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Topic

Converging Industrial Networks for Industry 4.0 – New challenges for wired Ethernet

Project Duration

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Research association

Forschungsvereinigung Elektrotechnik beim ZVEI e.V. (FE)

Research Institutes

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Ghent University
Technische Hochschule Ostwestfalen-Lippe
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1. Abstract

The main goal of the CINI4.0 project was to thoroughly investigate the applicability of technologies, such as OPC UA (Open Platform Communication Unified Architecture), Time Sensitive Networking (TSN) and Single Pair Ethernet (SPE) for industrial applications with the focus on seamless integration. According to the most recent studies, there is still a wide gap in understanding their potentials and also the performance limits while combining them with each other and integrating them in the current systems (both new and brownfield). The merging of IT and OT that is typical for the future Industry 4.0 is facilitated by these key technologies.

So far, the technology OPC UA is quite wide spread, however, but however typically implemented in relatively simple applications of data collection, not using the full power of its information modelling. Due to the fact that several working groups are dealing with this technology as a basis for concepts such a digital twin, there is still a need to investigate this technology more accurately in an heterogeneous industrial environment to check performance of different available implementations, scalability, interoperability, etc.

CINI4.0 also investigated new design methods for performant networks and network structures based on SPE and TSN, including implementation of more robust networks (EMI, built-in redundancy and security, etc.) and automation systems. Designing and testing migration paths (and even co-existence) for existing brownfield machines and plants are an inherent part of the project.

The project was organized in a very practical way. After short requirements analysis, the research partners prepared an overview about the current status of the addressed in the project technologies, including standardization activities, working groups, available products, starter kits, prototypes, etc. This process has been defined in the work plan as both literature study at the beginning. In parallel the first setups were built in the SmartFactoryOWL and in Belgian laboratories, which were gradually extended in the framework of this project with additional components into systems. Finally, industrial grade demonstrators were designed, a significant part of which was sponsored by the companies in the User Committee. These will be used to perform tests, evaluate performance of the addressed technologies as well as offer hands-on training to the SMEs; for some parts and tests, use cases in industry were used.

Out of the above described activities the research partners provided best practices, guidelines as well as scientific publications that provide an objective study of the potential of these technologies for the industrial use-cases. In the framework of this project, research partners setup a leading edge technology demonstrators which were used for different trainings, hands-on workshops with the focus on lifelong learning and support to SMEs in theirs problems related to network convergence issues in the broad sense. The SMEs benefit from the project especially by the practical findings based on practical evaluations of the research units. For SMEs it is difficult to setup their own technology demonstrators and spend much efforts on evaluation. Finally, the project findings will no doubt find their way into engineering student curricula, facilitating a long lasting effect on students, as well as on industry. It can be confidently stated that the research objectives were achieved.

2. Scientific-technical and economic challenge

2.1 Targeted Market Sector

CINI4.0 targets the sector of manufacturing industries and automation industries, including IT companies active in industrial IT.

EU manufacturing industries contribute about 22 % to the GDP, in Germany about 24 % [1]. Moreover, each job in industry creates two jobs in service sectors connected to industry [2].

In both Flanders and Germany, SMEs constitute a large part of the industrial sector; SMEs need additional support to technologically advance towards Industry 4.0, and can benefit from examples from large enterprises [3].

The User Committee reflects this: 10+ SMEs, a large system integrator (VMA), and some high-technological companies (both end-users and automation provider) will provide insights for the wide sector, and will be able to support the project partners.

In Germany, the industrial automation sector is economically very important and the biggest sub-branch of the German Electro and digital Industry. The automation companies currently have 261, employees. The turnover of the sector’s companies in 2022 was 58.5 billion euros.

The manufacturing industry in Flanders is technological and strong: the sector of the technological industries is among others represented by Agoria, counting 1700 members.

2.2 Economic Impact

The project puts one of its accents on lifelong learning by means of workshops, hands-on courses, and conferences aimed at industry. The participating labs of the project partners have a proven track record of facilitating industrially relevant training opportunities, and intensive cooperation with industry. The test set-ups, performance measurements, best practices and migration paths for brownfield will contribute to the knowledge and know-how of the SMEs.

The acquired knowledge will enable employees of SMEs to make educated decisions about the different characteristics. This safeguards their job position, on the one hand, directly through a higher level of qualification and, on the other hand, indirectly by empowering them to make appropriate recommendations for their companies in the future.

Furthermore, a technology shift like Industry 4.0 is always an opportunity for companies to advance in new technology fields, thus, creating additional jobs. Component developers can expand their portfolio, increasing product diversification and, therefore, lowering their risk of being too late or left behind if the market takes a shift towards these upcoming technologies. Component manufacturers are aided with their decisions on which communication technologies they should rely on for the coming years.

This is of major importance, because technologies in industrial production are set for long-term and poor choices can result in high expenses afterwards.

2.3 The Need

General technological background

The evolution towards Industry 4.0 (I4.0, "smart factories") merges Information Technology (IT) and Operational Technology (OT, industrial automation). Because of this, industrial data communication faces a (partial) convergence of IT and OT data networks, with new physical layers (Single Pair Ethernet (SPE), Advanced Physical Layer (APL)), Time Sensitive Networking (TSN), new demands for both network planning and maintenance, and the integration of middleware like OPC UA linking IT, OT and different network protocols.

More IO Devices in networks, more traffic for acyclic data (e.g. for predictive maintenance, condition monitoring, image processing and "edge computing"), more applications (in PLCs, DCSs) in one single network … require changes in the current – typically separated from IT – OT networks. One option is complete convergence of OT and IT networks, another option might be setting up "Industrial IT networks" ("distribution layer") between the current "access layer" OT networks and high level company networks "IT core layer" (See Figure 1[1]). The question is open …

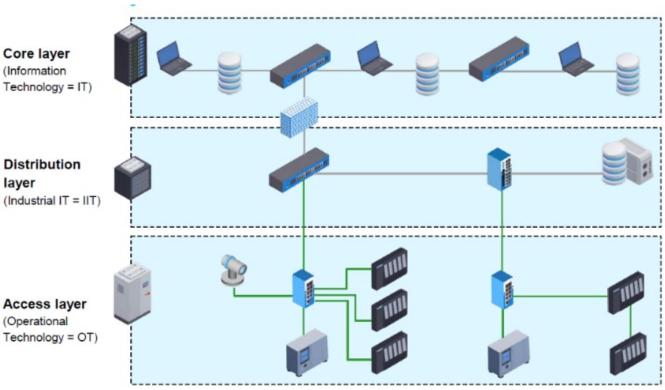

Figure 1 IT and OT layers

Open Platform Communication Unified Architecture (OPC UA) is a platform and vendor-independent, service-oriented middleware communication protocol, developed by OPC Foundation, aimed at reducing the complexity regarding data interoperability in the industrial environment [4]. OPC UA provides both Client-Server and Publisher-Subscriber mode of data exchange and uses TCP as well as UDP based communication [5]. Apart from the transport protocol, OPC UA provides a standardized information modelling mechanism in order to enhance the data semantics and seamless integration of information collected through different industrial applications.

These networks and the data and information transported through them, should not only be integrated, but also have a high robustness against EMI, feature built-in redundancy and security, etc.

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[1] "Sporadic and not predictable: application, network or EMC?"; René Heidl. Lecture on INCASE conference, 28/05/2019, Gent. 2nd lecture of Track 1, pag. 15, accessible via https://www.incase2seas.eu/download-conference-28-may-2019

The Need

Hence the urgent question from SMEs and enterprises in manufacturing and automation industries for developing knowledge about emerging physical layers (SPE, APL), TSN, middleware such as OPC UA, information modelling, and for know-how about best practices, design tools for implementation of new network structures suited for larger and more versatile applications.

Combining Single Pair Ethernet, Time Sensitive Networking, PROFINET protocol and OPC-UA will set the path to merging IT and OT, and significantly strengthen manufacturing and automation industry in the regions. The German and Belgian manufacturing industry and automation industry (e.g. small and midsize system integrators) urgently need to prepare for the high-end applications that will be possible. One of the key elements for realizing Industry 4.0 is education[2]; continuous training and lifelong learning is a key necessity for SME staff.

