

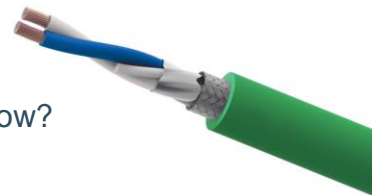
Single Pair Ethernet

CINI4.0 Conference Day – 16/06/2022 - Gent

Arne Verhoeven
Dimitri De Schuyter
Mathieu Troch
Philippe Saey (lecturer)

Outline

- Introduction
 - What is Single Pair Ethernet?
 - Advantages of Single Pair Ethernet
 - Single Pair Ethernet Standards
- SPE: full duplex over one single twisted wire pair – How?
- Ethernet frame – Signal encoding
- Power over Data Line (PoDL)
- Cabling and Connectors
- Ethernet Advanced Physical Layer (APL)
- Conclusion



What is Single Pair Ethernet?

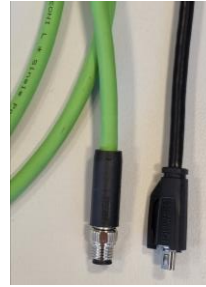
From 2 pair 100 Mbps
(e.g. PROFINET)



To 4 pair 1000 Mbps
(1 Gbps, difficult confection)



To 1 pair 10 – 100 - 1000 Mbps



Single Pair Ethernet (SPE) provides full duplex transmission (and power delivery) over a single balanced twisted wire pair

What is Single Pair Ethernet?

- SPE affects only the physical layer
 - Just like optical fiber, WiFi...
- Layers 2-7 remain unchanged

802.3 Standard Ethernet

Application	<ul style="list-style-type: none"> • End User layer • HTTP, FTP, IRC, SSH, DNS
Presentation	<ul style="list-style-type: none"> • Syntax layer • SSL, SSH, IMAP, FTP, MPEG, JPEG
Session	<ul style="list-style-type: none"> • Synch & send to port • API's, Sockets, WinSock
Transport	<ul style="list-style-type: none"> • End-to-end connections • TCP, UDP
Network	<ul style="list-style-type: none"> • Packets • IP, ICMP, IPSec, IGMP
Data Link	<ul style="list-style-type: none"> • Frames • Ethernet, PPP, Switch, Bridge
Physical	<ul style="list-style-type: none"> • Physical structure • Coax, Fiber, Wireless, Hubs, Repeaters

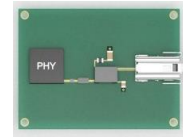
SPE Specific

Advantages of Single Pair Ethernet

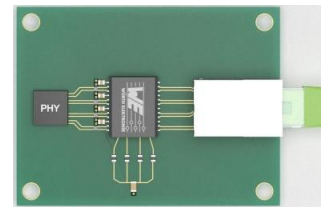
- Smaller connector + reduced footprint
- Lighter, more compact, cheaper and simpler cabling
- Simpler field assembly of connectors
- Power + data over 1 wire pair
- High bandwidth – up to 1000 Mbps
- Low bandwidth (10 Mbps) over 1000 m
 - With optional intrinsic safety
 - With optional re-use of existing fieldbus cabling

→ **Implemented in different standards!**

SPE (10BASE-T1L) PCB



RJ45 PCB



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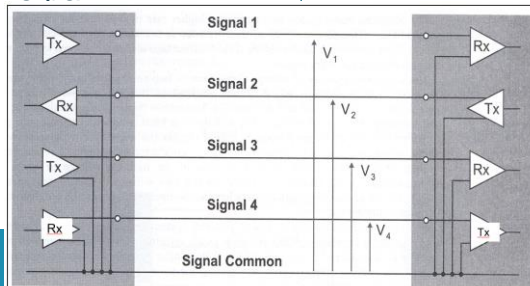
CINI4.0 Conference Day 16/06/2022- Single Pair Ethernet



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What is Single Pair Ethernet?

- **Single Pair Ethernet (SPE) provides full duplex transmission (and power delivery) over a single balanced twisted wire pair**
- **Interpretation - Challenges:**
 - **Balanced**
 - Twisted
 - Full duplex
 - Over *one* wire pair?
 - Signals
 - Power



Balanced (or differential) signals:

- **Unbalanced** = referred to the same common ground
- **Balanced/differential:** e.g. RS485, Ethernet
- Refer to "The Ethernet physical layer revisited" and "Assuring Cabling Infrastructure Readiness - Advanced cable testing for standard and Single Pair Ethernet" and "EMC - Introduction and industrial use cases"

Twisted:

- <> EMI (reduces radiation from the pair, improves rejection of external EMI, reduces crosstalk between neighboring pairs)

6

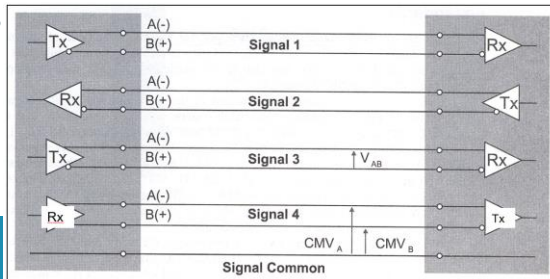
air Ethernet



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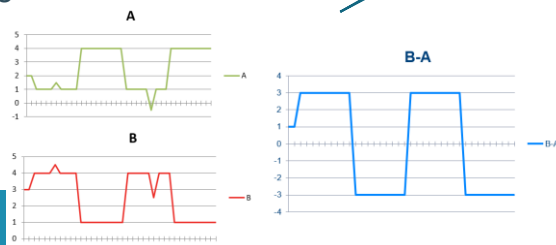
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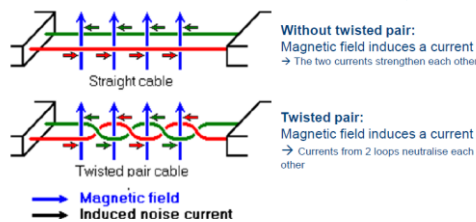
8



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Reduction of inductive coupling



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Single Pair Ethernet



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Full duplex:

- TX/RX possible at the same time
- **Your PROFINET cable has 4 wires, 2 wire pairs: TX and RX are nicely separated!**
- Measurement on 65 m PN cable, voltage signals on TX and RX at switch and IO-Device sides:
 - **Always signals on both wire pairs!** (Unlike e.g. RS232c or RS485)
 - Attenuation of the voltage levels: at one end, and only 65 m
- Refer to "The Ethernet physical layer revisited"

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What is Single Pair Ethernet?



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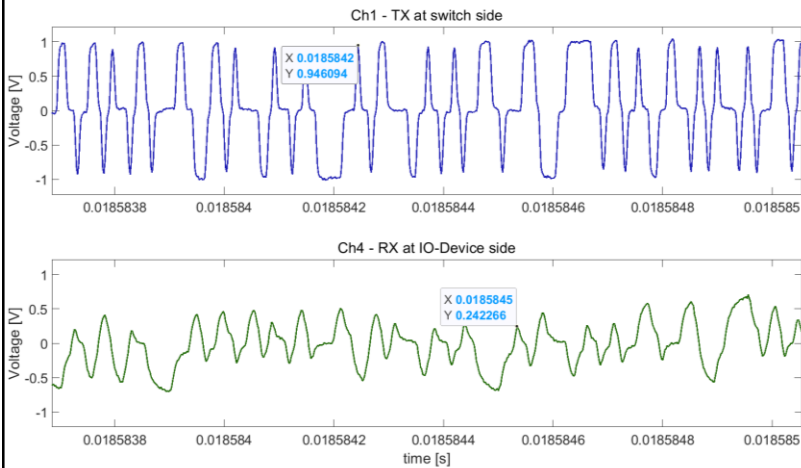
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What is Single Pair Ethernet?

- Single Pair Ethernet (SPE) provides full duplex transmission (and power delivery) over a single balanced twisted wire pair

• Interpretation - Challenges:

- Balanced
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- **Full duplex**
- **Over one wire pair?**
 - **Signals**
 - **Power**

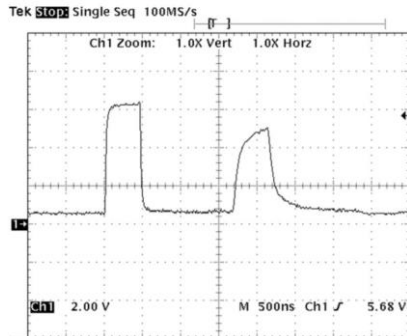
Over one wire pair ???

