D1a: Convergence of Industrial Networks for OT and IT within the Industry 4.0 Concept - a Survey

An Overview of the Technologies

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I. Introduction

Industrial networks for OT and IT are at the moment in a quite revolutionary transition period, with new technologies that will be introduced and effectively applied in factories and process plants in the near future. Furthermore, the classic separation between OT and IT networks may (start to) disappear in the coming years. This evolution opens new possibilities, leads to new issues, and will in any case require a lot of research, testing on industrial scale, benchmarking, training and education, etc. That is why KU Leuven, UGent, TH OWL, Fraunhofer IOSB-INA and FE ZVEI decided to apply for the CORNET project CINI4.0. "CINI4.0" is the acronym for "Converging Industrial Networks for Industry 4.0 – New challenges for wired ethernet" (www.cini40.eu, Fig. 1. This text is an introductory study – deliverable D1a – performed at the beginning of the project, aimed to bring the project partners together and to inform the industrial User Committee on the basics of the technologies that the project works on. These technologies are Single Pair Ethernet (SPE), Time-Sensitive Networking (TSN), OPC-UA PubSub and topics related to robustness, EMI/EMC, diagnostics and network planning.

Fig. 1. CINI4.0 Logo

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The remainder of this text is organized as follows: Chapter II briefly introduces general communication requirements for industrial applications, a target and benchmark that all existing and new communication technologies should (at least) comply with. Chapter III discusses the Physical Layer communication aspects, with an emphasis on Single Pair Ethernet (SPE), robustness and EMI; redundancy aspects are introduced in Chapter IV. Chapter IV discusses some aspects of the 2nd layer of the OSI model, the Medium Access Layer (MAC): PROFINET – the most widely used industrial data communication protocol in the EU and especially in the project countries Belgium and Germany – is fully described as the project had to build on an existing industrial protocol, and Time-Sensitive Networking (TSN) as – for industry applications – new Layer 2 standard. Chapter V describes Application Layer aspects: OPC UA and its PubSub model.

II. Industry 4.0 Communication Requirements

Typical requirements for industrial communication in terms of end-to-end timing between controller(s) and devices can for example be found in Table I. These should be seen as typical numbers and orders of magnitude, and can vary a lot in actual implementations. Table I also indicates the typical number of devices in a single network for the given application domain, and the typical payload/device. The technologies researched in the CINI4.0 project should thus at least comply with these target requirements; assessing this with industrial components in industry relevant test set-ups and in actual industrial applications is a major part of the work during the project.

TABLE I
TYPICAL REQUIREMENTS OF INDUSTRIAL APPLICATIONS – AFTER [1]

Industrial Application	Cycle Time (ms)	Synchronization Accuracy (µs)	Number of Devices	Payload/Device (Byte)
Condition Monitoring	100	1	1000	300
Process Automation	10-100	1000	300	1500
Machine Tool	1	0,5	20	20
Packaging Machines	1	5	60	20
Printing Machines	2	0,25	100	40

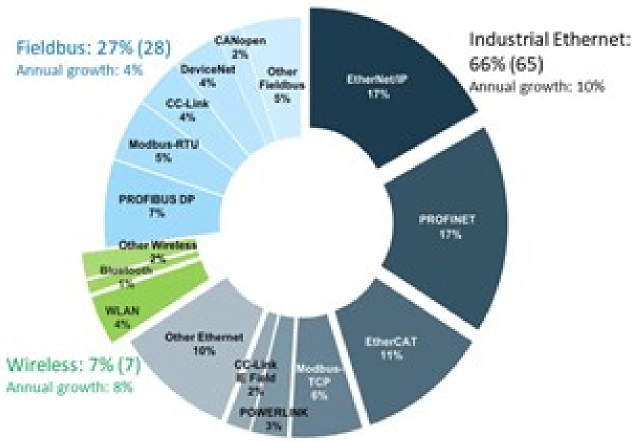

Fig. 2. Worldwide distribution of Fieldbus, Industrial Ethernet and Wireless industrial applications in 2022 – Figure after HMS [2]

TABLE II
ETHERNET CATEGORIES [4]

Cable Category	Cable Type	Max. Data Transmission Speed	Max. Bandwidth
3	UTP	10 Mbps	16 MHz
5	UTP	10/100Mbps	100Mhz
5e	UTP	1 Gbps	100 MHz
6	UTP or STP	1 Gbps	250 MHz
6e	STP	10Gbps	500 MHz
7	SSTP	10 Gbps	600 MHz
UTP = unshielded twisted copper pair STP = shielded twisted copper pair SSTP = screened, shielded twisted copper pair			

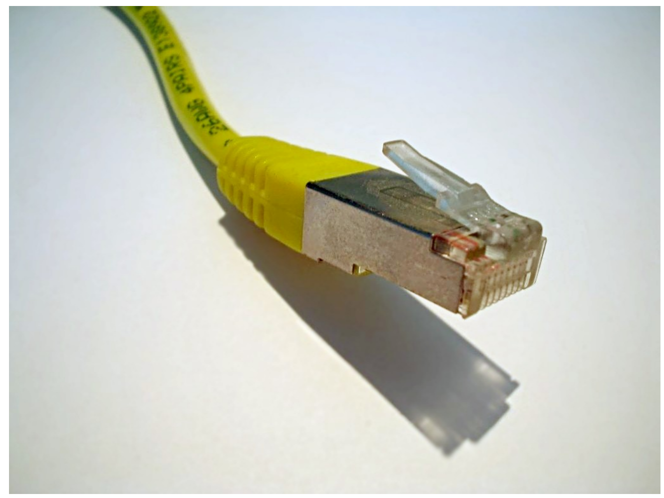

Fig. 3. RJ-45 Connector [5]

III. PHYSICAL LAYER COMMUNICATION ASPECTS

A. *Wired communication - Introduction*

The CINI4.0 projects focuses on “New challenges for wired Ethernet”. Indeed, the yearly overview of HMS [2] of the worldwide distribution of industrial network technologies (Fig. 2) clearly indicates that it was too early to focus on emerging industrial wireless applications such as WiFi6 and 5G. For Europe – and even more for the participating countries Belgium and Germany – PROFINET is the leading industrial protocol, hence the choice for PROFINET applications in the testing and set-ups of CINI4.0. It should however be noted that SPE, TSN, OPC UA and robust network (design) are in principle protocol independent.

B. *Ethernet based Systems*

Ethernet is a widely applied protocol. It is used in home networks and prevailed in industrial applications to connect various devices and computers. Due to the ability to be integrated in various applications, it became the de facto standard in modern networks [3].

The Ethernet protocol defines a wired connection. Ethernet over twisted pair uses eight copper wires. Two wires are twisted and build a pair to reduce the noise of crosstalk. In addition to that, the pairs and the cable itself can be shielded. This reduces the electromagnetic interference from outer sources. The typical material for shielding is aluminium, which is wrapped around the wires. This is especially important for higher data transmission speeds. Table II shows the defined categories for ethernet. Depending on the category, the shielding becomes more important the higher the ceil of the data transmission speed and the maximum bandwidth.

The wires are connected to a connector as a physical interface for devices. The most common connector is the RJ-45 connector. This is shown in Figure 3.

C. *SPE & APL*

1) The Single Pair Ethernet Concept:
Single Pair Ethernet (SPE) achieves full duplex communication over a single twisted wire pair, thereby reducing cable cost, weight and connector size compared to standard Ethernet. SPE finds several use cases in automotive and industry. Additionally, SPE supports power delivery over the same wire pair using Power over Data Line (PoDL).

Multiple SPE standards have been defined: 10BASE-T1S, 10-BASE-T1L, 100BASE-T1 and 1000BASE-T1. [6]–[9] 100BASE-T1 and 1000BASE-T1 provide high data rates over a short distance. 10BASE-T1L provides 10 Mbit/s Ethernet over long distance.

The functionality of 10BASE-T1L can be extended by the Ethernet “Advanced Physical Layer” (APL) [10]: APL

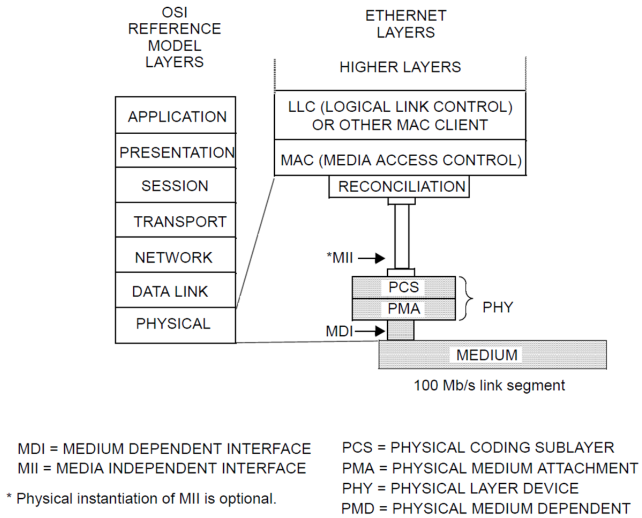

Fig. 4. Architectural positioning of 100BASE-T1 PHY [7]

provides intrinsic safety and allows – depending on the specific case – the re-use of existing fieldbus cable infrastructure.

