Industrial Ethernet networks:
Are they ready for Industry 4.0?

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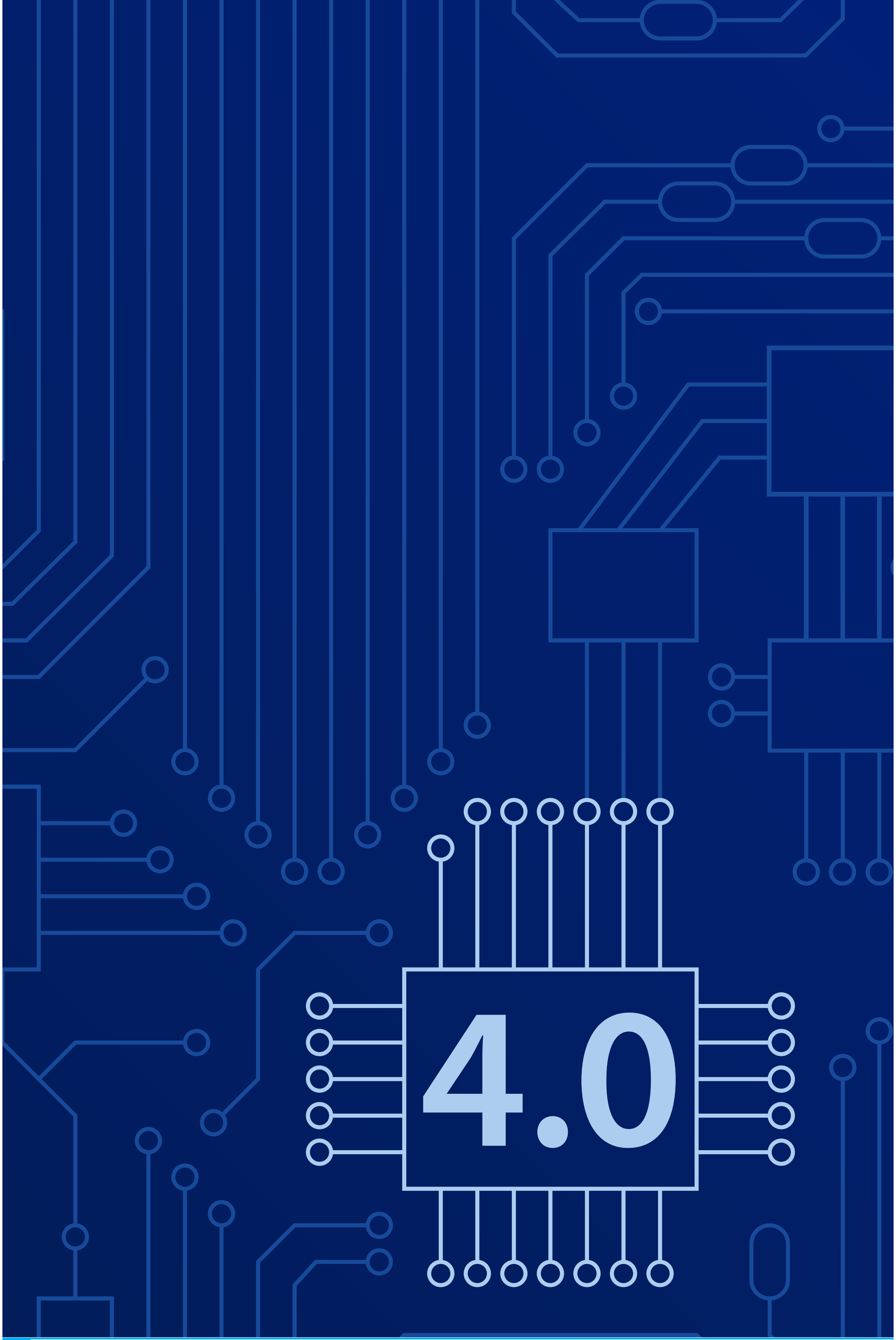
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Overview of the need for Ethernet networks with higher performances to embrace and enable Industry 4.0.

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Abstract

One of the overriding aspects of industrial networking that becomes clear when viewed over the last three decades - is the pace of change: the speed at which updates in technology now propagate throughout the marketplace are vastly quicker than before. Standards are also playing a part, sometimes following, sometimes leading change.