- **Superposition of signals** as these are always present
- Large one from the "near end" superimposes on the small one coming from the "far end"
- Some types of SPE cable are a 1000 m long ... up to 60 dB less signal (depending on the frequency)
- We see on both sides reflections ("echo") because of small changes in characteristic impedance along the way (passive connections, different cable types, ageing and wear, ...)
- We pick up disturbances along the way
- And ... PoE requires 4 wires ...

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Background: reflection – RS485 example

Open line ($R_t > Z_0$)



Reflection coefficient

- The way how a signal will be reflected can be calculated by the reflection coefficient:

$$\Gamma = \frac{Z_L - Z_S}{Z_L + Z_S}$$

- For short circuited lines:

A reflection coefficient of -1 = total and negative reflection

$$\Gamma = \frac{0\Omega - 150\Omega}{0\Omega + 150\Omega} = -1$$

- For open lines:

A reflection coefficient of +1 = total and positive reflection

$$\Gamma = \frac{\infty\Omega - 150\Omega}{\infty\Omega + 150\Omega} = 1$$

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SPE Standards in short

- 10BASE-T1S**
 - Half duplex, point-to-point or multidrop, 25 m
- 10BASE-T1L**
 - Full duplex, 1000 m, power, intrinsic safety
- 100BASE-T1**
 - Full duplex, power, 40 m
- 1000BASE-T1**
 - Full duplex, power, 40 m

Automotive

Industrial

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SPE Standards - Properties

	10BASE-T1S	10BASE-T1L	100BASE-T1	1000BASE-T1
Standard	802.3cg-2019	802.3cg-2019	ISO/IEC/IEEE 8802-3:2017/Amd 1-2017	ISO/IEC/IEEE 8802-3:2017/Amd 4-2017
Duplex type	Half duplex	Full duplex	Full duplex	Full duplex
Max. unshielded cable length (m)	15 (point-to-point) 25 (multidrop)	/	15	15
Max. shielded cable length (m)	15 (point-to-point) 25 (multidrop)	1000	40	40
Max peak-to-peak voltage level of transceiver (V)	1	1, 2.4	2.2	1.3
PoDL	Point-to-point: Yes Multidrop: in progress	Yes	Yes	Yes
Extra features	Multidrop	Ethernet-APL with intrinsic safety for process industry		

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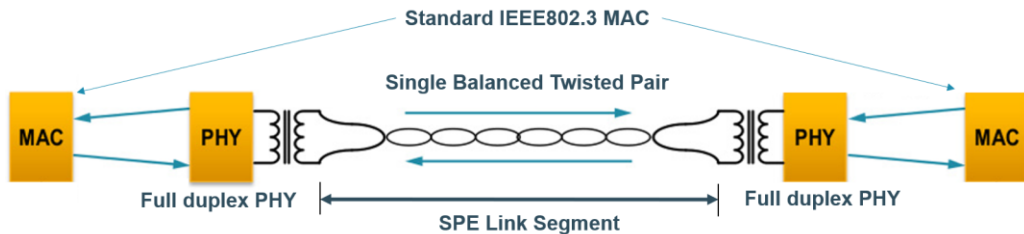
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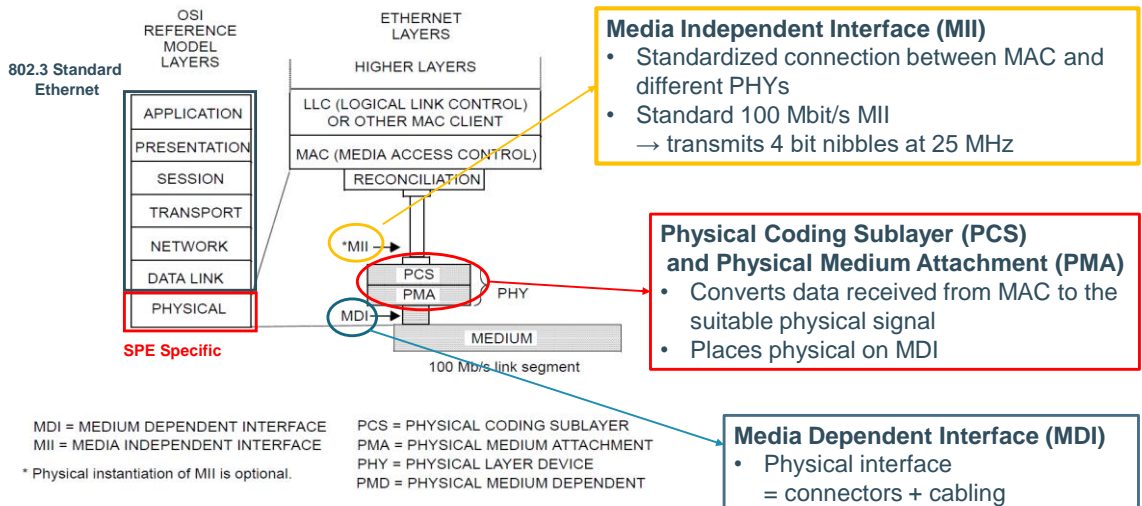
SPE: full duplex over one single twisted wire pair

- SPE affects only the physical layer
 - Just like optical fiber, WiFi...
- Layers 2-7 remain unchanged
- PHY interfaces with data link "MAC" layer using the standardized Media Independent Interface (MII) => also here reuse of (part of) the existing electronic design



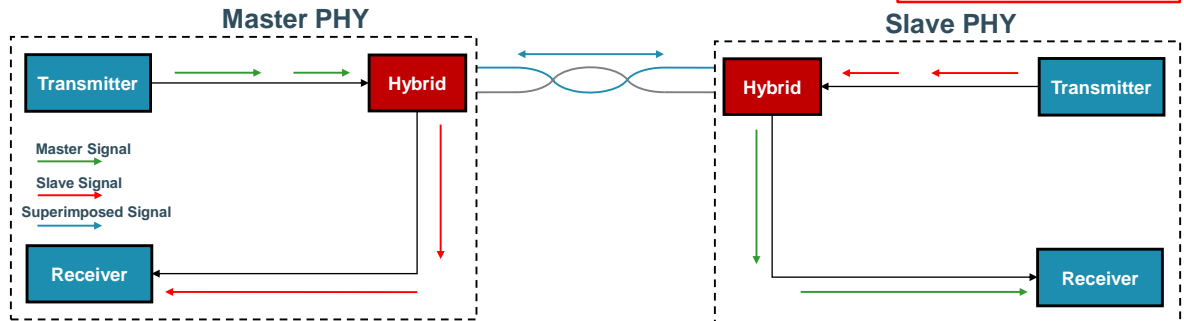
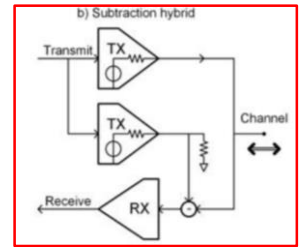
SPE: full duplex over one single twisted wire pair

Interfacing SPE PHY with standard 802.3 MAC



SPE: full duplex over one single twisted wire pair

- Both transmitters send simultaneously → signals are superimposed on cable
- PHY must separate transmitted and received signal → **hybrid** circuit



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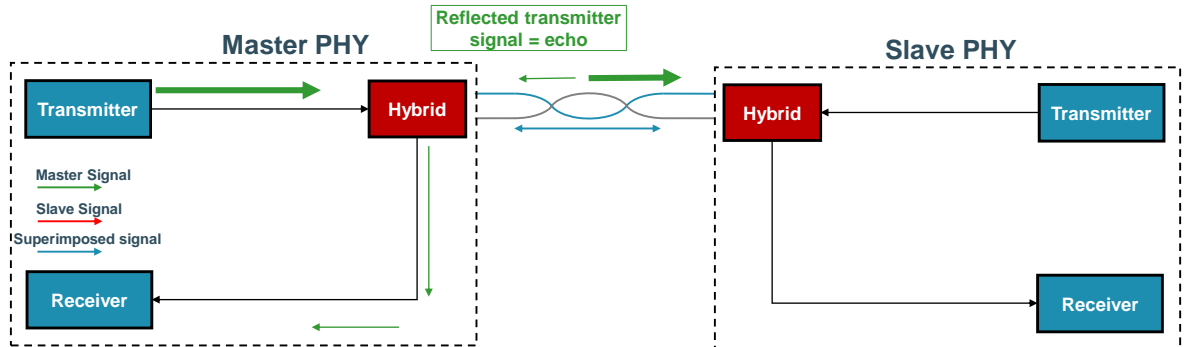
User committee