10BASE-T1S provides a half-duplex multidrop option using Physical Layer Collision Avoidance (PLCA) over short distances. It is mainly intended for automotive, and is not further covered in this paper.

An overview can be found in Table III.

2) Working principle:
SPE achieves full duplex communication using a single twisted pair cable. SPE uses differential signalling on a balanced transmission line, common-mode (CM) interference is rejected. The transmitter sends a signal that is identical in magnitude but opposite in polarity on both conductors. SPE operates on the physical layer of the OSI model and is implemented using a SPE PHY, the PHY being the component that translates the incoming data from the MAC layer to the physical signal on the cable [13].

In Figure 4, the architecture of a 100BASE-T1 PHY is shown. It consists of a Media Independent Interface (MII), Physical Coding Sublayer (PCS), Physical Medium Attachment (PMA) and a Media Independent Interface [7]. The MII interfaces with the MAC to retrieve the incoming data and sorts it into data blocks that are usable for the lower layers, the PCS and PMA scramble and modulate the data and place it on the MDI [14]. The MDI consists of the ethernet port and the twisted pair cable.

A simplified block diagram of a SPE PHY can be found in Figure 5. Both link partners transmit their signal simultaneously. Thus, both signals are superimposed on the cable, it is therefore not possible to distinguish the signals of both PHYs when visually inspecting the signal on the cable. The PHYs use a hybrid circuit (HYBRID) to isolate the receiver from the transmitted signal. In practice, reflections exist on the line due to impedance mismatches. FIR filters are used to cancel the echoes in the received signal [15].

All full duplex SPE standards use a slightly different modulation scheme. However, they do share common modulation principles:

1) Bit-to-bit conversions from the MAC to PHY using the MII
2) Scrambling (PCS)
3) Bit-to-ternary conversions
4) PAM3 modulation of the physical signal at the Medium Dependent Interface (MDI)

According to the OSI model, all Ethernet PHYs can communicate with the MAC using the MII. The MAC transmits data in fixed blocks at a fixed speed, e.g. 4 bits at 25 MHz for 100 Mbit Ethernet. This data stream is scrambled using a pseudo random code. Scrambling spreads the power of the signal over a wide frequency range, reducing radiated emissions.

In the next step, the scrambled bit stream is converted into ternary values (-1, 0, 1) using a conversion table. Two bit-to-ternary conversion tables are used, one for the link startup and one for regular operation. The ternary values are transmitted using Pulse Amplitude Modulation 3 levels (PAM3). The conversion from 4 bit scrambled data to PAM3 signalling for 100BASE-T1 during link startup – sending idles – is in Figure 6.

A SPE link consists of a master and a slave, determined during the PHY initialization at startup. In addition, the signal conditioning and echo canceler are trained, the clocks are synchronised and the slave locks in to the masters scrambling code. PHY initialization is a simplified version of IEEE802.3 auto-negotiation[1] [16], [17]. 10BASE-T1S uses a different modulation scheme due to its half-duplex nature, refer to 802.3cg for more information [6].

3) SPE PHY:
The 100BASE-T1 and 1000BASE-T1 PHYs are simplified in comparison to the 100BASE-TX and 1000BASE-T PHYs (Fig. 7). To achieve DC isolation, 100BASE-TX and 1000BASE-T PHYs use transformers on the PHY side with the centre tap connected to a DC reference on the board. On the connector side, the centre tap is connected to a “Bob-Smith” termination [18]. 100BASE-T1 and 1000BASE-T1 PHYs simply use two capacitors to provide DC isolation. This reduces the size of the chip [16]. Both PHYs use a common mode choke (CMC) to filter out CM noise.

4) SPE Link Segment - Cables and Connectors:
Industrial SPE connectors are defined in IEC 63171: interfaces for IP20 up to IP67 are defined. 4-way connectors with separate data and power are also available [19], [20]. An example of an industrial SPE M8 connector is shown in Figure 8 and Figure 9.

Shielded SPE cable for transmission characteristics up to 600 MHz and length of 40 m with a maximum of 4 in-line connectors, thus suitable for 100BASE-T1 and 1000BASE-T1, are defined in IEC 61156-11 (fixed installation) [23] and 61156-12 (flexible installation) [24].

[1]IEEE802.3 auto negotiation does not meet the automotive timing requirements.

TABLE III
FEATURES OF SPE STANDARDS [6], [8], [11], [12]

	10BASE-T1S	10BASE-T1L	100BASE-T1	1000BASE-T1
Standard	802.3cg-2019	802.3cg-2019	ISO/IEC/IEEE8802-3:2017/Amd 1-2017	ISO/IEC/IEEE8802-3:2017/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 [9]	Yes	Yes	Yes
Extra features	Multidrop	Ethernet-APL with intrinsic safety for process industry		

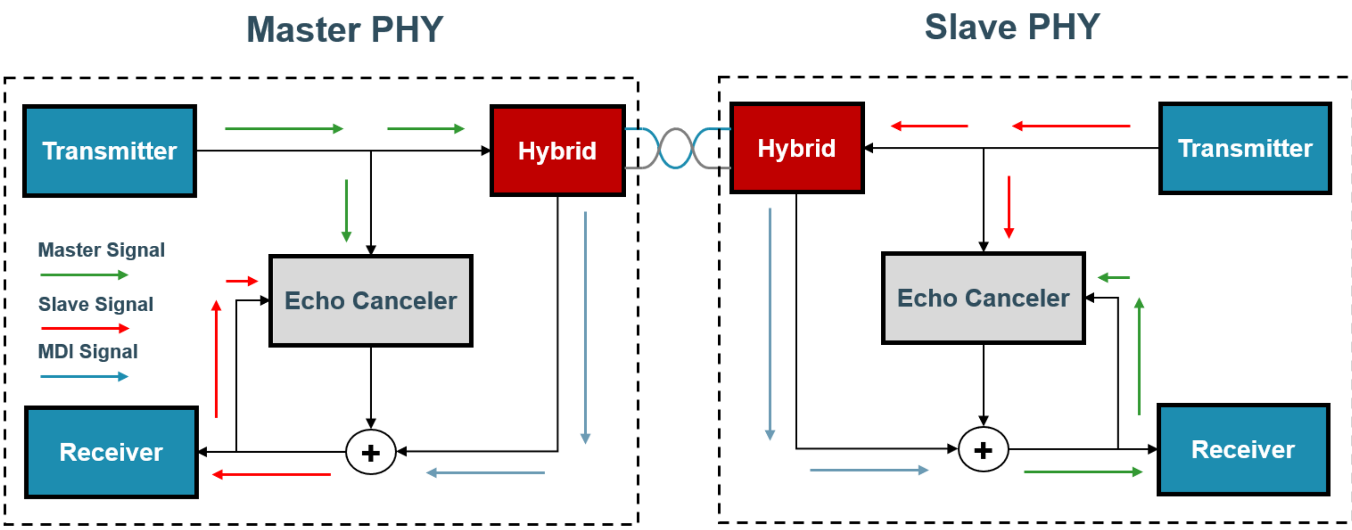

Fig. 5. A Simplified Block Diagram of a SPE PHY [16]

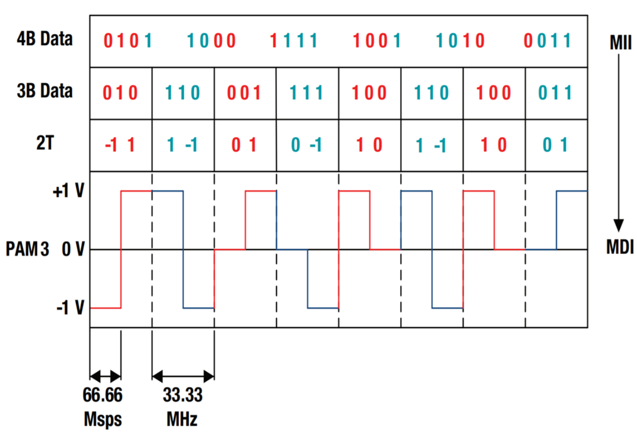

Fig. 6. 100BASE-T1, from scrambled data stream to PAM3-modulation

5) SPE Power over Data Line:

