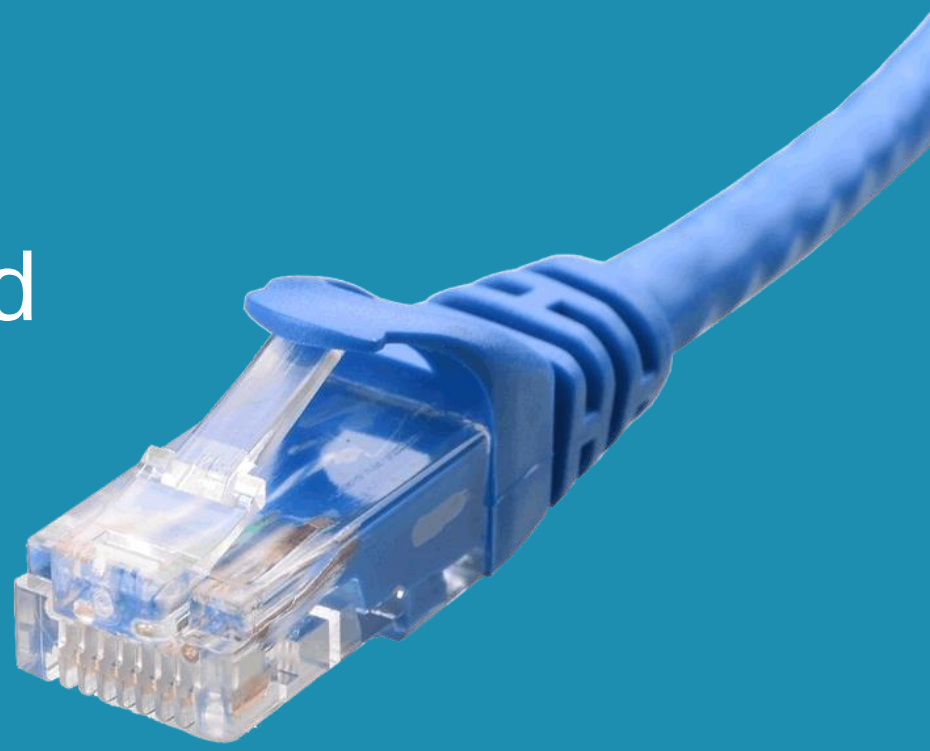
KU LEUVEN CINI4.0 cornet

The Ethernet physical layer revisited



CINI4.0 - Converging Industrial Networks for Industry 4.0

16 June 2022, RodeBol Events, Ghent

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Outline

- Technology classes – Copper cable
- The 100 Mbps Ethernet voltage signals
- Signal and packet measurement methods
- Conclusion

Outline

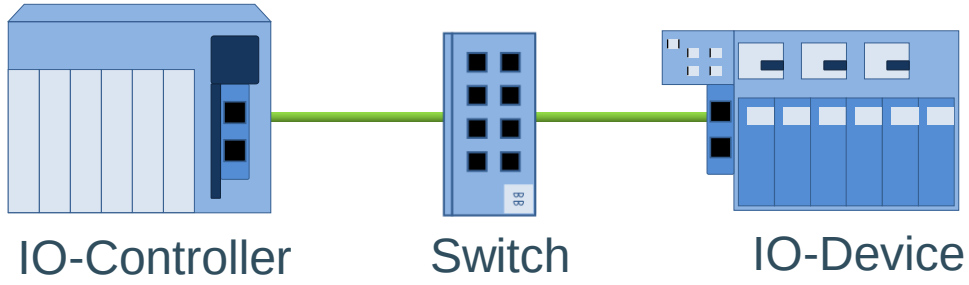
- **Technology classes – Copper cable**
- The 100 Mbps Ethernet voltage signals
- Signal and packet measurement methods
- Conclusion

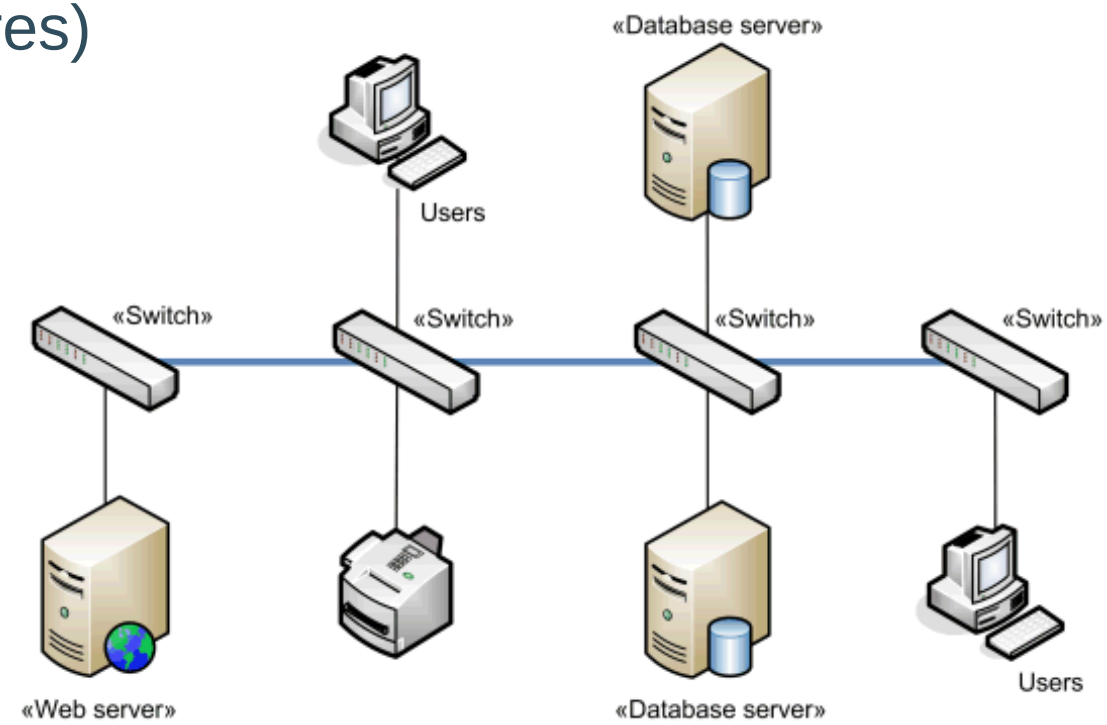
Technology classes

Physical media

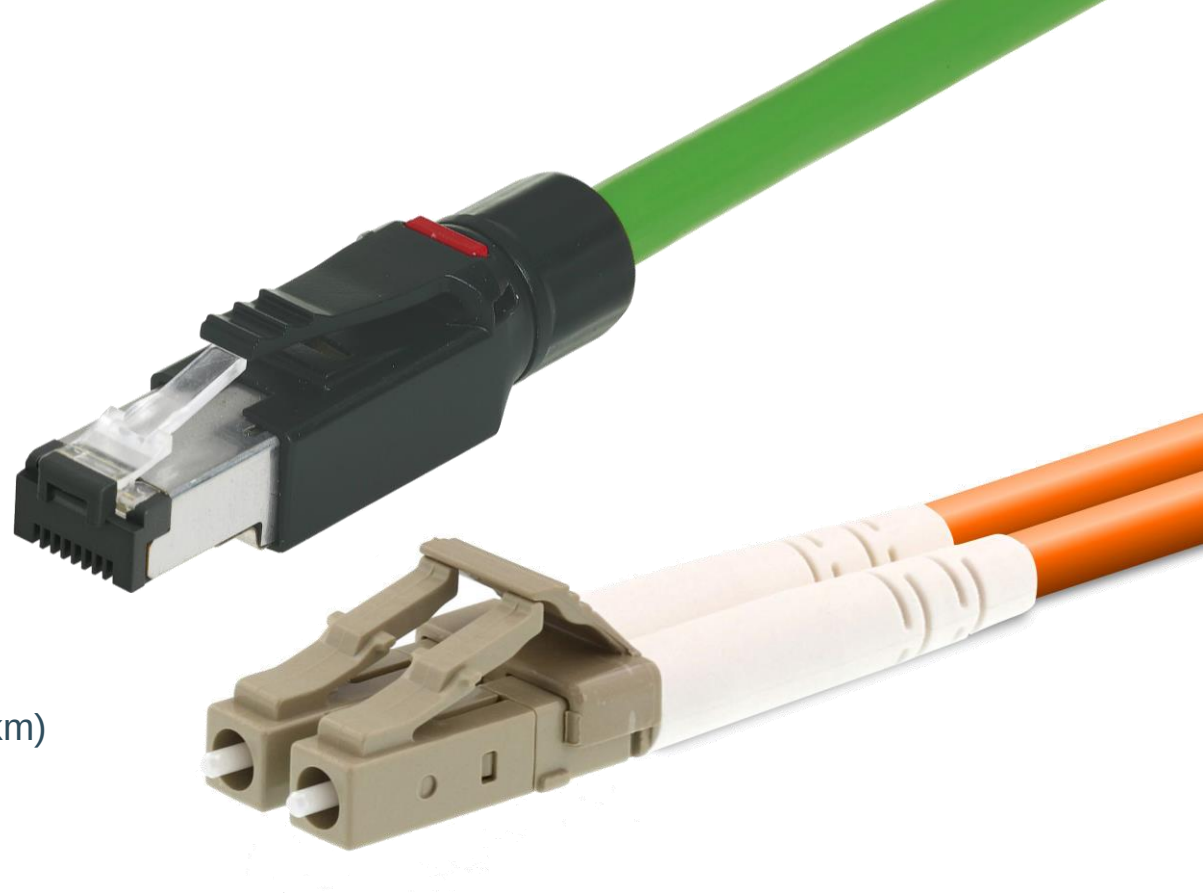
Technology classes – Switched/Fast Ethernet

- 100 Mbps
- Point-to-point links
- Full duplex => min 2 wire pairs (4 wires)
- Intelligent switching => collision free
- Topologies:
  - Star
  - Line
  - Tree
  - Ring





Technology classes



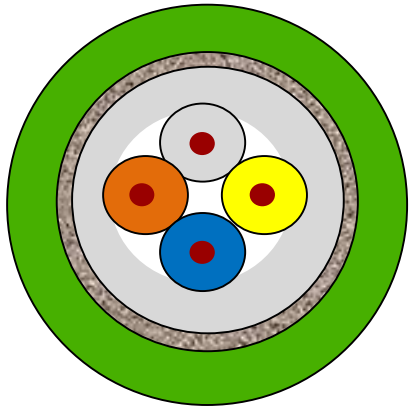
- **Copper wire (100BASE-TX) (IEEE 802.3u)**
- Fiber Optical Cable (100BASE-FX) (IEEE 802.3u)
  - Plastic Optical Fiber (50 m)
  - Hard Clad Silica (100 m)
  - Glass Fiber multi-mode (2 km) and single-mode (14 km)
- Wireless:
  - Wi-Fi (IEEE 802.11g) => limited to 54 Mbps & half duplex
  - Bluetooth (IEEE 802.15.1) => limited bandwidth either half-duplex or full-duplex