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SPE: full duplex over one single twisted wire pair

- But... impedance mismatches exist → part of transmitted signal reflected: “echo”
- Echo can not be interpreted as a received signal from partner PHY



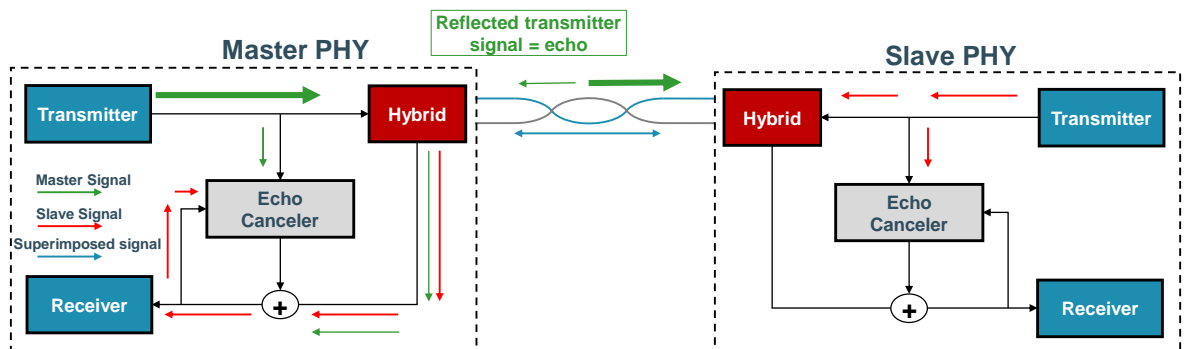
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SPE: full duplex over one single twisted wire pair

- But... impedance mismatches exist → part of transmitted signal reflected: “echo”
- Echo can not be interpreted as a received signal from partner PHY
→ **Removed by Echo Canceller** (signals drawn only on Master side)



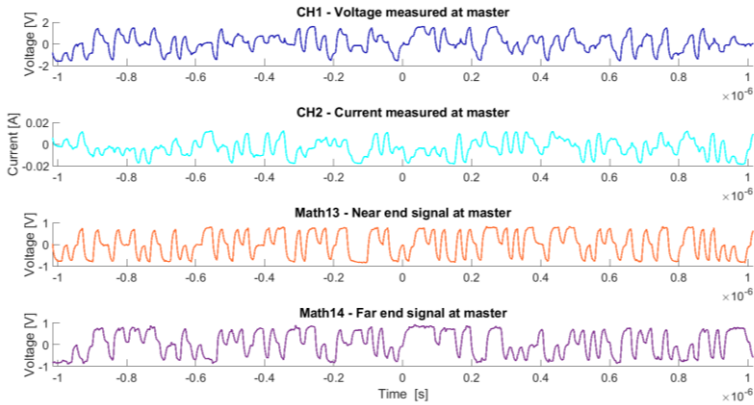
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SPE: full duplex over one single twisted wire pair

- How do 100BASE-T1 signals look like?



Measurements with 8 CH Tektronix, TEK specific measuring principle

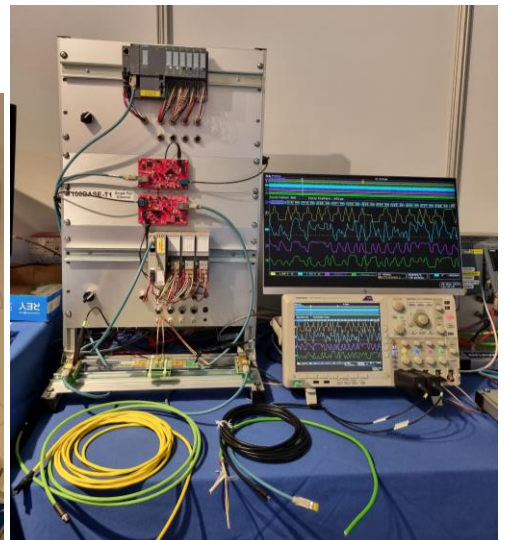
25

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SPE: full duplex over one single twisted wire pair

- How do 100BASE-T1 signals look like?



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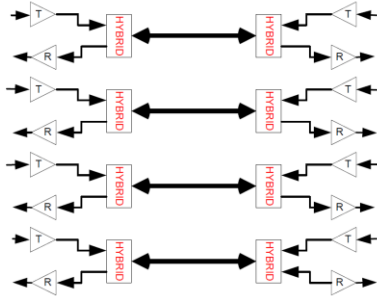
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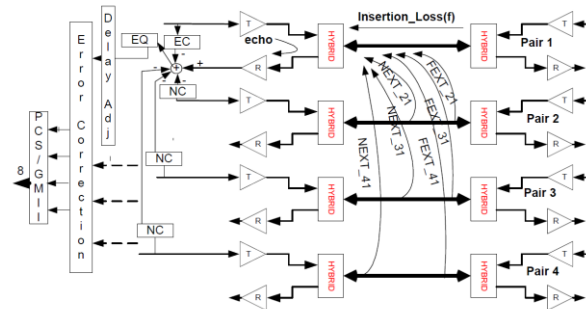
SPE: full duplex over one single twisted wire pair

- Surprise: it's nothing new ...
- Your 1 Gbps Ethernet uses ... SPE signaling

Use all four pairs with full-duplex transmission on each pair. (Requires hybrid.)



1000BASE-T uses DSP-based adaptive filtering to cancel the effects of echo, crosstalk and noise



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- Introduction
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 - Single Pair Ethernet Standards
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- **Ethernet frame – Signal encoding**
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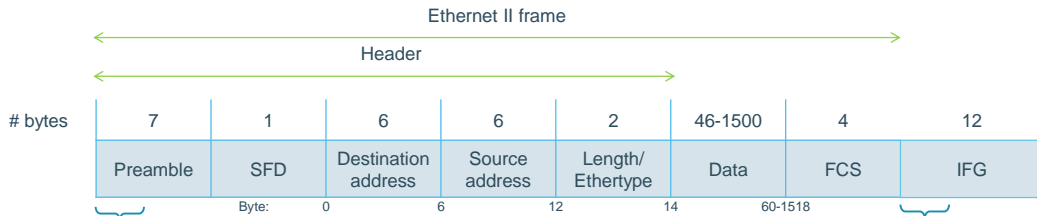


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The Ethernet Frame

- Ethernet frame remains the same, except preamble and Inter Frame Gap (IFG)
 - Start- and end-of-stream delimiter added (SSD and ESD)

Also in e.g. PRP redundancy and "in the wireless phase" in WiFi you get a header/trailer: invisible for end user



Start-of-Stream Delimiter (SSD)

- Replaces first x bits of preamble
 - 10BASE-T1L: 16 bits
 - 100BASE-T1: 9 bits
 - 1000BASE-T1: 9 bits

End-of-Stream Delimiter (ESD)

- Replaces first y bits of IFG
 - 10BASE-T1L: 16 bits
 - 100BASE-T1: 9 bits
 - 1000BASE-T1: 9 bits