Power over Data Line (PoDL) allows powering of devices over a single wire pair. The IEEE Std 802.3bu standard (PoDL) specifies the power distribution over a link segment for point-to-point connections. This link segment is then called a link section. Where Power over Ethernet (PoE) works on 2 pairs (IEEE 802.3af and IEEE 802.3at) or on 4 pairs (IEEE 802.3bt) [25]. PoDL delivers the power over 1 pair, shown in Table 10 [26]. A PoE Powered Device (PD) is connected through the central taps of the PHYs coupling transformers. A PoDL PD is directly connected to the wire pair, a lowpass/high-pass band splitting network is implemented to separate data and power. Power distribution is regulated by the PoDL Power Sourcing Equipment (PSE). There are 10 power classes starting from 0 to 9, shown in Table IV and V , with power delivery range from 0,5 (class 0) to 50 W (class 9). Depending on the class the voltage will be 12 Vdc (first four classes), 24 Vdc (classes 4 to 7) and 48 Vdc (classes 8 and 9) [27]. The PSE type specifies which Ethernet standards 10/100/1000BASE-T1 it supports

In the IEEE Std 802.3cg-2019 that defines 10BASE-T1L, six additional power classes are defined, shown in Figure 9.

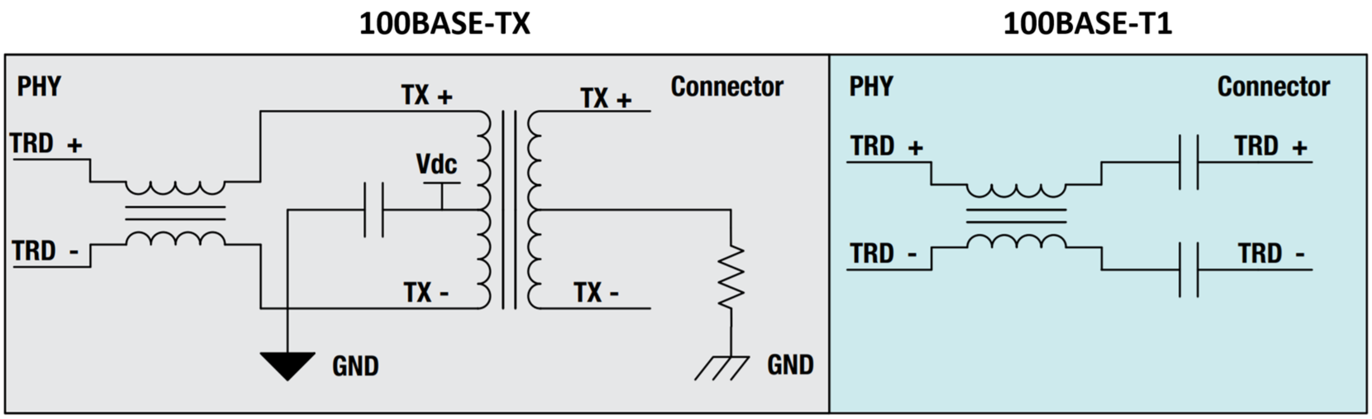

Fig. 7. PHY Comparison 100BASE-TX and 100BASE-T1 [16]

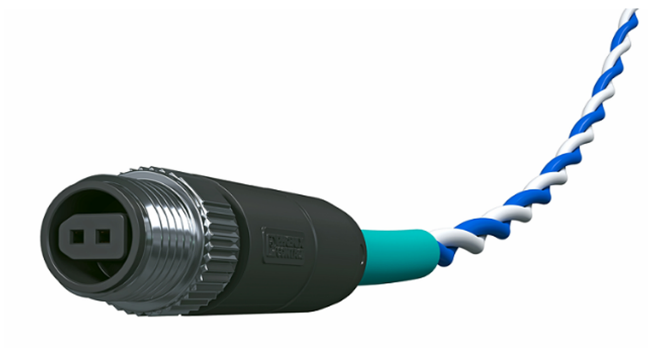

Fig. 8. Phoenix contact SPE M8 connector according to IEC 63171 [21]

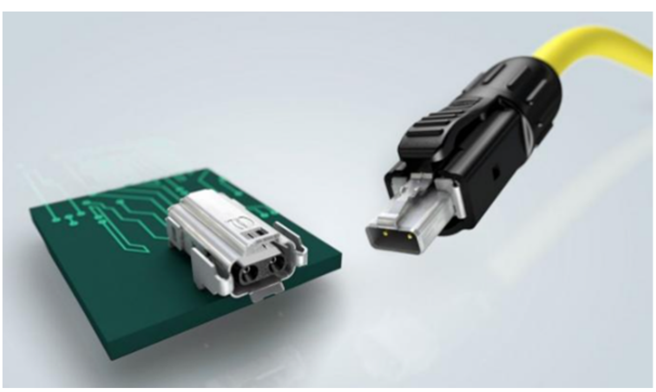

Fig. 9. Harting SPE industrial T1 plugin connector according to 63171 [22]

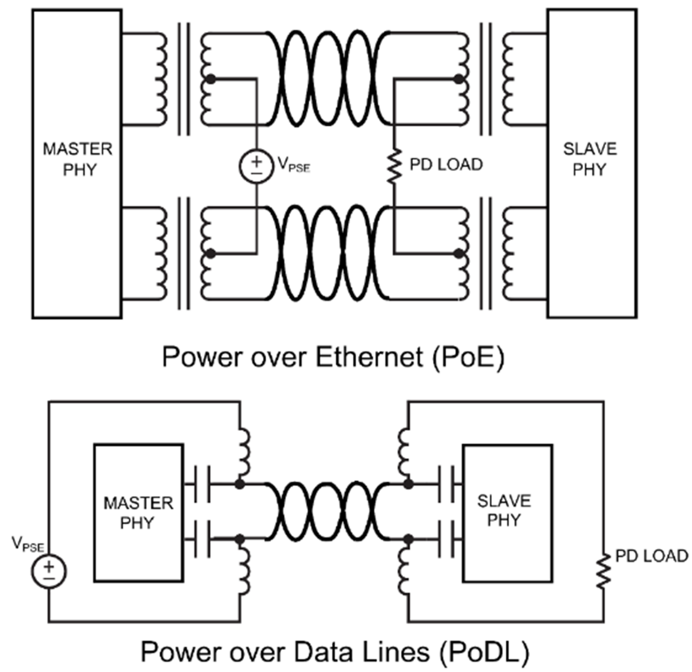

Fig. 10. PoE and PoDL schematics [26]

The PoDL SPE detects the PD with a 10 mA test current over a 4 V Zener diode. When a PoDL PD is detected the negotiation for the needed voltage and power is done by the Serial Communication Classification Protocol (SCCP) [20]. When the negotiation is completed the power is turned on by the PoDL SPE. When full power is not required the PoDL goes to sleep mode. Sleep mode continuously provides 3.3 Vdc to the PoDL PD at less than 1 mA. Fast startup operation is achieved by using predetermined voltage/current configurations.

6) Advanced Physical Layer:
The Advanced Physical Layer (APL) is an extension of 10BASE-T1L with provisions for PoDL, intrinsic safety (IEC 60079) [28], [29] and the option to re-use existing fieldbus type A cable (IEC 61158) [30]. The maximum cable length is 1000 m, up to 57.5 W of power can be delivered. APL defines two types of link segments: spur and trunk. The trunk provides high power and signal levels up to 1000 m, the spur carries lower power up to 200 m with optional intrinsic safety [10]. An example of an Ethernet APL topology is seen in Fig. 11. The

TABLE IV
SPE POWER CLASSES [27]

	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)[1]	18	18	18	18	36	36	36	36	60	60
$V_{PSE\_OC(min)}$ (V)[2]	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)[3]	101	227	249	417	97	339	215	461	735	1360
$P_{Class(min)}$ (W)[4]	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)[5]	0.5	1	3	5	1	3	5	10	30	50

[1] $V_{PSE(max)}$: Maximum allowed voltage at the PSE PI over the full range of operating conditions
[2] $V_{PSE\_OC(min)}$: Minimum allowed open circuit voltage measured at the PSE PI
[3] $I_{PI(max}$: Maximum current flowing at the PSE and PD PIs except during inrush or an overload condition
[4] $P_{Class(min)}$: Minimum average available output power at the PSE PI
[5] $P_{PD(max)}$: Maximum average available power at the PD PI

TABLE V
802.3CG-2019 SPE POWER CLASSES [6]

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

APL power switch connects the industrial Ethernet network (e.g. PROFINET, Ethernet IP) to the APL network. IT requires an auxiliary power supply to power its trunk network. APL field switches connect to the trunk network and are powered using PoDL, the segment between APL field switches has a maximum length of 1000 m. The maximum distance to the power switch is dependent on the power switch output voltage, required power, cross section of the cable and temperature of the trunk cable [10], [31].

