Industrial Ethernet

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Topics

I. Industrial communication systems
   – Introduction
   – Overview on industrial networks
   – IEC 61158 and IEC 61784 standards
   – RM model of industrial communication
   – Requirements on industrial digital communication
   – Real time in industrial networks
Topics

II. Industrial Ethernet

– Introduction
– Ethernet TCP/IP, UDP
– Historical overview on industrial Ethernets
– How does the Ethernet technology fit requirements from the industry world
– Industrial Ethernet’s principles
  • Mechanical robustness
  • Real/-time properties
Specification of serial communication systems for automation

1. Sensor/actuator bus  
   AS-interface, Interbus S, HART, proprietary I/O buses

2. Device bus  
   serial bus for electronic devices, measurement bus

3. Fieldbus  
   powerfull industrial communication bus

4. IE  
   Ethernet for industrial automation
Serial communication buses for automation

- Transmission of data, parameters and status
- Advantages:
  - Spare of costs for cabling
  - Simple commissioning
  - Rapid translation of huge data volume over one physical connection
  - Robustness
  - High availability
  - Possibility of diagnostics and remote parameter setting
  - Possibility of back up
  - Possibility of integration into the hierarchical control and communication pyramid
- Problems:
  - Non – sufficient standardization
  - Heterogeneous communication structures
Classification of fieldbuses

- Foundation Fieldbus
- Profibus
- FIP
- P-Net
- LonTalk
- CAN
- DeviceNet
- CANopen
- ControlNet
- Modbus (J-bus)
- Ethernet
- Interbus S
- HART
- AS-interface
Perspectives of industrial communication

- Industrial Ethernet replaces most fieldbuses and devicebuses in the future
- Wireless communication systems – starting to gain market share
Why to use Ethernet for industrial communication??

• De facto communication standard in IT and office
• Positive relation Power / Price
• Popularity
• Simple connection to Internet (possible distance maintenance, monitoring, diagnostics, asset management)
• More rapid than other industrial serial communication systems (fieldbuses and lower)
• Challenge for vertical integration by one communication system
Differences between industrial and office communication

**Industrial world**
- Harsh Industrial environment (requirements on mechanical and electrical robustness, EMC, …)
- Larger set of different communication devices (PLCs, analysers, sensors, actuators, others)
- Different length of data blocks (short data blocks from sensors and to actuators in rapid cyclic modus versus messages of status, diagnosis, maintenance in asynchronous – less rapid one)
- Data exchange among more than two entities
Standardization of industrial networks

**Fieldbus** – communication system for industrial communication connecting instruments and devices in the first control levels (process and control)

- IEC (International Electrotechnical Commision) – World Standardisation Organisation
- Standard Committees, Working groups
- SC65C worked 15 years to specify a “world fieldbus”
- Troubles, delays, bad cooperation, nevertheless - “The international fieldbus“ (year 1999) defined by standards
  - IEC 61784-1 (Digital communication in Industrial Control systems)
  - IEC 61158 (Fieldbus for Industrial Control systems)
Industrial communication standards
IEC 61158, IEC 61784-1

These standards replace CENELEC standards

- EN 50170 (General purposes field communication systems)
- EN 50254 (High efficiency communication subsystems for small data packages)

The IEC 61158 and IEC 61784-1 don’t specify a joint world fieldbus standard, but standardize 7 (seven) existing the mostly used fieldbuses: Foundation Fieldbus, ControlNet, Profibus, P-Net, SwiftNet, WorlFIP, Interbus-S
World fieldbus
IEC 61158, IEC 61784-1

Relationship between standards IEC 61158 and IEC 61784-1
Standard IEC 61784-1

Standard IEC 61784-1 defines profiles of communicating entities:

| CPF1 (FOUNDATION® Fieldbus) | CP 1/1 H1  
CP 1/2 HSE  
CP 1/3 H2 |
|-----------------------------|-------------|
| CPF2 (ControlNet™)          | CP 2/1 ControlNet  
CP 2/2 EtherNet/IP |
| CPF3 (PROFIBUS)             | CP 3/1 PROFIBUS DP  
CP 3/2 PROFIBUS PA  
CP 3/3 PROFinet |
| CPF4 (P-NET®)               | CP 4/1 P-NET RS-485  
CP 4/2 P-NET RS-232 |
| CPF5 (WorldFIP®)            | CP 5/1 WorldFIP  
CP 5/2 WorldFIP with subMMS  
CP 5/3 WorldFIP minimal for TCP/IP |
| CPF6 (INTERBUS®)            | CP 6/1 INTERBUS  
CP 6/2 INTERBUS TCP/IP  
CP 6/3 INTERBUS minimal subset of CP |
| CPF7 (SwiftNet)             | CP 7/1 SwiftNet Transport  
CP 7/2 SwiftNet Full stack |
The further development in industrial networks standardization