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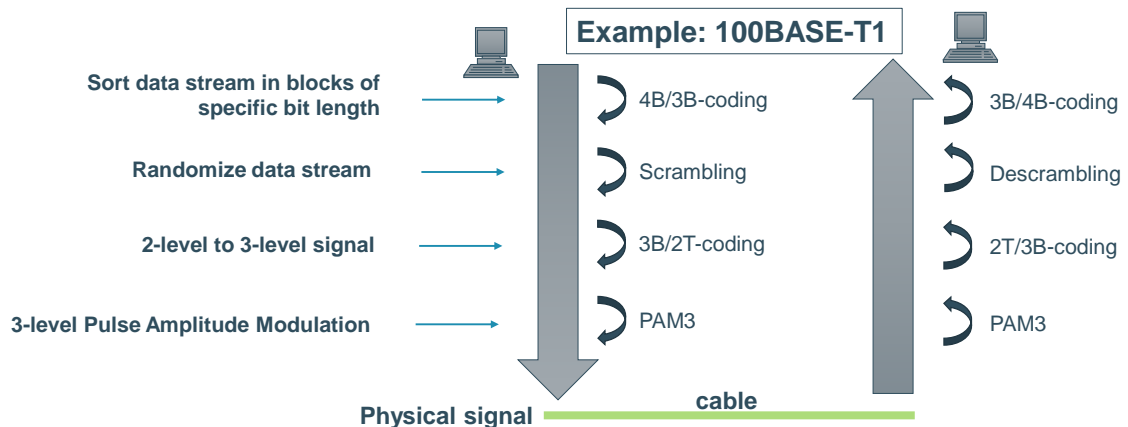
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100BASE-T1 Signal Encoding

- Different standards = different physical signals
- But... they share common encoding principles (except 10BASE-T1S)



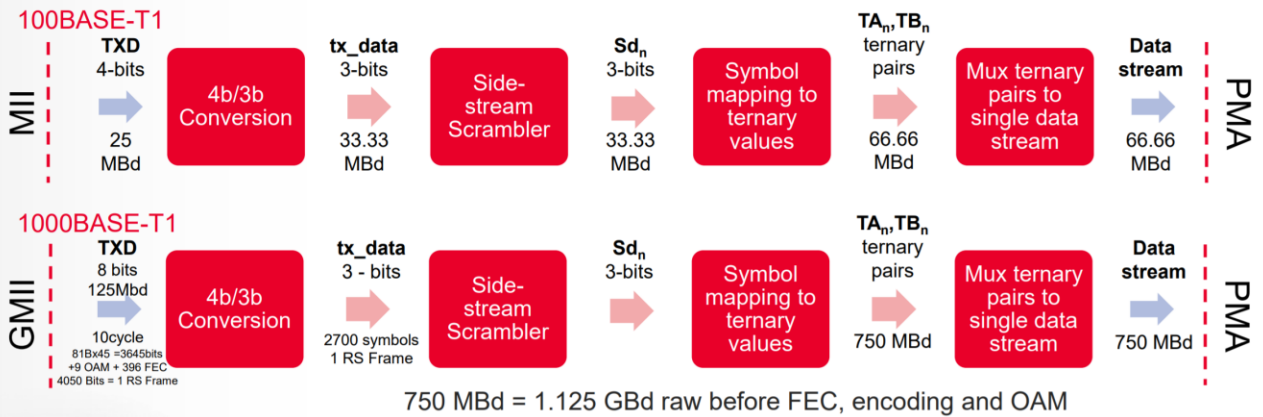
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100BASE-T1 and 1000BASE-T1



100BASE-T1 PCS

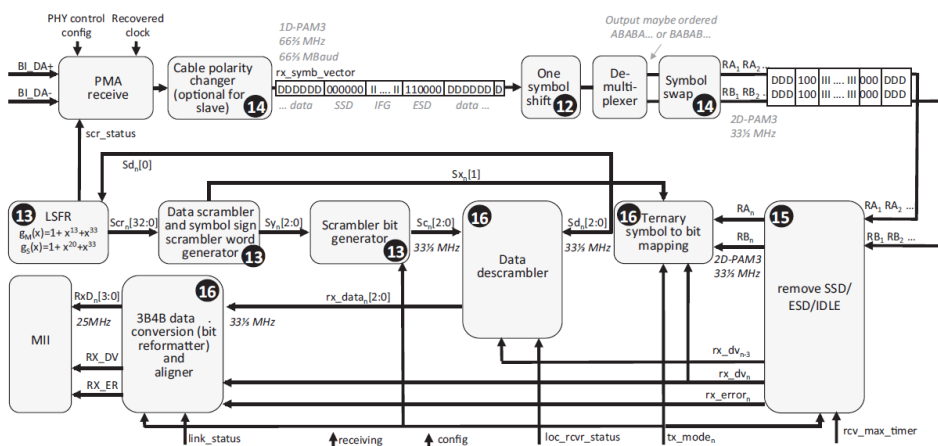
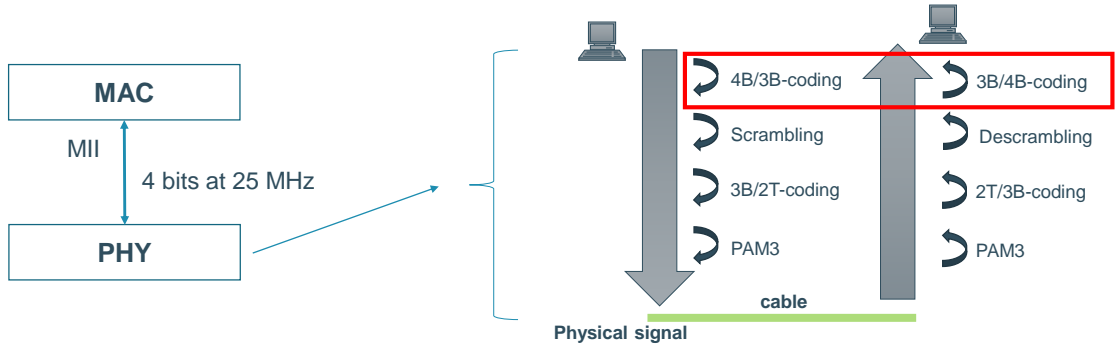


Figure 4.29 Example for elements of a 100BASE-T1/OABR PCS receiver.

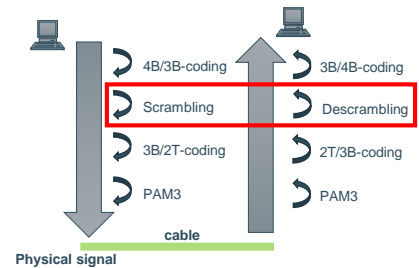
100BASE-T1 – 4bit/3bit Encoding

- Data stream from MAC layer → 4-bit nibbles at 25 MHz
- Convert to 3-bit blocks at 33,3 MHz

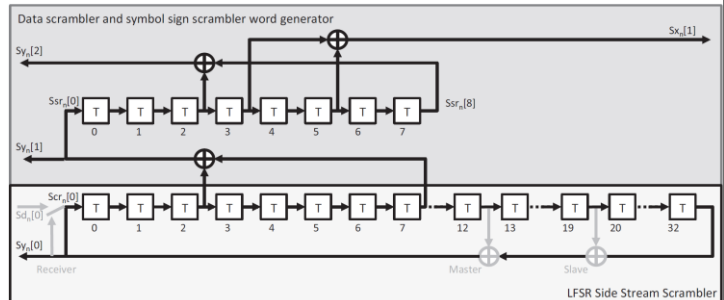


100BASE-T1 Scrambling

- Data stream scrambled using a pseudo-random code
- Prevent loss of synchronization between PHYs
- Spread transmit power over frequency band
- Reduces DC portion of signal
- Reduces electromagnetic interference
- Reduces radiated emissions



Scrambler function



100BASE-T1 – 3bit/2ternary encoding

- Ternary = 3-level value (-1, 0, 1)
- 3-bit blocks coded into 2 ternaries – 9 possibilities
- Coding table dependent on PHY status

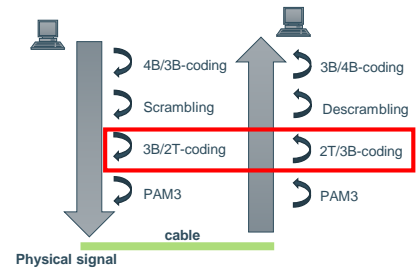


Table 96-2—Data symbols when tx_mode=SEND_N

Sd _n [2:0]	TA _n	TB _n
000	-1	-1
001	-1	0
010	-1	1
011	0	-1
Used for SSD/ESD	0	0
100	0	1
101	1	-1
110	1	0
111	1	1

