor of the future, enabled by the Fourth Industrial Revolution.

Keywords: 802.1AS, critical traffic, Ethernet, factory-floor, fieldbus, Fourth Industrial Revolution, 4IR, Industrial Internet of Things, IIoT, network, plant, reliability, scheduling, synchronisation, Time Sensitive Networking, TSN.

1. Introduction

The Internet of Things (IoT) is a cornerstone technology propelling the next generation of communication networks. It is fast gaining momentum and becoming a critical component of our everyday lives, experiencing an almost exponential growth as its market size is expected to double by 2021, reaching US $520B [1]. In a world where more and more smart devices are produced that are able to connect and interact with each other, the industrial sector is one notable use-case seeking to take advantage of these capabilities – Industrial IoT.

The emergence of IoT in industry is just one of many possible use-cases of the Internet of Things, however it is also one of the fastest-growing verticals. Columbus [2] in his market forecast showed that figures reported by IoT analytics see the market for the Industry 4.0 products and services growing from $119B in 2020 to $310B in 2023; here Industry 4.0 (also Industrie 4.0) is the subspace of the 4th Industrial Revolution that pertains to industries. African markets are not immune to this disruption and will variably be affected. It is a matter of how prepared they are to embrace the technology, including what aspects to consider in its adoption.

The devices participating in an IoT communication need some level of coordination in the way events are scheduled to occur. For example, as regards factory floor automation, a vehicle manufacturing plant which is in process of assembling cars and having one of the parts put in at the wrong time would create chaos in the production line, whose effect is likely to get multiplied if prolonged. Thus, reliable time synchronisation is of utmost concern in the controlled setting of the factory floor.

Traditionally, the landscape of factory floor automation has been monopolised by field-bus protocols and technologies. There are in excess of 30 industrial Ethernet technologies [3], but circa five stand above the others for their longevity and extended support in succouring machine communications at the plant. More recently, TSN (Time Sensitive Networking) has been included in this list.

Given the changes to the technology over the years it would be useful for factory managers and prospective industrialists to know what conventional methods have been successfully implemented, as well as what to look out for in future. This paper gives an overview of such technologies as well as the reasoning or factors behind their successful integration in industry.

This paper is thus organised as follows: Section 2 discusses briefly some factors contributing to the adoption of these technologies; Section 3 provides a snapshot of the state of the art in industry taken from a sample of the key technologies, detailing their features and differential characteristics; Section 4 presents a summary of the findings of the overview and a short discussion on what to consider when deciding which to adopt; Section 5 ends this paper with a conclusion on the methods discussed.

2. Advent of Ethernet Field Bus Technology

Machines constantly need to send signals back and forth in the plant. The components on the factory floor have had to evolve because it became apparent that TCP/UDP/IP could not be employed over the controllers at the time to garner a deterministic, real-time response from the sensors and actuators [4]. As posited by Hibbard [4], the industry realised that they could deliver such a response required by machine control applications through new real-time protocols designed to use standard and inexpensive hardware solutions, that is, the CAT5 Ethernet cables and a network interface card (NIC). Further, many proprietary Ethernet fieldbus protocols emerged as a result of this requirement for determinism on the plant floor. They were designed to be able to utilise such common hardware that would let the controllers generate a real-time response as they connect with the sensor and actuator components. These protocols are many in number for the mere fact that it is possible to reuse Ethernet in a myriad of approaches to the same effect. The protocols were developed with the following driving factors in mind:

1. **Low-latency solutions** to deliver on the real-time response requirement of deterministic industrial applications. This delay ranges from under 1 ms to 10 ms for equipment control [5].
2. **Lowered cost for equipment**: the fact that these protocols are based on common hardware lowers the overall cost for the equipment that they are built on. From [4], this design could save the company half the cost or even more compared to older configurations.
3. **Increased performance in machinery** to give a higher efficiency, for example, through monitoring and real-time adjustments.

Reliability is an attribute that is *sine qua non* when it comes to industrial IoT (IIoT) communications [6] – it is an indispensable condition for any mission-critical scenario and it manifests itself in short predictable latency times and unhindered activity on the plant level. That is why it is valued over other attributes in such networks, even over pure latency. Industrial communications strive for predictability because when a network is predictable it is reliable. And predictability is directly proportional to the efficiency of the network [7].

Ultimately the importance of reliability is often understated; it is an inferred rudimentary requirement of a time-sensitive communication, especially for industrial automation, where high reliability is not only desired, but required [5].