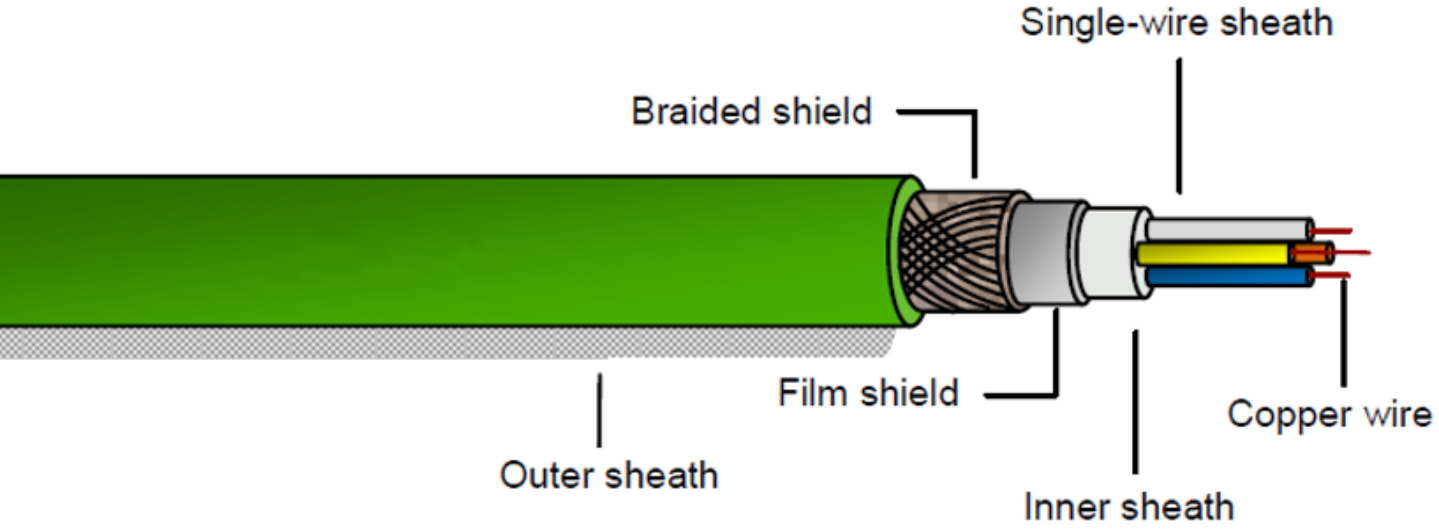
Typically industrial ethernet communication only uses 5 to 10% bandwidth of 100BASE-TX

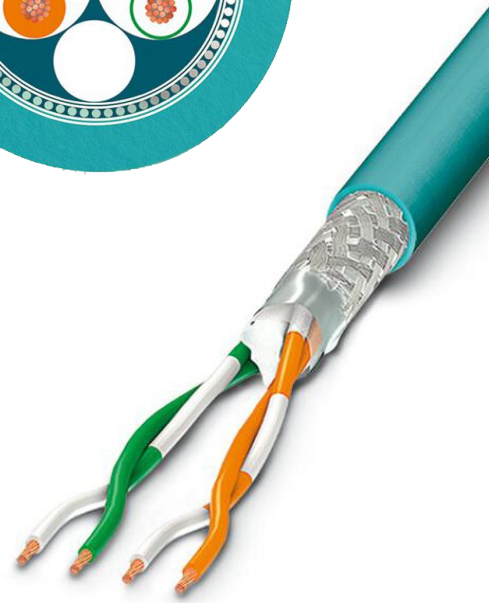
=> Wireless bandwidth can be sufficient but introduces more jitter and a less reliable medium

Technology classes: copper cable

- 4 core cable
  - 2 wire pairs -> Full duplex
    - Allows Power over Ethernet (Mode A)
  - Star-quad cable or Twisted pair
- Typically Shielded for Industrial use

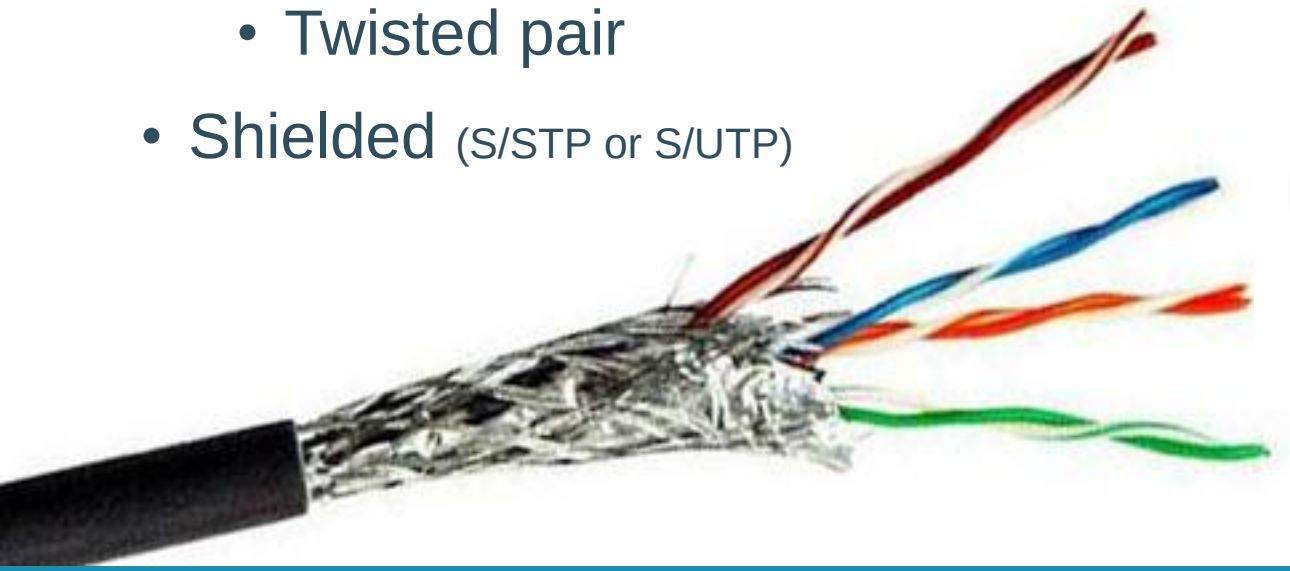


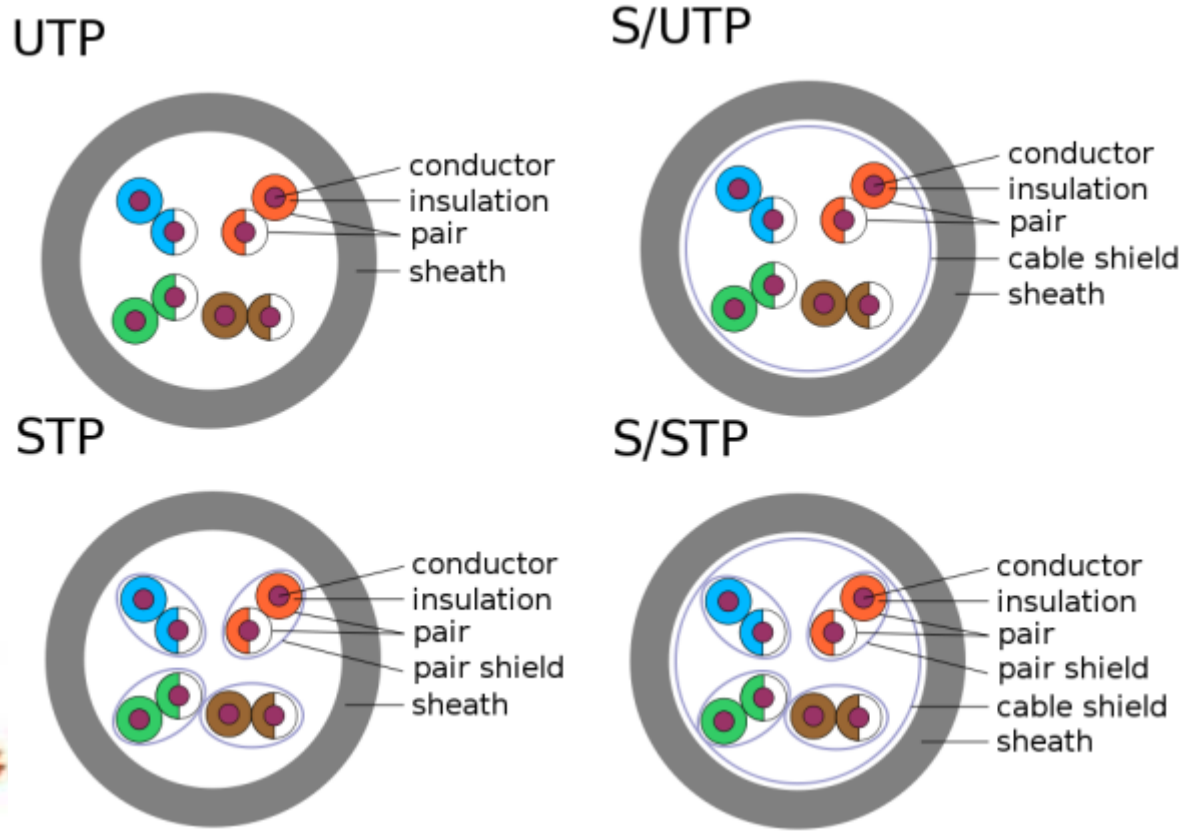




Technology classes: copper cable

- 8 core cable
  - 4 wire pairs -> Full duplex
    - Allows for 1Gbps communication and Power over Ethernet
      (Mode B and 4-pair mode)
  - Twisted pair
- Shielded (S/STP or S/UTP)



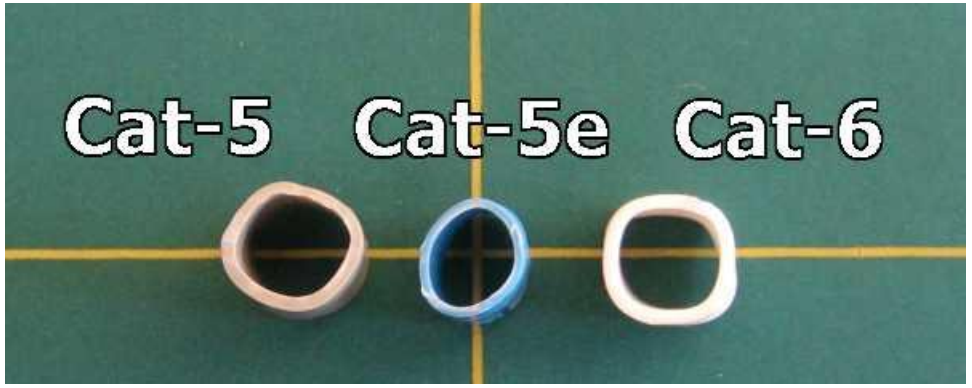


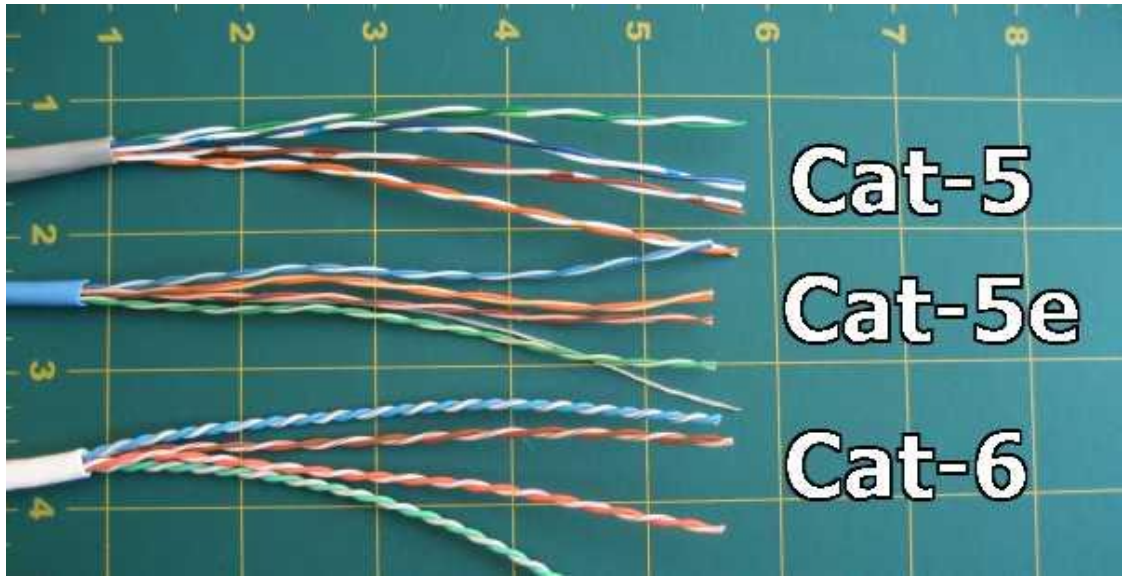
Technology classes: cable categories (CAT)