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[2] “Education is key to keeping Industry 4.0 moving forward” Suzanne Gill, Control Engineering Europe, Apr. 2019. https://www.controlengeurope.com/article/167692/Education-is-key-to-keeping-industry-4-0-moving-forward.aspx

3. Project objectives and solution

3.1. State of the Art and Technological Alternatives

Specific description of technological evolution

The evolution towards Industry 4.0 (I4.0, “smart factories”) merges Information Technology (IT) and Operational Technology (OT, industrial automation). Because of this, industrial data communication faces a (partial) convergence of IT and OT data networks, with new physical layers (Single Pair Ethernet (SPE), Advanced Physical Layer (APL)), Time Sensitive Networking (TSN), new demands for both network planning and maintenance, and the use of middleware like OPC UA linking IT, OT and different network protocols.

More IO Devices in networks, more traffic for acyclic data (e.g. for predictive maintenance, condition monitoring, image processing and “edge computing”), more applications (in PLCs, DCSs) in one single network … require changes in the current – typically separate from IT – OT networks. One option is complete convergence of OT and IT networks, another option might be setting up “Industrial IT networks” (“distribution layer”) between the current “access layer” OT networks and high level company networks “IT core layer” (See Figure 1[3]). The question is open …

Hence the urgent question from SMEs and enterprises in manufacturing and automation industries for developing knowledge about emerging physical layers (SPE, APL), TSN, middleware such as OPC UA, information modelling, and design tools and best practices for the design and implementation of new network structures suited for larger and more versatile applications. These networks and the data and information transported through them, should have a high robustness against EMI, feature built-in redundancy and security, etc.

At this moment, networks for company IT and networks for industrial automation (“OT” Operational Technologies) are typically separated, and a PLC (or DCS) is acting as “gateway” for the data transport between both networks.

IT networks typically carry long messages, are not (so) time critical, are mostly in office building conditions, and are administrated by IT staff.

For OT, factory automation networks (older name “field buses”) transport very short messages, and properties like short cycle time, determinism and sometimes redundancy are important.

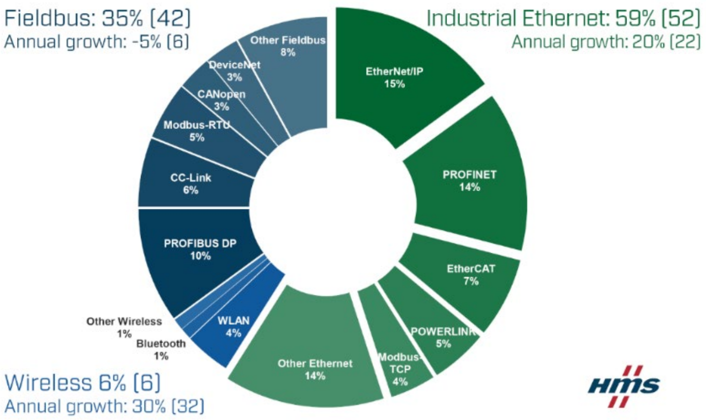

Figure 2 Industrial network market shares 2019 according to HMS

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[3] “Sporadic and not predictable: application, network or EMC?”; René Heidl. Lecture on INCASE conference, 28/05/2019, Gent. 2nd lecture of Track 1, pag. 15, accessible via https://www.incase2seas.eu/download-conference-28-may-2019

In OT, the PHYsical layer – the transmission medium – is for the vast majority wired: 94 % is wired, 6 % is wireless (Figure 2[4]). The table – indicating worldwide numbers – show it is mixed for cable type and for protocol. Non-Ethernet networks are still 35 % of the existing networks, with bitrates typically from 1.5 to maximum 12 Mbps (examples are PROFIBUS DP and Devicenet). Ethernet based industrial networks are at 100 Mbps, and are now at 59 % of the market share. Examples are PROFINET, Ethernet-IP, etc. Only 6 % are wireless connections, typically for non-time critical applications or configuration purposes.

In the special case of process automation there are additional requirements such as power over the data line, long cable lengths, Ex-environment (FISCO model), and transmission rates can be low (e.g. 31.25 Kbps for PROFIBUS PA).

At this moment, new physical layers (both wired and wireless) and network technologies are (being) standardized, and first basic products are being developed. These networks facilitate a more performant OT layer (access layer) and also support the convergence between IT and OT. For this convergence, OPC UA as middleware is being combined with the PROFINET protocol and will be run over TSN networks at higher speeds than 100 Mbps. These developments are international, and the central European manufacturing and automation industry need to step into these developments as quickly as possible.

Factory automation will – for Ethernet – move from 100 Mbps 2 pair (4 wires) Ethernet to 1 Gbps Single Pair Ethernet (SPE); the latter will offer several advantages compared to the current 1 Gbps 4 pair (8 wires!) Ethernet that we can find in e.g. office networks. Besides the move to a new cable and connector, TSN (Time Sensitive Networking) is the other major shift.

For process automation, the “Advanced Physical Layer” (APL) is being developed: 10 Mbps single pair Ethernet with cable lengths up to tot 1 km (compare with the 100 m of standard Ethernet) for use in Ex zones and power over the data line. This is the successor of PROFIBUS PA. It is worth mentioning that also IO-Link is preparing to move to SPE.

And what about wireless? Although the new wireless technologies – 5G, WiFi 6 – catch a lot of attention in the press and in research, it must be noted that the application in factory and process automation still has a lot of limits, and will for the foreseeable future probably be limited to moving objects (AGV, mobile small robot). Small cycle times, high determinism and robustness in the surroundings of steel and heavy constructions remain issues. WiFi 6 is emerging, and 5G applications are for the moment for private use and aimed at rather slow IoT applications. 5G does not seem to be able to massively replace cabled networks in an industrial environment (see earlier), also not for throughput. 100 MHz bandwidth in the 3.7-3.8 GHz band – as planned in e.g. Germany for local applications in factory automation – results in maximum 200 Mbps raw data rate, to be split over several applications [6]. For comparison: in a large industrial application, tens or hundreds of Ethernet cables of 100 Mbps full duplex can be used, and the bit rate will rise to 1 Gbps with the technologies covered in the project. CINI4.0 will however keep a “technology watch” to continuously cover the evolution in wireless industrial TSN and PROFINET.

Open Platform Communication Unified Architecture (OPC UA) is a platform and vendor-independent, service-oriented middleware communication protocol, developed by OPC Foundation, aimed at reducing the complexity regarding data interoperability in the industrial environment. OPC UA provides both Client-Server and Publisher-Subscriber mode of data exchange and uses TCP as well as UDP based communication. Apart from the transport

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[4] https://www.hms-networks.com/news-and-insights/news-from-hms/2019/05/07/industrial-network-market-shares-2019-according-to-hms

protocol, OPC UA provides a standardized information modelling mechanism in order to enhance the data semantics and seamless integration of information collected through different industrial applications.

Apart from the transport protocol, OPC UA provides a standardized information modelling mechanism in order to enhance the data semantics and seamless integration of information collected through different industrial applications. The fundamental building blocks of OPC UA information model are Nodes and References which are used to organize the OPC UA server address space[5]. Nodes are used for representing various “things” present in the system as well as the characteristics of the system. These “things” can be a device or its components, the type information of the device, a data value or its type, an executable process etc. There are various legacy industrial communication protocols and technologies like Fieldbuses (e.g. PROFIBUS, CAN, MODBUS etc.) and Real-time Industrial Ethernets (e.g. PROFINET, EtherCat, EtherNet/IP etc.) are available in the market, none of which is compatible with one another. OPC UA can be used in collaboration with these field-level networking technologies as well as with TSN to close the gap between these technologies and act as bridge in the heterogeneous industrial networking environment. Apart from OPC UA, there exist other middleware technologies like Message Queuing Telemetry Transport (MQTT) and Advanced Message Queuing Protocol (AMQP) which lacks the functionality of information modelling. AutomationML, on the other hand provides information modelling approach similar to OPC UA. It’s a Computer Aided Engineering Exchange (CAEX) based, open and vendor-neutral data exchange format for modelling physical and logical components of any production system. Although AutomationML follows similar object-oriented modelling paradigm like OPC UA information model, it’s primarily developed for exchanging static engineering data from the machines. Therefore, OPC Foundation and AutomationML consortium have worked together to develop an OPC UA companion specification for AutomationML [7].

