Industrial Ethernet: Challenges and Advantages

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***Abstract*—The IEEE 802.3 Ethernet standard was published in 1985 and quickly became the predominant standard of digital traffic in small, local networks all the way up to the internet itself. Paired with the TCP/UDP IP stack, it is responsible for nearly all internet traffic, including website-requests, file transfers and communication in general. Requirements for industrial applications are vastly different due to physical constraints and software necessities. The goal of this paper is to describe and categorize some variants of industrial ethernet protocols (IE), compare their efficiency, and evaluate their respective advantages and disadvantages. Due to its frame structure and protocol modalities, EtherCAT can reach lower response times than POWERLINK, Sercos III and PROFINET under normal circumstances.**

***Index Terms*—protocols, ethernet, process control, profinet, ethercat, sercos III, powerlink, industrial ethernet**

1. Introduction

Producing goods and tools is an inherently human trait. Utilizing steam power in factories was a key milestone in human evolution, often called industry 1.0. The second generation switched to electrical systems and machines, industry 3.0 saw the use of simple programmable controls and computers. We are currently implementing industry 4.0, combining information and production, physical and digital entities into a complex interconnected environment. Incorporating the IEEE 802.3 Ethernet in the majority of our information exchange was an important step of standardization, but the abilities it provides are not viable for use in industrial settings. The most important requests from manufacturers were “realtime guarantees, such as a maximum transfer time, a jitter [small fluctuation in the transmission time accuracy] not exceeding some threshold, or some guaranteed bandwidth” [1], conditions the aforementioned standard cannot provide. In turn, many companies had their own proprietary network solutions, not suited for interoperability and scalability [2]. This changed with the introduction of a number of industrial ethernet protocols, which will be discussed in section 5. They are based on the principles of a ‘master‘ node, which can be an ordinary computer providing data and telemetry for surveillance. This master is responsible for the actuation of several ‘slave‘ nodes, they are themselves control single machines, receive instructions from the master, execute them and possibly send information back to the master. The time needed to send data from the master to all connected slaves and receive their answers is called cycle time. Based on its protocol structure, EtherCAT can provide shorter cycle times than POWERLINK, Sercos III and PROFINET, which is shown in Section 6.

2. Physical Conditions in Industrial Environments

Native ethernet works best in well-controlled environments like offices or data centers. Industrial environments like factories or power plants have substantially different working conditions depending on manufacturing steps, used resources, possible chemicals and desired products, which affect networking if not sufficiently accounted for. Controller, machines, sensors and the cabling itself might be subjected to hazardous environments, high temperatures, dust particles, electromagnetic interference or vibrations [3], [4]. The induced loss of packets or wrong transmissions have to be solved in order to make ethernet viable in such conditions. Solutions are already available in the form of distinctive electronics and ethernet cables with IPX-rating for waterproofing, special isolation and Twisted Shielded Pair configurations against noise and interference, as well as industrial connectors between machine and cable.

3. Requirements of Industrial Ethernet

To implement an industrial ethernet protocol, it has to fulfill certain requirements dictated by the equipment on site. Cycle times should be as short as possible to improve reaction times of important components like motors, valves or robotic arms. Fluctuations in data transmission speed (jitter) should also be minimized to allow for more consistent cycle phases, which is very important for polling-style industrial ethernet like POWERLINK or PROFINET as they rely on time scheduling for sending their datagrams [5]. As connecting networks from a simple control level to the factory floor, enterprise level, and possibly all the way up to the internet is one of the goals of industrial ethernet, network security is of high concern to ensure a safe and reliable production environment.

4. Industrial Ethernet - State of the Art

A study on the usage of industrial ethernet done in 2022 revealed that PROFINET and Ethernet/IP are the most used protocols with both around 14%, and EtherCAT at around 11%. IE protocols as a whole are used by 66% of participants, field bus technologies like DeviceNet or

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PROFIBUS made up around 27% market share. Interestingly, 7% reported wireless networking as their main mode of networking [6].