7) SPE Measurement Principles:
As stated, it is not possible to visually inspect the signal on the SPE wires using an oscilloscope as both transmitters always send simultaneously to achieve full duplex operation. The signals must be separated, which can be done using a hardware test fixture using directional couplers, e.g. [32], [33]. Proprietary software signal separation techniques with oscilloscopes – without test fixtures – are also commercially available. [34], [35] Once the signals are separated, decoding options are available from several vendors [33], [35]. For basic commissioning, SPE cable testing tools are also being developed [36], [37].

D. Robustness and EMI

Ethernet for industrial applications has different application requirements and operation conditions than commercial ethernet. Related to operational conditions, resistance against mechanical stress (M), against ingress (I) and against climate and chemical impact (C) are defined in international standards. In this section, the focus is on the fourth MICE requirement, the electromagnetic environment (E).

Electromagnetic compatibility (EMC) is divided in emission problems and immunity problems. Considering the signals on digital communication systems, a common statement is that digital signals exhibit a high emission level but have intrinsic a high immunity level. This statement is true when comparing digital signals to analogue signals. The high emission is related to the steep voltage changes (dv/dt), generating a wide emission spectrum up to $\frac{1}{\pi . t_r}$, with t_r the rise time of the voltage. The high immunity is related to the limited number of voltage levels used to represent the carried information ('0' and '1') and improved with specific modulation schemes. Nevertheless, the industrial environment is a harsh environment for communication systems. The electromagnetic environment is filled with disturbances, entering the communication cable. The coupling can be conductive, meaning unexpected currents flow through the shield, or coupling can be established by magnetic and electric fields.

From the EMC point of view, the SPE system can be separated in the PCB with integrated circuits and the cable-connector system. Integrated circuits are considered as components and need no EMC certification in relation to the European EMC-directive. Though, for proper functioning, some requirements for the SPE IC are described in the standard IEEE 802.3cg. The standard refers to the IEC61967-4 and IEC 62132-4. The first describes the current extracting 1Ω/150Ω measurement method, to assess the RF emission between 150kHz and 1GHz. The second describes the direct power injection method to inject disturbances on an IC. Test methods at the level of the PCB are not defined in the standard. On the PCB, several precautions are taken to reject interferences. On-board EMI filters, including common mode rejection chokes, grounding capacitors and transient voltage suppression diodes (TVS) are used. As these filters have capacitive connections to ground, specific requirement towards safety are valid. Unshielded twisted pair cables and shielded twisted pair cables can be used for industrial ethernet. For shielded pair cables, braided shield or combined foil and braided shields are possible. The combination of the foil and braided shield gives a nearly 100% effectiveness against interference from external disturbances. There is no crosstalk internally as only one pair is used. Nevertheless, coupling to adjacent cables is still possible and countermeasures should be taken. The remaining weak point related to EMC is the connector. A metal connector properly connecting the shield to the PCB is required.

At system level, including switches and cables, the standards are less elaborated. This means the reader is pointed to the

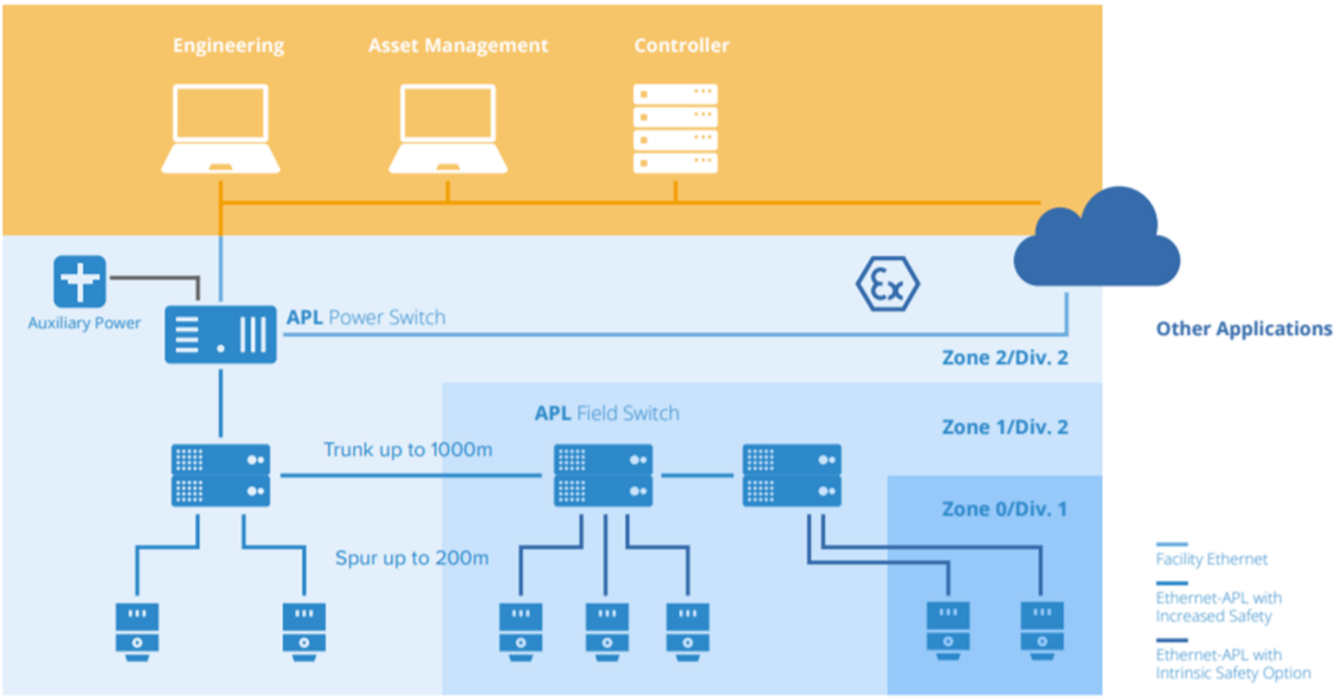

Fig. 11. Ethernet-APL Topology [10]

basic measurement standards. For immunity requirements, typical narrow band testing and broad band testing is performed. Narrow band testing refers to the frequency sweep test as described in IEC61000-4-6 (conducted) and IEC61000-4-3 (radiated), broadband testing refers to the fast transients testing from IEC61000-4-4. In 12, an injection clamp that conforms to IEC61000-4-6 is shown.

The IEC61000-4-6 standard describes specific coupling-decoupling networks (CDN) to inject disturbances into the single pair wires. The coupling devices are specific for shielded lines and for balanced lines. —Insert figure

Fig. 12. Disturbance injection clamp conform to IEC61000-4-6

The IEC61000-4-4 describes a capacitive clamp to inject broad band disturbances. The IEC61000-4-3 standard describes the radiated immunity test. This test requires an antenna and anechoic chamber. The main problem related to SPE is that this test is mainly developed for devices with short cables. The position of long cables will have a large influence on the results, which is not described in the standard.

As SPE can be used for long distances, the grounding system in the building or installation can have a large influence. Equipotential bonding is necessary for safety reasons, but is also necessary for functional reasons, referred to as functional bonding. Depending on the bonding between the cable shield and the switch and further bonding of the switch to the protective equipotential (PE) bonding or functional equipotential (FE) bonding, equalizing currents can flow through the shield. These currents can invoke new hazards as potential high voltages can enter the system. One solution to avoid this is connecting a capacitor between the shield and the FE bonding. In this way, high frequency disturbances can pass through the shield, but low frequencies currents cannot flow through the system. These capacitors can be part of the connector. Although the capacitors are theoretically a good solution, it is preferred to find the root cause of the returning current and solve this by improving the bonding circuit.

Related to EMC, several considerations can be made.

The major challenge is related to long cables. As stated communication up to 1 km is possible. Longer cables mean that resonances will occur at lower frequencies. To prevent reflections, the cables have to be terminated in a proper way. The characteristic impedance of the cable is 100Ω. Given the long cables and high speed signals, the full SPE system should be matched to the characteristic impedance, to prevent reflections. When using a shielded cable, also the path between conductor and shielding has a characteristic impedance. Therefor, not only a termination between the active pair is required, but also towards the shield, leading again to possible safety issues.