<table>
<thead>
<tr>
<th>CPF2 (ControlNet™)</th>
<th>CP 2/2 EtherNet/IP</th>
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<tbody>
<tr>
<td></td>
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<td>CP 3/3 PROFINET CBA</td>
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<td>CP 3/4 PROFINET I/O</td>
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<td>CP 16/4 SERCOS III</td>
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Hence – the final product will be 11 standards each of which will have more as one communication profile
Basics of industrial networks

• Communication architecture
• Real – time
• Determinism
• Stability/availability
• Safety
• Security
• Heterogenity/standardization
# OSI reference model

## Description of communication interface:
- Communication stack (protocols)
- Network interface (electrical, optical, mechanical and timing parameters)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Application layer</td>
<td>Application specific services, interface to App’s</td>
</tr>
<tr>
<td>6. Presentation layer</td>
<td>Transformation of data to be “understandable”</td>
</tr>
<tr>
<td>5. Session layer</td>
<td>Session management incl. flow control</td>
</tr>
<tr>
<td>4. Transport layer</td>
<td>Reliable data transmission</td>
</tr>
<tr>
<td>3. Network layer</td>
<td>Network addressing &amp; routing</td>
</tr>
<tr>
<td>2. Data link layer</td>
<td>Flow control, transmission timing, access control</td>
</tr>
<tr>
<td>1. Physical layer</td>
<td>Electrical and mechanical interfaces, bit timing</td>
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## Reduced reference model

Automation networks often use reduced reference model:

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<td>Link layer addressing (e.g. MAC address)</td>
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<td></td>
</tr>
<tr>
<td>4. Transport layer</td>
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<td>6. Presentation layer</td>
<td></td>
</tr>
<tr>
<td>7. Application layer</td>
<td>Services of unnecessary layers are handled by the application layer</td>
</tr>
</tbody>
</table>

**LonWorks:** 7 layers  
**BackNet, FF:** 4 layers  
**Many others:** 3 layers only
Basics of industrial networks

• Communication architecture
• Real – time
• Determinism
• Stability/availiability
• Safety
• Security
• Heterogenity/standardization
RT in industrial networks

Two aspects of RT system function

**timeliness** – control or communication system response to the predefined **deadline**
RT in industrial networks

Two aspects of RT system function

Synchronism – synchronism of action single communication entities by predefined accuracy of the $t_d$ (nominal response time), thus in a defined time tolerance area (jitter)
Real-time systems

Real time requirements of the controlled system:

• Soft real-time system
  – Once the deadline is missed, the utility function slowly declines
  – Deadlines are “soft” and can be missed
  – Miss of deadline causes less efficient operation

• Hard real time system
  – Once the deadline is missed, the utility function is zero or negative
  – Deadlines are “hard” and must not be missed
  – Miss of deadline is “catastrophic”
RT in automation applications

Soft real time system’s utility function
RT in automation applications

Hard real time system’s utility function
Basics of industrial networks

- Communication architecture
- Real – time
- **Determinism**
- standardization
Industrial networks have often been classified into three classes:

- **Soft-real time** (e.g. non-deterministic communication systems)
- **Hard-real time** (e.g. deterministic communication systems)
- **Isochronous real-time** (e.g. isochronous and time triggered …)

**Soft RT or Hard RT is always property of the controlled system, not the property of communication.**

Real-time performance of networks can be expressed in terms of:

- cycle time
- jitter
Performance of industrial communication systems

Cycle time (latency)
- How long does it take to pass some information

Jitter
- How deterministic the communication is:
  - Non deterministic (stochastic) – e.g. CSMA based
  - Deterministic – e.g. Master/Slave based
  - Isochronous – synchronized and time triggered systems

Throughput
- How many messages (bytes) we can get through per second
Part I - Conclusion

I. Industrial communication systems

- Introduction
- Overview on industrial networks
- IEC 61158 and IEC 61784 standards
- RM model of industrial communication
- Requirements on industrial digital communication
- Real time in industrial network
Part II. – Overview

- Ethernet (IEEE 802.3 and other)
  - new and the most dynamic challenge in industrial communication
  - 1st and 2nd ISO/OSI layers
  - TCP/UDP/IP standard protocols
  - Metal, optic, wireless (IEEE 802.11)
  - Industrial Ethernet

- RT, wireless

- Perspectives of industrial communication
  - Industrial Ethernet replaces most fieldbuses and devicebuses
  - Wireless communication systems - growing importance
Trend: Vertical Integration through Ethernet-TCP/IP

Structure of Communication

legacy structure
inhomogeneous

future structure
homogeneous

IT World
(Office, Internet)

Backbone

Control Level

Process Level

Gateways
Ethernet
Fieldbus
Future Ethernet Subsystems (?)