Hence, with industrial Ethernet having now overtaken traditional fieldbus technologies in terms of the number of new nodes being installed [1], and influences such as Industry 4.0 having a profound impact on development, how well is industrial Ethernet suited to the demands of industrial network communication going forward?

Aims

This paper aims to consider the technical aspects of industrial Ethernet technology, its variations and their suitability to the demands of current and future application scenarios.

Background

The impetus of change

The classic model for the spread of any given technology, i.e. Innovation / early adoption / proliferation / consolidation / standardization / replacement - is relevant, but here there are also sweeping changes being wrought by outside influences which are disrupting the usual sequence of events.

Industry 4.0 is a case in point, it is driving change from a conceptual standpoint, the resulting practical challenges such as cross platform integration, big data and now the burgeoning proliferation of artificial intelligence (AI) are all significant external forces affecting network technology development.

The proliferation of Ethernet in industrial control network applications has been very swift when compared to the adoption and consolidation of fieldbus, which is still in progress. There is no doubt that the open nature of Ethernet as a technology is also fueling already furious development schedules. Logic dictates that equally swift consolidation and standardization should then follow.

The speed of change means that as we embark on the journey to Industry 4.0, businesses need to carefully consider how to build their industrial communications infrastructure in order to remain competitive and thrive.

While Industrial Ethernet networks can provide a futureproof system, their performance can determine the success or failure of an enterprise.

What are the key features that make a network efficient

Solution

Industry 4.0 and the Industrial Internet of Things (IIoT) demand seamless interconnection from the smallest sensor up to enterprise-level systems and beyond. Thus, the future depicted by these concepts is going to be built on data, and lots of it. This unprecedented volume of data can provide an actionable insight into the manufacturing processes.

The automation networking landscape

In order to succeed, it is necessary to make the best use of all this data without the volume crippling the very communications systems being used to transmit it.

We may not know exactly what these future communications infrastructures will look like, but we can already see some clues in cloud computing. We will soon see the likes of virtual PLCs and virtual SCADA in the cloud, collecting data from and sending it to plant floor devices in real time.

Therefore, Industrial Ethernet networks are likely to remain a mainstay in industrial communications, helping to control industry, infrastructure and utilities by connecting different devices, machines, systems and users, regardless of where they are.

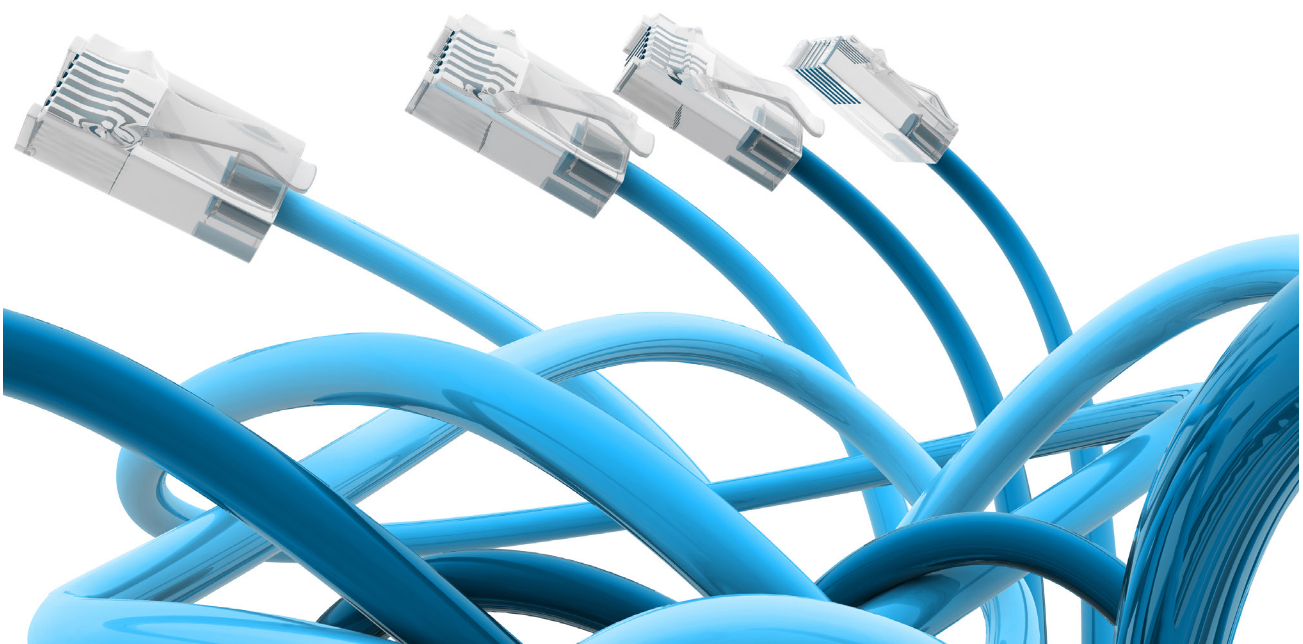
Not all Industrial Ethernet networks are equivalent, though.