Higher category means:

- Less crosstalk (XT), less alien crosstalk (AXT) and less near end crosstalk (NEXT)
- Higher speed/bitrate due to higher bandwidth

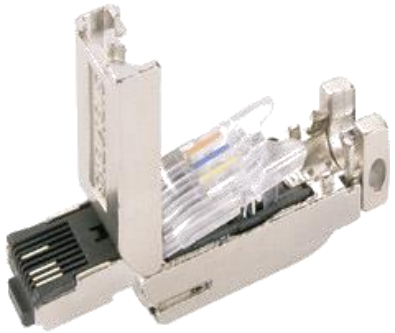
Category	Length (meters)	Speed/bitrate	Bandwidth (MHz)
Cat-5	100	Up to 100 Mbps	100
Cat-5e	100	Up to 1 Gbps	100
Cat-6	100 (55m for 10 Gbps)	Up to 10 Gbps	250
Cat-6a	100	Up to 10 Gbps	500





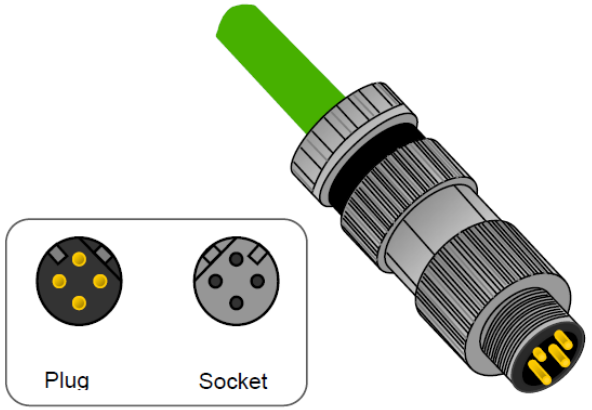
Technology classes: copper connector

RJ45



Signal	Colour	Pin number
TD+	Yellow	1
TD-	Orange	2
RD+	White	3
RD-	Blue	6

M12



Signal	Colour	Pin number
TD+	Yellow	1
TD-	Orange	3
RD+	White	2
RD-	Blue	4

As we use shielded copper cables the connectors need to be shielded for a correct interconnection of the shielding

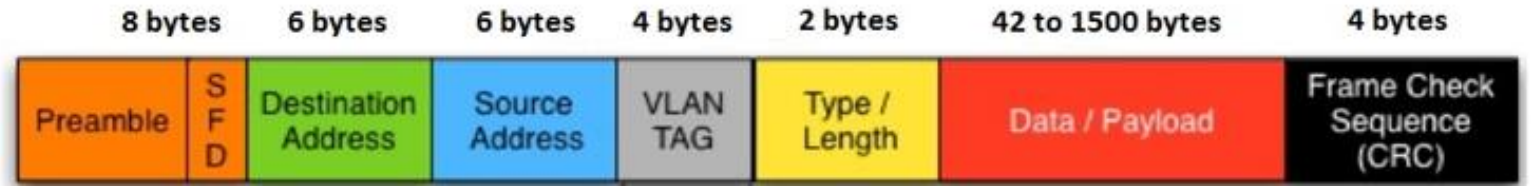
Outline

- Technology classes – Copper cable
- **The 100 Mbps Ethernet voltage signals**
- Signal and packet measurement methods
- Conclusion

The 100 Mbps Ethernet voltage signals

Ethernet signal decoding – Ethernet II frame format

- Data is sent in frames, also called packets
- Frames consist of bytes (groups of 8 bits)
- MAC-address communication at switch level (Data link layer)
- Payload depends on protocol used (TCP/IP, UDP/IP, …)

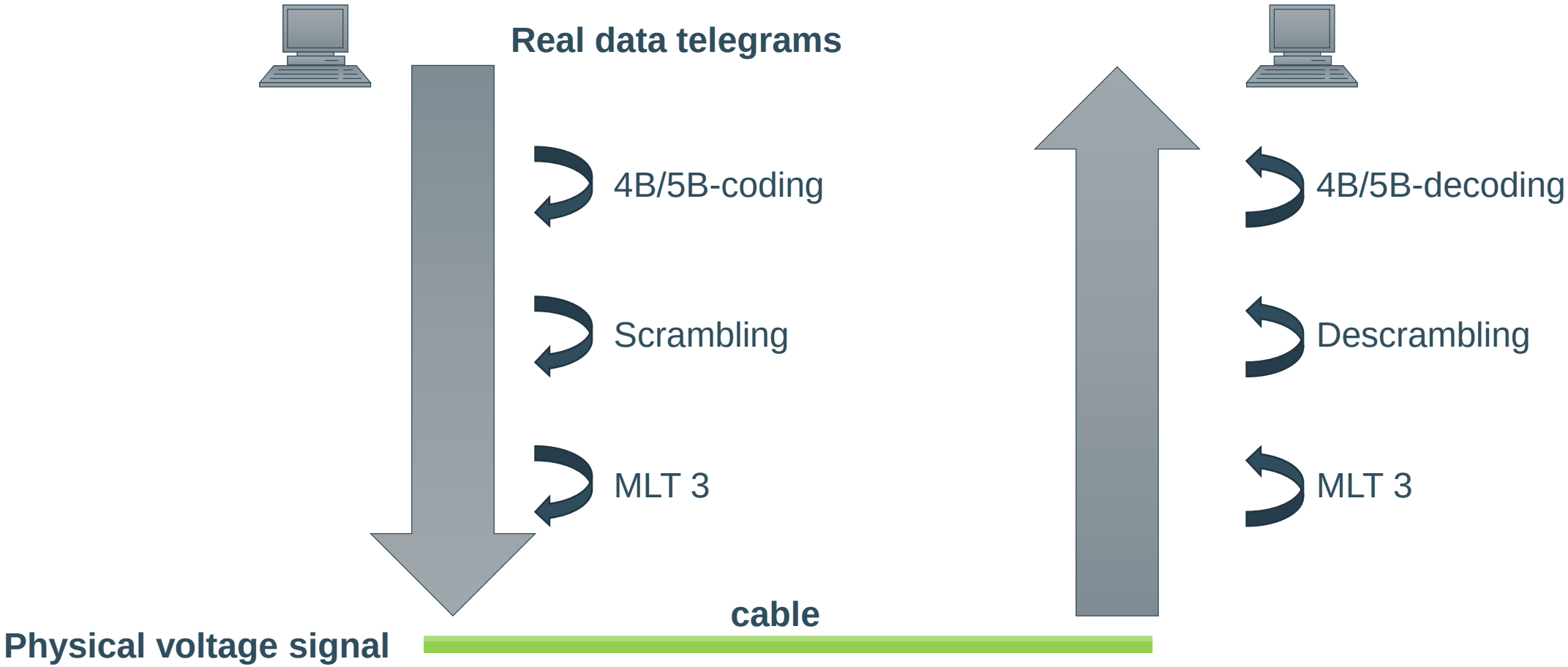


SFD = Start of Frame Delimiter
CRC = Cyclic redundancy check

Situating Ethernet in the OSI model

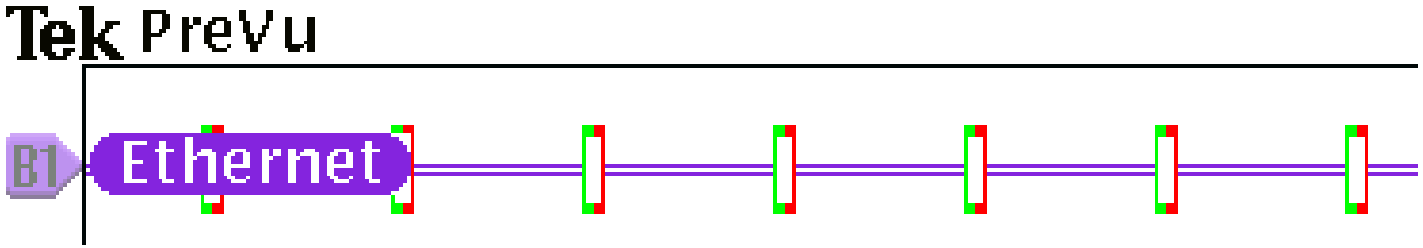
Application	• End User layer • HTTP, FTP, IRC, SSH, DNS
Presentation	• Syntax layer • SSL, SSH, IMAP, FTP, MPEG, JPEG
Session	• Synch & send to port • API's, Sockets, WinSock
Transport	• End-to-end connections • TCP, UDP
Network	• Packets • IP, ICMP, IPSec, IGMP
Data Link	• Frames • Ethernet, PPP, Switch, Bridge
Physical	• Physical structure • Coax, Fiber, Wireless, Hubs, Repeaters

Ethernet signal decoding - overview



4B/5B-coding

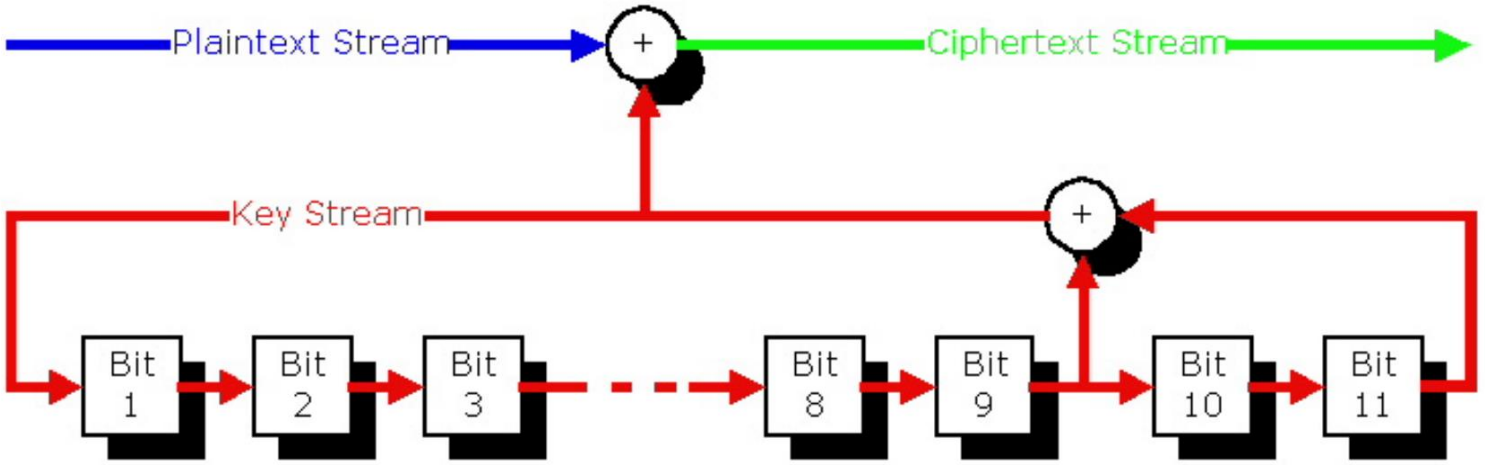
- Raw IO-data: possible loss of synchronisation
  For long series of ‘0’: possible loss of synchronisation between transmitter and receiver
- 4 data bits = 5 bits on the line
- Extra signalling codes possible
- Resulting in 125 Mbps