3.2 Innovation Target

The aim of this project was to find innovative technical approaches for:

- Integrating OPC UA solutions into existing frameworks which will act as a mediator between the IT and OT networks. These approaches could lead to the extension of existing OPC UA information models, development of new models, modification and improvement of certain products from different vendors and integration of certain hardware and software platforms.
- Design methods for robust converged OT and IT networks and systems, and migration paths for brownfields towards the new concepts, derived from experiments, theoretical analysis, discussions with companies, etc.

3.3 Research Method

In this project, we investigated the viability of merging IT and OT networks and adopting OPC UA as middleware into robust industrial networks. The research methodology involves:

- Surveying state-of-the-art OPC UA solutions available in the market and studying them rigorously in order to understand how they can be adopted into industrial networks.
- Development of specific industrially relevant test cases to validate and demonstrate the practical implementation of the technologies and components
- Aggregating the knowledge and know-how into training courses and exercises, that will be used for hands-on workshops and training of engineers and higher technicians.

Research questions are among others:

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[5] "AutomationML in a Nutshell," AutomationML consortium, 2015.

- Is SPE and its standardized new connector better than current 4 pair 1 Gbps PHY from EMI point of view, better for confectioning, …
- How do existing redundancy mechanisms (MRP, PRP, HSR) compare with the built-in redundancy of TSN?
- What are the limitations of existing and emerging technologies? How does it compare with e.g. APP (Automation Protocol Prioritization)?
- How can data interoperability be achieved via the information modelling mechanism of OPC UA? What are its performance characteristics?
- How does the PROFINET companion specification model compare with other relevant information modelling mechanisms?
- Which tools, hardware and software can be used for OPC UA implementation?
- What are the better design strategies for networks, in order to merge (or let live together) OT and IT?
- How to integrate OPC UA into a larger system? Validation through running standardized tests.
- Is the built-in security for PN-TSN-OPC UA sufficient, and easy applicable for SMEs?
- How do TSN, PN RT and IRT combine in one network, and co-exist with other network traffic types?
- How to design for robustness: network planning, overall network on-line diagnosis, EMC-compliant design, OPC UA and overall security in industrial networks
- Validation of best practices and strategies in industrial grade applications.
- Which migration strategies are possible for brownfield sites? What are the best practices?

3.4 Project Results

The following table gives an overview of the achieved results. An extensive overview will be given in the following chapter.

Work Packages	Results, successes and issues
WP1 Literature Study	Contains a thorough theoretical study of the new technologies covered in this project; used for the dimensioning and requirements of components and measuring methods.
WP2 Measuring concepts and experimental quantification on component level: PHY and DLL	Measuring equipment and methods proved difficult to acquire and/or design by the project partners, especially for the use in industry use cases. Several options were tested, feedback was given to the constructors (e.g. Tektronics, Allegro Packets). Own software (e.g. MATLAB analysis of frame captures including preempted frames) and hardware (e.g. TSN monitor Fraunhofer IOSB-INA) has been developed. The resulting large amount of test and measuring tools and methods has been used extensively in quantification and verification, were physically moved during "exchange moments", and proved very useful and successful in demonstrators, in industrial use cases, and in workshops.
WP3 From data to information: OPC UA as middleware	OPC UA as middleware has been researched, tested and demonstrated mainly by the German project partners. On some events (e.g. Conference Day 2023 in Gent, IEEE ETFA workshop 2022) the German colleagues joined us for the dissemination actions on this topic.

WP4 Experimental quantification at system level	All project partners worked intensively on complete systems, hereby developing multivendor implementations, showcasing that this is actually possible at this stage of the technology. During the project, extensive collaboration and joint experimenting has been done by the project partners, end of 2022 even in a large scale "PlugFest" in the Smart Factory OWL in Lemgo. This allowed for experiments with high line depth (a lot of TSN bridges in series), and of course mutual discussions on the measurement methods and results. Operational properties of several TSN implementations and configurations have been measured (T4.2, D4b), and design rules and good practices for robustness against EMI have been developed and tested on Single Pair Ethernet (both specific cables and legacy ("brownfield") PROFIBUS PA cable which is very important for migration of current industrial installations), standard industrial Ethernet en (legacy) PROFIBUS DP communication links.
WP5 Validation using large lab setups or industrial use cases	Workpackages 1-4 were in close cooperation with the UC member companies, with a focus on the innovative technology providers. Workpackage 5 (and largely also WP 6 Knowledge Transfer) is (also) in close cooperation with innovative end-user companies, providing real-world applications and feedback to the project partners and technology providers. They are early adopters of technology, and in many cases offer a wide range of industrial communication networks that already have basic measurement Test Access Points; ideal for large scale experiments, incorporating equipment and tools developed by other UC members and by the project partners. Besides large scale experiments, the migration paths and implementations aspects in existing brownfield applications is put to live test.
WP6 Knowledge transfer	The KPIs for WP6 Knowledge transfer were set high, in particular keeping in mind that the beginning of the project still suffered from "CoVid influence" (e.g. the VOKA open company day where this project was presented, was still with masks!). Providing 325 FTE days of high end training and lectures in a 2 year project was reached, and 81 companies in Flanders indicated that they would use some or all of the technologies in the future. Besides website and promotional activities (including among others presence on Indumation 2022, the bi-annual automation fair in Flanders), the 2 "conference days" in Gent experienced a great success (also thanks to the input of UC members!) with around 180 external participants - very focused on these technologies - from about 60 companies. Feedback from those participants forms a large part of the "bevraging van de doelgroep" described further in this document. 9 companies participated to a 5 days hands-on workshop, that given to the limited duration of the project was in the last months of CINI4.0. However, 3 new chapters in engineering student courses, 4 papers and a full day workshop (hands-on, and only by the project partners) on IEEE ETFA (Emerging Technologies in Factory Automation) 2022, also provide lasting effect.

WP7 Project management	Given the not so large distance between Gent/Kortrijk and Lemgo in Germany, coordination went very well; live meetings - often combined with additional "technology exchange days" - do help a lot on top of Teams meetings. It was decided for practical (time consuming) reasons that the UC meetings were always joint German and Flemish. The Flemish meetings were organized live in the lab, during the joint part individually in Teams. The Flemish UC members had (and took) the opportunity to discuss the lab setups and tests after the joint virtual (Teams) meeting. Besides a large number of communications and individual Teams meetings, the project partners had about 10 project management meetings in the 2 year period.

4. Performed work and results

4.1. WP1 Literature Study

In work package 1 of CINI 4.0 (Converging Industrial Networks for Industry 4.0), an extensive literature research was initially carried out with the research institutions (Catholic University of Leuven / University of Ghent / Technische Hochschule OWL & Fraunhofer IOSB-INA) on the key areas of TSN (Time-Sensitive Networking), SPE (Single Pair Ethernet) and OPC-UA (OPC Unified Architecture). The focal points were initially defined among themselves. The common goal is to look at the different standards and, together with the research partners (industrial companies), to create a joint knowledge network based on publications, presentations and technical demonstrators.

4.1.1. Introductory Study

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. The introductory study is fully available as “CINI4.0 Overview Paper” on the website www.cini40.eu. The following subsections give a brief overview of the content:

4.1.1.1. Single Pair Ethernet

Single Pair Ethernet (SPE) stands as a transformative technology streamlining industrial connectivity with data and power transmission through a single pair of twisted wires. This innovation revolutionizes network infrastructure, offering high-speed communication and Power over Data Line (PoDL) capabilities in industrial IoT applications. SPE's compactness and cost-effectiveness cater to constrained spaces while enabling data rates up to 1 Gbps over distances of 1,000 meters. Its efficiency in reducing cable complexity and weight, alongside compatibility with existing Ethernet protocols, positions SPE as a key enabler for Industry 4.0, facilitating seamless integration, increased data flow, and enhanced performance in smart manufacturing and automation systems.

4.1.1.2. Time Sensitive Networking

Time-Sensitive Networking (TSN) marks a breakthrough in network technology, ensuring deterministic, low-latency data delivery crucial for real-time applications in industries like automation and automotive. By standardizing Ethernet, TSN synchronizes data transmission, prioritizes traffic, and guarantees timely delivery, fostering a dependable ecosystem for critical systems. TSN's capabilities include precise time synchronization, bandwidth allocation, and congestion prevention, enabling diverse devices to share a network without compromising performance. This innovation promises enhanced reliability, reduced latency, and improved communication consistency, vital for synchronized operations in interconnected systems, ultimately paving the way for dependable, high-performance networks in the era of Industry 4.0 and beyond.