The transfer of data can vary greatly among the various Ethernet solutions available. As a result, their performance influences their ability to handle current and future data sharing needs.

Whatever network and system performance we believe to be adequate for today's requirements, in the future we're going to need much more of it. In fact, if this is insufficient, businesses may fall behind, as they cannot successfully embrace Industry 4.0 or gain useful insight into their manufacturing processes.

What are the elements to consider when determining the performance of a given network? What are the capabilities of current Ethernet solutions?

This report discusses the properties that affect data transfer on industrial Ethernet networks. In addition, it looks at the design of CC-Link IE Field, how it compares with other solutions and how this technology addresses the requirements of Industry 4.0.



Chapter 1. How data is transmitted

In order to determine the performance of an industrial network, it is important to understand what types of data need to be shared and how the network transmits them.

Data types

Within an industrial network, the top priority is for controllers to share information correctly with other control systems, e.g. from PLCs or sensors to process controllers. The data being transmitted is used to regulate a specific control task, such as adjusting a summing point in a closed-loop control application. As a result, the message is time-dependent, needs to be exchanged periodically and is generally characterized by a data packet of constant size [2]. Therefore, this kind of information is known as cyclic data or process data.

As the transfer of cyclic data is time-critical, any delays or failures to deliver the message can interrupt the application as well as the entire production process. To avoid that, control networks must be deterministic and real-time, i.e. meet the time-dependent requirements of their intended applications by means of low, specific latencies. Nonetheless, the demand for cyclic transmission resources is known in advance, thus the control network can be set up accordingly [3].

In addition to communications between controllers, an industrial network may also be used to share additional messages between controllers and higher enterprise systems. In this case, the information is known as service, asynchronous or transient data, as its transfer occurs irregularly and through data packets of various sizes.

While network needs for transient data transmission cannot effectively be predicted, this kind of information is seldom time-critical and has low latency requirements. Consequently, transient data is currently transferred when the real-time, deterministic transmission of cyclic data is not affected.

Data transfer

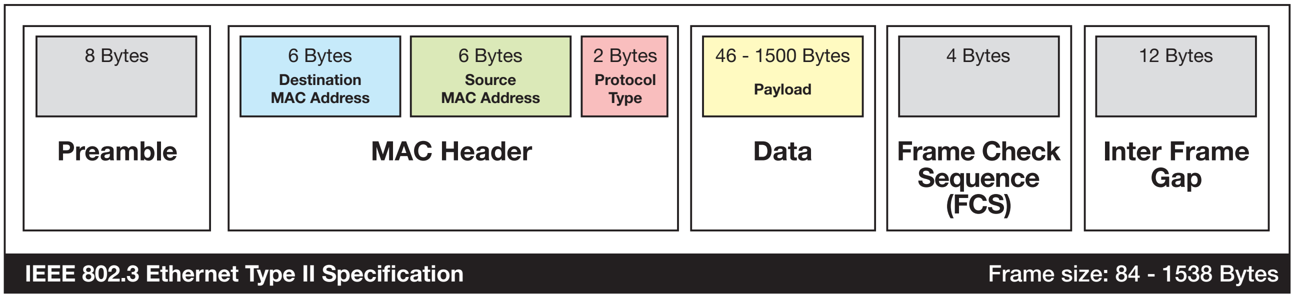
Both cyclic and transient data are shared across Ethernet networks in frames. These are containers of data responsible for the error-free transmission of information. To do so, the Ethernet frames need to contain several fields of information in addition to the actual data message, such as source and destination addresses.

As a result, all these pieces of information need to be stored in the frame in a highly structured and ordered manner. The governing standard defining the frame format for industrial Ethernet networks is the IEEE (Institute of Electrical and Electronics Engineers) 802.3 [4], based on Ethernet Type II specifications [5].