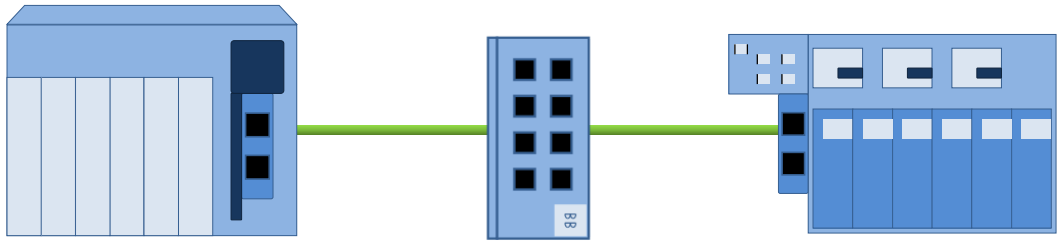
Bin 4b	Code	Bin 5b	Description
0000	0	11110	Data
0001	1	01001	Data
0010	2	10100	Data
0011	3	10101	Data
0100	4	01010	Data
0101	5	01011	Data
0110	6	01110	Data
0111	7	01111	Data
1000	8	10010	Data
1001	9	10011	Data
1010	A	10110	Data
1011	B	10111	Data
1100	C	11010	Data
1101	D	11011	Data
1110	E	11100	Data
1111	F	11101	Data
	I	11111	Idle
	J	11000	SSD (Part 1)
	K	10001	SSD (Part 2)
	L	01101	ESD (Part 1)
	R	00111	ESD (Part 2)
	H	00100	Transmit Error

Scrambling

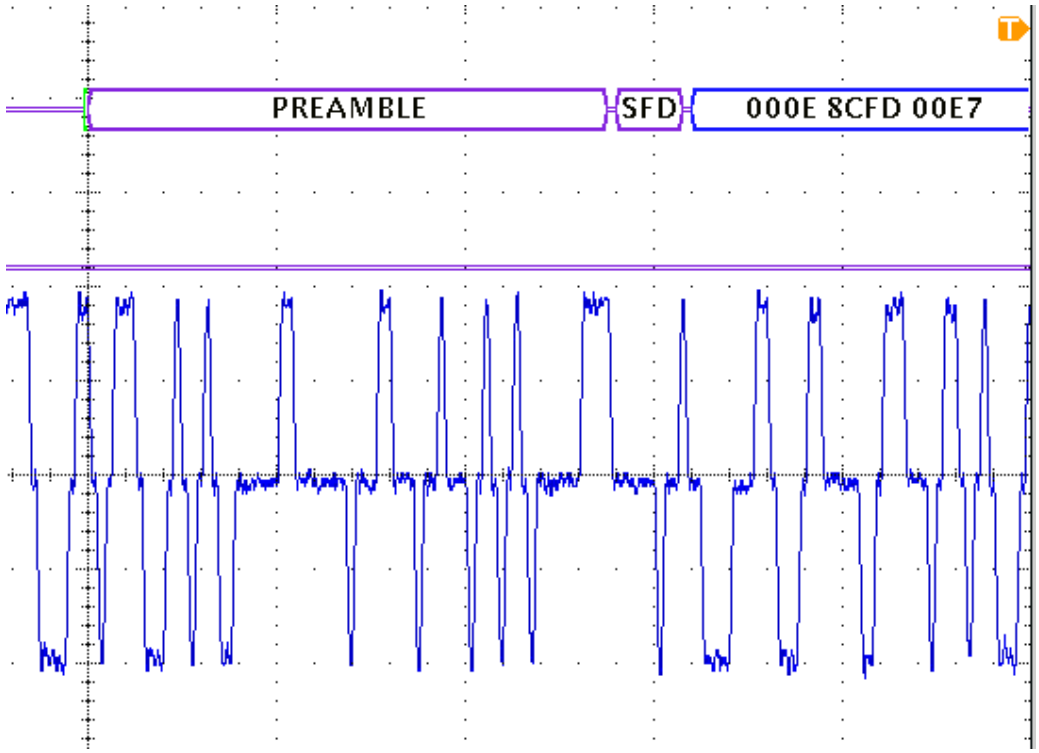
- Reduce number of signal transitions -> lower signal frequency
- More robust data communication
- Using pseudo-random seed
- Through an 11 bit XOR shift register



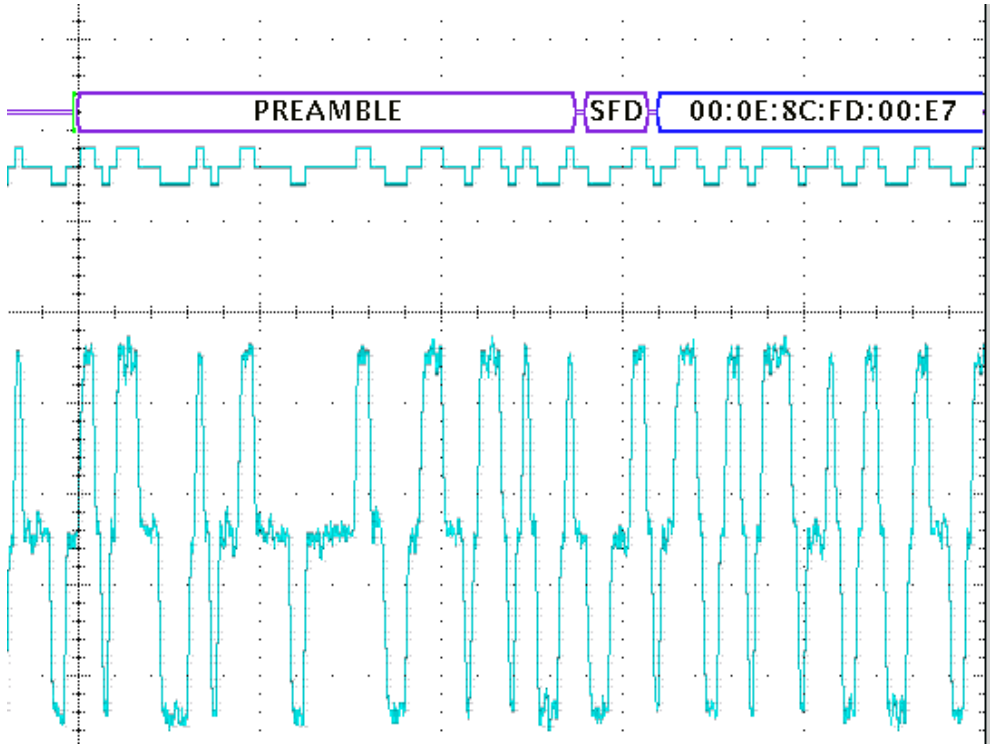
Scrambling



Signal before switch



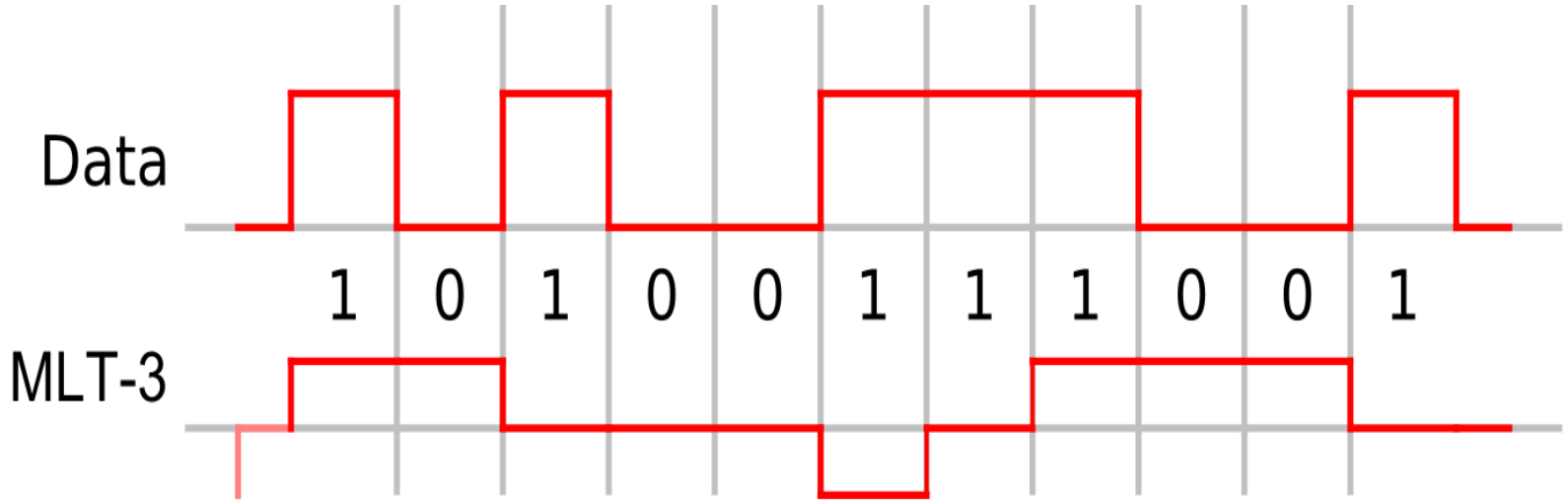
Signal after switch



MLT 3

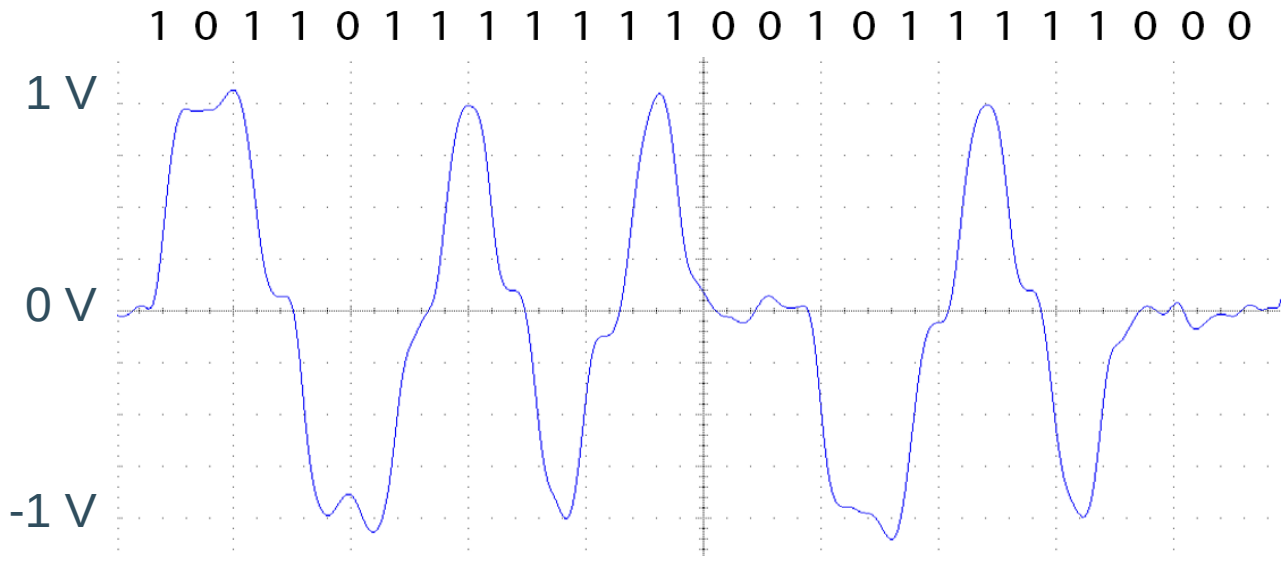
- Multi-Level Transition 3: Working principle
  - Logic high bit = Signal transition
  - Logic low bit = Constant signal level