5. Implementations

The following sections describe the functionality of four different industrial ethernet implementations, their frame/packet structure and network layouts.

5.1. Ethernet

Ethernet conforming to the IEEE 802.3 standard is the basis of commercial, office-related and international digital traffic. It allows for a uniform way of TCP/IP connections, file and mail transfer as well as some implementations of industrial ethernet, i.e., PROFINET, EtherCAT or Ethernet/IP.

The ethernet frame as shown in Figure 1 consists of a few fields [1]: starting with a 7 Byte preamble, followed by a 1B start of frame field. After that, the destination and source MACs are addressed with 6B, respectively. The Ether-Type is transmitted in a 2B field if its value is above or equal to 1536, or the total frame length if it is below or equal to 1500. The next one houses between 46B and 1500B of user-data, which can, for example, be an IP-, ICMP-, or an IE-packet. It is completed by the 4B long FCS field, which is used to verify the frames correct transmission.

5.2. PROFINET

Mainly defined by Siemens and supported by PROFIBUS International, the PROFINET protocol suite is a group of follow-up protocols to PROFIBUS [2], [5], [8]. There are currently four classes of PROFINET named CC-A through CC-D, providing different levels of network traffic. Class A is for cyclic and acyclic data transfer, class B builds upon class A and allows for reduced cycle times and real-time traffic. Following up, class C enables isochronous traffic while shortening cycle times even further, and the latest version (CC-D) released in 2019 incorporates time-sensitive-networking [4], [9].

PROFINET uses singular frames addressed to individual devices in the network, a procedure called individual frame (IF) [10]. Further developments make use of fast forwarding, dynamic frame packing and fragmentation of TCP/IP telegrams to increase throughput and decrease cycle times down to 31.25μs [5]. However, this cycle time is not achievable in real world applications, as transmission errors and switches introduce time delays. To mitigate time losses and decrease network jitter, special cut-through switches are needed, which unlike normal managed network switches do not operate in the store-and-forward mode [1], [8]. Also, both the master and slave devices need particular hardware in the form of ASICs to handle the fast processing of data [8].

The PROFINET telegram is made of a few key elements, such as a 2B Frame-ID, the payload itself and status control-fields, as seen in Figure 2a.

A typical PROFINET cycle has two distinct phases: first, cyclic real-time data is sent from the master to each slave device, awaiting the respective answer, followed by acyclic real-time data used for alarms and non-real-time data like TCP/IP. Should a slave miss its allocated time slot for sending data to the master, the information is simply discarded and the device can try to do so in the next cycle [5], [8]. PROFINET networks can have a number of topologies, e.g. line, ring or star [8], and can “Operate properly and keep temporal guarantees” in the presence of 802.3 compliant node [1]. According to a paper by Prytz [8] and [5], PROFINET can achieve a network jitter of 1μs and a minimum cycle time of 31.25μs.

This paper will focus on the PROFINET IRT (CC-C) variant in the evaluation section.

5.3. POWERLINK

Similar to PROFINET, POWERLINK uses individual frames and a cycle consisting of cyclic and acyclic phases, but with the added benefit of being completely software-based. The master/slave designation for network devices is given in the form of managing nodes (MN) and controlled nodes (CN) [11], [12].

A POWERLINK telegram contains fields for the message type, 8bit each for target and source node, plus a 61B to 1497B payload. Figure 2b shows additional space reserved at the beginning for the future.

Each cycle starts with the start of cycle (SoC) message sent via broadcast by the MN to ensure synchronization of all CNs. In contrast to PROFINET, the MN polls every CN individually by sending a poll request (PReq) packet and thus allowing the corresponding slave node to send a poll response (PRes) to all nodes. Again, PRes packets which are not received in a given timeframe are disregarded and the MN moves on to the next CN. To mark the end of this phase, a start of acyclic (SoA) message is broadcast and CNs are polled for non-real-time traffic. Finally, the cycle goes through an idle period and starts all over again. A paper by Cena et al. [13] simulated the cycle time to be 1.3ms, while B&R Industrial Automation GmbH [11] lists it around 100μs.

