Ethernet in industrial applications
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1 Introduction

Ethernet, originally developed for use in the office world, is increasingly being used in industrial environments. The trend is towards providing each field device with an Ethernet port. The conventional fieldbus is being displaced. The office world and the field level are ever growing closer together.

In addition to the application environment, the demands on Ethernet have also changed. The main task in the office is to transfer greater data volumes between PCs whereas the communication between conventional field devices mainly consists of very short telegrams. The field level requires very short response times which must be highly deterministic as well (4) - demands which cannot be fulfilled by the "normal" Ethernet. These changed demands have led to the development of different protocols based on the Ethernet hardware which partly require the separation of real-time and normal Ethernet networks.

Lenze offers communication modules meeting the requirements of the following Ethernet protocols:

- Ethernet
- Ethernet POWERLINK
- PROFINET®
- EtherCAT®
- EtherNet/IP™

The following chapter explains some basic Ethernet mechanisms. Then the differences between the individual Ethernet protocols are briefly described and information on the architecture of the Ethernet network is provided.
2 Basic information

At the beginning of the 1970s, an idea was born at the "Xerox Palo Alto Research Center" concerning the shared use of a printer by several staff members. This resulted in the first Ethernet standard (IEEE802.3) published in 1983, which has been consequently further developed since that time. Even today, some of the original mechanisms are part of the Ethernet, although they make the use outside the office environment difficult, particularly due to collision problems.

In the meantime, the most different organisations have developed activities to enable an efficient use of the Ethernet in industrial applications. As a result, several specifications competing with each other have been created. The most important ones will be briefly described in the following chapters, in particular the EtherCAT fieldbus system, which is supported by Lenze. Following this section, you will find some basic definitions and explanations. Then the individual systems will be briefly described and the advantages and disadvantages will be highlighted.

2.1 Determinism

The term determinism means that the development of a system is based on strict rules and strictly determined times. Referred to communication technology, this means that the time when a value is transferred from one node to another can be determined exactly.

Telegram collisions are the main problem for a real-time capable Ethernet. The problem occurs when two nodes want to send telegrams at the same time. In this case, the Ethernet controllers detect a collision and cancel the telegram transmission. Following the CSMA/CD method, they try to repeat the transmission. This is why determinism is not possible with the standard Ethernet.

2.2 Jitter

Between the triggering of a signal and the response of the receiver there is a delay time. If the delay time is not constant, this is called a jitter. In "Motion Control" systems, values lower than 1 μs are expected.

2.3 Cycle time

A (communication) cycle is the time required to provide all nodes with new setpoints and read the current actual values of all nodes. The shortest possible cycle time, therefore, always depends on the number of bus nodes.
2.4 Switched Ethernet

With the original Ethernet, all nodes were connected to one cable. This leads to collisions when several nodes are sending telegrams at the same time. In the further development of the Ethernet, hubs (star couplers) were used. In this way, a point-to-point connection is created between node and hub. The hub connects all nodes without delay, i.e. it is very fast. However, collisions can still occur. This is avoided by the new star coupler generation (switches). They only send messages directly to the individual nodes and retain them, if necessary, to prevent collisions.

- Advantage: Collisions are no longer possible.
- Disadvantage: Switches delay the messages. The delay time depends on the network load. Hard real-time performance cannot be achieved in this way.

2.5 Time-slot method

The non-deterministic Ethernet protocol is superimposed by a time-slot method. Each node only "communicates" when its time share of the overall cycle is active. In this way, the collisions that would impair determinism are avoided.

- Advantage: Determinism is completely controllable.
- Disadvantage: All nodes of a network segment must know the superimposed time-slot method. One wrong node is enough to impair the determinism.

2.6 Clock synchronisation

Each device on the bus is equipped with an internal clock. A special synchronisation protocol (IEEE1588) is used to ensure the synchronous running of all clocks. This ensures that all nodes carry out certain actions at the same time.