4.1.1.3. OPC UA

OPC-UA PubSub (Publish-Subscribe) represents an extension of the OPC Unified Architecture (UA), designed to facilitate efficient data exchange in industrial automation and IoT environments. This protocol enables the seamless publication and subscription of data, offering a standardized framework for transmitting information between devices and applications. OPC-UA PubSub optimizes data delivery by distributing information only to relevant subscribers, enhancing scalability, and reducing network overhead. Its decentralized nature empowers interoperability across diverse systems, ensuring secure and reliable communication while supporting various data models. This technology plays a pivotal role in establishing flexible, interoperable, and efficient communication networks, fostering a cohesive infrastructure for Industry 4.0 ecosystems.

4.1.1.4. EMI/EMC

Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) address the impact of electromagnetic fields on electronic devices and their ability to function without interference. EMI refers to unwanted disturbances that disrupt equipment performance, caused by electromagnetic radiation emitted from various sources. EMC, conversely, ensures devices can operate in their intended electromagnetic environment without causing or experiencing interference. Through shielding, grounding, and filtering techniques, EMC aims to mitigate EMI effects, maintaining device functionality and compliance with regulatory standards. This discipline plays a critical role in industries like telecommunications and electronics, ensuring reliable device operation amidst the myriad electromagnetic signals present in modern technological environments.

4.1.2. Internal Survey

In the CORNET research project CINI4.0 (www.cini40.eu), different emerging technologies were investigated. The investigation is among others based on the prior knowledge and the use cases for each technology the user committee provides. To provide an overview and to establish a baseline, a survey was performed among the members the user committee. This survey is primarily based on questions that are aimed at the topics Time Sensitive Networking (TSN), Open Platform Communication Unified Architecture (OPC UA), Single Pair Ethernet (SPE) as well as for the topics Electro Magnetic Interference and Compatibility (EMI/EMC), Network Redundancy, Power over Ethernet (PoE), Power over Data Line (PoDL) and Advanced Physical Layer (APL).

The survey itself was filled out by 23 participants that answered the question “What type is your business?” with “Private Company” from 19 different companies. The companies can be technology providers and/or end users. The distribution is depicted in the table below:

Topic	Technology Provider	End User
OPC UA	10	7
TSN	5	8
SPE	6	4
EMI / EMC	5	4

Network Diagnostic	8	4
Network Redundancy	4	4
PoE	1	5

Table 1 Number of technology providers and end users of the user committee

Table 1 shows an overview of the number of technology providers and end users for every major technology in CINI4.0. It shows that the most technology providers are in the field of OPC UA followed by Tools for Network diagnostic and TSN. On the other hand, there are seven companies classified as end users for OPC UA and eight participants are end users of devices, which implement TSN.

4.1.2.1. Internal results

The summary focuses on data that are comparable and on possible conclusions. Besides that, some free answers were slightly modified to anonymize the answers. The results are depicted and summarized in the following paragraphs.

Topic	SPE	TSN	OPC UA	Network and Diagnostic	PoE, PoDL and APL	EMI & EMC	Network Rendundancy
Yes-selections	20	19	17	17	15	14	13

Table 2 Survey reults: Demand for a workshop

The survey results show a high demand for in-depth workshops and - as feedback from the UC sessions - training materials for every major topic. The results are summarized and ordered in the table. The highest demand is on the topics of SPE followed by TSN. After that, OPC UA and Network Diagnostic show the most demand. This is expected as most participants are at least using OPC UA “server” (or call it “driver”) software in their applications. Although the topic Network Redundancy has the lowest number on Yes-selections, it has a substantial number of selections; this feels logical, because the investment mainly pays off when the cost of standstill is high or when interruptions (can) result in a lot of damage.

Topic	OPC UA	Network and Diagnostic	Network Redundancy	PoE, PoDL and APL	EMI/EMC	TSN	SPE
Results, formatted as: Freshman, Basic Understanding, Expert - selections	4, 12, 6	7, 10, 5	4, 14, 4	4, 17, 1	13, 5, 2	9, 12, 1	15, 4, 3

Table 3 Survey results: Overview of previous experience with major topics of CINI4.0

In addition to the demand for workshops, the existing (at the start of the project) experience and knowledge with these topics was surveyed and the results are summarized in Table 3. If the participant was familiar with the topic, it was possible to estimate the complexity of the technologies. The topic which was the most known was OPC UA, where six participants estimated themselves as “Experts” and 12 as “Basic Understanding”. Only four answered this question with “Freshman”. On the other hand, 15 participants estimated themselves as “Freshman” on the topic Single Pair Ethernet. This result explains the high demand for workshops on this topic. The participants estimated themselves mostly as “Basic Understanding” for all other topics. For the topic TSN, nine participants estimated themselves as “Freshman” and 12 as “Basic Understanding”. The complexity of TSN was mainly estimated as moderate to complex, which also explains the high demand for workshops. The second to last question aims for specific results within the scope of the project CINI4.0. Most participants state that industrially relevant use cases are most important to them as a result. The second most selected answer was in-depth workshops as well as hands-on courses. This is followed by Migration paths for brownfields and a multivendor reference system/test3bed. Although these answers were mainly selected, all suggested topics have a significant number of selections, indicating that the planned project results are within the scope of expectation of the participants. This is also reflected in the fact that there are very few additional suggestions submitted as response to the last question.

The full results of the survey as well as an evaluation are available under the download area of the CINI4.0-webpage: www.cini40.eu/results

4.2. WP2 Measuring concepts and experimental quantification on component level: PHY and DLL

4.2.1. Design of measuring methods

KU Leuven and Ghent University performed initial EMI/EMC tests on different types of network (cables) in the week of 20/06/2022. The goal was to (start to) measure and compare the robustness of the different cable types and network technologies (PROFIBUS DP using RS485, PROFINET using CAT5E and CAT6A Ethernet cables, and Single Pair Ethernet) in a larger set-up.

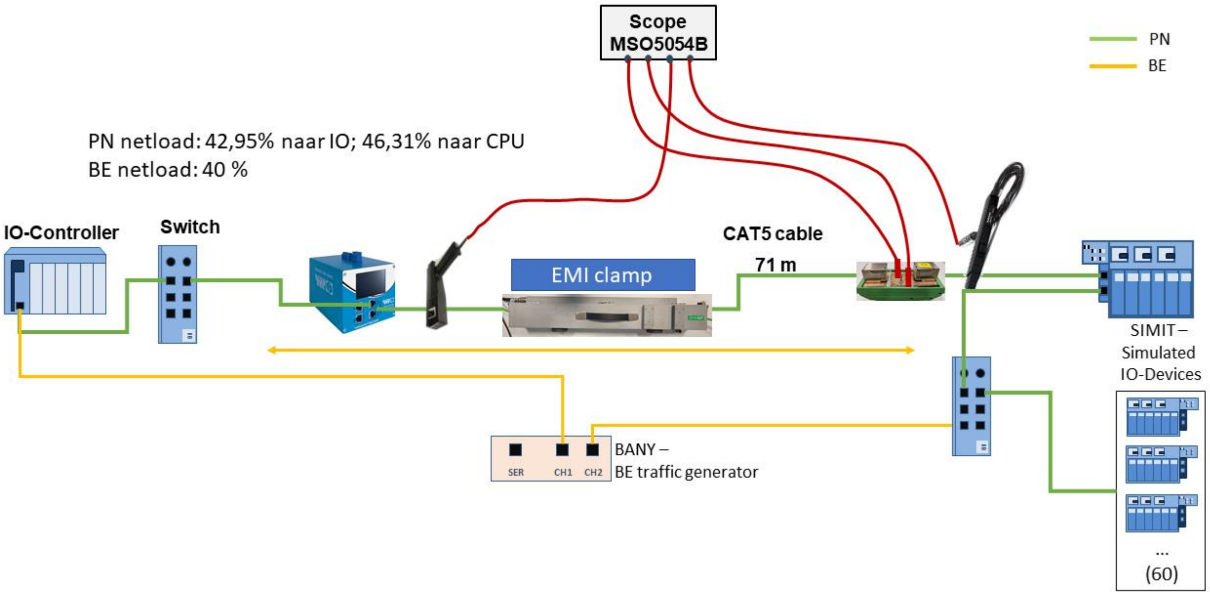


Figure 3 EMI/EMC test setup

A basic PROFINET network was created with a IO-controller (Siemens S7-1516), 1 real IO-Device (Siemens ET200SP) and 60 virtual IO-Devices; the PN network has an update time of 1 ms. This creates a PROFINET netload of appr. 42 %, and maximizes the “chance” of dropped frames. The virtual IO-Devices were created by the Siemens SIMIT Unit PN. A Siemens BANY XM400 is used to insert artificial IT network load over the link under. An arbitrary waveform generator, a broadband amplifier and EMI clamp are used to disturb the signals on the cables. Each cable type (that is for Ethernet and SPE) and combination e.g. passive connectors is tested - also for future reference and repeatability - with an AEM cable tester.