In principle, POWERLINK supports any topology like star, ring or daisy-chain for up to 240 devices per network [11].

5.4. EtherCAT

Contrary to PROFINET and POWERLINK, the EtherCAT master does not send an individual frame to each slave, instead a single frame with positional fields directed at each slave is sent per cycle. The frame passes through one node after the other and updates its content on the fly until the last slave is reached, which sends the frame back to the master using the full-duplex mode of ethernet [14]. This method is called Summation Frame (SF) and allows for a very basic implementation of the master node, which can be fully realized in software requiring only standard ethernet hardware [8], [10]. Slave nodes, however, need to be able to quickly process the datagram and possibly change their allocated space along with calculating a new FCS, therefore they rely on an EtherCAT slave controller with the necessary hardware capabilities. Up to 65535 devices can be connected to a single EtherCAT segment [14].

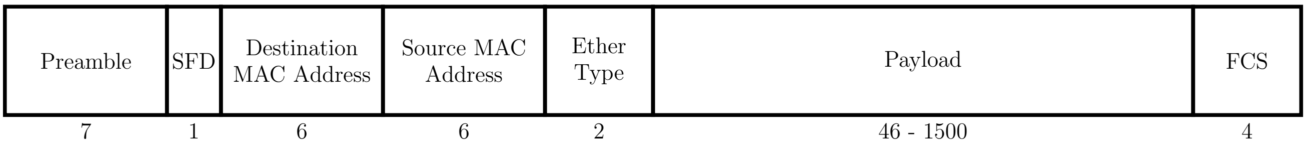
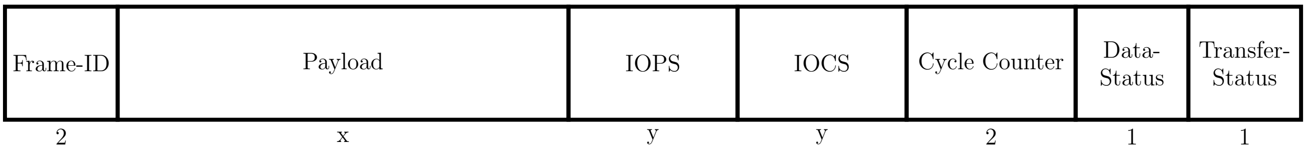
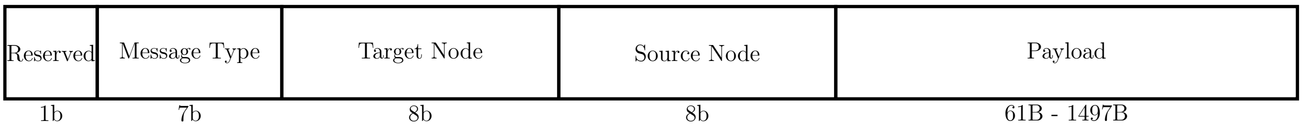


Figure 1: IEEE 802.3 Ethernet frame fields and their respective sizes in Byte [7]



(a) PROFINET, field sizes in Byte [10]



(b) POWERLINK, header fields in bit, data in Byte [11]

Figure 2: A PROFINET IRT frame, and a POWERLINK frame

The frame itself consists of a 2B EtherCAT header and a number of telegrams addressed to the slaves. Each telegram starts with a 10B telegram-header, followed by the actual payload and a 2B working counter as displayed in Figure 3. This counter is used for telemetry and diagnostics, but it can also be deactivated to increase packet space for user transmissions [10].