- Advantage: Determinism is possible with standard Ethernet.
- Disadvantage: Special hardware (with internal clock) is required, also for the switches. In addition, only cyclic events can be controlled in real time.
2 Basic information

2.7 Ports

An Ethernet node can simultaneously provide different programs (server services) in the network. Each service "listens" to a port. This enables clients, i.e. other Ethernet devices, to activate a certain service. Most services are able to serve several clients at the same time.

**Examples**

<table>
<thead>
<tr>
<th>Server service</th>
<th>Port</th>
<th>Multi client</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web (HTTP)</td>
<td>80</td>
<td>yes</td>
</tr>
<tr>
<td>E-mail (SMTP)</td>
<td>25</td>
<td>yes</td>
</tr>
<tr>
<td>DNS</td>
<td>53</td>
<td>yes</td>
</tr>
<tr>
<td>File release (SMB)</td>
<td>445</td>
<td>yes</td>
</tr>
</tbody>
</table>

Some routers, firewalls and other infrastructure components do not let pass all possible ports for safety reasons. Therefore, it is necessary to know which ports are required for the communication with an Ethernet node.

2.8 Hubs or switches

Today, Ethernet systems are typically wired in star configuration. Normally, two nodes are not directly connected but via a star coupler. Two star coupler types are common: hubs and switches. In the past, hubs were standard in the office world whereas today more and more switches are used. They have the advantage that almost any number of switches can be connected in series, which serves to create tree network structures. A switch receives telegrams and decides via which switch port they will be forwarded. In this way, Ethernet nodes always communicate without any collisions. If a switch is accessed by several nodes at the same time, it must buffer the messages and pass them on afterwards. This results in random delay times which makes it critical to use switches for real-time applications.

Only a limited number of hubs may be connected in series since, if more than two hubs are connected in series, the collision detection CSMA/CD does not function any more. One clear advantage of hubs still is the short delay time compared to switches since they only repeat the telegrams and output them at every port without interpreting them. Therefore, hubs are much better suited for use in networks for real-time applications. If, in addition, collisions are prevented by a superimposed protocol such as Ethernet POWERLINK, hubs are the better alternative for the field level.
2.9 Addressing

Each Ethernet node has a MAC address. The MAC address is a physical address which is assigned to an Ethernet device when manufactured and which cannot be changed. It is unique worldwide and cannot occur twice. It is often printed on the device. This unique address enables the device to be addressed, independently of the other Ethernet devices on the bus. An address conflict cannot occur. The MAC address is represented by six bytes. Hence $2^{48}$, i.e. approx. 280 trillion different MAC addresses exist, which make it possible to unambiguously identify each Ethernet device. The MAC address is usually represented in hexadecimal form, the single bytes being separated by dots. The first three bytes serve to identify the manufacturer, the other bytes serve to identify the device. Example: 00.0A.86.00.00.0A (Lenze’s manufacturer code is 00.0A.86.)

Since the MAC address must always be changed when a device is replaced, there are logical addresses (the IP addresses) in addition. Each network node is assigned an additional IP address which must be unique within a network. It is a “logical” address, which can be changed via the software and consists of 32 bits. It is always indicated by four decimal numbers separated by a dot (dot notation) for better readability. The IP address consists of the net ID and the host ID. The net ID identifies the network segment and the host ID identifies the node. The division of the 32 bits into net ID and host ID depends on the class of the IP address, which can be determined from the first byte.

Only nodes located on the same network segment (subnet) can directly communicate with each other. If they are located on different network segments, routers must be used which reroute the telegrams to the corresponding target segment. The maximum size of a network segment depends on the length of the net ID. Further graduations are possible by means of the network mask.
2 Basic information
Addressing
Example

2.9.1 Example

The IP address is 192.168.10.1
The network mask is 255.255.255.0

<table>
<thead>
<tr>
<th>IP address</th>
<th>192</th>
<th>168</th>
<th>10</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>11000000</td>
<td>10101000</td>
<td>00001010</td>
<td>0000001</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network mask</th>
<th>255</th>
<th>255</th>
<th>255</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>11111111</td>
<td>11111111</td>
<td>11111111</td>
<td>00000000</td>
<td></td>
</tr>
</tbody>
</table>

Description of the example:
All nodes which want to communicate with the device in this example must have an address which begins with 192.168.10, too. Only the last byte of the IP address must be different. Otherwise, a router must be used for communication. In this case, the IP address specified for the router must be that of the standard gateway. Routers (gateways) transmit packages between different networks. A system knows its own network. All packages for systems on other networks are sent to a router. A system knows certain routes: ”To get to network x, router y must be used.” Packages for all unknown networks are sent to the standard gateway (default gateway). The routing must also function in the other direction, otherwise there will be no reply!