Multiple frequency sweeps were executed between 1 MHz and 230 MHz. The effect of Frequency Modulation is tested. During the measurement the PROFINET communication is interrupted in different frequency ranges.

Further testing is required to interrupt communication repeatedly and consistently. Some frequency ranges that have been found to (often) induce dropped frames are:

3 - 6 MHz at 103 dBµV

23 - 106 MHz at 102 dBµV

66 - 106 MHz at 100 dBµV

4.2.2 Experimental quantification of operational properties

SPE Measurement Report

Single Pair Ethernet (SPE) is a physical layer which enables Ethernet communication over one wire pair. It is developed by the automotive industry, but the technology may also prove useful in industrial automation. There are multiple SPE standards, which differ in transmission speed, permitted cable length, power delivery, and intrinsic safety. These are the following:

- IEEE 802.3cg-2019: 10BASE-T1S and 10BASE-T1L
- IEEE 802.3bw-2015: 100BASE-T1
- IEEE 802.3bp-2016: 1000BASE-T1

Single Pair Ethernet (SPE) Measurement Reports detail the performance and integrity of SPE networks. Measurements cover both the physical level and decoding level, each using several measurement tools. They validate compliance with SPE standards, ensuring the network's reliability, speed, and adherence to specifications for efficient data transmission. It could be shown that the available directional couplers RT-ZF7A from Rohde & Schwarz (100Base-T1), EVAL-ADIN1100 from Analog Devices (10Base-T1L) and DP83TC811EVM from Texas Instruments (100Base-T1) show insufficient results due to attenuations. Additionally, a delay measurement was performed on the SPE-Gateway i-NOVATIVE Auto-Link-G 100BASE T1 (100/1000BASE-T1) and the DP83TC811EVM from Texas Instruments. The following figure shows the measurement setup for the delay measurement:

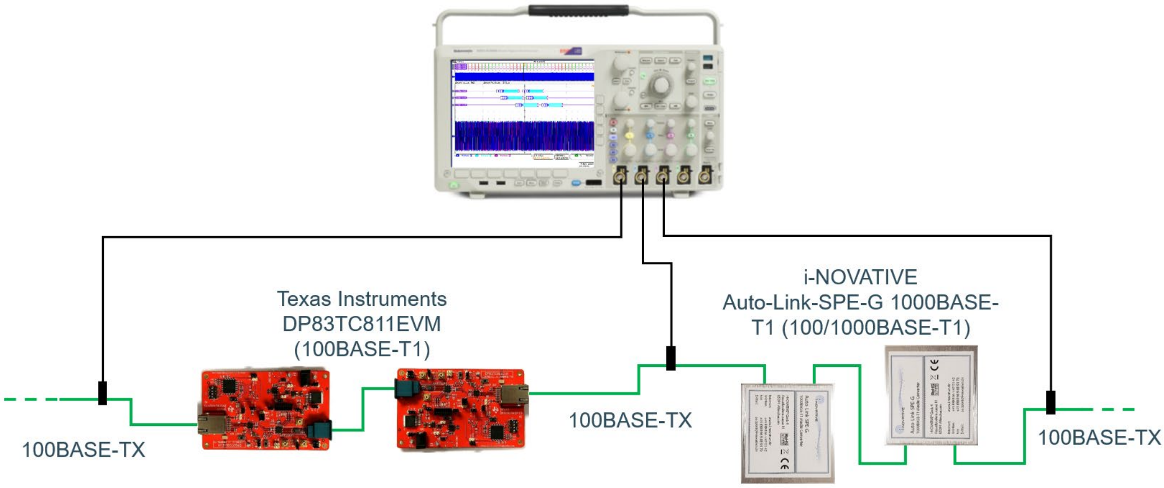


Figure 4 Measurement setup for delay measurement on 100Base-T1 media converters

The results can be seen in the following table:

Media converter	Delay (µs)
Texas Instruments DP83TC811EVM	1,20
i-NOVATIVE Auto-Link-SPE-G 1000BASE-T1	4,36

Table 4 Delays for 100BASE-T1 media converters

<u>Measurement Report - Experimental quantification at component level Relyum RELY-TSN-BRIDGE (TAS – 100BASE-TX)</u>

PROcess Field Net or PROFINET (PN) is an open industrial Ethernet standard compatible with standard Ethernet. It is described in IEC 61158 and IEC 61784. PN has a Real Time (RT) and an Isochronous Real Time (IRT) variant. The real time behaviour of PN RT is achieved using IEEE 802.1p Quality of Service (QoS). In large networks (or even small networks with high line depth), this results in considerable jitter in the presence of even little IT traffic.

The experiments compares a setup of PROFINET-devices, including an IO-Controller, 50 simulated IO-Devices, a traffic generator (BANY) and three switches. The following figure shows the topology of the measurement setup:

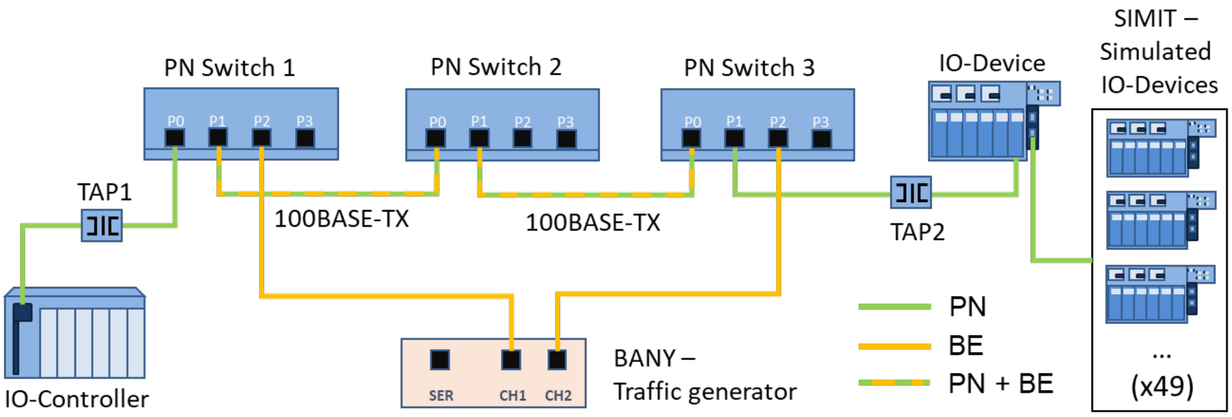


Figure 5 PRORFINET measurement setup

In this setup, the end-to-end delay from the IO-Controller to the IO-Devices was measured. The traffic generator is generates traffic to increase the load of the network. The results were compared to a similar setup, where the switches were replaced with TSN-capable switches. In this case, the TSN-feature Time Aware Shaping (TAS) was configured.

In this brownfield PN test, TAS only results in bandwidth protection, it doesn't result in a timing advantage on 100BASE-TX. TAS is designed for scheduled synchronized traffic and not for bandwidth reservation. Other standards exist specifically for bandwidth reservation, for example 802.Qci – Ingress Protection. It protects the TSN domain from netload bursts and it ensures that only PN frames have a high priority (this is used in PROFINET). For brownfield PROFINET RT over TSN, 802.1Qci – Ingress Protection can replace TAS as it was used in this experiment.

4.2.3 Verification of robustness at component level

Due to the extensive content, it was decided to integrate the full report as an appendix to this document. The full report can be found in Appendix A.

4.2.4 Intensive technical exchange days

Technical exchange week ("TEW") in Lemgo – 06-08/10/2021

The first technical exchange week took place from 06.10.2021 to 08.10.2021 in Lemgo (DE). Members of the project from the OWL University of Applied Sciences (Lemgo, DE), Fraunhofer IOSB-INA (Lemgo, DE), the Catholic University of Leuven (Ghent, BE) and the University of Ghent (Ghent, BE) were present.