There is also the EtherCAT P variant to supply slave nodes with power and data using the same ethernet cable. Just like POWERLINK, many network topologies are feasible with EtherCAT [14]. At the Hannover Messe in 2012, the EtherCAT Technology Group demonstrated an EtherCAT network with a cycle time of 12.5μs, more than twice as fast as PROFINET [14].

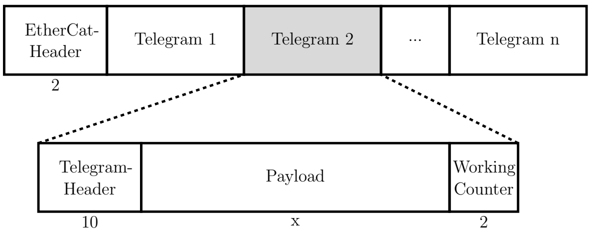


Figure 3: EtherCAT frame fields, sizes in Byte [10]

5.5. Sercos III

Sercos III is similar to EtherCAT in the way that it also uses a summation frame method, however the path on which frames are sent is not limited to a single direction. Rather, when a slave device is finished with modifying the frame of the current cycle, it can propagate the changes to multiple neighboring devices [1].

“Sercos supports direct cross communication, which enables real-time data exchange between any Sercos devices within one communication cycle” [15].

The real-time data field houses the main master to slave data transfer as well as any other possible device-device traffic, independent of the nodes’ role. Slave to slave communication has its own fields in the frame, named CC channel connection 1 to n as seen in Figure 4. Others are used for hot-plugging new devices, meaning connecting additional nodes without a network restart. Cycle times can be as low as 31.25μs, just like PROFINET [1], [15].

In a line configuration, the master sends its telegram sequentially to the daisy-chained slaves, and the last device loops it back allowing all devices to see changes made by all others. A ring topology ensures additional protection against downtime by redundant cabling, should errors occur [15]. With nodes using standard 802.3 Ethernet in the same network, temporal guaranties for telegram transmission are lost [1].

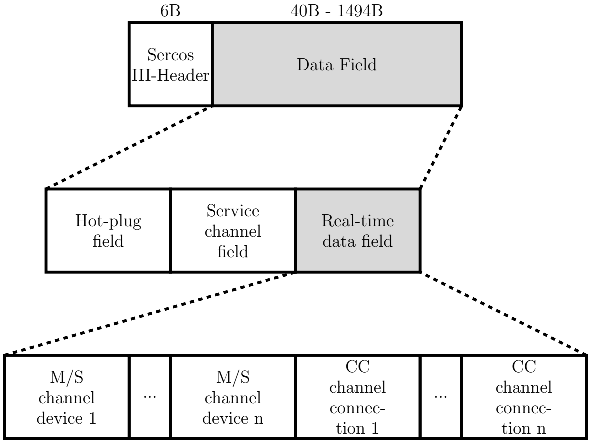


Figure 4: A Sercos III frame with its data fields [15]

6. Evaluation

As PROFINET IRT and EtherCAT are currently among the most prevalent IE protocols, most research papers are only comparing these two. Therefore, this section will rely on data from the respective developer