2.9.2 Network classes

- Class A
  - Addresses from 1.x.x.x to 126.x.x.x
  - Network mask 255.0.0.0
  - Permits 126 networks with up to 16 million hosts each.

- Class B
  - Addresses from 128.0.x.x to 191.255.x.x
  - Network mask 255.255.0.0
  - Permits 16000 networks with up to 16000 hosts each.

- Class C
  - Addresses from 192.0.0.x to 223.255.255.x
  - Network mask 255.255.255.0
  - Permits 2 million networks with up to 254 hosts each.

- Subnetting: Longer network mask than possible according to class.
2.9.3 Reserved IP addresses

- 127.0.0.1, "local host"
  This address enables the node to access itself only.
- xxx.xxx.xxx.0, identifier for network segment
  Must not be used as a node address.
- xxx.xxx.xxx.255, "broadcast"
  Accesses all nodes of a network.

Some address areas are reserved for private networks and must not be used on the Internet:

- 10.0.0.0 ... 10.255.255.255
- 172.16.0.0 ... 172.31.255.255
- 192.168.0.0 ... 192.168.255.255

2.9.4 Assignment of the IP address

In principle, the following applies: As soon as an Ethernet device is to be connected to an existing network, the responsible network administrator must be contacted. He is responsible for the assignment of an IP address. Moreover, he must decide whether the device may be directly connected to the network or whether separation measures such as firewalls are required.

It is not allowed to simply use any address!

The address must go with the existing network and must not occur twice.

For setting an IP address, several mechanisms are available. In an industrial environment, IP addresses are usually assigned permanently. In the office environment, DHCP servers are frequently used, which dynamically assign an address to each device when being started. In the industrial environment, however, this method is rather unusual.

If a PC wants to communicate with a field device via the IP protocol, the IP addresses must be adjusted. At first, it must be checked which IP address the field device has or the desired address must be set. Afterwards it must be ensured that the PC has an IP address which is located in the same subnetwork or that a router exists in the network which forwards the telegrams from one network segment to another. If required, settings in the system control of the PC are necessary. Concerning this, please contact your system administrator.
3 Variants of the "Industrial Ethernet"

3.1 Ethernet/IP™ (CIP sync)

Ethernet/IP™ has been specified by the ODVA (Open DeviceNet Vendor Association) user group which is dominated by Rockwell. IP stands for the industrial protocol extension CIP™ (Common Industrial Protocol™), which forms the application layer. CIP is also used as the application layer for DeviceNet™ and ControlNet™ and has therefore been defined by ODVA and "ControlNet International". Synchronisation functions for real-time applications have been added and the name has been changed to “CIP sync”.

Main statements:
- Only standards are used (IEEE 802.3, IEEE 1588).
- Special switches are required (with boundary clocks for clock synchronisation).
- Can be combined with standard Ethernet components.
- Safety technology via CIP
- "Safety" is possible.

3.1.1 Principle

The real-time capability principle is based on the fact that each Ethernet node is equipped with a precise internal clock. The clocks are regularly readjusted via a well-defined protocol (IEEE 1588) to ensure that all clocks in the system indicate exactly the same time. Furthermore, the data packages have to be prioritised. However, only cyclic events can be controlled in real time.

More information about Ethernet/IP (CIP sync) is available ...

3.1.2 Network architecture / topology

Ethernet/IP permits usual Ethernet topologies such as the star or tree topology. Special switches with boundary clocks must be used as infrastructure components. Standard network analysis tools can be used.
3.2 EtherCAT®

EtherCAT® is a registered trademark and patented technology, licensed by Beckhoff Automation GmbH, Germany.