AS-Interface
DeviceNet
IO-Link
CompoNet
Industrial communication systems

- Process control
  - Sensor Bus
  - Devicebus
  - Fieldbus
  - Industrial Ethernet
- Logical control
  - Simple devices: bit
  - Complex devices: byte, block
Differences between industrial and office communication

Office and IT world

- No special requirements on robustness, IP class, stability, EMC in the office and IT world
- Small set of different communication entities
- Standard Ethernet TCP/IP protocol suite
- Point to point connection mostly
Ethernet for office and IT

- Ethernet TCP/IP, IEEE 802.3, WiFi (wireless alternative)
- De facto standard from begin of 80th for LAN for office, IT
- Non-deterministic, CSMA/CD
- Design for office only
- Appropriate EMC (robustness against EMI)
- Internet compatible
- Continuously growing rapidness (10Mbit/s, 100Mbit/s – fast Ethernet, 1Gbit/s, 10Gbit/s, and, and …)
- Rapidly growing relation performance/price
- Switched – decreasing collision areas
- Different structures of interactions
- Structured cabling
Ethernet basic - repetition

• Communication structures
  – Physical topologies
    • Bus
    • Ring
    • Star
    • Daisy chain
  – Logical topologies
    • Broadcast
    • Unicast
    • Multicast messages
Media access methods

**Deterministic** (Master/Slave, Token passing, TDM, …)
- Suitable for hard real-time control
- Less flexible as for bandwidth use
- Guaranteed and predictable timing
  - In error free state
  - When error occurs (message loss, bus overload)
- Collision free

**Non-deterministic**
- Suitable for soft real-time control and slower systems
- Event driven communication
- More flexible (runtime adaptability may be possible)
- Collisions may occur
Non-deterministic communication

Stochastic principles are used to for media access

Data transmission may be described by rules like:

- Message $M$ is sent in time $t$ with probability $p$.
- With bus utilization of e.g. 10% there is probability $x$ that message $M$ will collide with some other message.
- … there exist a probability $y$ that a message will experience $n$ collisions prior successful transmission.

Almost all guarantees are given using stochastic description. This is far from ideal as for automation and feedback control systems.
Historical evolution towards Ethernet

- ALOHA
- Slotted ALOHA
- CSMA
  - Pure CSMA
  - CSMA/CD
  - CSMA/CR
  - CSMA/CA
ALOHA

Radio network for computer communication at Hawai University

Pure Aloha:
Rules: “If you have data then transmit”. If no ACK, the resend.
Bandwidth utilization: less than 18%

Slotted Aloha:
Added definition of equal length timeslots (TDMA predecessor)
Added Rule: “Transmission may start at the beginning of a timeslot”
Bandwidth utilization: less than 37%
(Collision affects one timeslot only)
CSMA

CSMA = Carrier Sense Multiple Access

Rules:
- Listen for silence before you start transmission
- If the line is busy then wait
- Once you transmit, wait RTT + ACK for acknowledgment
- If no acknowledgement comes then retransmit the message

Bus utilization: depends on RTT and frame length

CSMA Types: 1-persistent, p-persistent, non-persistent
1-persistent CSMA

Rules:
1. If line is free then transmit
2. If line is busy, then wait for free line and then start immediately transmission.

Properties:
• Good when bus utilization is low
• Shortest average delay of messages
• When two stations wait for free line then collision always occurs.
• Bus utilization: Below 60%

Ethernet IEEE 802.3 uses 1-persistent CSMA
**p-persistent CSMA**

**Rules:**
1. If line is free then transmit with probability $p$, i.e. with probability $(1-p)$ the transmission is delayed by one TU (usually TU = RTT)
2. If line is busy, then wait for free line and then go to step 1.

**Properties:**
- Compromise between delay and bandwidth use
- Probability $p$ can be adapted to fit the actual bus load
- When two stations wait for free line then collision always occurs.
- Peak bus utilization
  - 0.01 persistent CSMA: above 90%
  - 0.5 persistent CSMA: below 70%

LonWorks enables to tune the $p$ and also adds priority slots.
non-persistent CSMA

Rules:
1. If line is free then transmit
2. If line is busy, then wait for random time and then go to step 1.