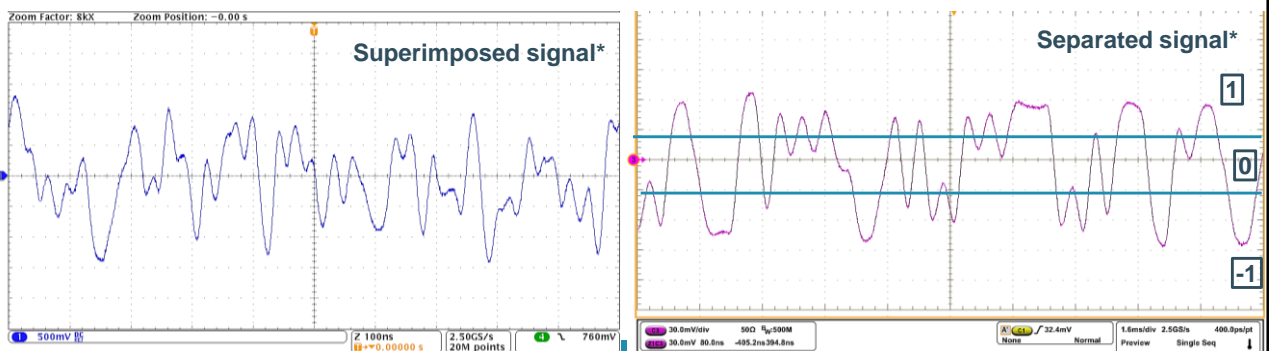
Encoding example

3B	001	100	111
2T	-1, 0	0, 1	1, 1

TI : 100BASE-T1 Ethernet: the evolution of automotive networking

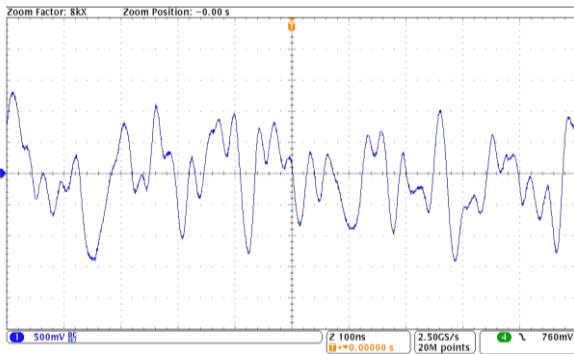
PAM3-Modulation

- 3-level Pulse Amplitude Modulation (PAM3)
 - 3 amplitude levels (Ternary) → -1, 0, 1
- Transmitted at 66,6 MHz, 1 ternary every 15 ns
- Full duplex transmission → 2 PAM3 signals superimposed on cable

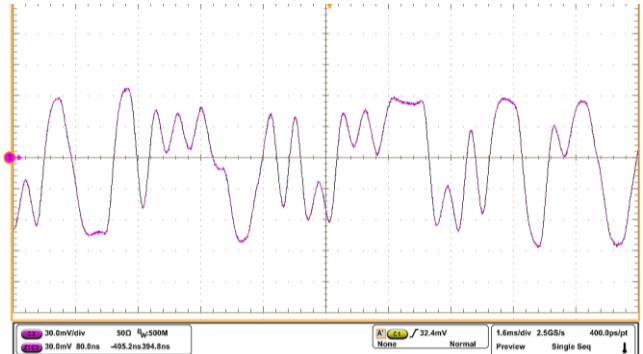


PAM3-Modulation

Superimposed signal*



Separated signal*



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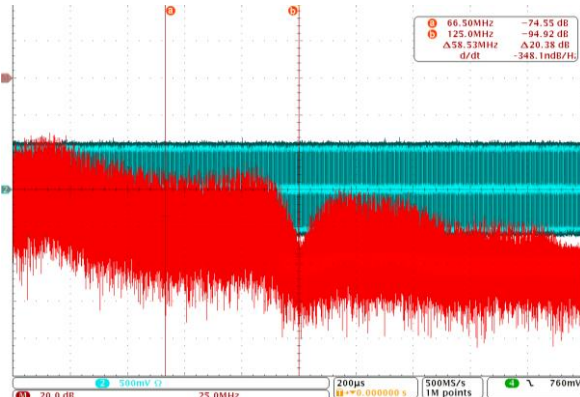
*Measurement methods discussed during demo CINI4.0 Conference Day 16/06/2022- Single Pair Ethernet



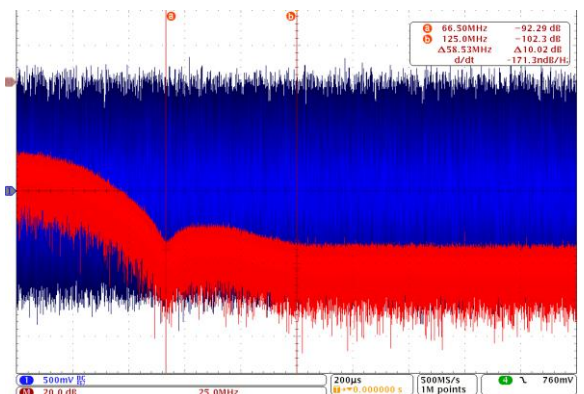
PAM3-Modulation

- 100BASE-T1 has a reduced frequency content compared to 100BASE-TX

100BASE-TX



100BASE-T1

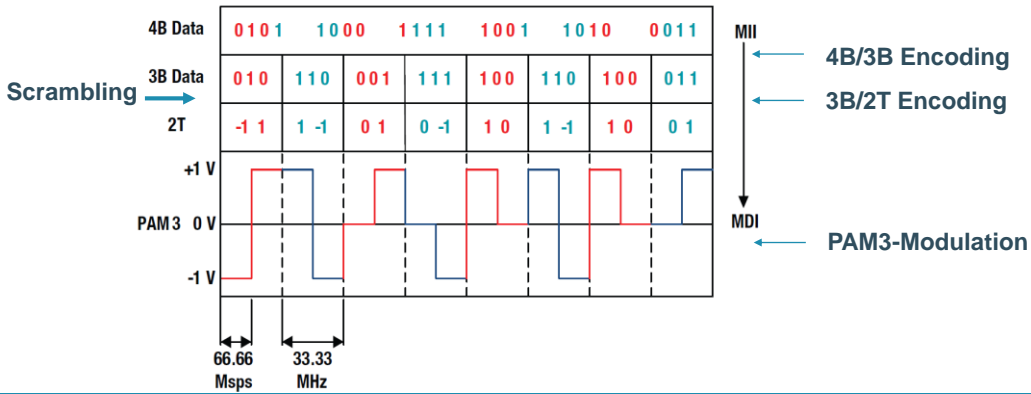
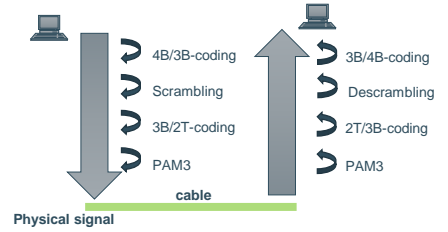


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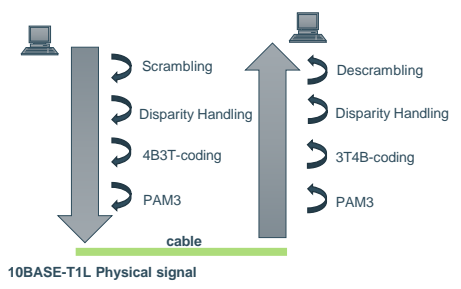


100BASE-T1 Summary



10BASE-T1L Encoding

- 2 Amplitude options: $1 V_{ptp}$ and $2.4 V_{ptp}$
- Max cable length: 1000 m
- Encoding systems
 - Scrambling, Disparity handling, 4B3T, PAM3



- Disparity = difference between transmitted “+1” and “-1” symbols
- Disparity handling
 - **Goal** → Achieve DC-free PAM3 transmission = DC-free 4B3T coding
 - **How** → Change 4B3T coding table based on disparity

10BASE-T1L Disparity handling

- Default disparity = 2
- E.g. data stream
0011 1001 1100
↙ Disparity +1 ↓ Disparity +1 ↘ Disparity -1
- 4B3T Coding
 00+ +-+ +-
 Resulting disparity = 3