The “EtherCAT Technology Group” (ETG) user group was founded. Membership to this group is free of charge, the member companies only have to allow the user group to use their company logos. The user group and its “members” do not own any legal rights for the system.

Main statements of Beckhoff company:

- Fully Ethernet-compatible.
- Communication completely in hardware; maximum performance
- Highly efficient protocol
- Use of standard Ethernet cards
- Any topology
- Mixture of real-time data and standard TCP/IP possible.
- Ethernet as backplane

The particular strength of the system is its use as backplane bus system for terminals. Two physical variants are available: E-bus and Ethernet.

E-bus is based on differential voltage signals (LVDS), only suited for short distances (<10 m, e.g. within a terminal) and does not ensure electrical isolation. The E-bus physics are used because they offer better run-time conditions than the Ethernet physics. The use of real Ethernet (standard plug, connection to other Ethernet devices, etc.) requires, however, the use of the Ethernet physics.

3.2.1 Principle

The data are read from and/or written to the Ethernet telegram during the telegram throughput (“Interbus principle”).

More information about EtherCAT is available ...
- on the Internet at www.ethercat.org.
3.2.2 Network architecture / topology

Basically, the topology of an EtherCAT system is free. The standard topology seems to be a line topology, but it actually is always a ring. Branches are possible via I/O couplers. A star can only be implemented if the PLC has enough Ethernet ports (network interface cards on a PC). It is not possible to use standard switches to create a star. Tree topologies are possible by using I/O terminals with stubs. In this way, however, you cannot implement any tree topologies you like. Switches are only permitted between the master and the first EtherCAT node. Standard Ethernet components can either be connected to this switch or to special switch port terminals. The standard components and the EtherCAT devices never communicate directly, but always via the so-called "virtual switch" in the PLC, i.e. indirectly, which costs runtime and represents a bottleneck.

Special analysis devices are required for network analyses because the data stream depends on the measuring point.
3.3 PROFINET®

PROFINET® is defined by the PROFIBUS & PROFINET International (PI) user organisation. PROFINET® is the logical replacement for PROFIBUS®.

It is distinguished between the PROFINET component model (CBA, V1), whose main aim is the interconnection of automation components, and the PROFINET I/O, which is the further development of PROFIBUS. With the component model, communication is based on standard TCP/IP. This method is not real-time capable and therefore not relevant here. With the PROFINET I/O, two variants are distinguished. The first variant, SRT (Soft Real Time, V2), is real-time capable, however, with performance data which are not suitable for motion control applications. Basically, this variant can be implemented on every controller supporting Ethernet. The achievable performance corresponds more or less to that of PROFIBUS. Furthermore, there is the IRT variant (Isochronous Real Time, V3), which is the only variant suitable for motion control applications. The implementation requires special ASICs from Siemens.

Main statements:
- Coexistent use of real-time and TCP-based IT communication on one line
- Uniform protocol both between the components and between control and field device
- Scalable communication

3.3.1 Principle

- Soft Real Time (SRT):
  - Switched Ethernet to avoid collisions
  - Optimisation of the TCP/IP protocol stack
  - Reduced telegram length and shorter cycle times
  - Prioritisation of data packages according to IEEE 802.1Q (Prio 6)

- Isochronous Real Time (IRT):
  - Time-slot method: the communication cycle is divided into a deterministic part (real time) and an open part (standard Ethernet)
  - Implementation on hardware basis (special ASIC)
  - Cycle synchronisation and time-slot reservation implemented in the hardware

More information about PROFINET is available ...
3 Variants of the "Industrial Ethernet"
PROFINET®
Network architecture / topology

3.3.2 Network architecture / topology

Basically, the topology of a PROFINET network is free. Switches can be used as star couplers. For PROFINET SRT (V2), the switch must support the prioritisation of data packages according to IEEE802.1Q. For PROFINET IRT (V3), you can only use special switches which contain the PROFINET-ASIC from Siemens. So far, only 4-port switches are possible here.

Line topologies are also possible by means of switches integrated into field devices.