On October 6, 2021, the Belgian partners arrived in Lemgo and then visited the company premises of Phoenix Contact in Bad Pyrmont, which is an industrial partner in the project.

The following day (07.10.2021) was started by TH-OWL and Fraunhofer IOSB-INA together with a guided tour of the Smart Factory OWL to present current laboratory setups in the form of demonstrators for different protocols (Profinet, OPC-UA), as well as the series of Ethernet standards TSN (IEEE 802.1AS, IEEE 802.1Qbu, IEEE 802.1Qbv) from IEEE 802.1 and the transmission of Ethernet via a pair of copper wires (SPE). An overview document (SF_Projects.pdf) was created for the Belgian partners and technical discussions were held to exchange information. Subsequently, measurement and evaluation equipment (UART/Ethernet decoding oscilloscopes, 2 connection methods for probes on the Ethernet cable, MATLAB decoding of standard 100BASE TX) and network analysis tools (PN Inspector, ATLAS II, BANY) as well as topology scans (TH Link, ATLAS II, ProScan Active) were presented and discussed.

The last day (09.10.2021), before the departure of the Belgian partners, was used for administrative purposes and the next steps and priorities in the project were discussed. For the second exchange week in Belgium, the date from 18.01.2022 to 20.01.2022 was set, an exact date for the TSN Plugfest 2022 has not yet been decided, but is to take place in the SmartFactory OWL. The CINI 4.0 Conference Day will take place at the end of May in Ghent; an exact date has also yet to be found. In addition, the current results and next steps of the "Introductory study (T1_1 and deliverable D1a, Milestone 1)" and the "Internal survey (T1_2 and deliverable D1b)" were discussed and debated (see: Report_211006_TEW_v2.pdf)

Technical exchange week in Flanders – 18-19/01/2022

From 18.01.2022 to 20.01.2022, the second exchange week did not take place at the Technology Campus Ghent (BE) in Belgium due to Corona, but was held in the form of an online meeting on two days (18.01 and 19.01). The participants were: Dimitri De Schuyter (KU Leuven), Jos Knockaert (U Gent), Oliver Konradi (TH-OWL), Philippe Saey (KU Leuven), Jochen Schäfer (Forschungsvereinigung Elektrotechnik beim ZVEI e.V.), Mario Schoppmeier (Fraunhofer IOSB-INA), Sebastian Schriegel (Fraunhofer IOSB-INA), Mathieu Troch (KU Leuven), Arne Verhoeven (KU Leuven) and Lukasz Wisniewski (TH-OWL).

18.01.2022:

The WP6 Dissemination summary encompasses various key performance indicators (KPIs) and upcoming events crucial for outreach, knowledge transfer, and project visibility. This includes evaluating outreach efforts, planned activities for upcoming exhibitions like Hannover Messe and Indumation, communication strategies, and engagements planned for the CINI4.0 Conference Day in Gent. The agenda covers potential topics for presentations, demonstrations, and discussions on subjects such as OPC UA, TSN, and SPE, involving industry collaborations and academic insights. Moreover, it outlines plans for workshops, courses, papers, and conferences, emphasizing lifelong learning and industry-focused engagement. There's a meticulous plan for lectures, panel discussions, and demonstrations, highlighting TSN concepts, survey results, EMC measurements, and fault generator testing. Integration of partner work and practical implementations are also crucial focus areas within this comprehensive summary.

In addition, two specialist lectures followed by a discussion round were held:

a) TSN Discussion and demo

The TSN hardware: “Relyum TSN Bridge” with the TSN standards: IEEE 802.1AS – Timing and Synchronization (PTP), IEEE 802.1Qbv – Time Aware Shaper (TAS), IEEE 802.1Qav – Credit Based Shaper (CBS), IEEE 802.1Qcc – Centralized Network Configuration (CNC), IEEE 802.1CB – Frame Replication and Elimination for Reliability (FRER) and the measurement equipment (Siemens BANY, XM400, BANY without TAP, Hilscher netANALYZER, Tektronix ethernet decoding oscilloscope) were presented.

b) EMC and Industrial Communication Cables

Electromagnetic Compatibility (EMC) is crucial in industrial communication cables to ensure seamless data transmission without interference. These cables are designed to meet stringent EMC standards, minimizing electromagnetic emissions and susceptibility to external disturbances. Employing shielding techniques like braiding or foil wrapping, they safeguard against electromagnetic interference (EMI) that could disrupt communication signals. Industrial communication cables, such as Ethernet, Profibus, or DeviceNet, facilitate reliable data exchange in harsh industrial environments. Their robust construction, impedance control, and shielding ensure uninterrupted connectivity, enabling efficient communication between machinery, devices, and control systems, crucial for the seamless operation of automated processes in manufacturing and industrial settings.

19.01.2022:

The administration meeting for WP7 and the project's general status involved discussing key performance indicators (KPIs) and strategic planning. Ensuring proof of attendance and interest for effective KPI tracking was emphasized, outlining the necessary elements for evidence, including slides, texts, participant lists, questionnaires, etc. Report uploading guidelines for the project were detailed, especially for Vlaio (German application). Time-sensitive considerations amidst COVID-19 waves were highlighted, aligning with the upcoming Timing of Technical Exchange Weeks (TEW) and Project Management meetings. Planning, reporting, and deliverables for WP1 were discussed, including updates for a survey paper and internal questionnaires. UC3 outcomes and presentations, TSN concepts, demonstration plans, workshops, and courses were key agenda items. The focus on lifelong learning initiatives for industry engagement and readiness to cater to a broader audience were prominent. Detailed discussions also covered integrations of partner work, including fault generator testing, NXP/Relyum TSN evaluations, and related presentations, aligning with the project's objectives and deliverables.

4.2.5 M. Sc. Thesis projects

a) (Translated from Dutch to English) Analysis of EMI and faults within an industrial stationary welding station

Abstract: A production station within a welding plant is the heart of a car factory. This is where the first parts are made for a car; thus, these are very crucial to the production unit. The process of spot welding involves large currents to form the necessary weld pool in the welding process to join the sheet metal together. Currents of up to 12 kA with a welding current frequency of 2 kHz are used in these production stations. The combination of high currents and high frequencies can affect neighboring signal and data cabling. This is also the case at Volvo's Ghent production plant where there are problems with analog resolver signals on the one hand loss of digital communication via industrial Ethernet on the other.

Just as the problem definition arises, the research is divided into two main parts namely: the problem definition in analog resolution signals and the problem definition in digital communication.

b) Investigating the performance and interoperability of hardware and software interfaces for TSN-capable Linux Devices

Abstract: Due to the combination of both IT and OT into IIoT for Industy 4.0 the common communication medium Ethernet has become an important aspect of industrial communication. IEEE 802.1's Time-Sensitive Networking (TSN) is crucial for real-time communication within an industrial network. The IEEE/IEC 60802 describes the usage of TSN standards and their configuration for industrial automation. However, as of the writing of this Research Project this Profile is still in draft status (v.1.3). Linux's prevalence in industrial automation, coupled with its open-source nature, makes it advantageous for TSN integration.

The intent of this research Project alongside an overview of IEEE TSN and TSN-adjacent standards is to provide an overview of potential Hardware and Software Combination intended for an IEEE/IEC 60802 compliant device. This profile is separated into two different conformancy classe (cc), i.e. ccA and ccB of which the Endstation requirements (ESR) are used as requirements for the device. To enable real-time capabilities, the Linux Kernel is patched with the mandatory PREEMPT_RT patch.

Analysis methods, including lab setups and source code review, are used to investigate the devices IEEE/IEC 60802 ESR capabilities. The devices is partially compliant in the requirements, which include the synchronization via the generalised Precision Time Protocol (gPTP/IEEE 802.1AS) as well as the Time aware shaper (TAS) according to IEEE802.1Q.

It is proposed to await the maturity of the ptp4l gPTP implementation, to become compliant with the latest gPTP version released in 2020. This compliance is mandatory for the IEEE/IEC 60802 Profile.

4.3. WP3 From data to information: OPC UA as middleware

Work package 3 takes a closer look at OPC UA. The operational aspects and information models of OPC UA are examined in greater depth. In addition, the built-in security functions are shown and categorized.