Default ↗

Sd _n [3:0]	Disparity = 1		Disparity = 2		Disparity = 3		Disparity = 4	
	Ternary Triplet	Disparity Change	Ternary Triplet	Disparity Change	Ternary Triplet	Disparity Change	Ternary Triplet	Disparity Change
0000	+0+	2	0-0	-1	0-0	-1	0-0	-1
0001	0-+	0	0-+	0	0-+	0	0-+	0
0010	+0-	0	+0-	0	+0-	0	+0-	0
0011	00+	1	00+	1	00+	1	--0	-2
0100	-+0	0	-+0	0	-+0	0	-+0	0
0101	0++	2	-00	-1	-00	-1	-00	-1
0110	--+	1	--+	1	--+	-1	--+	-1
0111	-0+	0	-0+	0	-0+	0	-0+	0
1000	+00	1	+00	1	+00	1	0--	-2
1001	+++	1	+++	1	+++	1	---	-3
1010	++-	1	++-	1	++-	-1	++-	-1
1011	+0-	0	+0-	0	+0-	0	+0-	0
1100	+++	3	+-	-1	+-	-1	+-	-1
1101	0+0	1	0+0	1	0+0	1	-0-	-2
1110	0+-	0	0+-	0	0+-	0	0+-	0
1111	++0	2	00-	-1	00-	-1	00-	-1

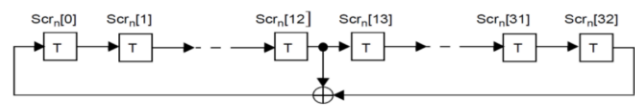
4B3T Coding based on disparity

10BASE-T1L Scrambler

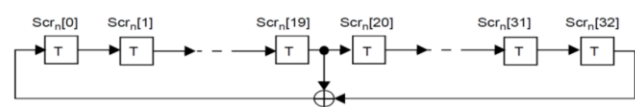
$$g_M(x) = 1 + x^{13} + x^{33}$$

$$g_S(x) = 1 + x^{20} + x^{33}$$

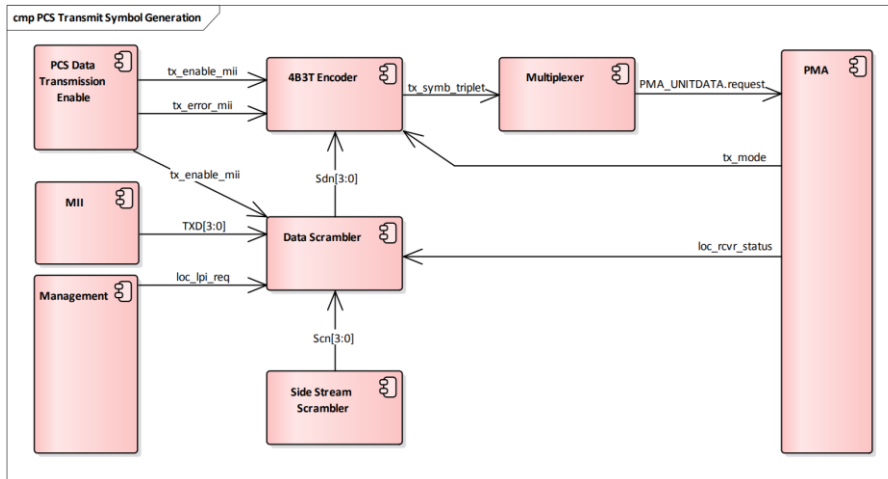
Side-stream scrambler employed by the MASTER PHY



Side-stream scrambler employed by the SLAVE PHY



10BASE-T1L Transmit Symbol Generation Block Diagram



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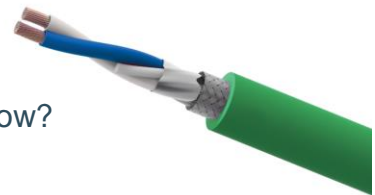
https://www.ieee802.org/3/cg/public/Sept2017/Graber_3c115a_0917.pdf



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Outline

- Introduction
 - What is Single Pair Ethernet?
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- **Power over Data Line (PoDL)**
- Cabling and Connectors
- Ethernet Advanced Physical Layer (APL)
- Conclusion



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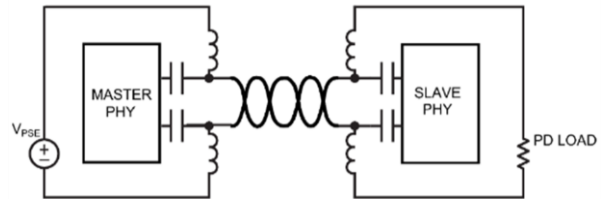
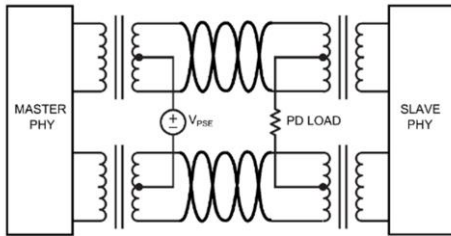
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PoE and PoDL Principles

*Power to device

2 Types of devices

- Load: Powered Device PD
- Source: Power Sourcing Equipment PSE
- **Power over Ethernet (PoE)**
 - PSE and PD connected through transformer center taps
 - 44-57 V
 - Max. 25,5 W* (802.3at, **4-wire cabling**)
- **SPE – Power over Data Line (PoDL)**
 - PSE and PD Connected through highpass/lowpass band splitting network
 - 12, 24, 48 V
 - Max. 50 W (802.3bu)



"A Quick Walk Around the Block with PoDL", D. Dwelly. IEEE P802.3bu Power over Data Lines Tutorial
– November 2015 IEEE 802.3 Plenary

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PoDL power classes (802.3bu)

	12 V Unregulated PSE		12 V Regulated PSE		24 V Unregulated PSE		24 V Regulated PSE		48 V Regulated PSE	
Class	0	1	2	3	4	5	6	7	8	9
$V_{PSE(max)}$ (V)	18	18	18	18	36	36	36	36	60	60
$V_{PSE_OC(min)}$ (V)	6	6	14.4	14.4	12	12	26	26	48	48
$V_{PSE(min)}$ (V)	5.6	5.77	14.4	14.4	11.7	11.7	26	26	48	48
$I_{PI(max)}$ (mA)	101	227	249	417	97	339	215	461	735	1360
$P_{Class(min)}$ (W)	0.566	1.31	3.59	6.79	1.14	3.97	5.59	12	35.3	65.3
$V_{PD(min)}$ (V)	4.94	4.41	12	10.6	10.3	8.86	23.3	21.7	40.8	36.7
$P_{PD(max)}$ (W)	0.5	1	3	5	1	3	5	10	30	50

$V_{PSE(max)}$ → Maximum allowed voltage at the PSE PI over the full range of operating conditions

$V_{PSE_OC(min)}$ → Minimum allowed open circuit voltage measured at the PSE PI

$I_{PI(max)}$ → Maximum current flowing at the PSE and PD PIs except during inrush or an overload condition

$P_{Class(min)}$ → Minimum average available output power at the PSE PI

$P_{PD(max)}$ → Maximum average available power at the PD PI

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IEEE802.3bu

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Extended SPE power classes for 10BASE-T1L (802.3cg)

Also refer to the APL lecture

Class	10	11	12	13	14	15
$V_{PSE(max)}$ (V)	30	30	30	58	58	58
$V_{PSE_OC(min)}$ (V)	20	20	20	50	50	50
$V_{PSE(min)}$ (V)	20	20	20	50	50	50
$I_{PI(max)}$ (mA)	92	240	632	231	600	1579
$P_{Class(min)}$ (W)	1.85	4.8	12.63	11.54	30	79
$V_{PD(min)}$ (V)	14	14	14	35	35	35
$P_{PD(max)}$ (W)	1.23	3.2	8.4	7.7	20	52

$V_{PSE(max)}$ → Maximum allowed voltage at the PSE PI over the full range of operating conditions

$V_{PSE_OC(min)}$ → Minimum allowed open circuit voltage measured at the PSE PI

$I_{PI(max)}$ → Maximum current flowing at the PSE and PD PIs except during inrush or an overload condition

$P_{Class(min)}$ → Minimum average available output power at the PSE PI

$P_{PD(max)}$ → Maximum average available power at the PD PI

* Single-pair Power over Ethernet (SPoE) use these classes. Refer to Ethernet Alliance.