Voltage levels: -1, 0, 1 V

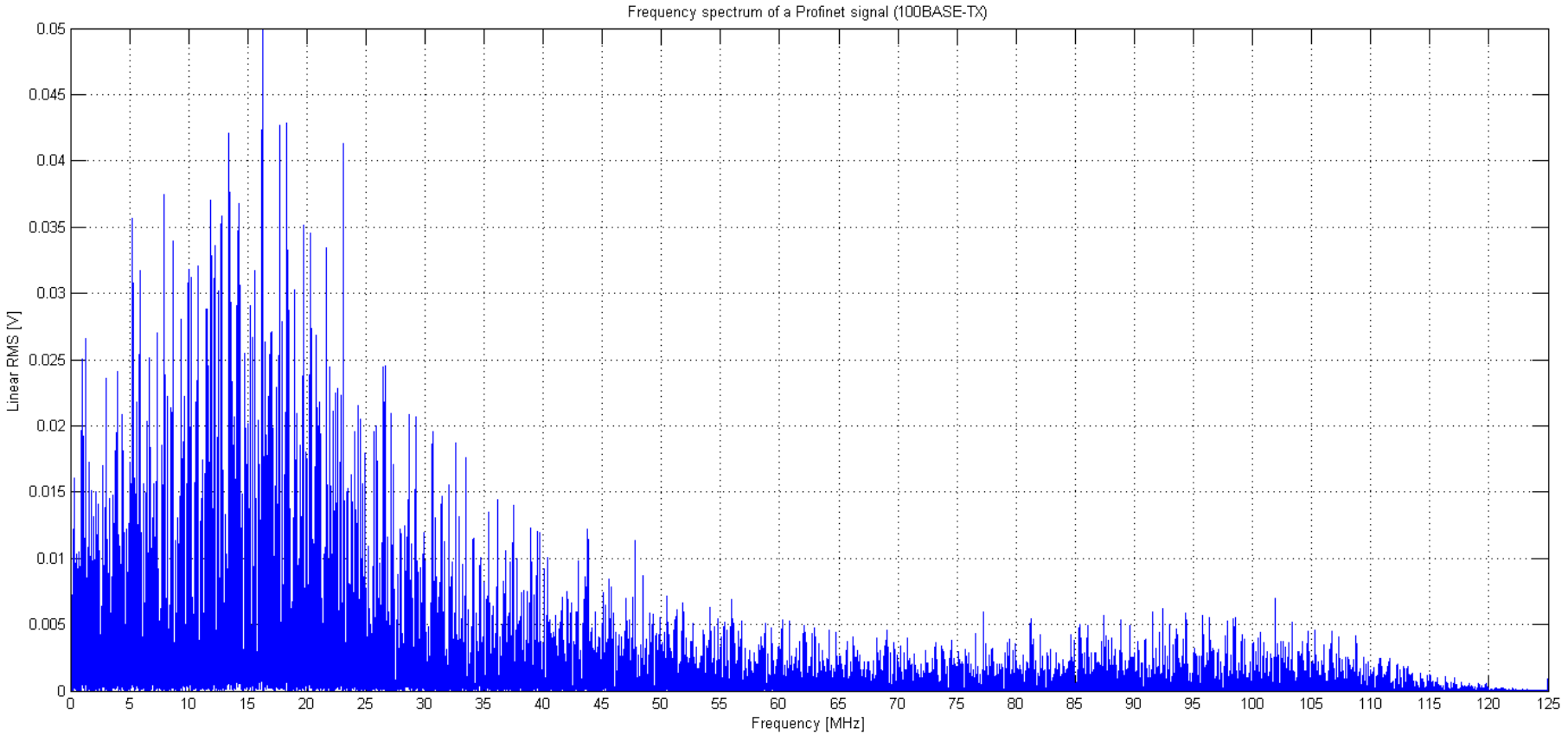


MLT 3

- Multi-Level Transition 3
- Reduces the maximum signal frequency
- Differential voltage measured on 1 wire pair



Frequency components



Peak amplitude at a frequency of 15,625 MHz

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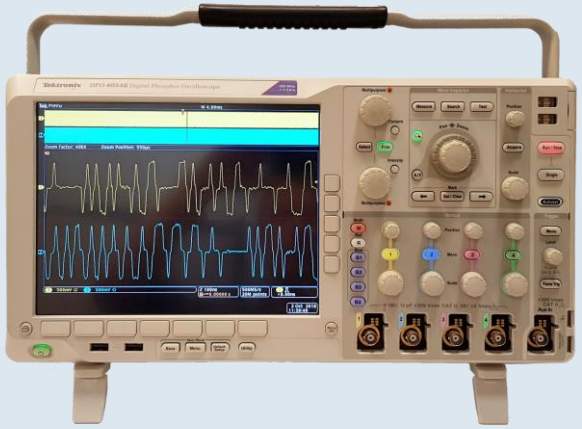
Signal and packet measurement methods

for industrial applications

Wireshark

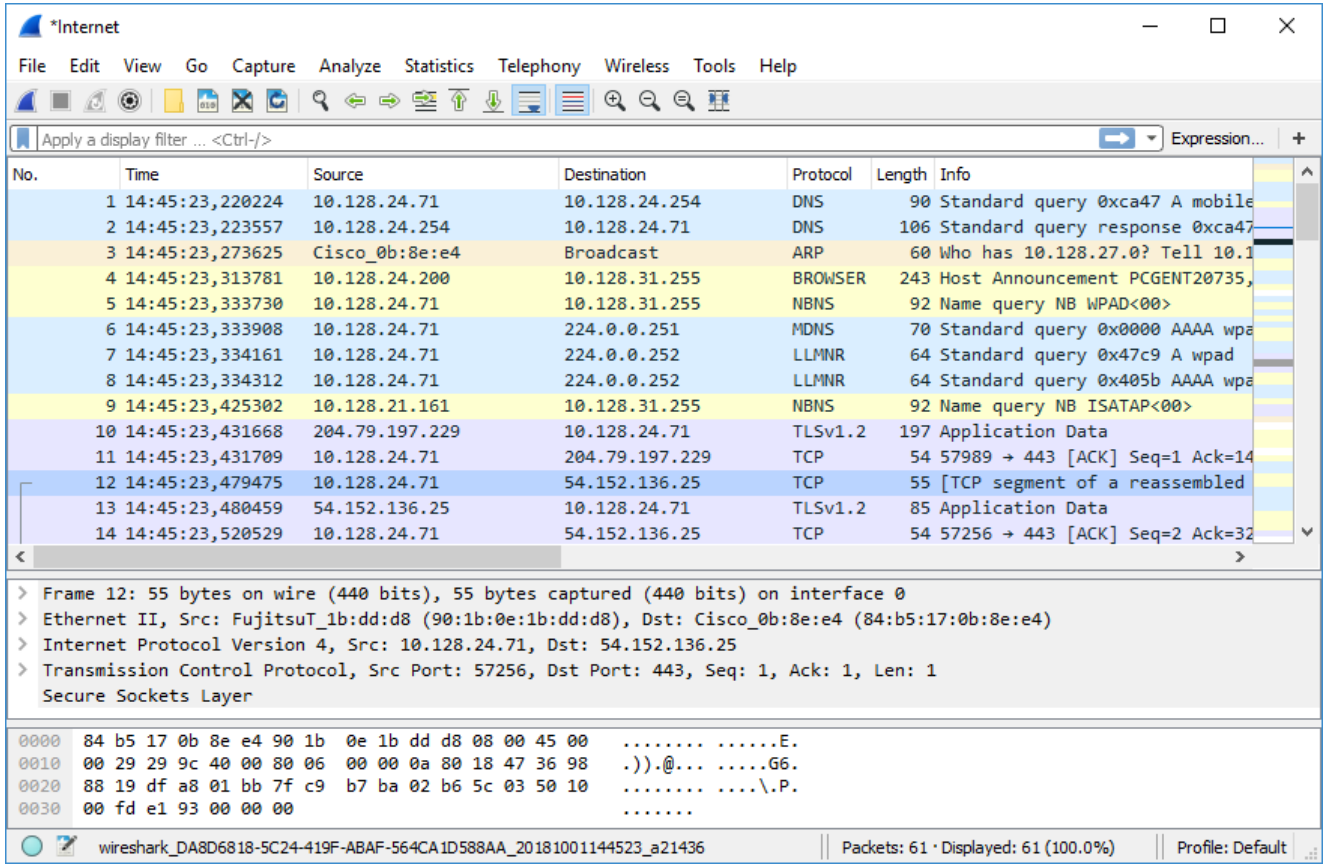
Oscilloscope



Wireshark – a free software tool

- High level diagnostics
- Short loggings
- Measure all Ethernet traffic
- Where to measure?
  - Connect to normal switch port
  - Connect to mirror port

    (Throughput & switching priorities)
  - Use Ethernet tap
  - Export pcap-file from diagnostic devices



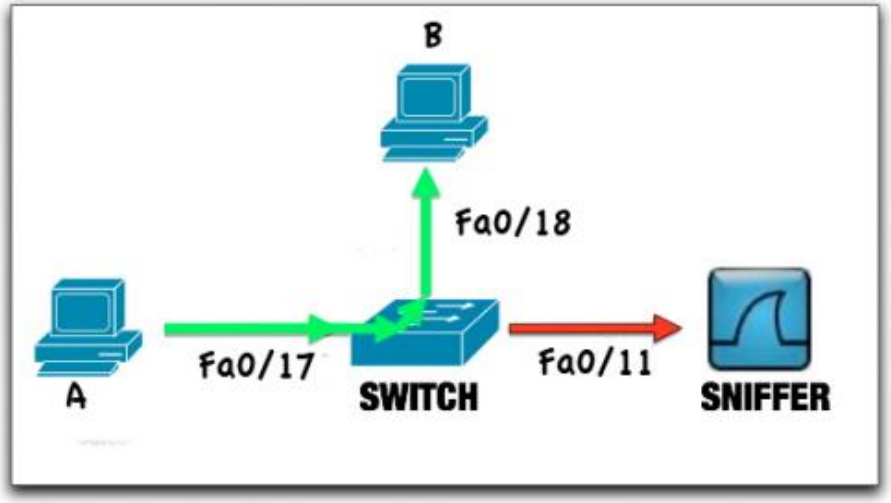
Website: https://www.wireshark.org/

Wireshark – Where to measure

Using a switch

- Connect to normal switch port
- Connect to mirror port

Inaccurate timestamps!

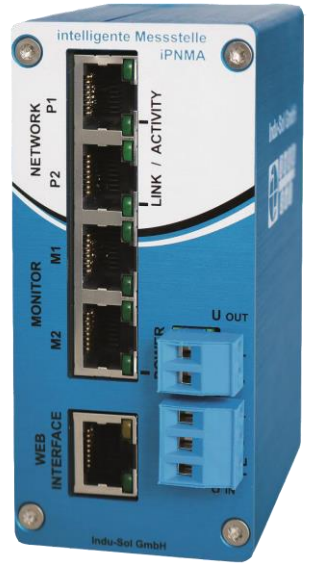


Examples of industrial switches

Wireshark – Where to measure

Using an Ethernet TAP (Terminal Access Point)

- As USB connected ethernet adapter
- Or connected directly to a PC's ethernet port



Examples of Ethernet TAPs

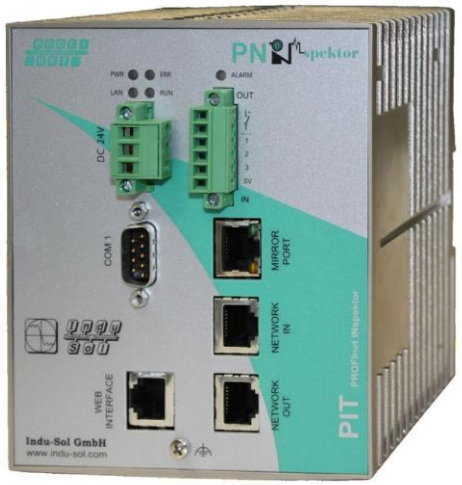
Wireshark – Where to measure

Using Diagnostic devices

- Passive connection in the network
- Permanently monitors the communication
- Snapshot are taken on specific trigger conditions