SPE includes DoPL. This means that the conductors can have an increased cross section. This can have an influence on the EMC behaviour, as skin effect and attenuation can be influenced. Additionally, capacitive coupling can be higher due to the larger conductors.

When considering a single pair, cross talk is less common. Cables should be as long as required, but an excess of cable length should be cut and not be coiled.

The other three MICE requirements will have an influence on the electromagnetic behaviour. Ingress and corrosion can cause oxidation and bad connections. Mechanical stress on the cable, due to periodic movements will wear out the cable shield and influence its effectiveness. An example is bending, where specific limits of the bending radius are given by manufacturers.

IV. Medium Access Layer Communication Aspects

As the Ethernet was developed for the Home and Office environments, the real-time requirements were not taken into account during design and development of the standard. The fair usage of the communication medium, which was the biggest advantage for the commercial users, became a big challenge for the applications, where prioritised traffic handling services were required. Since the standard Ethernet was able to support only best effort data flows, two other approaches had been developed to support real-time applications, namely 802.4 Token Bus and the 802.5 Token Ring. Both technologies use similar medium access approach by passing a token, defining the transmission opportunity for the one holding the token. The main difference between them was that in the token bus, the token is passed in the linear network structure and in the token ring the token is passed around the ring topology. Because of many limitations both technologies are not commercially used anymore. The fast Ethernet allowed to completely exclude collisions from the communication, however, there was still problem of traffic congestions. Such congestion situation may happened whenever a stream of traffic from more than one port has to be forwarded by a switch device on exactly the same port. Such situation may lead to tremendous delay of particular messages, and in the worst case dropping of messages, since queues of a switch have limited capacity. Emergence and popularisation of the multimedia devices and applications like telephone or video over IP lead to diversification of the Home and Office environment requirements. To allow provision of such services, the network infrastructure has to support real-time data exchange. To support this kind of applications, IEEE established a working group 802.1p, which was responsible to extend the standard with an approach that would provide Quality of Service (QoS) at the data link layer (MAC). They came up with a solution, where VLAN (Virtual Local Area Network) Tag introduced by the 802.1Q extension was used to assign priority class to a particular frame. The VLAN Tag allows to set up to 7 priority classes. For the network devices like switches, it means that different classes of traffic has to use different queues, where queues with the higher priority are served before the others. This was enough for the video and voice streaming (at least at that time), as requirements coming from the industry were met only partially. This followed to the emergence of several new proprietary solutions that were using standardised RJ45 interface as well as used Ethernet MAC as a basis for communication principle. In order to achieve real-time performance several changes has been made in order to achieve high real-time performance or determinism. However, this has been done for the price of compatibility with each other. Different Ethernet based solutions typically modified the democratic mediums access method to the one allowing to assign priorities to different traffic sources and at the same time isolate it from the best effort traffic. Several different approaches were developed in order to achieve the required performance. One for the approaches used in PROFINET technology will be discussed in details in the following subsection. The constantly increasing requirements coming from the entertainment domain, in which time sensitive audio and video data has to be transported has followed to the creation of the Audio Video Bridging (AVB) working group which was responsible for making IEEE Ethernet real-time capable. Due to the high interest of the automation industry in this activity, the focus of the group has been broadened by including industrial application requirements. At the same time, the name of the working group has been changed to more generic, Times Sensitive Networks (TSN). An important aspects of this activity was to offer by IEEE standardised low cost devices that require minimal configuration effort and support variety of industrial applications. Details about the way TSN achieve its performance and also the current status of development of TSN amendments will be presented in the following subsection.

A. PROFINET

1) Some basic Concepts of PROFINET:
PROcess FIeld NET or PROFINET (PN) is an open industrial Ethernet standard compatible with standard Ethernet. PI International is responsible for developing PROFINET [38]. PROFINET is described in the IEC 61158 and REF 61784 standards [30], [39]. PROFINET has RT (Real Time) and IRT (Isochronous Real Time) variants for the communication.

PN RT uses a VLAN and standard QoS (Quality of Service, IEEE 802.1P) to achieve real time behaviour. In principle standard switches can be used, although these are not really suited for industrial environments. PROFINET IRT requires special switches, as it reduces the free access to the medium by reserving an IRT channel: it's time based communication, contrary to RT and other Ethernet traffic which are address based).

A PN network participant is called a PN node; the following PN nodes are defined: IO-controller (PLC), IO-device (Distributed field device), IO-supervisor (programming device, e.g. personal computer), IO-Parameter Server, and network infrastructure components (switches, wireless access points).

PROFINET uses the provider-consumer model, IO-controller and IO-device each send cyclic messages at a fixed interval – the "update time" – that is configurable per IO-device [40], [41]. A typical default value is 2 ms, practical requirements are generally ranging from 0.5-1 ms for high-

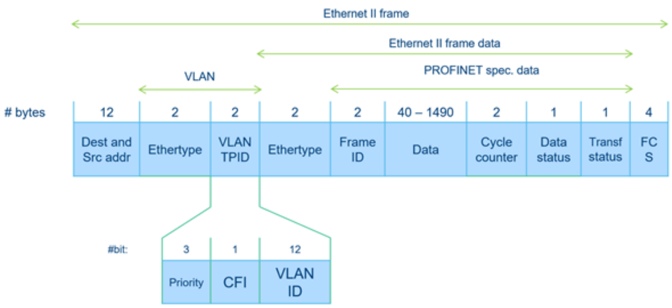

Fig. 13. PROFINET RT Frame [40]

end drive applications, over 2-8/16 ms for factory automation and 32 ms (and higher) for process applications, up to e.g. 128 ms for switch diagnostics.

2) Timeliness:
PROFINET makes use of three performance classes:

- Non Real-Time (NRT)
- Real-Time (RT)
- Isochronous Real Time (IRT)

NRT is only used for parameterisation and acyclic read requests, not for mission critical cyclic data exchange. “Standard” PN RT is suitable for cyclic mission critical data, the Ethernet II frame for PROFINET RT consists of the following parts (Fig. 13):

- Desination address (MAC address)
- Source address (MAC address)
- TPID: Tag Protocol Identifier, always 0x8100 for a frame with VLAN tagging
- VLAN
  - Priority: 0 to 7, PN RT is priority 6, the same as voice
  - CFI: Canonical Format Indicator (always 0 for Ethernet)
  - VLAN ID: identifies to which VLAN the Ethernet frame belongs
  - Ethertype: always 0x8892 for PN RT
  - Frame ID: indicates the inner communication channel
  - Data
  - Cycle counter: used to check if messages are received twice at the consumer (increments every 31,25 µs)
  - Data status: information about the data and provider
  - Transfer status (always 0)
  - FCS (Frame Check Sequence)

This method does not guarantee fully deterministic communication: especially in networks with a lot of traffic, jitter in the PN traffic can arise. This is practically speaking allowed for most PN applications if the jitter does not compromise the cycle time. PN RT does provide sufficient real-time capabilities to meet the requirements of most industrial applications. This flexibility in timing requirements allows for integration of other physical media such as wireless if the application’s timing requirements are not too high.

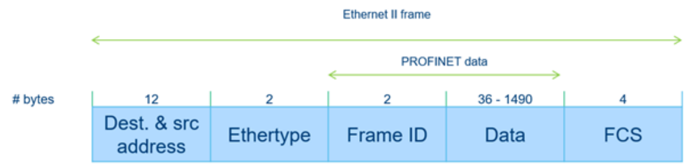

Fig. 14. PROFINET IRT Frame [40]

Applications with strict timing requirements, such as motion control, can make us of PN IRT. PN IRT facilitates deterministic communication with low jitter and latency. It adds bandwidth reservation, scheduling and synchronization to PN RT. This allows for deterministic communication with cycle times up to 31.25 µs – for standard industrial components practically speaking 125 or 250 µs – with 1 µs jitter. The Ethernet frame for PROFINET IRT has an equal form as the frame of PROFINET RT frames, a PN IRT frame is shown in Fig. 14. The only difference is that PROFINET IRT frames do not contain a VLAN tag. This means the Ethertype for PROFINET IRT is always 0x8892. To reduce latency, IRT uses cut-through switches (PN RT can run on store-and-forward switches). The clocks of all IRT components are synchronised using the Precision Timing and Control Protocol (PTCP, REF IEEE 1588 [42]). Using the synchronised clocks and Time Division Multiplexing, a reserved time slot is reserved for PN IRT messages, allowing for deterministic time controlled communication. PROFINET Version 2.3 adds fast-forwarding, dynamic packing and fragmentation to PN RT.