According to this, all frames must contain the actual information being transmitted, called Network Data, in the Payload portion. This can fit between 46 and 1,500 bytes of data. This interval was defined to reduce the error rate on any networks.

More precisely, the minimum payload size ensures the packet is long enough for the sender to detect a collision with other frames before it finishes sending a message. Similarly, the 1,500-byte threshold was selected to maintain an efficient data throughput on the earliest Ethernet systems. Furthermore, while bigger frames can use the payload more efficiently, in certain situations end users may want to use smaller frames in order to reduce the latency.

In addition to the Payload section, each frame includes an 8-byte Preamble, a 12-byte Inter-Frame Gap, a 6-byte Destination Media Access Control (MAC) Address, a 6-byte Source MAC Address, a 2-byte Protocol Type (or Length), and a 4-byte Frame Check Sequence (FCS), such as a Cyclic Redundancy Check (CRC). Therefore, the overall size of a frame can vary between 84 and 1,538 bytes.



Network performance

Based on the type and structure of data that needs to be shared within a factory, the performance of a network is determined by the speed and rate at which both cyclic and transient data can be transmitted, both in terms of frame- and byte- rate.

Therefore, the main parameters to evaluate include: a network’s bandwidth, cycle and response times, ability to transfer both cyclic and transient data quickly, as well as use of additional bytes within the Ethernet frames.

Chapter 2. Network performance: Bandwidth

The first indicator of network performance is the speed at which the frames (and the bytes) can be sent [6]. Therefore, it is important to determine the network's bandwidth.

Bandwidth, expressed as b/s or bps, is a measurement of capacity: it is the maximum amount of data that can be transmitted over a period of time across a given network. Therefore, the larger the bandwidth is, the faster data is transferred, i.e. the better the network performance. Furthermore, sufficient bandwidth ensures that operations can be completed in time, avoiding any delays that can result in downtime for all processing operations.

Networks featuring large bandwidths are also less affected by the volume of small or large frames, as the system can transfer time-critical data efficiently whilst keeping the latency low with either format.

Currently, there are three different types of bandwidth for industrial Ethernet networks. These were developed as Ethernet standards by different task forces from the IEEE 802.3 working group through the years. The standards produced aim to support the transmission of frames and address physical layer specifications. These three different Ethernet standards are schematized below:

Name	Bandwidth	IEEE Standard
Ethernet	10 Mb/s	802.3
Fast Ethernet	100 Mb/s	802.3u
Gigabit Ethernet	1 Gb/s (1000 Mb/s)	802.3z

At present, there is only one Ethernet technology for automation networks with 1 Gb/s bandwidth: CC-Link IE Field, whereas, the vast majority of Ethernet solutions exhibit only 100 Mb/s capabilities.

Even as the latest technologies, such as Open Platform Communications Unified Architecture (OPC UA) and Time-Sensitive Network (TSN), become increasingly popular, the bandwidth of a network will likely remain a mainstay in industrial communications.

These new solutions will enable the efficient transfer of cyclic traffic independently on the network's bandwidth, a factor that is extremely beneficial for applications characterized by low volumes of transient data. However, as factories become more interconnected and human-machine interactions continue to develop, the transient traffic will continuously increase to include material such as images and videos.

Therefore, while OPC UA, TSN and similar systems clearly have an important role to play, they are not replacements for existing networking protocols, but rather complementary technologies.

2.1 Bandwidth comparison between Ethernet networks

The following calculations show the difference in frame and data throughput between 10, 100 and 1000 Mb/s Ethernet standards.

With a **minimum** Payload size of 46 bytes and using Ethernet Type II frame format:

Gigabit Ethernet	
Maximum throughput	1,488,095 frames/s
Maximum data transmission	68,452,370 Network Data bytes/s

100Mbit Ethernet	
Maximum throughput	148,809 frames/s
Maximum data transmission	6,845,214 Network Data bytes/s

10Mbit Ethernet	
Maximum throughput	14,880 frames/s
Maximum data transmission	684,480 Network Data bytes/s

With a **maximum** Payload size of 1500 bytes and using Ethernet Type II frame format:

Gigabit Ethernet	
Maximum throughput	81,274 frames/s
Maximum data transmission	121,911,000 Network Data bytes/s

100Mbit Ethernet	
Maximum throughput	8,127 frames/s
Maximum data transmission	12,190,500 Network Data bytes/s

10Mbit Ethernet	
Maximum throughput	812 frames/s
Maximum data transmission	1,218,000 Network Data bytes/s

Chapter 3. Network performance: Cycle and response times

As mentioned earlier, industrial networks need to transfer PLC or sensor data to the process controllers rapidly enough for the latter to complete their scan and control cycle, and transfer the output status back to remote I/O registers or process actuators. The optimal time interval should meet the time-dependent requirements of the intended control application. This set time period is called cycle or scan time.