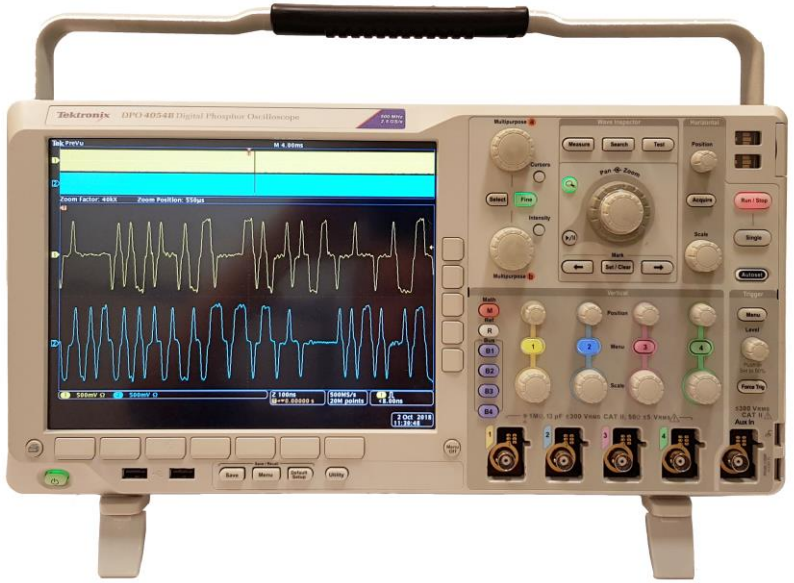
  Snapshots can be exported as pcap-files (Wireshark format)
- Allows for packets to be mirrored

  to a dedicated port



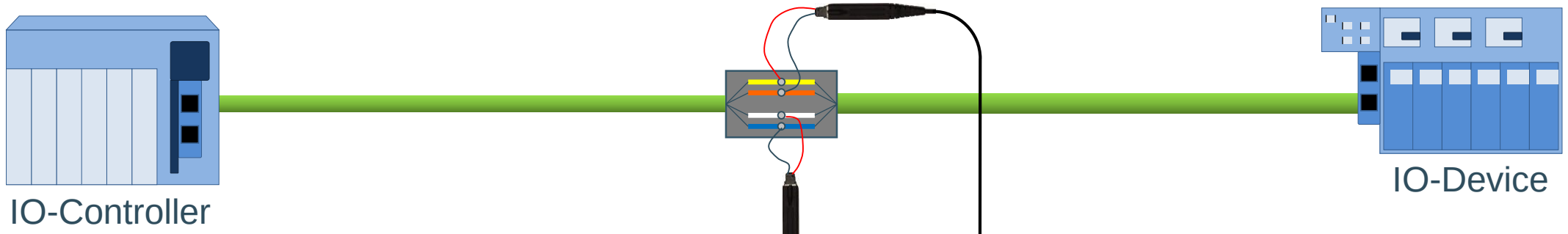
Examples of diagnostic devices

Oscilloscope

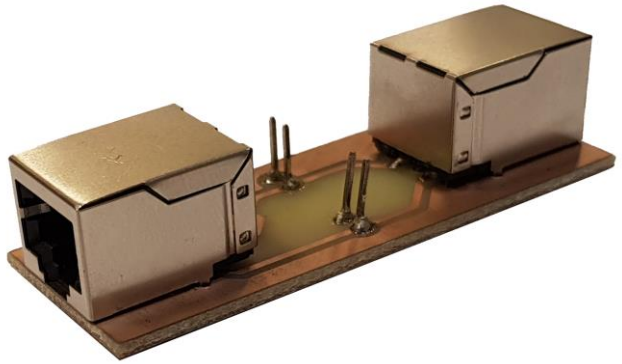


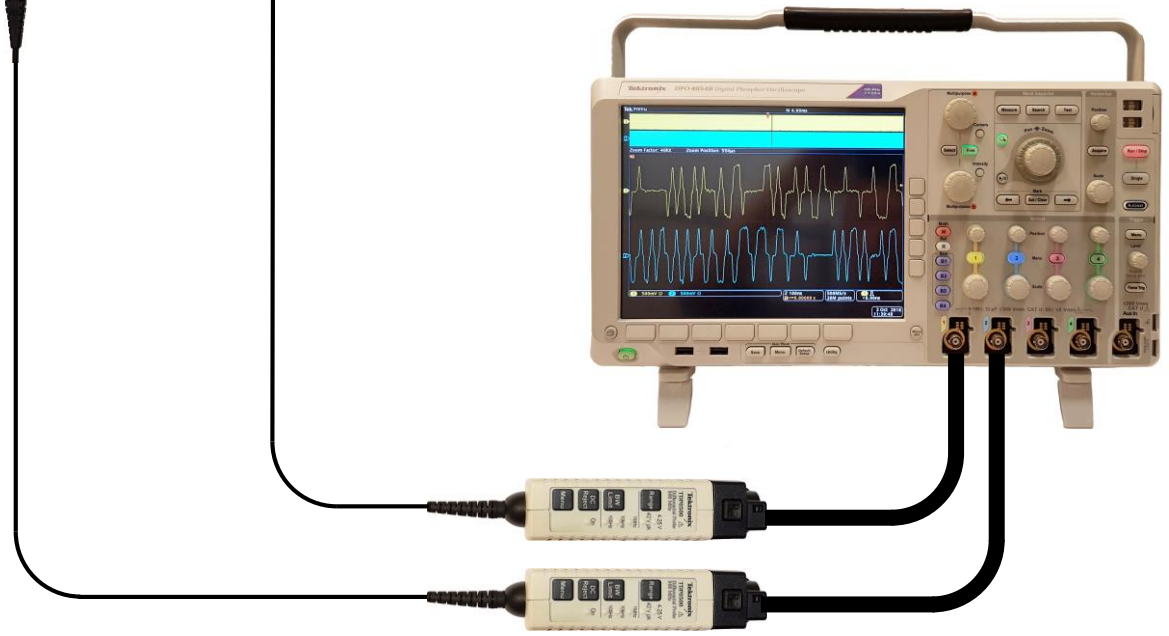
- Why?
  - Visual voltage signals and accurate timestamps
  - Allows measurement on multiple locations in the network
  - Combination of analog signals and network frames
- Waveform can be seen
  - But can’t be decoded by hand
  - Amount of data can be measured/analysed at once
    - 500 MS/s, 20 MS/ch => 40 ms
    - 500 MS/s, 125 MS/ch => 250 ms
  - Useful for highly accurate timing measurements
- Decoding possibilities
  - Some scopes can decode a clean and distortion free ethernet voltage signal

Oscilloscope – How and where to measure



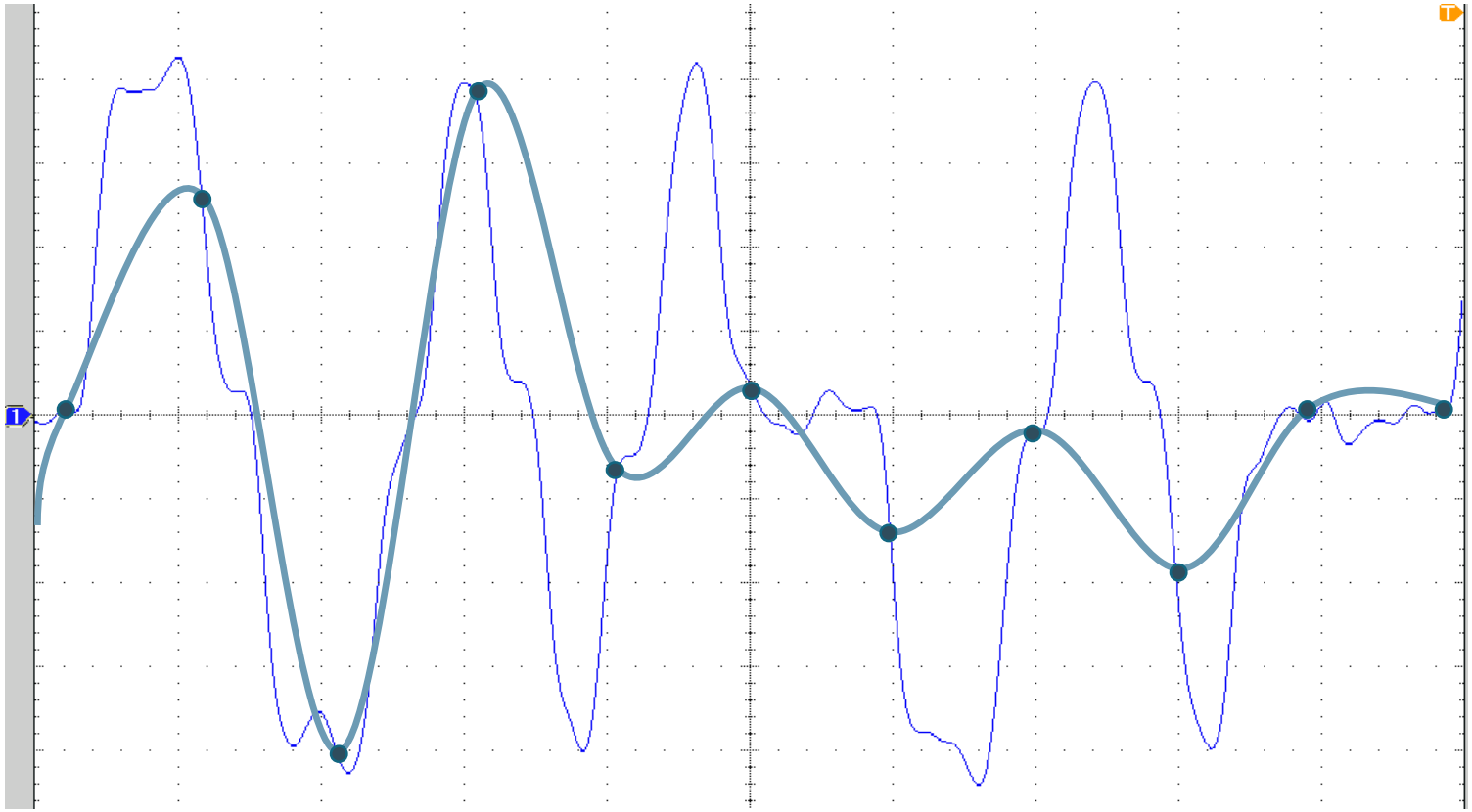
- Breakout board is needed with 2 differential probes