PN Devices are classified by their Conformance Class (CC). Four CCs currently exist: A, B, C and D. CC-A is suitable for cyclic IO data with real-time properties but does not support extensive diagnostic functions. E.g., CC-A switches are not actively integrated in the network configuration of the IO-controller. The functionality of CC-A is extended by CC-B. CC-B provides extended topology discovery and diagnostic capabilities, for example the use of the Simple Network Management Protocol (SNMP) to easily exchange diagnostic data. CCA-A and CC-B are suitable for PN RT. CC-C supports PROFINET IRT; an overview can be found in Fig. 15 [40], [43].

Conformance Class D (Fig. 16) holds among others Time Sensitive Networking (TSN) and Remote Service Interface (RSI). The complete communication (cyclic and acyclic) between controller and device takes place on Ethernet layer 2. Please refer to IV-B for “PROFINET over TSN“.

3) Reliabililty - Watchdog and Fail-safe state:
A Frame Check Sequence (FCS) is used to check if the frame is correct. A frame with faulty FCS is discarded. Ethernet uses a 32 bit Cyclic Redundancy Check (CRC) as its FCS.

The producer-consumer communication is guarded by a watchdog timer which is a multiple of the update time . The watchdog timer is reset every time a frame is received. When the watchdog timer expires, the cyclic communication

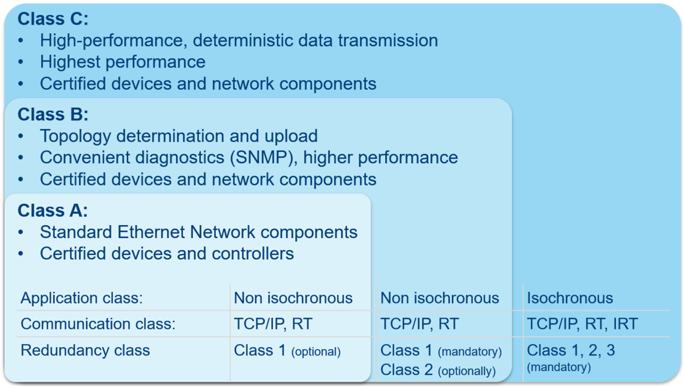

Fig. 15. PROFINET Conformance Classes [40]

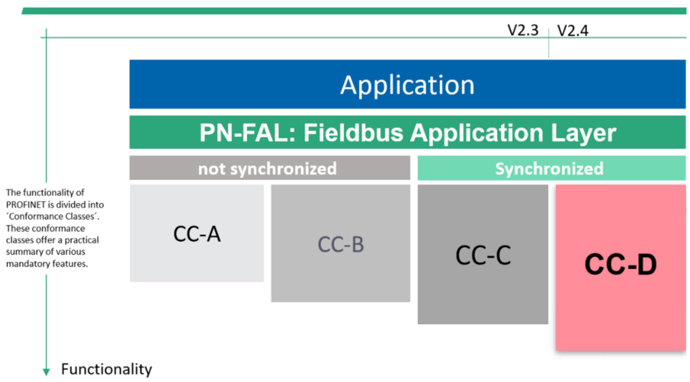

Fig. 16. PROFINET Conformance Classes with CC-D [44]

is stopped, an alarm message is sent and the device goes into its fail-safe state. The fail-safe state can be configured, and typically is a low or high state, or maintains the last received output state. More complex devices, such as electrical drives, can operate more complex fail-safe behaviour.

4) Redundancy:
The purpose of redundancy is to minimize downtime of the network and application. The general idea is to create an extra network path that can be used when the original path fails.

There are multiple types of redundancy; three Redundancy Classes (RC) are defined. RC-1 defines ring redundancy with a network recovery time up to 200 ms, e.g. the Media Redundancy Protocol (MRP). The implementation of MRP is an optional PN feature. RC-2 defines seamless redundancy for RT requirements, e.g. Parallel Redundancy Protocol (PRP) and Highway Seamless Redundancy Protocol (HSR). Lastly, RC-3 defines seamless redundancy for IRT applications, e.g. Media Redundancy for Planned Duplication (MRPD) [40].

HSR and PRP provide seamless redundancy for PN RT networks; specific hardware is required. It allows for an interruption in the physical layer without any effect on the application.

5) Engineering and Configuration:
IO-devices are configured using a General Station Description XML file (GSDML). This is a standardized file in which all the necessary device properties are described. The standardized GSDML facilitates the easy configuration of PN networks with nodes of different vendors.

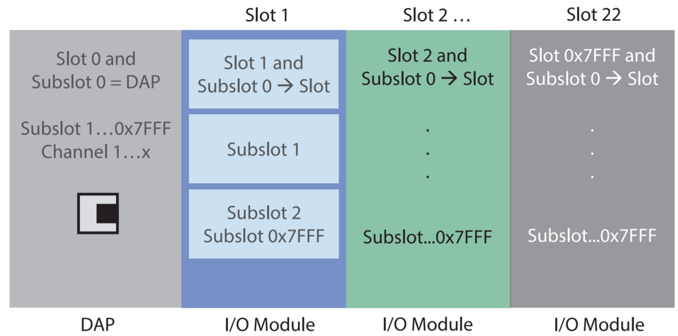

Fig. 17. PROFINET Device Model [45]

An IO-device usually consists of a communication module (called Device Access Point or DAP) and physical or virtual modules. The device model consists of slots, subslots, modules, submodules and channels as is seen in Figure 17.

In addition to the basic PN features, optional features also exist. These include among others Fast-Startup (FSU), shared IO-devices, system and device redundancy, simple device replacement, application profiles. Discussion of these topics is beyond the scope of this overview text [38].

6) Diagnostics and Diagnostic Tools:
A PN network integrates by default diagnostic capabilities. The most basic ones are the alarms: when an event occurs a PN device will send a priority low or high alarm, containing information about the event that occurred. In addition, PN devices use the Link Layer Discovery Protocol (LLDP) to acquire information about their neighbours. This is supported by all PN devices.

PN devices have integrated diagnostics. The diagnostic data is stored in two Management Information Bases (MIBs); the Device MIB and the LLDP MIB are standardized. This data can be read by the IO-controller using acyclic read messages or by other diagnostic devices using SNMP (SNMP is supported from CC-B onwards, with CC-B devices being the most common) [43]. This means that the IO-controller has the capabilities to acquire diagnostic and topology information of its PN network; controllers also implement a diagnostic buffer that stores historical diagnostic information.

Separate PN diagnostic devices and tools can be used to monitor and manage a network. Two types of PN diagnostic devices/tools exist: active and passive monitors.

Active monitors use protocols as SNMP, Address Resolution Protocol (ARP) and Internet Control and Message Protocol (ICMP) to acquire information from all PN devices in the networks. Using the LLDP info from each individual device, it can piece together a topology map of all the devices in the network. In addition, it can centralize all relevant info from all the PN devices on a single dashboard.

An active diagnostic tool is not capable to create "new" diagnostics, all information is already stored on devices in the network. These devices have an IP address and are visible in the network, they can also be located anywhere.

Passive diagnostic devices take a different approach, and “create” new diagnostic information. Passive monitors typically make use of a Test Access Point (TAP) to monitor the PN traffic on the link. Analysing the PN traffic gathers information on jitter, netload, alarm messages, error frames etc. Most tools allow export of frame captures to general tools like Wireshark [46]. A passive diagnostic device is typically placed in the link between controller and the first switch so it can monitor most traffic. Some diagnostic devices combine passive and active features. [47]–[52]

B. TSN

For the CINI 4.0 project, the general requirements for industrial communication were not newly collected, but derived from the IEC/IEEE 60802 TSN-IA working group.

This standardization committee defined 35 basic use cases for industrial Ethernet TSN-based communication. The standardization committee includes globally important companies such as Siemens, ABB, Beckhoff and Rockwell Automation. Figure 1 illustrates the IEC/IEEE 60802 standardization workflow. From the 35 basic use cases, the most important ones were derived in Table VI, which leads to the requirements for the communication system (Table VII). First of all, 10 important use cases were decided upon, but these can still be modified or supplemented. This in turn results in the requirements for the field devices, which expected minimum requirements and experimental quantification will be further developed during the project. [53]–[55]

1) Basic Information:

Industry 4.0 describes dynamically networked production with frequent reconfiguration of machines and systems as well as the use of cloud technology and data-based smart services. This requires continuous, powerful and flexible communication from the field level to the Internet, in which different protocols can be used simultaneously. Under the name Ethernet TSN (Time Sensitive Networks), the IEEE is developing standards for Ethernet-based real-time communication that can achieve this. The use of Ethernet TSN for industrial automation is currently defined in the profile standard IEC/IEEE 60802 TSN-IA.