IEEE802.3cg

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https://ethernetalliance.org/wp-content/uploads/2021/07/EA_TechBrief-SPE-SPoE_FINAL.pdf

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(Industrial) Cabling for Single Pair Ethernet

"The standard makes the impossible possible in terms of utilizing Ethernet for two-wire long-distance communications" (TI ⁽¹⁾)

• 100BASE-T1, 1000BASE-T1

- 40 m
- Shielded
- Defined in IEC 61156-11 (fixed installation) and IEC 61156-12 (flexible installation)
- 600 MHz bandwidth required
- 100 Ω characteristic impedance

Refer to lecture "Assuring Cabling Infrastructure Readiness - Advanced cable testing for standard and Single Pair Ethernet"

• 10BASE-T1L

- (Minimum) 200 m ($1 V_{ptp}$), 1000 m ($2.4 V_{ptp}$) ($TI: 1000\text{ m} (1 V_{ptp}), \text{ up to } 2000\text{ m} (2.4 V_{ptp})$)
- Shielded
- 20 MHz bandwidth required
- Cabling requirements fit Fieldbus type A cable (e.g. PROFIBUS PA, Foundation Fieldbus)
- 100 Ω characteristic impedance

50 (1) Application Report: Extend Network Reach with IEEE 802.3cg 10BASE-T1L Ethernet PHYs, Texas Instruments

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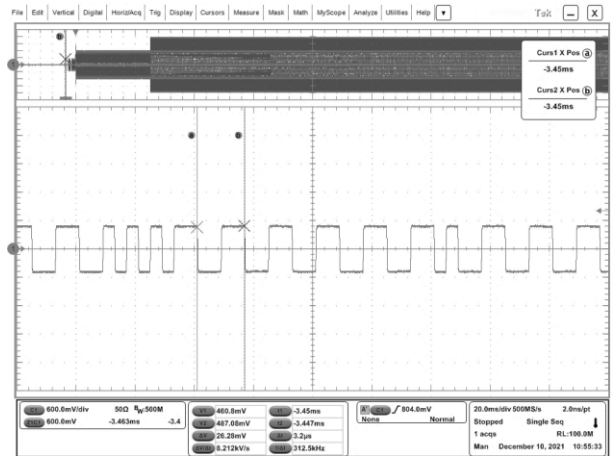
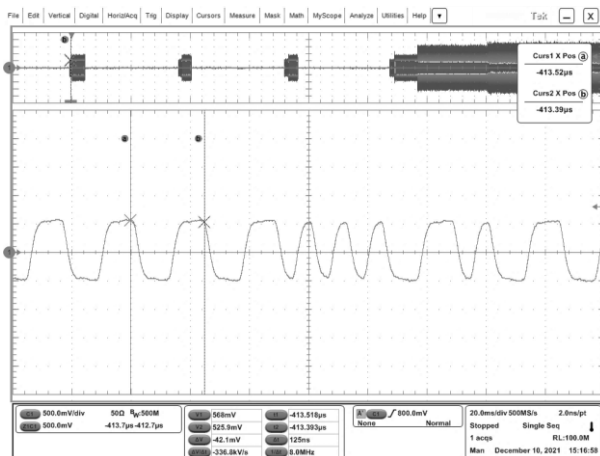


Negotiation phase has different requirements !

100BASE-T1 negotiation
Lowest frequency 8 MHz

10BASE-T1L negotiation
Lowest frequency 315,5 kHz

- (Long) Brownfield cables with high insertion losses around 500 kHz may limit the T1L length



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https://www.ieee802.org/3/cg/public/Sept2017/Graber_3cg_15a_0917.pdf

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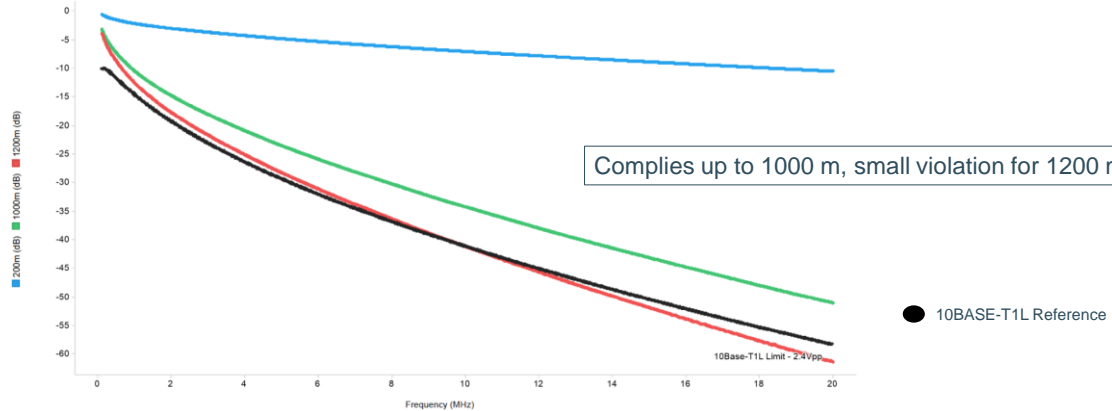


Cabling Parameters – Measurement example

- Insertion loss measurements on fieldbus cable (*Refer to Texas Instruments measurements*)
- Black is the reference. Cable complies (also for auto-negotiation), until 1000 m (and up to 2000 m in forced mode for “negotiation”)

Siemens 6XV1830-5EH10 Cable

Insertion Loss vs. Cable Length



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Application Report: Extend Network Reach with IEEE 802.3cg 10BASE-T1L
Ethernet PHYs, Texas Instruments

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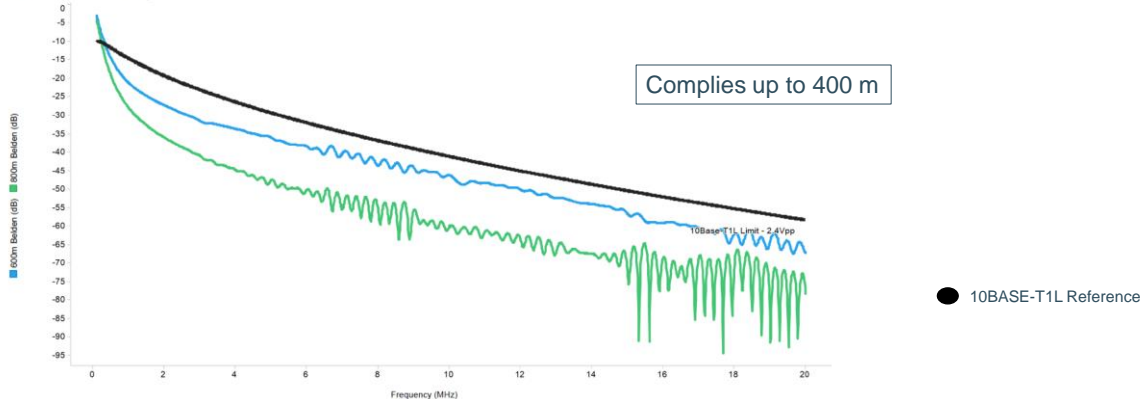
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Cabling Parameters – Measurement example

- Insertion loss measurements on fieldbus cable (*Refer to Texas Instruments measurements*)
- Black is the reference. Cable does not comply for these lengths (for auto-negotiation until 260 m OK), and up to 600 m in forced mode “negotiation”.