Oscilloscope - Effect of the sampling rate

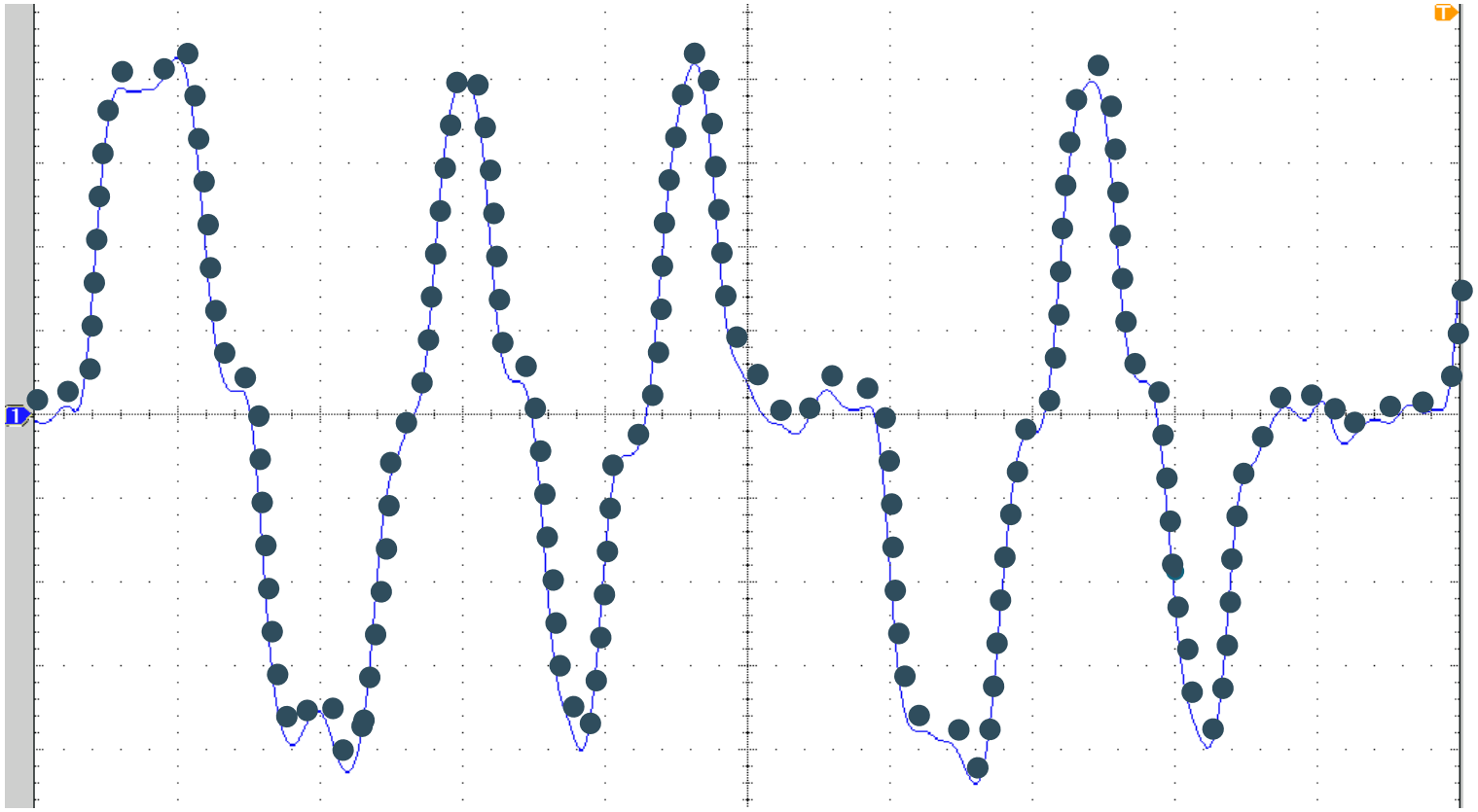
- Low sampling rate
  → Wrong signal



Oscilloscope - Effect of the sampling rate

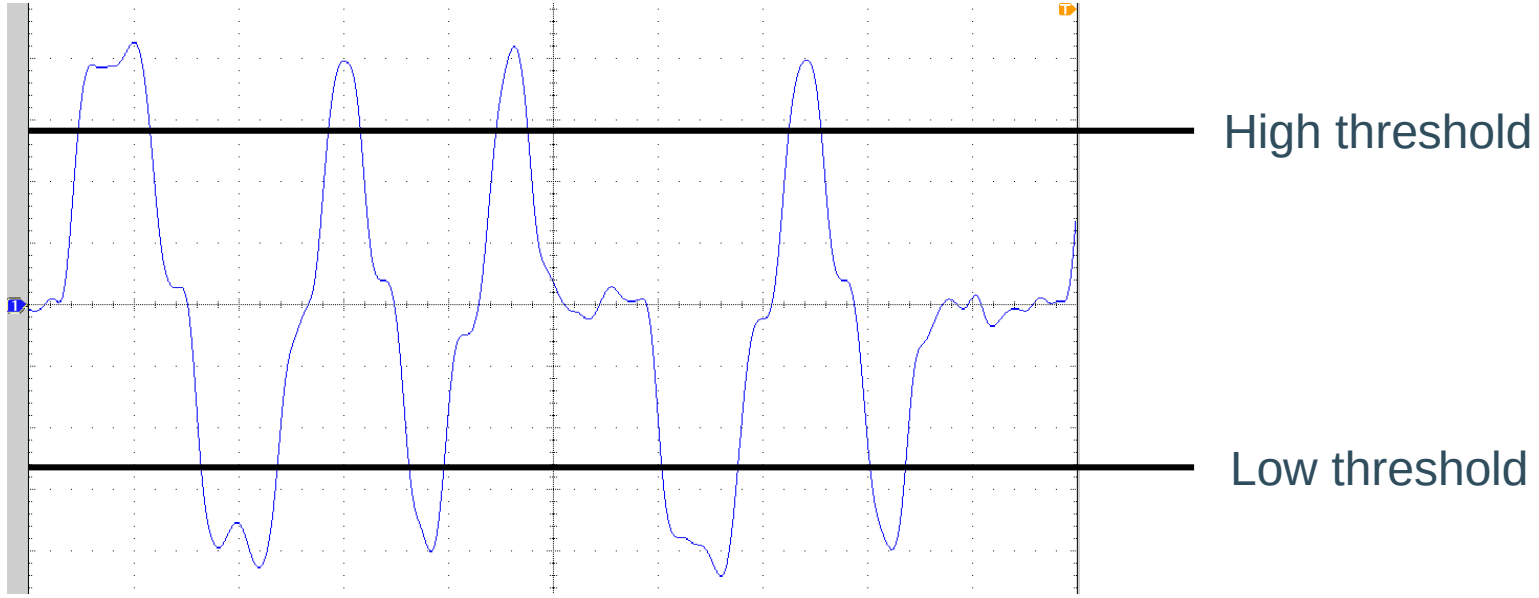
- Low sampling rate
  → Wrong signal
- High sampling rate
  → Correct signal

In practice: 500 MS/s



Oscilloscope – Setting signal levels for decoding

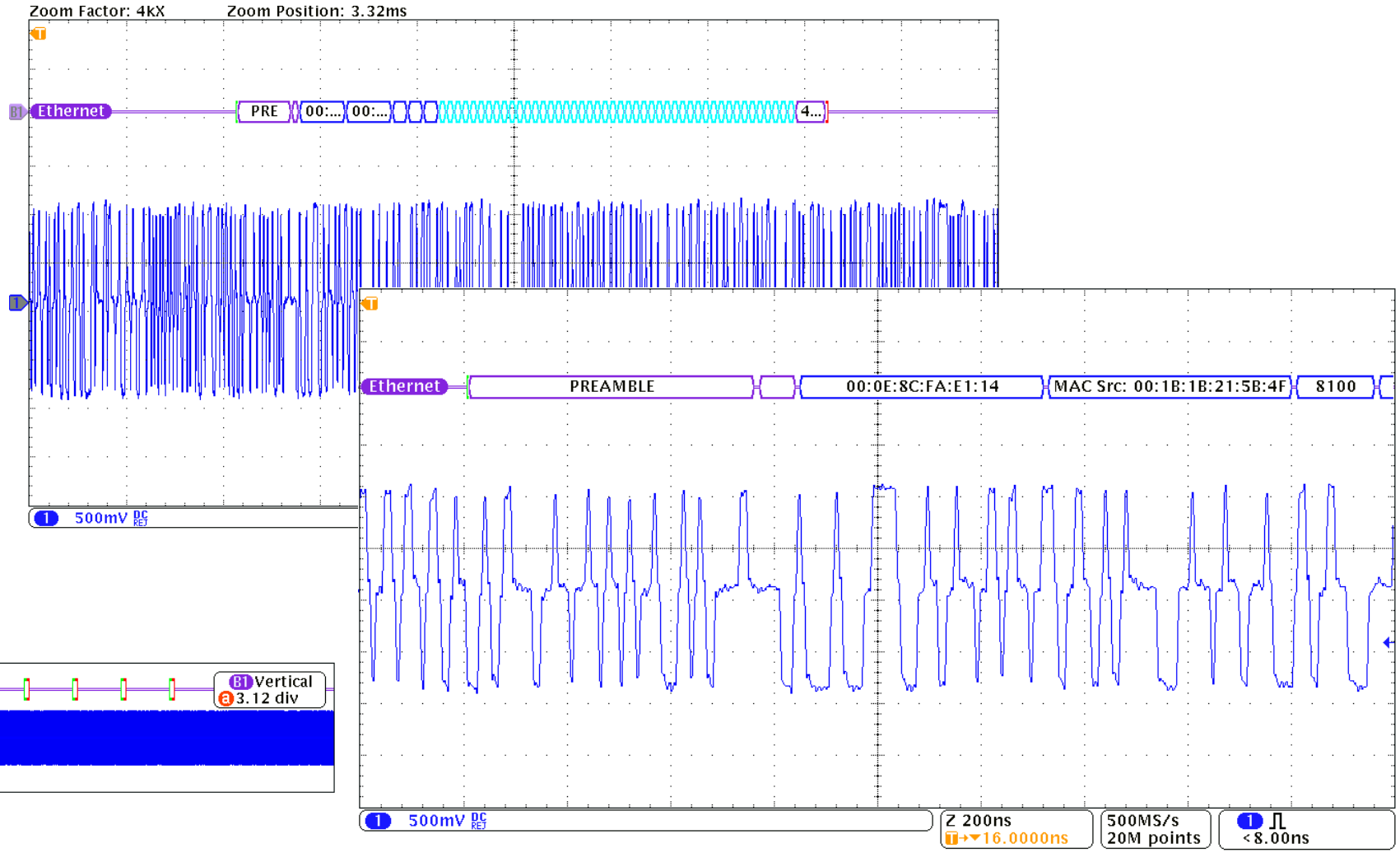
- Determine voltage levels
- When will the signal be seen as a high/low level?

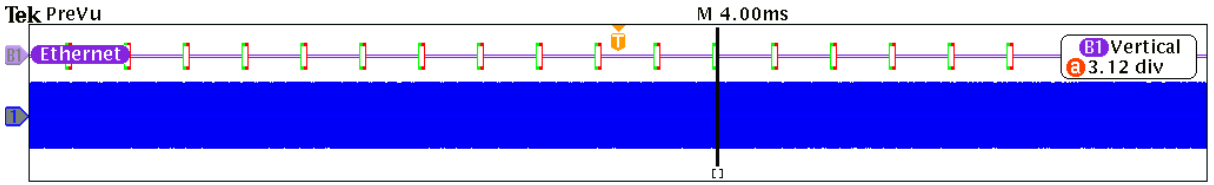


Oscilloscope – Decoding

- All bytes decoded
  (except ESD and IFG)