Other non-technical factors matter too in the adoption of these technologies, such as the degree to which a protocol conforms to standards, the protocol's interoperability, and the nature of its openness/interoperability.

3. Review of the Technologies

As mentioned, there are quite a few standards and protocols built over Ethernet that are presently available for automation on the factory floor. This section starts a review of the current chief fieldbus and other technologies that guarantee deterministic delays in communication, and how they compare to each other. Something noteworthy is that some major technologies including those under review are all built on open standards. Many other technologies are not open, since, either the aspects of their implementation require use of proprietary devices from the vendor, or their source code is not available.

3.1 – PROFINET

Process Field Network, or PROFINET, is a "100% Switched Ethernet" [8] protocol that complies with IEEE 802.3 and which seeks to address factory automation. It is an open standard that was developed and is maintained by the PROFINET International group [8]. PROFINET can be scaled to meet different functional requirements by the combination of Conformance Classes, which build upon one another in increasing layers to extend each other's functionality, as seen in Figure 1 below redrawn from the source in [8, Fig. 1]. In line with these classes, PROFINET comes in three versions: Versions 1, 2 and 3.

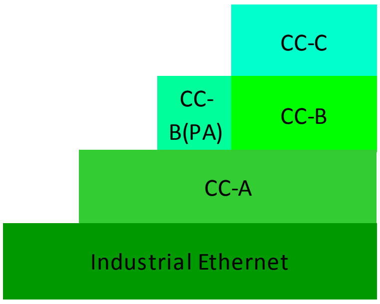

Figure 1: Conformance Classes of PROFINET

Version 1 is based on Conformance Class A (CC-A) and, according to [9], it provides component-based automation. It is not time-sensitive because, according to Rostan [9], it is built on best-effort messaging principles. On the other hand, versions 2 and 3 are the main approaches since they are more time-aware. Version 2, based on CC-B, engulfs a "soft" real-time (RT) approach [9] and is thus known as PROFINET RT. (A hard real-time system is very restrictive and so has higher performance metrics and shorter delays. If an operation misses just one deadline, this corresponds to a system failure. In contrast, a soft real-time system has a higher tolerance, and it can miss more than one deadline. Although, if this happens too often it will degrade the overall performance of the system.) It allows the transmission of high-priority Ethernet frames through channels that have VLAN (virtual local area network) prioritisation schemes in place [3]. According to AMMC (Applied Machine & Motion Control) Golden Motion analytics, with PROFINET RT, systems can hope to experience cycle times (response time) of 1-10 milliseconds, hence it is best suited for those I/O (input/output) applications that require precise digital or analogue I/O control [3]. In comparison, version 3, based on CC-C, is an isochronous real-time (IRT) approach [9]. It employs hardware-synchronised switches to cater for applications that work on even shorter cycle times: below one millisecond according to [3]; examples include motion control applications. Another important feature of this PROFINET IRT, as documented by Hibbard [4], is in its ability to reserve bandwidth. This bandwidth can be used to transmit critical data frames immediately and reliably as needed [3].

PROFINET RT and IRT are collectively called PROFINET I/O [9].

3.2 – EtherNet/IP

The IP in the name stands for Industrial Protocol. EtherNet/IP is an industrial network solution for providing manufacturing and process automation by employing the Common Industrial Protocol (CIP) [10]. CIP is so named because it provides both a common data organisation and a common messaging for control systems in industry [11]. It utilises both connection-oriented and connectionless protocols, that is, TCP/IP and UDP/IP respectively, to transfer data; and this it does through various communication mechanisms: event triggers, multicast, and point-to-point connections to name a few [3]. In fact, the main distinguishing feature of EtherNet/IP lies in how it encapsulates its data in the transport layer. In [3], it is able to distinguish between two kinds of messaging: implicit (data only) and explicit (requests and denies); the implicit I/O messages, it sends using UDP, while the explicit messages are sent by TCP/IP. Under the technologies compared in this section it is the only real-time technology based completely on Ethernet standards [4].

In as far as machine-to-machine communications is concerned: the CIP Motion architecture discussed in [12] allows for a peer-to-peer connection to be set up through which a producing controller can propagate high-speed motion data to consuming controllers or devices via a single multicast connection [12]. The use cases documented by Zuponcic [12] saw the producing controller sharing axis information to coordinate the other devices such as motors. These devices receive a common reference, and, in this way, CIP Motion allows for synchronising and coordinating the speed at which devices operate. It could be used for robotics control in the factory floor among other things.