Cycle times will depend on the network and the type of industrial automation components in the network. For example, for a motion control application, where precise control is required, cycle time may be as short as a few microseconds (μs).

As asynchronous (transient) data takes place only when the real-time, deterministic cyclic traffic is not affected, it follows that when the regular exchange of cyclic data occurs over long periods of time, the network can easily transfer large volumes of transient data without affecting the cyclic traffic. However, when the time intervals are short, it may be challenging to transmit even small amounts of transient content.

Therefore, the current data sharing approach limits IIoT applications, for example; as transient data is not perceived as a priority and its transfer can take significant amounts of time. Furthermore, this method does not provide the optimum environment for determinism, as it does not consider the impact of possible delays, e.g. caused by module read/write times, communication over networks and inside decentral periphery (IO module / IM times).

These possible delays define the so-called response time, which can coincide with the cycle time in optimal conditions or take as long as multiple consequent cycle times.

Within the interconnected factory of the future, the volume of transient information that needs to be transferred will grow significantly. Therefore, the efficient transfer of cyclic and transient data is becoming increasingly challenging.

CC-Link IE Field manages cyclic and transient traffic differently. In order to guarantee a stable data transfer cycle for cyclic data whilst creating room for transient traffic, CC-Link IE Field actively assigns a portion of bandwidth for transient communications.

Thanks to the Gigabit capabilities of the network technology, the allocated transient bandwidth does not interfere with cyclic data transmission, so control and business messages can take place simultaneously. As a result, high-speed determinism for high-quality factory operations is ensured [7], while still allowing for significant amounts of non-real time (transient) communications.

In addition, CC-Link IE Field uses token passing for data transmission control. This method results in increased communication throughput and provides deterministic data exchange and constant link cycle time by eliminating the possibility of data collisions [8]. Furthermore, this method empowers the network technology to match cycle and response times at all times.

Chapter 4. Network performance: Overhead size

In some cases, Ethernet frames feature an additional Overhead in the Payload, which further reduces the Network Data size. This variable affects a network's performance as well.

The Overhead is the amount of unusable bandwidth within the Payload necessary to transmit the actual Network Data. Fields within the Overhead portion can include information such as source port number, destination port number and checksum [9].

Each individual Ethernet protocol may specify Overhead of different sizes. For example, the headers of Transmission Control Protocol (TCP), User Datagram Protocol (UDP), Internet Protocol Version 4 (IPv4) and IP Version 6 (IPv6) have minimum Overhead sizes of 20, 8, 20 and 40 bytes, respectively [10].

By contrast, CC-Link IE Field's protocol does not have any additional headers and the Overhead size is null, thus Payload and Network Data are equivalent values.

Overhead Frame Size (Minimum)

Name	Bytes
CC-Link IE	0
TCP	20
UDP	8
IPv4	20
IPv6	40

As a consequence, even when networks have similar bandwidths, they may differ greatly in their overall performances, due to their specific Overhead size. In fact, a protocol without Overhead can not only transfer more Network data, but also maximize the asynchronous (transient) traffic efficiency, whilst minimizing its impact on controller communications.

4.1 Overhead comparison between Ethernet networks at 1 Gbit

The following calculations show the difference in frame and data throughput between CC-Link IE Field, TCP/IP and UDP/IP.