Properties:
• Probability of collision is reduced
• Significant average message latency
• Simple implementation
• Better average throughput than 1-persistent CSMA.
Collision handling

CSMA
Collision is not detected, collision results in message loss, corrupted message is not acknowledged (e.g. LonWorks over RS-485)

CSMA/CD – CSMA with Collision Detection
Collision is detected by the sender as well as receiver
No need to wait for “not acknowledged” timeout
(e.g. Ethernet IEEE 802.3, LonWorks over twisted pair)

CSMA/CR – CSMA with Collision Resolution
Collision is detected by the sender and is resolved so that exactly one message survives. (e.g. CAN)

CSMA/CA – CSMA with Collision Avoidance
Message loss is prevented e.g. by sending special jamming signal prior sending the payload (e.g. Wi-Fi)
Ethernet basic - repetition

– Communication based interactions
  • Client – server
  • Consumer – producer
  • Publisher – subscriber

• Specification of communication structures
  – Logical topology as much as possible independent from physical one
  – Interactions as much as possible independent from logical topology
Ethernet basic

Physical topologies
- Bus no more popular and used in industrial communication
- Ring is a closed bus
- Star used more for office then for industry
- Daisy chain becomes popular again (three Ethernet interfaces integrated into each device)
Ethernet basic

Broadcast messages
• One message to each communication partner (specified by IP addresses and the subnet mask definition)

Unicast messages
• Enable the application of logical topology where each communication partner is directly and exclusively connected with all other communication partners. A device with a local network IP address (e.g. 192.168.10.26) will reach the devices with the IP address 192.168.10.83 by sending a message to his address. All other devices will not receive it since the switches will route the message only to the receiver.
Ethernet basic

Multicast messages

- Something like in-between of broadcast and unicast messages
- Will be received by a set of receivers belonging to a multicast group. A multicast group is characterized by its multicast IP address. This address is within the address range 224.0.0.0 and 239.255.255.255.
Ethernet basic

*Structures of communication based interactions*

- Client – server
- Publish – subscribe
- Producer – consumer

All these major structures have their individual benefits and drawbacks – thereby differ with respect to the applicability for certain problems.
Ethernet basic

**Client server structure**
- Data exchange between two entities mainly
- After one request and one response – finished
- Mainly implemented by unicast messages
- One example – MODBUS / TCP protocol
- Efficient for explicit data exchange for communication of two partners (PLCs)
- Not available for cyclic mode for sensor data flow to PLC (within each cycle, PLC requires a request from the sensor which is not necessary)
- If more than one control device requires the sensor data the problem will enlarge – a great communication load
Ethernet basic

*Publish – subscribe structure*

- Move from unicast to multicast *message* (grouping entities requiring the same data)
- Grouping entities are stored and maintained by the publisher
- Each partner requesting data send the request to the publisher
- Publisher integrates each new subscriber and send cyclically the data to all members of its subscriber list by multicast messages
- In case of a small subscribe list, publisher send unicast messages to each subscriber (at the same moment or as fast as possible) in order to reduce the maintenance effort.
**Ethernet basic**

*Producer – consumer structure*

- The data sets are also transmitted via multicast messages.
- In contrast to publisher – subscriber within the producer – consumer the groups of communicating partners which are interested in the same data sets are not maintained by a communication partner.
- To enable grouping each set of data is labeled by special communication identifier.
- The first consumer of a data set is sending a request to the producer of data, together, both, the producer and the first consumer will negotiate a multicast address as well as a communication identifier for the messages containing the data set of interest.
Ethernet basic

**Producer – consumer structure**
- The producer will now start to send the data set to the defined multicast address.
- If any other consumer is interested in the same data set it will request the multicast address and the communication identifier from the producer or an other consumer and can then start to filter out the messages with the data set of interest from the set of transmitted multicast messages.
- The joint and leave process for a multicast (and hereby a producer – consumer – group) is managed by IGMP messages.
- Example can be the EtherNet IP protocol.
Industrial Ethernet basics
Industrial Ethernet basics 1/3

IE is no more the IEEE 802.3 standard of 80\textsuperscript{th} – successful way to a powerful fieldbus and something/much more:

**Quazideterminism**
- Priority in MAC mechanism
- UDP instead of TCP
- Producer – consumer
- Publisher - subscriber
- Switching/ collision less domains
- More appropriate physical and logical topologies
- Segmenting and routing into real – time and non – real – time domains
- Communication planning
- High speed
- Full duplex modus
Determinism
- Synchronization (PTP protocol by IEEE 1588)

Robustness
- Physical
- Electrical robustness (EMC)
- Safety
- Security by implementing of security mechanism from IT
Industrial Ethernet basics