IEEE 802.1AS defines a clock synchronization protocol for use in packet-switched networks. The basic principle is a cyclic sending of time information (synchronization frames) from a timer (Grandmaster GM) to timekeepers (also called slaves or Ordinary Clocks (OCs)). The OCs synchronize their clock to the received timing information. However, due to transmission times or signal delays, the timing information ages. For this reason, the transmission time of the synchronization frames is determined and compensated. In the area of the highest synchronization accuracy requirements, the individual determination of the line delays and the delays of the frames in the bridges is used. This timing compensation takes place in each bridge. A bridge that can compensate for timing information without an I-controller (integration controller), thus contributing to better overall synchronization accuracy, is called a Transparent Clock (TC). [56]–[61]

TABLE VI
DEFINITION OF APPLICATIONS [53]

Description	Short description
Isochronous with guaranteed low latency	Guaranteed low latency with application synchronized to communication (isochronous), which can be used for fast control loops, for example.
Non-isochronous with bounded latency	Control communication with guaranteed latency on which a non-synchronized application can run.
Redundant networks	The TSN Profile shall define the supported industrial topologies.
Mixed link speeds	A TSN network must be able to be set up with different data rates.
Auto domain protection	A TSN domain is automatically protected against unplanned communication.
Vast number of connected stations	Many devices can be networked with each other.
Machine-to-machine communication	In addition to networking a central control unit (PLC) with decentralized field devices, machines should also be networked with one another.
Pass-through traffic	The TSN networks should be able to be used by applications that only use the network infrastructure and have no other common application or project with the TSN domain.
Dynamic plugging and unplugging of machines, production cells or production lines	With the TSN networks, machine parts are to be dynamically separated and connected. The communication network must be able to be reconfigured both smoothly and automatically.
Add machine, production cell or production line	Adding and removing a machine/cell/production line shall not disturb existing installations.

TABLE VII
REQUIREMENTS FOR THE COMMUNICATION SYSTEM [54]

Property	Value
Latency	1 us/Bridge
Time Synchronization accuracy	1us
Network Diameter	64
Data rate	10 MBit/s - 10 GBit/s
Number of networkable devices	10.000
Topologies	line, star, ring, any mixtures

2) Preemption:

In order to be able to achieve low latency, in addition to TAS, a second mechanism called Preemption was included in the IEEE 802.1Q standard [802.1]. Preemption allows frames that are currently being sent on an Ethernet port to be interrupted in order to send a higher priority frame, as Figure 19 shows. A frame that can be interrupted is called preemptable. A frame that is allowed to interrupt other frames as ”preemptive”.

Preemptable requires, in addition to the extensions in the IEEE 802.1Q standard, the Express-MAC mechanism of the IEEE 802.3 standard. The minimum fragment length of interrupted frames is 64 bytes. Depending on the data rate, it is therefore not possible to interrupt at arbitrary times. For this

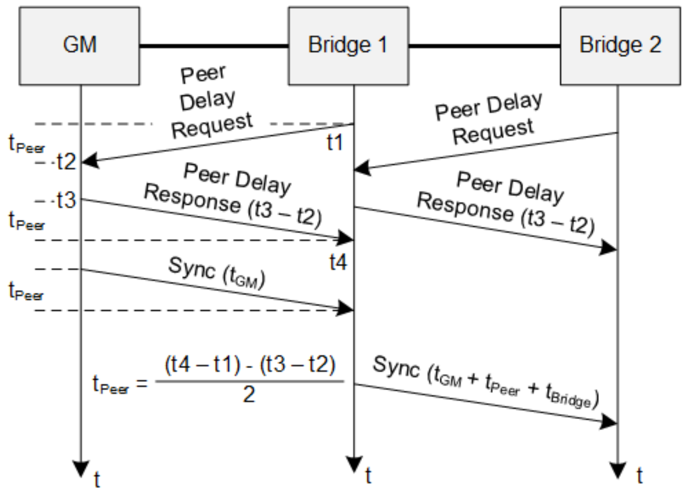

Fig. 18. IEEE 802.1AS protocol

reason, at 100 Mbit/s TAS is better suited than preemption for achieving the lowest delay times. At a data rate of 1 GBit/s, the waiting time of frames for the start of transmission at a TX port drops to ¡ 1 µs. Here, TAS and Preemption are comparable in performance. [56]–[61]

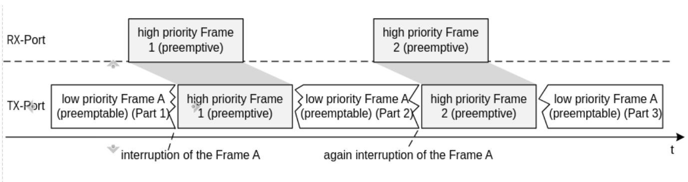

Fig. 19. Preemption

3) Time Aware Shaping (TAS):

In order to achieve low latency, Time Aware Shaping (TAS) was included in the IEEE 802.1Q standard [802.1]. The function makes it possible to determine by configuration which queues can send frames at which times. This is called queue masking. So-called gates are connected upstream of the queues and suppress transmission at the output port ("egress") as shown in the Figure 20. [56]–[61]

V. Application Layer Communication Aspects

The fourth industrial revolution is characterized by the possibility to connect various devices. This becomes a challenge if many devices with low memory and computation capacities are involved in the network. Widely applied application layer protocols like HTTP are not suitable for such an environment. The main focus of HTTP is web applications. Such applications are typically unidirectional, are designed for Client/Server models, and could only be used for one-to-one communication. These do not fulfill requirements by IoT devices, and it becomes especially an issue if the application has real-time requirements. Therefore, other protocols have prevailed.

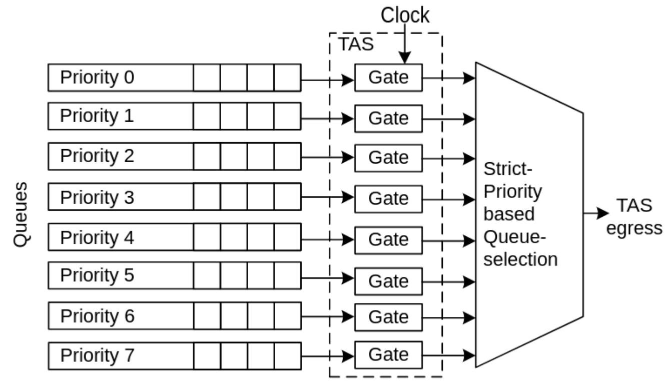

Fig. 20. Time Aware Shaping (TAS)

On the field bus level, MQTT and AMQP are lightweight protocols to distribute data on devices with low resources. The computation that requires most resources is located on the broker. These are located in the same network to forward the messages to the recipients. This model enables scalable application on field devices.

Although these are common and well known protocols, they are missing a common information model. This can be extended with the information model of OPC UA. OPC UA is a standard for communication with a flexible information model. In addition to that, it is platform independent, interoperable and is scalable. This section describes the infrastructure of an OPC UA PubSub model at first and continues with a description of the participating entities.

A. OPC UA

OPC and later OPC UA evolved from the problem, that Human Machine Interfaces (HMI) and Supervisory Control and Data Acquisition (SCADA) systems required a custom driver to access the data to device. Especially in industrial environments, many devices are involved. Maintaining these devices became fault-prone to extensions and adjustments.

As a result, OPC-DA was created to solve this problem. OPC-DA is a client/server model based on Microsofts technology OLE. OLE was later combined in COM and DCOM. OPC-DA sets a framework for data structures and abstracts the underlying protocol. In order to access the data, an OPC-DA client is needed. This obsoletes the necessity for custom driver [62].

Even though OPC became successful, some disadvantages became clear. OPC was only compatible with Windows. Linux systems must emulate a Windows system in order to execute OPC. Besides that, security was not considered and therefore left security vulnerabalities. Another major disadvantage is that the same data can not be grouped by an OPC-DA and a OPC-A&E as well as other OPC server. This increases the complexity as they server must be synchronized. These problems are countered by the successor OPC UA.