Reference Point

Payload for an Ethernet frame is 46 – 1,500 bytes/transmission

- 1Gbit Ethernet with a minimum payload transmits 1,488,095 frames/s
- 1Gbit Ethernet with a maximum payload transmits 81,274 frames/s

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CC-Link IE Field - no additional Ethernet header(s) are required

When the Payload size is 46 bytes – the Network Data is 46 bytes

- It can transmit a maximum of 68,452,370 Network Data bytes/s at 1 Gbit

When the Payload size is 1,500 bytes – the Network Data is 1,500 bytes

- It can transmit a maximum of 121,911,000 Network Data bytes/s at 1 Gbit

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TCP/IPv4 - the IPv4 Header requires 20 bytes and the TCP header 20 bytes

When the Payload size is 46 bytes – the Network Data is 6 bytes

- It can transmit a maximum of 8,928,570 Network Data bytes/s at 1 Gbit

When the Payload size is 1,500 bytes – the Network Data is 1,460 bytes

- It can transmit a maximum of 118,660,040 Network Data bytes/s at 1 Gbit

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TCP/IPv6 - the IPv6 Header requires 40 bytes and the TCP header 20 bytes

When the Payload size is 1,500 bytes – the Network Data is 1,440 bytes

- It can transmit a maximum of 117,034,560 Network Data bytes/s at 1 Gbit

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UDP/IPv4 - the IPv4 Header requires 20 bytes and the UDP header 8 bytes

When the Payload size is 46 bytes – the Network Data is 18 bytes

- It can transmit a maximum of 26,785,710 Network Data bytes/s at 1 Gbit

When the Payload size is 1,500 bytes – the Network Data is 1,472 bytes

- It can transmit a maximum of 119,635,328 Network Data bytes/s at 1 Gbit

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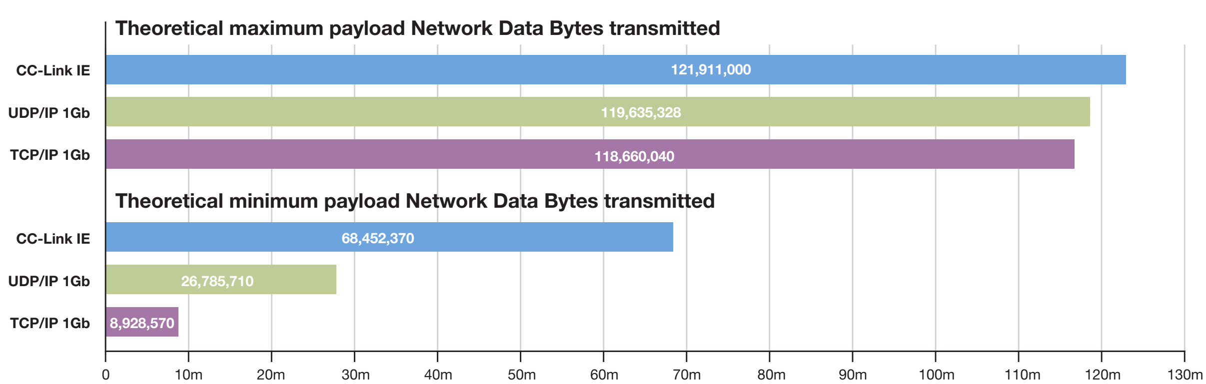
UDP/IPv6 - the IPv6 Header requires 40 bytes and the UDP header 8 bytes

When the Payload size is 1,500 bytes – the Network Data is 1,452 bytes

- It can transmit a maximum of 118,009,848 Network Data bytes/s at 1 Gbit



Chapter 5. Overall network performance comparison

CC-Link IE Field Ethernet technology was designed to address the challenges of Industry 4.0 and provide optimal performance. This is achieved by offering large bandwidth, allocating bandwidth for transient communications, minimizing delays by equaling response time to cycle time, as well as maximizing usable bandwidth within Ethernet frames.

Here is a comparison of the network performance of CC-Link IE Field with conventional industrial Ethernet technologies.

Name	Bandwidth	Transient data	Response time	Overhead size
Conventional industrial Ethernet technologies	10-100 Mb/s	Irregular traffic. Transferred when bandwidth is available	≥ Cycle time	28-60 bytes/frame
CC-Link IE Field	1 Gb/s	Regular traffic. Allocated bandwidth portion	= Cycle time	0 bytes/frame

When comparing Overhead size, CC-Link IE Field has the theoretical ability to offer a 667% bytes per second performance increase over TCP/IP, and a 155.5% increase over UDP/IP when transmitting with a minimum payload, due to its larger Network Data size, supposing that general purpose Ethernet networks could reach gigabit speeds (which they currently don't).