4.3.1. Operational aspects of OPC UA and information modelling

4.3.1.1. Operational aspects

The scope of OPC UA is the exchange of data and the presentation of information for the data exchange. These actions are exclusively performed on a specific instance of an asset. For better visualization and to categorize OPC UA into a modern industrial life cycle, Figure 6 depicts OPC UA into the Reference Architectural Model Industry 4.0 (RAMI 4.0).

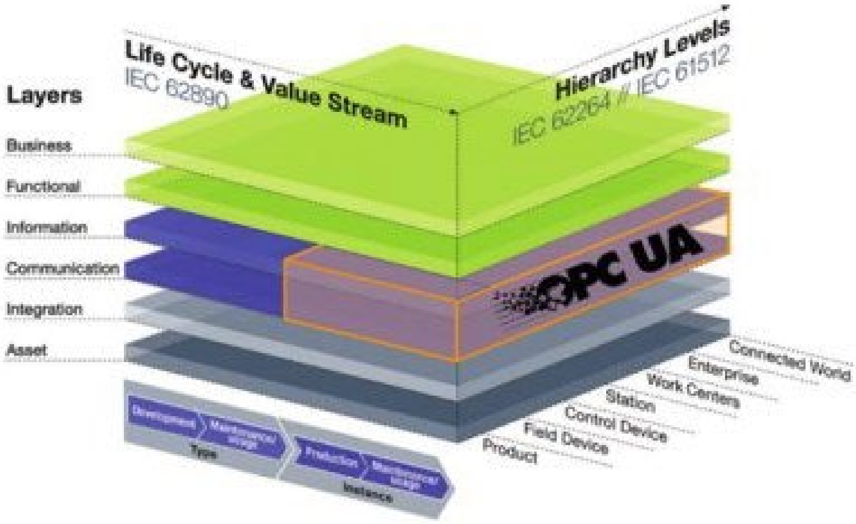


Figure 6 Mapping of OPC UA into the RAMI 4.0 model

RAMI 4.0 is a framework for developing products and business models in industry 4.0. OPC UA's responsibilities are mainly in the production phase on the information and communication layers with sensor-to-cloud connectivity [8].

For the communication layer, OPC UA provides two different communication models. These models are the Client/Server model, and the newer PubSub model [5]. The Client/Server model is a one-to-one connection in which a client requests services and information from a server. On the other hand, the PubSub model provides a one-to-many connection, where one publisher sends information to one or many subscribers. The following paragraphs give a brief overview of these models and highlight the main differences:

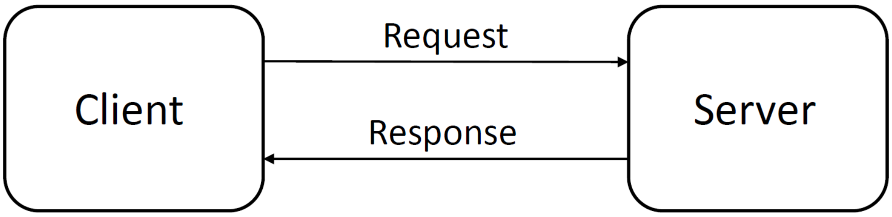


Figure 7 Simple client/server communication

Figure 7 illustrates a simple client/server communication. A client initiates a connection to a server, so a communication channel is negotiated. After establishing a communication channel, the client can request information on the server's information space. The available information is restrictable by the server and depends on the role of the client and the security constraints by the server. For the transmission of the messages, OPC UA specifies two protocols. One of these protocols defines a Webservice-oriented method using HTTPS. The second protocol is a binary transmission over TCP for better performance. Complementary to this model, a new specification adds the alternative communication model PubSub.

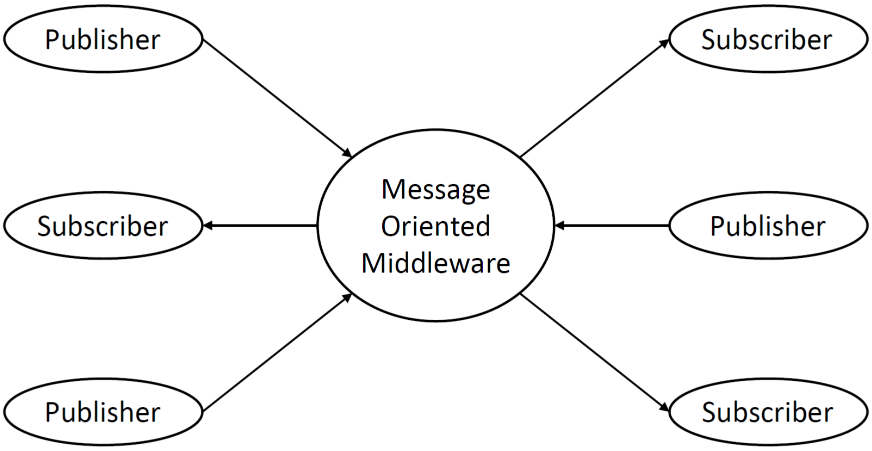


Figure 8 Basic OPC UA PubSub infrastructure

The PubSub communication model of OPC UA is depicted in Figure 8. A publisher continuously sends data to a set of subscribers. The subscriber will filter the received messages and processes them further. Ultimately, the messages will be consumed. Between the publisher and subscriber, OPC UA specifies the Message Oriented Middleware. However, depending on the transport protocol, the infrastructure is either broker-less or broker based. Broker-based implementations involve protocols such as MQTT or AMQP, while the broker-less approach implements a UDP transportation protocol or directly on Layer 2 Ethernet.

Both approaches have their area of responsibility. For vertical communication in the automation field, a configuration using Webservices with HTTPS in combination with either the Client/Server model or even with MQTT and AMQP transport protocols is suitable. For time-critical applications, TCP or a broker-less for the PubSub model is considerable. OPC UA offers the necessary flexibility for a variety of applications. The requirements of the application determine the necessary configuration and feature set.

Besides the communication aspects, OPC UA specifies an extensive concept for information models. Such information models are designed by dedicated groups of experts that agree on a standard model for a specific technology. The topic of information models will be elaborated in Section 4.3.1.2.

4.3.1.2. Information Model

Besides the data exchange, OPC UA also defines abstract models to represent data in a commonly understandable structure. OPC UA defines the fundamental models and built-in information models and dedicated working groups design companion specifications on top of these models. Additionally, the architecture allows vendor-specific extensions. This structure is visualized in Figure 9.

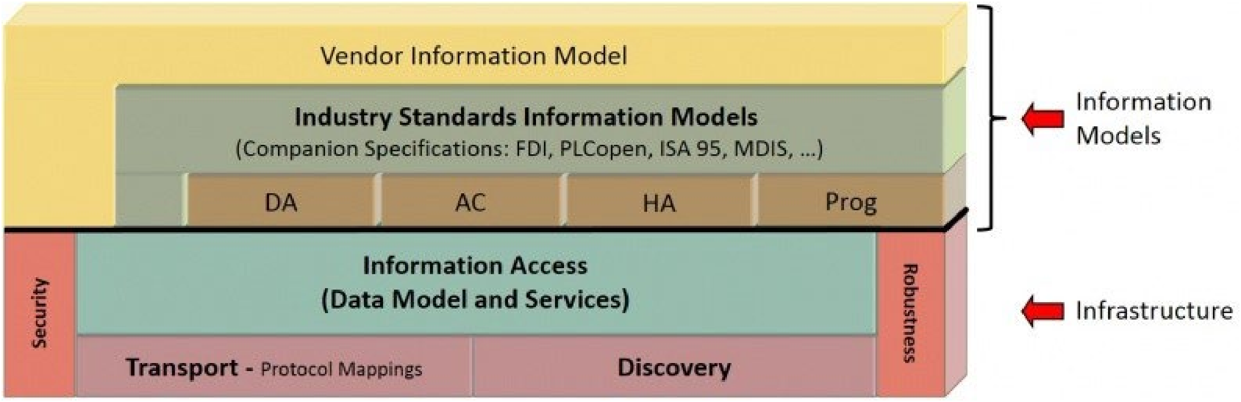


Figure 9 OPC UA Overview

Figure 9 gives an overview of the communication and information model components of OPC UA. On the upper layers, OPC UA defines several information models, and custom information models can extend these by adding a custom model. Every information model built in the context of OPC UA relies on the OPC UA meta model. The following part gives an overview of these specific models and submodels.