Common communication technology in the entire information and control pyramid

- High efficiency of design
- High efficiency of commissioning
- Simple Internet access
- Possibility to utilize Internet technologies
- Remote monitoring
- Low cost standard Ethernet interface modules
Historical overview of IE

- 1985–94 Sinec H1 mezi S5-115, 135
Industrial Ethernet in DCS

Historical overview of Ethernet implementation in industrial automation

- 1985–94  Sinec H1 among S5-115,135
- 1990–96  PLS 80E in system bus
- 1994–98  Simatic PCS in system bus
- 2000–02  Rapid rise of Industrial Ethernet
  - Among PLC (automotive industry)
  - Distributed I/O (datalogger, embedded Ethernet in 32-bit processors)
- 2002
  - Next processors with Ethernet interfaces (Net+ARM, Rabbit, etc.)
  - Ethernet TCP/IP direct or indirect internet connection of sensors and actuators (SEN 2000P with 16-bit smart processor Ubicom)
  - Direct internet connection of single sensors and actuator still non-economic
- Therefore the main role of industrial Ethernet in DCS remains in redundant real-time system bus.
Industrial Ethernet mechanisms for RT functions

1. Switched Ethernet – non-collision domains, each entity has its own physical bus segment

2. Segmentation - allocation of the LAN into time non – and time critical (real-time) parts, optimization of packet path (minimum switches) in the RT parts of the network, physical separation of RT and non-RT messages evokes shorter response time for RT messages (higher throughput)
Industrial Ethernet mechanisms for RT functions

3. High data transmission rate (100Mbits/s and higher in the near future) – shorter message collision interval

4. Priority slots in the Ethernet protocol by IEEE 802.1p (higher priority packets are signed by the higher priority and are transmitted with higher priority)

5. UDP instead of TCP (connectionless service provides message delivery still in the next transmission after a communication failure)

6. Jitter decreasing by the PTP (Precision Time Protocol) by the standard IEEE 1588 – Ethernet synchronisation
Synchronisation in the industrial Ethernet

- Ethernet TCP/IP – principal non-deterministic
- By using distributed real-time clocks a decoupling of the execution time grid of the application and the communication time grid can be achieved
- Synchronization protocols from the IT world as NTP and SNTP cannot fulfill the special requirements of automation
- Necessity to implement a cheap synchronization mechanism into the Ethernet TCP/IP protocol in order to improve its real time ability.
- The mechanism must not load much performance of individual entities
- Perspective solution - PTP (Precision Time Protocol) by the IEEE 1588 standard
Synchronisation in the industrial Ethernet

- Synchronization by means of distributed real-time clocks
- Enables the Ethernet TCP/IP to achieve better synchronization as by actual fieldbuses
- Already implemented in actual industrial Ethernets standards dedicated in time critical applications (drives for axes control), energy distributed systems (correlation of measured values in distributed energy networks), or in back up systems for information networks (lose of GSM connections) and others.
- Applied by the EtherCAT, Ethernet IP(CIPsync), ETHERNET Powerlink, Profinet V3
Communication models of actual industrial Ethernets

Three principal versions of protocol stack
Both the real-time as well as non-real-time data exchange are carried out over the same way (TCP/UDP/IP) stack by encapsulating of real-time data in the application sub layer.
Communication models of actual industrial Ethernets

Three principal versions of protocol stack
The time critical data flows over a real-time SW bypass parallel to the TCP/UDP/IP, time no-critical data and messages carried out over the TCP/UDP/IP.
Communication models of actual industrial Ethernets

**Three principal versions of protocol stack**
real-time data are carried out by a HW bypass of the TCP/UDP/IP stack, non time critical data flows over the standard Ethernet TCP/UDP/IP, special Ethernet HW is unavoidable
Actual structure and activities of working group SC65C
The further development in industrial networks standardization

<table>
<thead>
<tr>
<th>IEC Standard</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>IEC 62030</td>
<td>MODBUS-TCP</td>
</tr>
<tr>
<td>IEC 62405</td>
<td>Vnet/IP</td>
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IEC 61158

IEC 61784-2
The further development in industrial networks standardization

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|                         | CP 3/5 PROFINET IRT                     |
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| CPF6 (INTERBUS®)        | CP 6/2 INTERBUS TCP/IP                  |
|                         | CP 6/4 INTERBUS RTE                     |
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| CPF11 (TCnet)           | CP 11/4 TCnet                            |
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| CPF14 (EPA)             | CP 14/4 EPA                              |
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Hence – the final product will be 11 standards each of which will have more as one communication profile
References

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