For PROFINET IRT (V3), special analysis devices are required for network analyses because the data stream depends on the measuring point.
3.4 Ethernet POWERLINK

Ethernet POWERLINK is a real-time Ethernet system. The original idea for Ethernet POWERLINK came from the B&R company (version 1.0). The openness and further development of the system is ensured by the "Ethernet POWERLINK Standardisation Group" (EPSG). These activities have led to a generally accepted industry standard (version 2.0), which ideally combines the technical features of the Ethernet with the demands for real time and integration capability.

3.4.1 Principle

Ethernet POWERLINK avoids collisions through a superimposed software procedure, the "Slot Communication Network Management". This is a time-slot method where the master (Managing Node) explicitly provides each slave (Controlled Node) with active sending rights. All nodes can always receive messages.

Comparison with CAN: CAN also includes a master which starts the new cycles. The bus arbitration, however, is automatically controlled through the CAN functions.

In every cycle, it is possible to transmit a non-real-time-capable telegram (a). Here, any Ethernet telegram can be sent (e.g. general TCP/IP telegrams). For these telegrams, too, the master (Managing Node) provides exactly one slave (Controlled Node) with sending rights.

More information about Ethernet POWERLINK is available ...
► on the Internet at www.ethernet-powerlink.org
► in the brochure "Real Time Industrial Ethernet is Reality".
The advantages of consistent communication made possible through the use of uniform cable types and standards are clear. However, this makes the existing system-inherent separation between office and field level more obvious. Still the Ethernet network structures should not be removed completely for the following reasons:

- Safety and access protection
- Creation of network segments
- Segmentation required for system-inherent reasons

Segmentation of a network is useful in any case. It is not necessary that each node permanently communicates with every other node. If you combine the nodes permanently communicating with each other in a network segment, you can separate other network branches from this bus load.

In general, office and field level are strictly separated in large company networks, even when the same bus system is used for both levels. Connections between these networks are possible (by means of routers), access to another network is, however, only allowed after applying specific rules. The routers thus provide access protection since not every office PC is allowed to access any field device. In addition, this separation also ensures that faults in one network segment do not lead to faults in other segments.

Especially when real-time Ethernet and non real-time Ethernet are coupled, the routers have to fulfil further functions. The Ethernet POWERLINK nodes must not be operated together with standard Ethernet nodes in one and the same network segment. Since the standard nodes do not know the real-time protocol, this would lead to collisions which would impair the real-time behaviour of the bus.
3.5 SERCOS III

SERCOS III wants to combine the tried-and-tested SERCOS mechanisms with the advantages of the Ethernet physics. The existing mechanisms, profiles and telegram structures have remained largely unchanged and have been transferred to the Ethernet physics. In addition, the following aims are pursued:

- Reducing the costs for hardware interfacing
- Possible integration of TCP/IP protocols
- Cross communication
- Transmission of safety-relevant data
- Fault tolerance in the event of a cable break

3.5.1 Principle

SERCOS III provides an IP channel for the transmission of standard Ethernet telegrams. This channel does not replace the SERCOS service channel which continues to be transferred with the cyclic data. The IP channel can be switched off and is usually not considered in typical calculation examples.

Similar to the Interbus, a summation frame is transmitted in every communication cycle. Each slave takes its data from this summation frame or writes its data into it. This is why the implementation requires a special hardware (ASIC or FPGA).

More information about SERCOS III is available ...

3.5.2 Network architecture / topology

The original SERCOS always has the structure of an optical fibre ring. The ring topology has also been transferred to the Ethernet physics. Since every Ethernet connection has a forward and a reverse channel, there is a double ring. In this way, redundant systems can be established. When a slave fails, the logical ring is interrupted, but communication is still possible.

With a line topology, redundancy is not possible, but one connection less is required. For extensive systems, this can mean considerable cost savings.

Start topologies are not possible with SERCOS. Star couplers such as hubs or switches cannot be used.

SERCOS III networks are always separate networks. Connection to higher-level systems is only possible via the motion controller or the PLC. This transition has so far not been defined.

Special analysis devices are required for network analyses because the data stream depends on the measuring point.