Belden 3076F Cable

Insertion Loss vs. Cable Length



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Application Report: Extend Network Reach with IEEE 802.3cg 10BASE-T1L
Ethernet PHYs, Texas Instruments

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Industrial connectors for SPE

- Defined in IEC 63171
- IP20-IP67
- M8, M12, Plugin connectors
- 4-wire connectors with 2 data and 2 power pins exist

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Industrial connectors for SPE



ISO/IEC 63171

CONNECTORS FOR ELECTRICAL AND ELECTRONIC EQUIPMENT

	IEC 63171-1	IEC 63171-2	IEC 63171-3	IEC 63171-4	IEC 63171-5	IEC 63171-6
Company	Commscope	PxC, WM, RdM	SIEMON	BKS	PxC, WM, RdM	Harting
Picture						
Type	LC-Style	Rectangle	TERA IP	Square-shaped	M8 / M12	Rectangle / M8 / Push Pull
#Pairs	1	1	1 / 4	1	1 / 4	1
Degree of protection	IP20	IP20	IP20	IP20	IP67	IP20 / IP67

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Ethernet – APL (Advanced Physical Layer)

- Ethernet-APL is more than just Single Pair Ethernet.
- Ethernet-APL is made up of
 - Single Pair Ethernet (IEEE 802.3cg-2019, 10BASE-T1L)
 - 2-WISE: 2-Wire Intrinsically Safe Ethernet (IEC 60079) (compare to FISCO)
 - Type A fieldbus cable (IEC 61158-2, for intrinsic safety).
- The Ethernet-APL cable specification is important because end users can potentially re-use existing installed Type A fieldbus cable.
 - Characteristic impedance 100 Ω .
 - Type A two-wire cable with shielding is polarity independent to reduce installation errors.
 - Up to 10 connections: 

Refer to lecture “APL - Advanced Physical Layer: SPE for the process industry”

- Few tools (screwdriver, wire preparation tools to physical connect) needed.
- Analog Devices showed on the HM 2022 combined TSN and T1L in one device, including cable “ageing and wear” detection.

Also refer to Lapp (and Helmholtz), Igus, Indu-Sol for “ageing and wear” detection.

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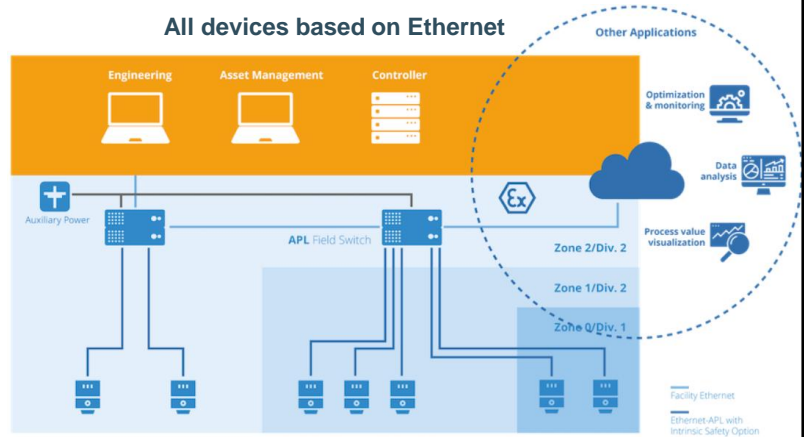
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The Goal of Ethernet-APL

“Bring Ethernet to the field”

- 1 Ethernet network for Field and Control level
- Facilitate IIoT and Industry 4.0
- Allow easy migration from existing brownfield



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What is Ethernet-APL

“Extension to 10BASE-T1L for use in the process industry”

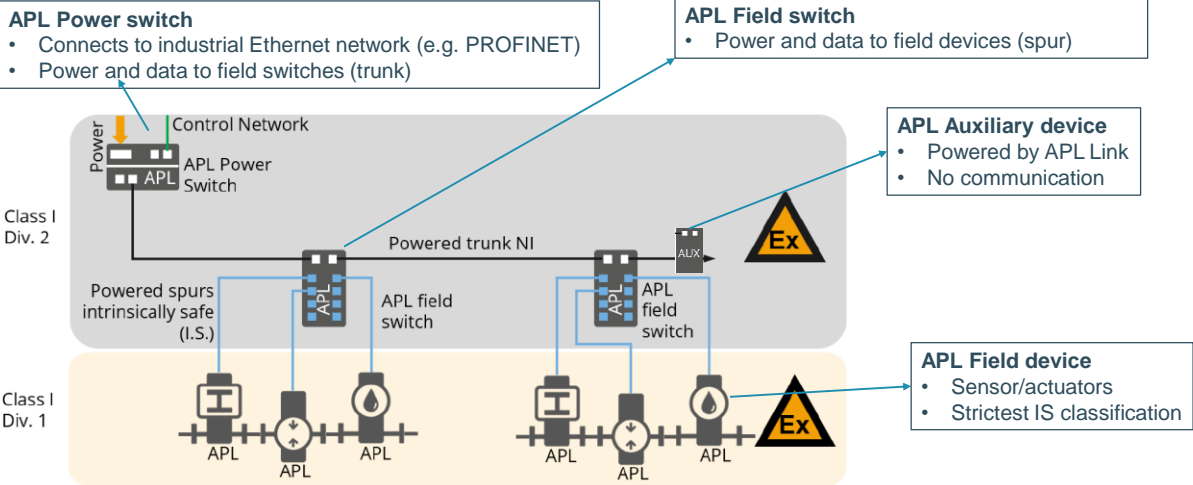
- 10 Mbit Ethernet (10BASE-T1L)
- 2-Wire cabling, optional re-use of existing Fieldbus infrastructure
 - Reference cable is fieldbus type A cable, IEC 61158-2 (e.g. PROFIBUS PA, Foundation Fieldbus)
- Long distances up to 1000 m
- Up to 10 inline connectors
- Power + data over a single wire pair
- Optional intrinsic safety with 2-Wire Intrinsically Safe Ethernet (**2-WISE**, IEC TS 60079-47)

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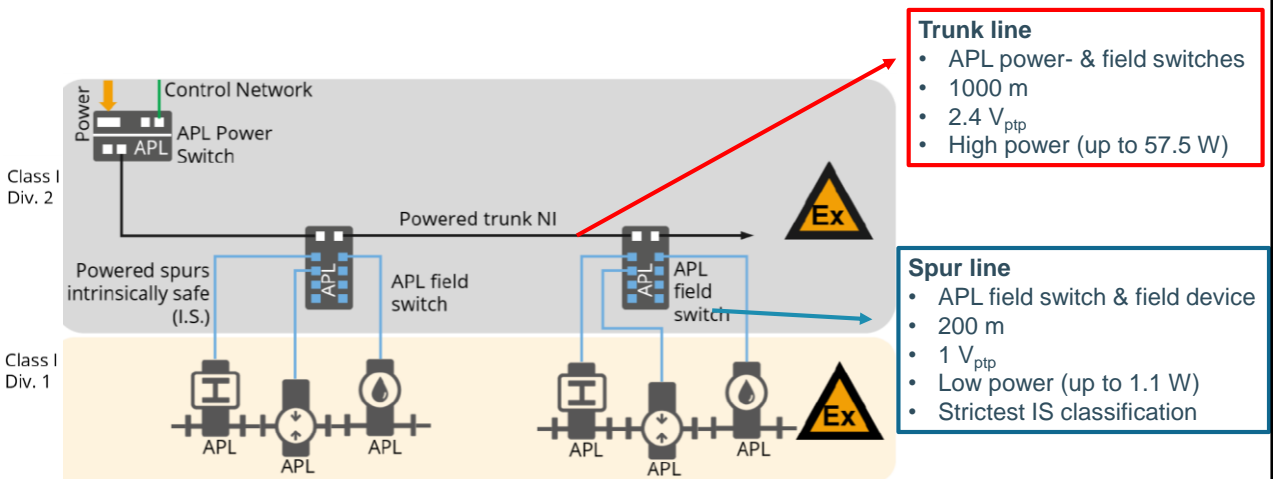
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APL Topology – Device types



APL Topology – Link Types



APL Topology – Power

- Source power class 4 is still in progress

Source power class	Maximum voltage, minimum output power	Permitted segment class	Permitted load power classes
A	15 V DC / 0.54 W	S	A
C	15 V DC / 1.1 W	S	A, B, C
3	50 V DC / 57.5 W	T	3
4 ⁶	50 V DC / 92 W ⁶	T	3, 4

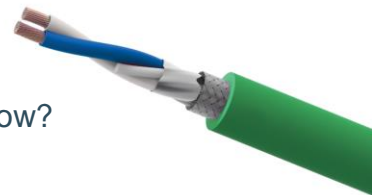
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Single Pair Ethernet

- SPE provides another physical layer that can be used by network design engineers
- ... But with some distinct advantages!
 - Smaller, lighter, simpler cabling and connectors, simpler field assembly
 - Nothing changes in the OSI Layer 2-7
- Different SPE standards allow for flexible network design
 - High bandwidth
 - Long distance
 - Power over Data Line
 - Ethernet-APL
 - ...

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Questions?

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