Rinaldi in [13] highlights the advantages of EtherNet/IP over other technologies like PROFINET, the chief of these being: it uses all the transport and control protocols of traditional Ethernet such as TCP and IP, and media access and signalling technologies from common off-the-shelf Ethernet interface cards; a range of devices with widely varying features can be accessed using one common mechanism; and lastly, it requires no special hardware because it is simply an application layer protocol sitting on standard Ethernet and TCP/IP. Its main disadvantage is its limited bandwidth and speed [4], [13].

3.3 – Sercos III

As a technology that follows the master-slave structure, Sercos III provides deterministic communication by allowing for devices to be very precisely synchronised: according to [14], up to 100 devices can have a Time Error of 1 microsecond. Sercos III is the third generation of the Sercos Interface, according to the founding company. It is a portmanteau for Serial Realtime Communication System. The technology supports both cyclic and acyclic communication, that is, deterministic or scheduled, and best-effort communication. Nsaibi et al. [14] explained that the master node will send "cyclically real-time data" to its slave I/O components by incorporating summation frames. A summation frame will contain the data of several devices in it in a sort of accumulating or "summing" effect. The summation frame principle can only be used, however, when the network node topology is a daisy chain (a single ring) or closed ring [3]. Once the frame size is at its maximum then any new information is appended to another frame [14].

Different sources have classified frames according to different criteria, although examining them reveals that they fit into one another. In [9] there are two classifications of data frames: a frame for input data and another for output data. According to Szancer et al.

[15], the master node issues two frames, classified as: Master Data Telegrams (MDT) and Acknowledge Telegrams (AT). A configuration of these telegrams in the Sercos communication cycle is shown in Figure 2 [16].

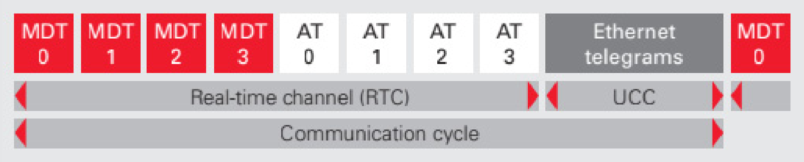

Figure 2: Configuration of the Sercos Communication Cycle [16]

Details on these telegram types in [15] reveal that MDTs help the master relay information to its slaves and are thus filled by the master and read by the slaves; whereas, ATs are a way for the slaves to provide responses back to the master and to communicate with other slaves, and so they are filled up by the slaves. The Sercos organisation [16] maintains that each slave will populate its assigned device channel in the AT before passing it on to the next slave device. And, in line with the summation frame principle, if the AT reaches its maximum size then another AT will be used for the next device. The same goes for MDTs. So, in this way, the MDTs being issued out to slaves can be regarded as input, and the ATs that are fed back to the master from the slaves as output, which supports the classification by Rostan [9]. Another key feature of Sercos as documented by Hibbard [4] is that each real-time telegram is processed twice per cycle: a telegram as it passes through a slave node will be processed once as it leaves that node, and once as it returns on its way back. This characteristic allows for devices to execute communication amongst each other in a single cycle without having to route their data back to the master [4].

3.4 – EtherCAT

Ethernet for Control Automation Technology (EtherCAT) is another master-slave arrangement that caters for hard and soft real-time computing. It shares all but a few of the features of Sercos III. As in Sercos, frames are still "processed on the fly" by slaves [9], that is, they are processed without stopping. But in this case, with the use of special slave controllers that can be implemented in different options: as FPGAs, ASICs, or as microcontrollers [9]. From Wang et al. [17], the master node is connected to its slaves in a logical ring topology over standard Ethernet cable. It is as well a summation frames network, so each frame will be processed from node to node in sequence until it reaches the end slave, after which it turns back.

The mode of operation of EtherCAT allows for cycle times to be drastically reduced, according to Hibbard's analysis in [4], leaving EtherCAT able to deliver the most deterministic response among all industrial real-time Ethernet systems dealt with in this review thus far. For a telegram of length 122 µs and at 44% bus load, results in [9] showed that EtherCAT had a cycle time of 276 µs. In comparison with the cycle times of other technologies, they revealed the following performances: Sercos III peaked out at 479 µs; PROFINET IRT at 763 µs; PROFINET RT at 6355 µs; and another popular protocol Powerlink V2 at 2347 µs. In all this, EtherCAT still had 56% of its bandwidth to spare. It also has other advantages such as permitting incredibly precise synchronisation (<< 1 µs).