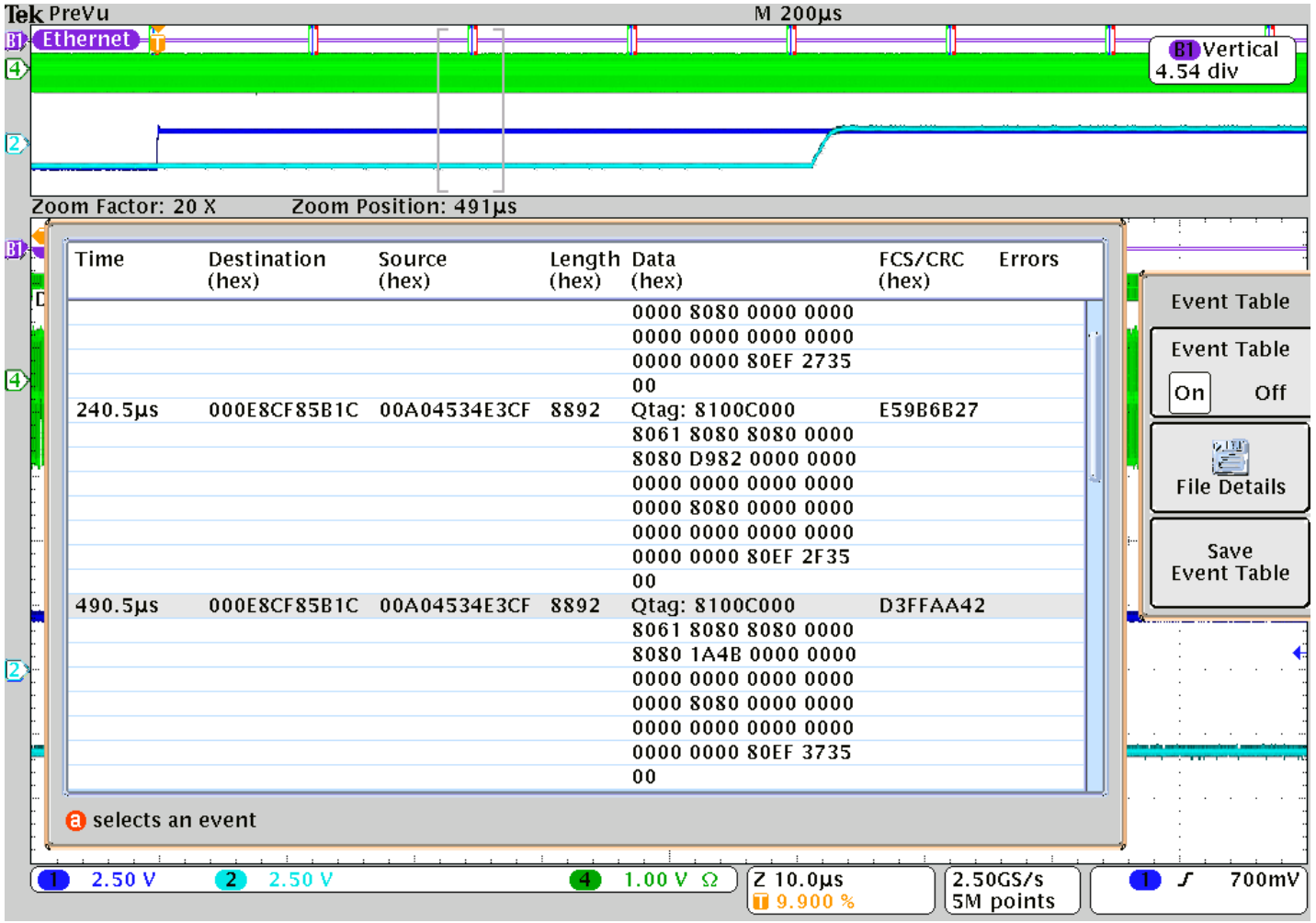
ESD = End of Stream Delimiter
IFG = Inter Frame Gap





Oscilloscope – Decoding

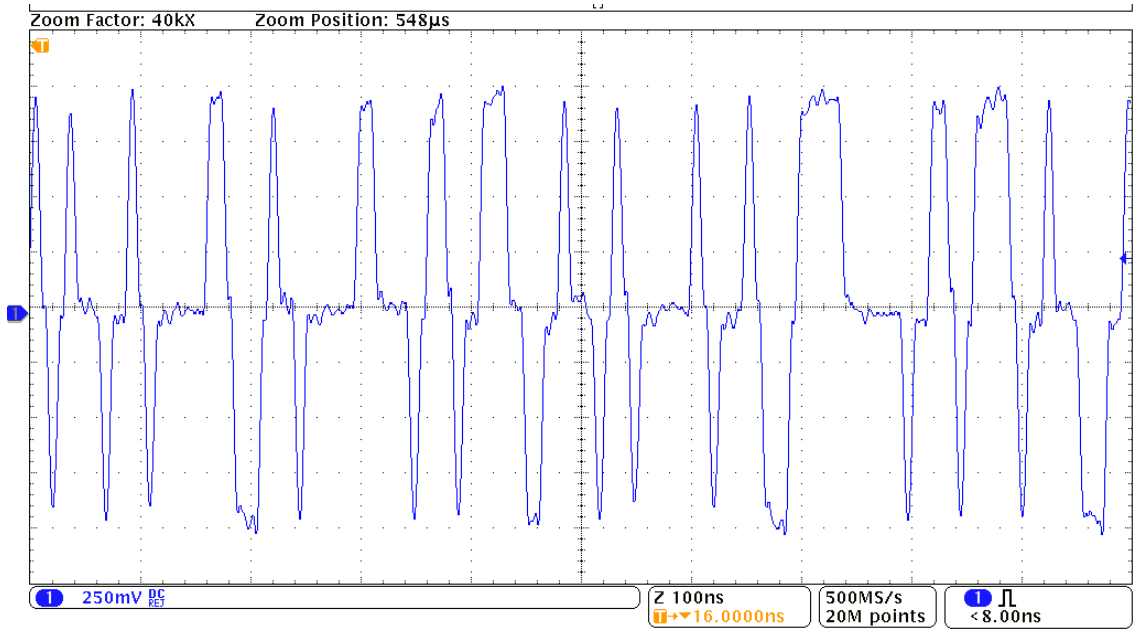
- All bytes decoded
  (except ESD and IFG)
- Event Table



Conclusion from measurements

Effect of too many connectors

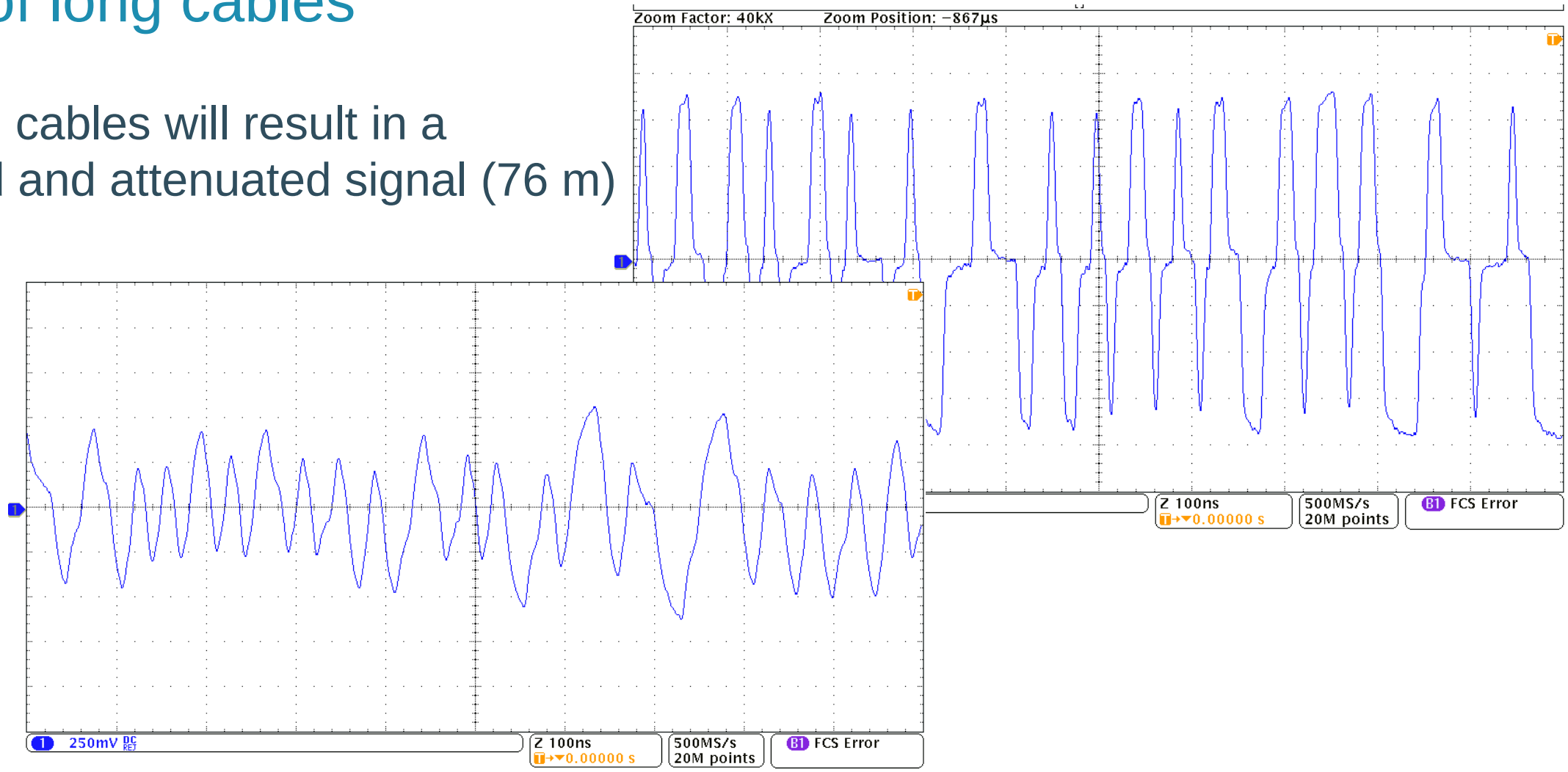
- Too many connectors



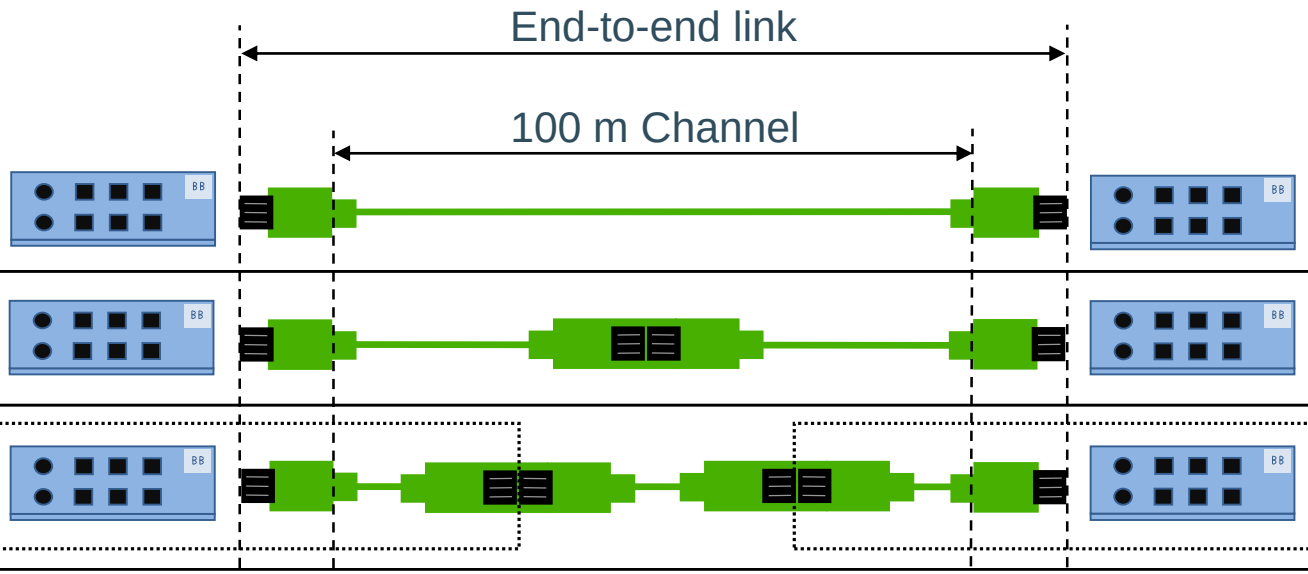
Conclusion from measurements

Effect of long cables

Too long cables will result in a distorted and attenuated signal (76 m)



Copper cable and connectors guideline

Cabling example of two network components	Number of pairs	Maximum distance
	2	100 m
	3	100 m
	4	100 m
		

Pay attention – Design guideline

Outline

- Technology classes – Copper cable
- The 100 Mbps Ethernet voltage signals
- Signal and packet measurement methods
- **Conclusion**

Conclusion

Conclusion

Physical layer on copper has been discussed

- MLT3 and Scrambling reduce the frequency of the voltage signal on the lines
- Voltage signals are not easily interpreted
- Cable length and amount of connectors have a measurable influence on signal quality
- Consult the Design Guidelines of the implemented Industrial Ethernet Protocol

A number of measuring methods have been discussed

- Measuring method will depend on application and the to-acquire data
- In most cases Wireshark will suffice for analysis of packets and communication
- An oscilloscope can be used for accurate timing measurements

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Questions?