The Open Platform Communication Unified Architecture (OPC UA) is a standard that defines communication between

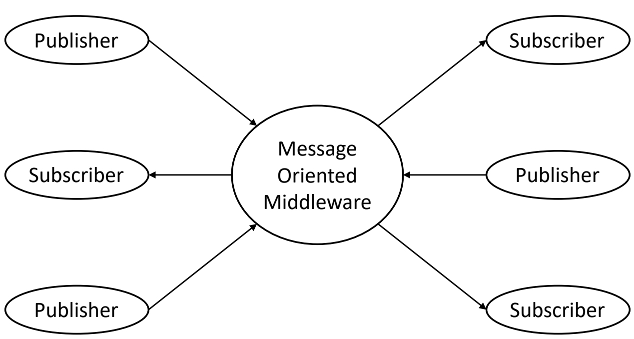

Fig. 21. Basic OPC UA PubSub infrastructure[2]

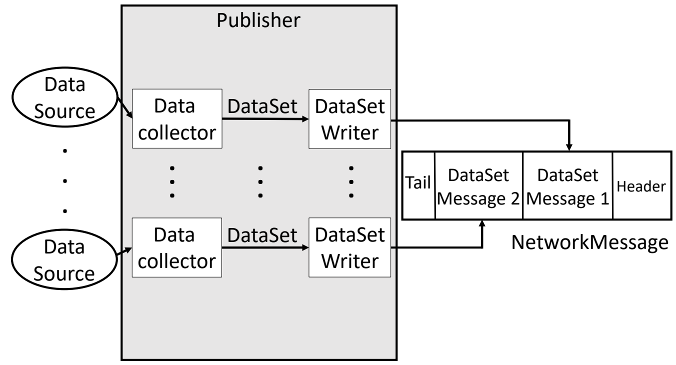

Fig. 22. OPC UA Publisher[4]

various devices and systems for industrial applications. It unifies the previous OPC specification and obsoletes them to enable platform and vendor independence. The communication is based on a Client/Server model, where a client sends requests to a server to which the server will send appropriate responses. In order to do that, a client establishes a (secure) channel to the OPC UA Server and requests the information of the servers *AdressSpace* [63].

OPC UA complements the Client/Server model with the PubSub model. A publisher offers various *DataSets* to subscribers. A subscriber chooses the *DataSets* that are of interest and subscribes to it to retrieve the messages. If a predefined event is triggered, the publisher sends *NetworkMessages* to its subscribers. Other than in the Client/Server model, the publishers and the associated subscribers are loosely coupled, and many-to-many communication is enabled. Another difference is scalabliity. OPC UA Server have to perform most of the computation and have therefore typically a larger footprint than OPC UA Clients. However, by using the PubSub model, the compuatation power is shifted to a so called Message Oriented Middleware. The main responsibility is to forward messages to the correct address. Due to the set of possible middleware solutions, the applications on the end devices are scalable [64].

A simplified PubSub infrastructure is depicted in Figure 21.

Multiple publishers and subscribers are connected via a *Message Oriented Middleware*. The subscribers register themselves on a registry to the publisher [3]. The publisher send their *Dataset* as a payload of *NetworkMessages* via the *Message Oriented Middleware*. The middleware distributes the messages to the associated subscriber. OPC UA defines two types of Message Oriented Middleware, the broker-less and the broker-based middleware.

A broker-less middleware uses protocols such as UDP and IP multicasts to transmit the data to the subscriber. If a publisher is triggered to send a message, it will send the *NetworkMessages* as UDP packets to a multicast address. The message will then be forwarded to the preregistered subscriber. This type of message distribution is implemented without additional software components. In this case, a typical network device e.g. a router is able to relay the messages.

OPC UA also specifies the concept of a broker-based middleware. It does not specify the protocols but rather uses known protocols like MQTT or AMQP. In this case, the *Message Oriented Middleware* is a broker, which handles the relay of the messages. Depending on the protocol and the configuration, the broker receives messages from publishers and filter them. The filtered messages will be forwarded to the associated subscriber. The *NetworkMessages* are transmitted with common transport protocols such as TCP or UDP.

The NetworkMessages are built and sent by OPC UA publishers. The data flow and internal structure of an OPC UA publisher are depicted in Figure 22.

A publisher is either triggered or collects data by an external Data Source. The internal entity Data Collector retrieves this data and converts it to a DataSet. A DataSetWriter adds metadata, encodes the Dataset, and formats it into a DataSetMessage. The DataSetMessages will be the payload of the NetworkMessage. The message will be sent to the subscriber via the Message Oriented Middleware. The subscriber is equivalent structured as the publisher. The data flow and internal structure of the OPC UA subscriber are shown in Figure 23.

Upon receiving the NetworkMessages, the subscriber must filter the messages as they might be either not relevant for the subscriber or unreadable. If the messages are readable and of interest to the subscriber, they will be decoded by the DataSetReader. The decoded message is the DataSet, sent by the publisher. The DataSet is either processed or dispatched further. If an OPC UA Server is integrated, these data are able to be integrated into the information model.

VI. Converged Industrial Communication System

A converged network consists of hosts, which provide different services via a single network. Such a structure offers benefits such as low cost material, efficient usage of the

[2]Based on Figure 1 of [64]
[3]The registry entity is not depicted in the figure
[4]Based on Figure 3 of [64]
[5]Based on Figure 7 of [64]

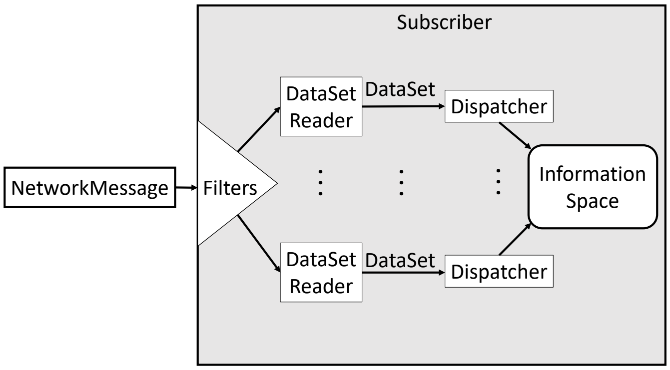

Fig. 23. OPC UA Subscriber[5]

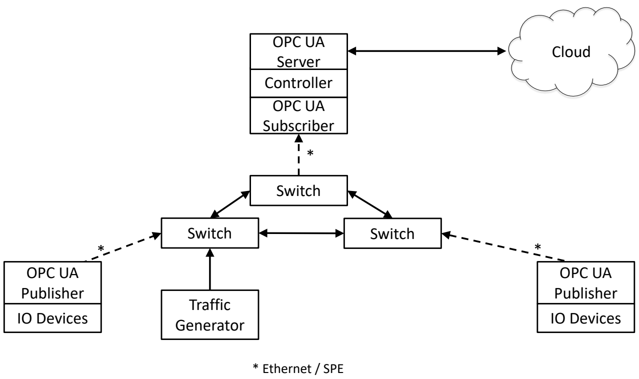

Fig. 24. Converged Network

network ressources as well as flexible and scalable reconfiguration. Especially industrial application take advantage of such networks and will become more important in regards to the fourth industrial revolution. Best effort applications as well as real-time application share and coexist in the a network. Such a composition, requires state-of-the-art technologies to share the bandwith, time and data to enable a reliable network communication [65].

New technologies were developed to enable industrial converged networks. The technology SPE and APL enables continuous integration of ethernet from OT and IT systems. Devices with real-time requirements are able to coexist with best effort applications in a single network by using TSN. In addition to that, OPC UA enables interoperability for applications with a standardized information model. Such an industrial converged network composed of the mentioned technolgies is depicted in Figure 24.

Figure 24 shows an examplary converged network. Mutlitple devices are connected in a star topology via switches. In this setup, two devices implement an OPC UA publisher each. The OPC UA publisher send their data to the OPC UA subscriber, which consumes the messages. All three entities share a common information model and are interoperable. In addition to that, the messages are send in real time to the subscriber. This is enabled by TSN, which is implemented on the switches and on the end devices. Finally, the transmission media is exchangable with common Ethernet and Single Pair Ethernet. This network is extended with a best efford application. The entity Traffic Generator is included to send its data over the same network to an OPC UA Server, which provides the data to a cloud application.

Each of the mentioned technologies, have a different scope and are located on different layers of the ISO/OSI Model. This allows the network and the devices to take advantage of every technology without excluding the other. Ethernet and especially Single Pair Ethernet are located on the physical layer and the data link layer. TSN is a mechanism, which focuses on the data link layer as well and is considered to be an extension of Ethernet. OPC UA is located on the application layer, on the presentation and session layer as well as on the transport layer.

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