Beside CC-Link IE Field, there is no other 1Gbit general purpose Ethernet network readily available and open on the industrial market. Therefore, in real life, the comparison should account for existing, slower 100 Mbit general purpose Ethernet networks.

The following calculations show the difference in frame and data throughput between CC-Link IE Field and slower 100 Mbit general purpose Ethernet TCP/IP and UDP/IP.

When the Payload size is 46 bytes –

CC-Link IE Field Network Data is 46 bytes

- It can transmit a maximum of 68,452,370 Network Data bytes/s at 1 Gbit

TCP/IPv4 Network Data is 6 bytes

- It can transmit a maximum of 892,854370 Network Data bytes/s at 100 Mbit

UDP/IPv4 Network Data is 18 bytes

- It can transmit a maximum of 2,678,562 Network Data bytes/s at 100 Mbit

When the Payload size is 1,500 bytes – the Network Data is 1,500 bytes

CC-Link IE Field Network Data is 1500 bytes

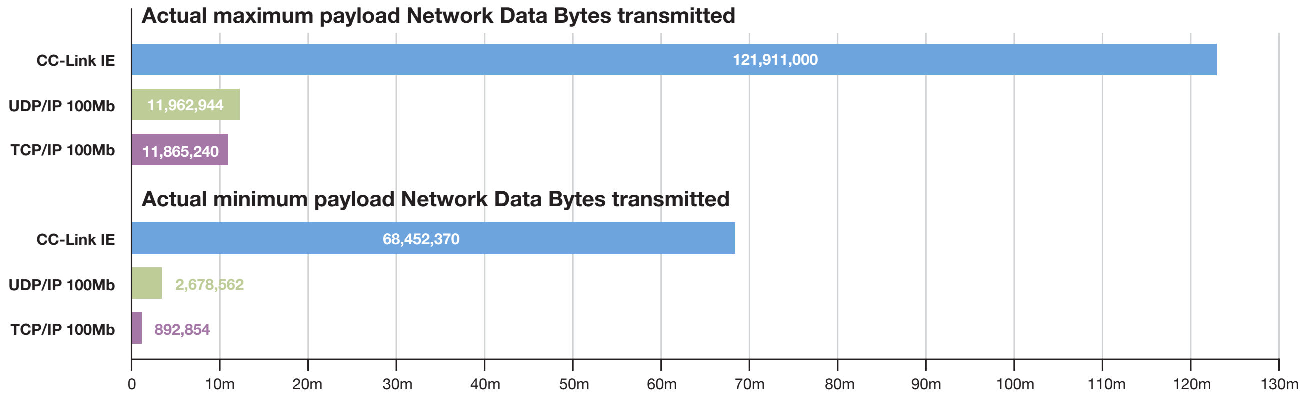
- It can transmit a maximum of 121,911,000 Network Data bytes/s at 1 Gbit