As mentioned, it processes frames on the fly like Sercos III, also using the summation frame principle, which are both major reasons for their comparable fast speeds. It however utilises ASICs and FPGAs, and herein lies its chief disadvantage: the slave elements need to incorporate a specific hardware ASIC to implement EtherCAT [13], that is, extra hardware is needed for its implementation. Rinaldi [13] also noted how its data model is quite complex in nature.

3.5 – OPC UA

Open Platform Communications Unified Architecture (OPC UA) is a protocol maintained by the OPC Foundation. It is not exactly a protocol or technology on the same level as the others, but it can be used to work hand in hand with them, more specifically with TSN. As its name suggests it is vendor-independent, unlike its predecessor, simply OPC, whose communication model used a Microsoft Windows proprietary technology: COM/DCOM. In fact, this is the reason for its very inception; to address the need to unify industrial communication systems. It will allow data exchange and interoperability through these systems from sensor and actuator levels to central servers and clouds [18].

It transports data in two ways: firstly, through the client-server model, and secondly, through its own OPC UA PubSub (short for publish-subscribe). The client-server mechanism follows a request / response pattern to access information from the server, whereas the PubSub model is guided by a Publish / Subscribe pattern, where the server informs the clients rather than a client needing to pull data from the server. PubSub enables a many-to-many connection between the servers that publish information, and the receivers that subscribe to those that interest them. Should any changes happen to the publisher's data, the receivers that subscribed to it are automatically informed [19]. It is this PubSub that is developed and used alongside TSN to provide real-time communications, to address the limitations of OPC UA with critical real-time processes [18].

The OPC Foundation is carving out a path to becoming "the industrial interoperability standard", as is stated in its logo. Over the years, it has signed numerous Memoranda of Understanding with many organisations and companies that produce and/or promote the use of industrial communication technologies and protocols, such as those mentioned in this review. These signed agreements pertain to the following matters: to intensify cooperation on Industrie 4.0; to ensure interoperability for IoT; to provide common interfaces for Industrie 4.0 and Internet of Things; and other issues as regards real-time data and open IT traffic with OPC UA [20]. Drahoš et al. [18] have shared that the initial results of these agreements was the distribution of the communication space in the following manner: these successful industrial Ethernet (IE) protocols hold the communication space at the field level, while the OPC UA protocol unifies vertical and horizontal higher production levels. With OPC UA, all these other communication technologies can be consolidated over a unified connection.

Although it is stated that OPC UA agreements left other IE protocols with a kind of dominion over the communication space in the factory floor, more recently, the Foundation has sought to extend OPC UA's standards and specifications, including TSN down to this field level. With the help of its new task force and various working groups, it hopes to provide vendor-agnostic end-to-end interoperability down to field level devices for all relevant industrial automation use-cases [22].

Because OPC UA is more than just a communication system (it is a standard for data exchange and semantic interoperability) [18], the writers believe that, employed together, OPC UA PubSub and TSN are two standards that will set the bar in the near future for leading industrial communications.

3.6 – TSN

IEEE 802.1 Time Sensitive Networking has been adopted to introduce the determinism that is deemed necessary in applications with stringent timing requirements, doing so over a standard Ethernet connection. According to Brooks and Uludag [23], TSN is meant to assure the end-to-end network latency despite how heavy the workload is at the time, even for the most challenging motion control and safety applications. As a collection of Ethernet standards developed and maintained by the TSN Task Group in [24], it seeks to provide deterministic messaging for time-sensitive applications. It does this mainly through the use of the following key standards:

1. **802.1AS** [25] – As the predecessor to **P802.1AS-Rev** [26], It handles **timing and synchronisation** between TSN devices existing in networks that consist of full-duplex IEEE 802.3 (Ethernet) and 802.11 LANs (Wi-Fi) [27]. In order to have a deterministic communication, TSN devices need to have a shared concept of time [7]. 802.1AS allows for this.
2. **802.1Qbv** [28] – At the heart of TSN communication is the **scheduling** of traffic in queues in order to provide the sought-after deterministic messaging. This scheduling operation is governed by the "time-aware shaper" (TAS) principle [29] that is standardised as 802.1Qbv [28]. With the introduction of these queues, messages will only be allowed to transmit during their scheduled time windows [29].
3. **802.1Qbu** [30] – TAS guarantees the upper limit of latency in a network, ensuring that critical messages will always be immune to interruption in their transmission, but it sets no minimal latency for the network. This is where **802.1Qbu** [30] comes in with its **frame pre-emption** mechanism. Essentially, for optimum network utilisation there needs to be accounting for the delivery of critical messages that take precedence over non-critical messages, even though according to the schedule they currently do not have right of transmission. With 802.1Qbu in effect, a link with frames of lower-priority can be interrupted mid-way to transmit higher-priority frames, all without losing the original messages [23]. In fact, upon completion of the critical frames, the first message frame can continue its transmission from the exact point it left off [29].

There are other standards which promote the goal for reliability, such as **802.1CB** [31] – Frame Replication and Elimination for Reliability (FRER), and **802.1Qcc** [32] – Stream Reservation Protocol (SRP) Enhancements and Performance Improvements.

4. Overview of Performance

To compare the response times of these fieldbuses more visibly, the author replicates the table in [4, Fig. 1]:

Table 1: Real-time comparison of the various real-time methods [4, Fig. 1]

Organisation	Response Time (for 100 axles)	Jitter	Data Rate
EtherNet/IP, CIPSync ODVA	1 ms	<1 ms	100 Mbit/s
Ethernet Powerlink, EPSG	<1 ms	<1 ms	100 Mbit/s
Profinet-IRT, PNO	<1 ms	<1 ms	100 Mbit/s
SERCOS-III, IGS	<0.5 ms	<0.1 ms	100 Mbit/s
EtherCAT, ETG	0.1 ms	<0.1 ms	100 Mbit/s

The online Industrial Ethernet Book (IEB) table considers the case of an application and its real-time behaviour in a scenario where it is synchronously controlling 100 axles with these different protocols and technologies employed. It shows how they fared out. The two criteria whose performance measures are analysed are the response time (cycle time) and the jitter (or variation in response time).

It needs to be mentioned that end users are not ultimately concerned with the real time method with the highest performance output, but their choice is based rather on whether a method can support their application requirements [33]. So, a response time of a few milliseconds thought to be dire in certain applications might be quite tolerable for other scenarios such as the control of multi-axle drives in the case mentioned. As in the earlier discussed factors in Section 2, this delay ranges from under 1 ms to 10 ms for most robotic and industrial automation applications.

In doing a flat comparison across the existing commercial technologies discussed so far, EtherCAT is seen to be the most capable technology for factory automation. It quite capably records minimal latency across the performance measures.

The main drawback of using these standard technologies stems from the fact that they are not interoperable; they are proprietary solutions (that is why the IETF has a group dedicated to supporting deterministic networking, providing standards for the same, but over a single technology). They are not compatible with one another as is [34]. TSN can integrate with these open technologies and work alongside them. Furthermore, per [23], TSN is an IEEE communication standard that allows interoperability between standard-conformant industrial devices from any vendor. In fact, where TSN is concerned, vendors should conduct interoperability testing to ensure an open platform for data exchange within control systems.

5. Conclusion

From the protocols described thus far, it is fair to ascertain that the smart factory of the future will have determinism at the forefront of all its activities. Whichever the method or protocol picked it has to be able to provide this. These factories will be highly predictable and thus reliable since a predictable industry environment is a direct result of its deterministic network capabilities. As stated, predictability varies directly with efficiency. So high predictability is the key to increased throughput, which can only be realised through coordinating activities with precise synchronisation and highly accurate schedules.

This discussion helps to contextualise the present state of factory floor automation technologies as they relate to 4IR (the Fourth Industrial Revolution). Conclusively, although local industries are still a way from being deemed as smart factories, it is a good opportunity to consider what technologies are presently available and at their disposal. The work provides a baseline or reference point from whence they can begin to plan the way forward. In this regard, TSN is a most viable solution, and, used in conjunction with OPC UA, it assigns flexibility to the network, allowing for a common administration and smooth interoperation not just on the plant level, but seeping from end-to-end into higher levels of the production hierarchy as well. In future we hope to provide common mini use cases for the technologies we presented, to illustrate some examples for their use in an African context. Through these, we hope to paint a clearer picture on the application of these technologies that could further advise those seeking to or already adopting them similarly.

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