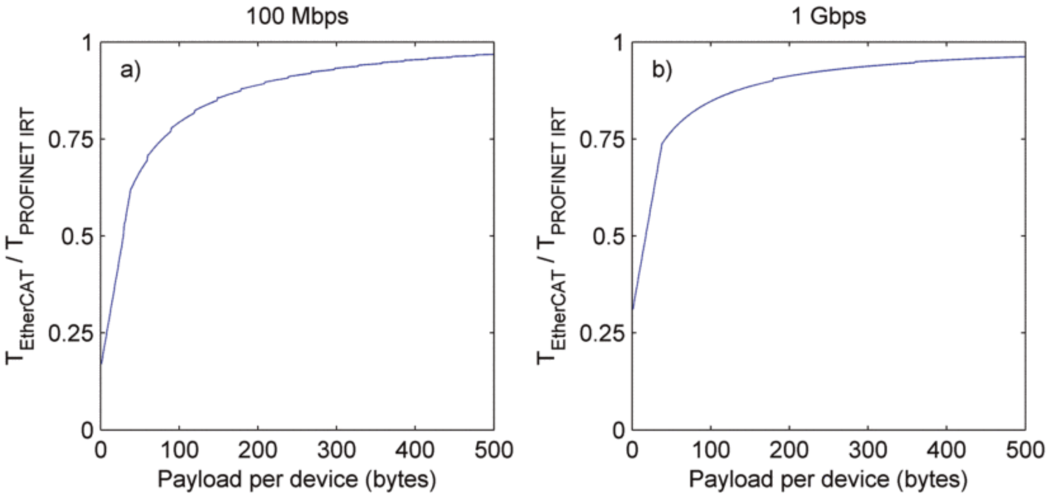


Figure 5: Relative performance of EtherCAT and PROFINET in a line topolgy network with 50 devices [8]

of POWERLINK and Sercos III, with the request not to consider the data as scientifically proven. The open-source POWERLINK manual "Communication Profile Specification" [11] names a lower bound of 100μs as its cycle time. Sercos III is specified to have a cycle time between 31.25μs and 1000μs, depending on the slave device number, the datagram size per slave, and whether the cross-device communication is enabled [15].

The following diagrams and data were produced in papers by Prytz [8] and by Wu and Xie [13]. Prytz presented a total of six experiment configurations with payload sizes of 16, 32 and 100B, combined with bandwidths of 100 MBps and 1 Gbps. The paper by Wu and Xie tested "an industrial NCS [networked control system] with 5 controlled plants [. . .] deployed with 5 sensors and 5 actuators connected onto the network backbone in a line topology" [13]. Their proceedings found that using a line topology, cycle times are shorter for EtherCAT for each payload size and both bandwidths [8]. The conclusion for relative performance of EtherCAT and PROFINET in a line topology is exemplary shown in Figure 5.

The authors have already justified their findings [8], [13]: EtherCAT being an SF protocol means a single frame containing all information is sent per cycle; PROFINET has to send an individual ethernet frame to every node, creating a lot of overhead and subsequently lowering performance. Especially in use cases with small payloads and a low number of slave devices, EtherCAT has substantially better performance than PROFINET, as that configuration is the most optimal for EtherCAT while simultaneously being suboptimal for PROFINET. When accounting for transmission errors, however, IF protocols could achieve a higher performance compared to SF protocols, depending on the error rate. As errors in the transmission only affect single devices, the impact of erroneous transmission is contained to a single cycle of a single device, instead of all connected slaves.

7. Conclusion

This paper briefly explained four different industrial ethernet protocols, compared their approaches to provide realtime control of various devices and evaluated the performance of EtherCAT and PROFINET in a number of situations.

Of course, developers of protocols want to present their implementations in the best possible way, but their performances are often more theoretical than actually achievable. Although cycle times as low as 31.25μs are impressive, in the case of Sercos III they were achieved in a network made of only seven devices, not using the slave-slave communication which made that protocol unique, with the optimal line topology and without the presence of any transmission errors [15]. In the author's opinion, these conditions are more akin to a lab environment than an industrial one with physical challenges, as described in section 2.

Currently, most devices can run successfully on only a few bytes of process information per cycle, in the future more data might have to be shared with individual nodes in ever larger networks, which would make SF protocols less viable. Advances in faster and more specialized hardware for IE protocols as well as more streamlined software will shape the future development of industrial applications. Although ethernet jumbo frames with up to 9000B of payload space exist, that might just be not enough one day. The need to provide both workplace safety for the personnel on the factory floor and digital security for appliances arises as connecting previously separated industrial networks to the corporate structure becomes more common; some protocols already incorporate such measures, and a proposal was made by Giehl and Plaga in their paper [16]. Industrial ethernet forms the backbone of today's production systems and will most certainly be used and improved upon in the future.

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