TCP/IPv4 Network Data is 1460 bytes

- It can transmit a maximum of 11,962,944 Network Data bytes/s at 100 Mbit

UDP/IPv4 Network Data is 1472 bytes

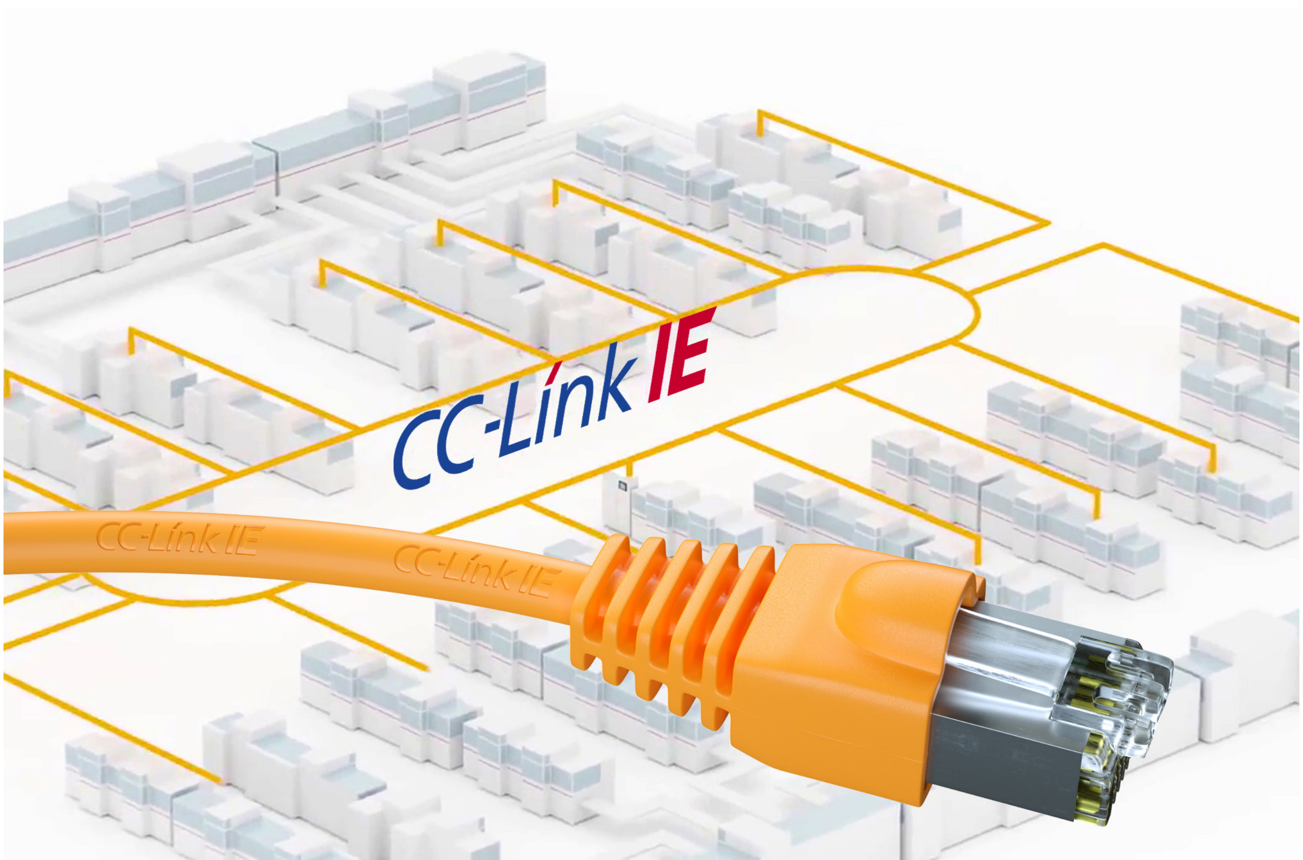
- It can transmit a maximum of 11,865,240 Network Data bytes/s at 100 Mbit



As a result, CC-Link IE Field can actually offer up to a 7,567% bytes per second performance increase over 100 Mbit TCP/IP, and nearly 2,500% increase over 100 Mbit UDP/IP.

These results show that not only is Gigabit Ethernet extremely advantageous, but also that the absence of additional headers contributing to Overhead can greatly contribute to a fast and efficient network.

The large bandwidth offered by CC-Link IE Field allows the preservation of portions of bandwidth for sharing transient data continuously without affecting cyclic messages. In addition, the structure of this network technology maintains short response times, which coincide with cycle times at all times.



Chapter 6. Conclusions

Industrial communications networks are the basis of an efficient factory, as they allow different devices to share data, regulate processes and operations, as well as gain actionable insights on productivity and other key performance indicators (KPIs).

Over the years, industrial communication technologies have made increasingly large leaps and will likely continue to do so, developing key innovations over shorter periods of time, as we enter the fourth industrial revolution (Industry 4.0).

While we may not know what the communications infrastructures of the future will look like, current industrial trends suggest that there is no question if faster networks will become an accepted part of the IT landscape, just when and how.

The main parameters that influence network speed and performance are bandwidth, response time, Overhead size and management of cyclic and transient traffic. Therefore, it is possible to compare existing Ethernet technologies to determine which one is more suited for IIoT and Industry 4.0 applications both now and in the future.

Based on these network performance factors, this whitepaper shows how CC-Link IE Field Ethernet technology provides the highest network performance currently available, as the solution outperforms other networks in terms of bandwidth, transient data transfer, response time and Network Data capabilities.

The comparisons presented show how significant the current advantage of CC-Link IE Field is in providing greater capacity to implement upcoming Industry 4.0 requirements. It appears clear how industries that use CC-Link IE Field are benefiting from a futureproof solution, which gives the unique opportunity to get their industrial automation systems ready for Industry 4.0 and IIoT.

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