In order to establish a common understanding throughout all information models, OPC UA defines a Meta Model in [9]. This section describes the fundamental elements of OPC UA and includes the introduction of OPC UA-specific terms and explaining various core concepts. These fundamental elements are referred to as the OPC UA Meta Model.

OPC UA defines a framework for model information. This framework enables an OPC UA Client to access and understand the information of an OPC UA Server. The visible set of information of an OPC UA Server is referred to as the AddressSpace. The AddressSpace consists of Objects based on an ObjectModel, defined by OPC UA. The ObjectModel is depicted below:

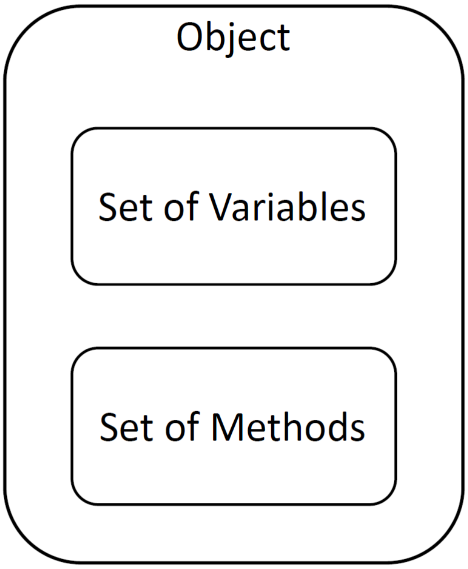


Figure 10 ObjectModel

Figure 10 visualizes the ObjectModel of OPC UA. An Object consists of a set of variables and a set of methods. Variables hold data and methods to trigger an event or retrieve a return value based on given arguments.

The concept of objects and their components are derived from known concepts of, e.g., object oriented programming languages. Objects in OPC UA are realized as Nodes according to the Node Model of OPC UA.

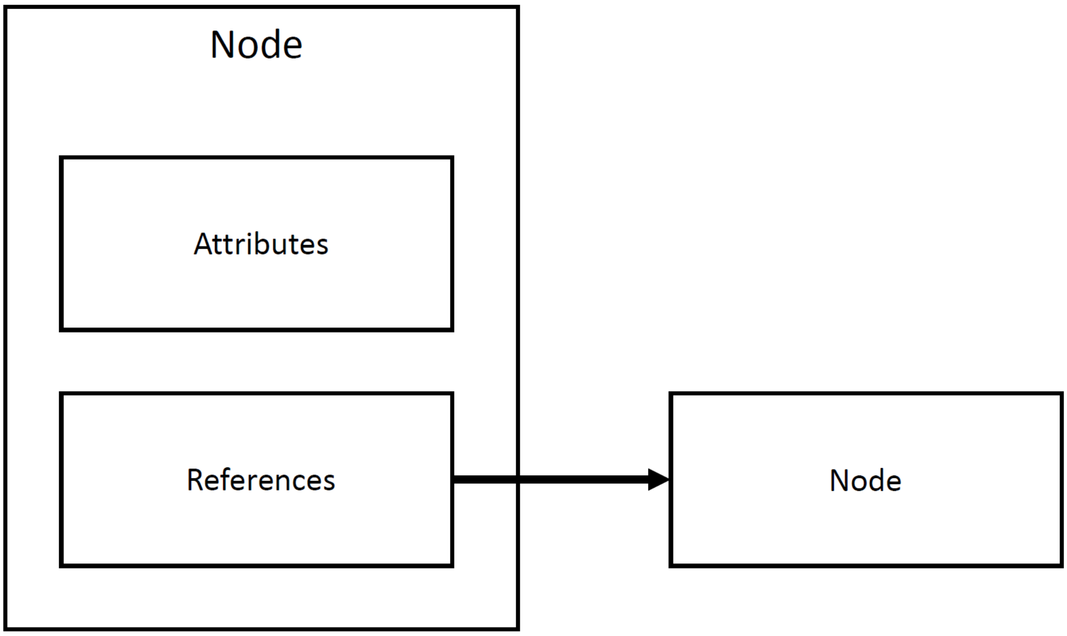


Figure 11 Node Model

Figure 11 shows the NodeModel of OPC UA. Every Node consists of attributes and references. Attributes hold data elements and reference pointers to another node. NodeClasses define the number and type of attributes and references. There are, in total, nine standard NodeClasses defined by OPC UA. The list of NodeClasses is as follows:

- Base NodeClass
- ReferenceType
- View
- Object
- ObjectType
- Variable
- VariableType
- Method
- DataType

The above explained concepts and models form the foundation for customizable information models. However, OPC UA defines a built-in information model with standardized nodes in [10]. It is not required that every OPC UA Server implements every node in this information model.

4.3.2. Assessment of the built-in security aspects

OPC UA has includes several security features. This assessment of the OPC UA security features should identify the important security functions and put them into context. In order to be able to classify the security features, OPC UA defines seven security objectives. The security objectives are defined as follows:

- **Authentication**

Authentication ensures that the identity of a user or a device is verified before allowing access to the system's resources or even before the establishment of a session.

- **Authorization**

If a user or a device is authenticated, it is authorized to perform certain actions. OPC UA defines role-based access control to ensure that entities can only perform actions permitted by their assigned roles.

- **Confidentiality**

Sensitive data require protection a disclosure to unauthorized parties. OPC UA ensures confidentiality by encrypting data that is transmitted, preventing eavesdropping.

- **Integrity**

If a message has been received, the receiver has to be sure that the message was not intentionally changed during the transmission. This is realized with digital signatures.

- **Availability**

This principle ensures that the system's resources are available to authorized users when needed.

- **Non-Repudiation**

Every authenticated entity is identified and cannot deny that a certain action has been performed. This principle is ensured by digital signatures as well, because it is created with a secret that only the sender possess.

- **Auditability**

Once an action has been carried out, all actions must be traceable by all entities. OPC UA supports this objective through logging mechanisms.

The coverage of these objectives vary for the Client/Server model and PubSub model, because of the inherent difference in these models. The security features are becoming active right before the actual exchange of data, during the session establishement. In the following, coverage of the objectives are covered for each model.

The session establishment for the Client/Server model is depicted in the figure below:

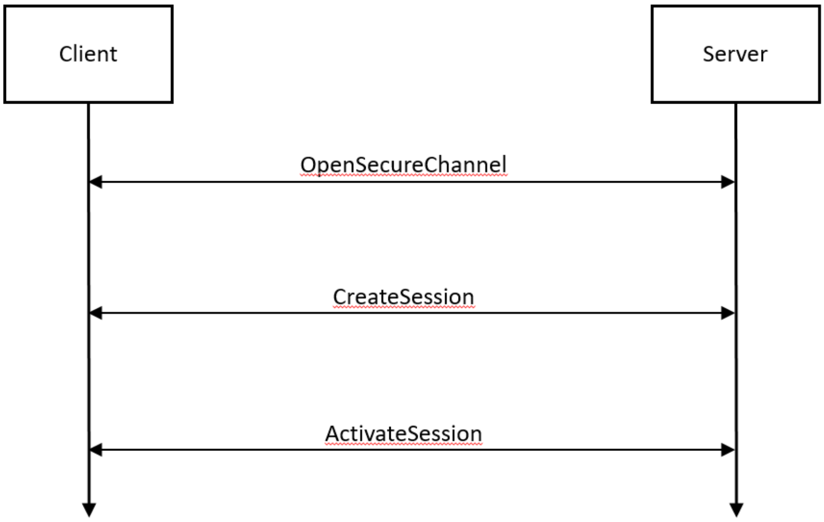


Figure 12 Secure Channel establishment

Figure 12 shows the protocol steps for the establishment and activation of a communication channel. During this establishment, the client and the server must authenticate themselves to the other communication partner. This is based on the concept of Public Key Infrastructures (PKI). The PKI includes a central authority, called the Certification Authority (CA). A CA builds the common trust source for every communication party and issues certificates. These certificates include a public key, information about the subject and a signature of the CA. Before the session is established, both parties send their certificates to each other and must verify the signature. If the signature is valid, the validating entity can be certain that this certificate was issued by the given CA. However, this validation process is only one part of the authentication process. The whole authentication is done via the Challenge/Response Authentication, which is described below:

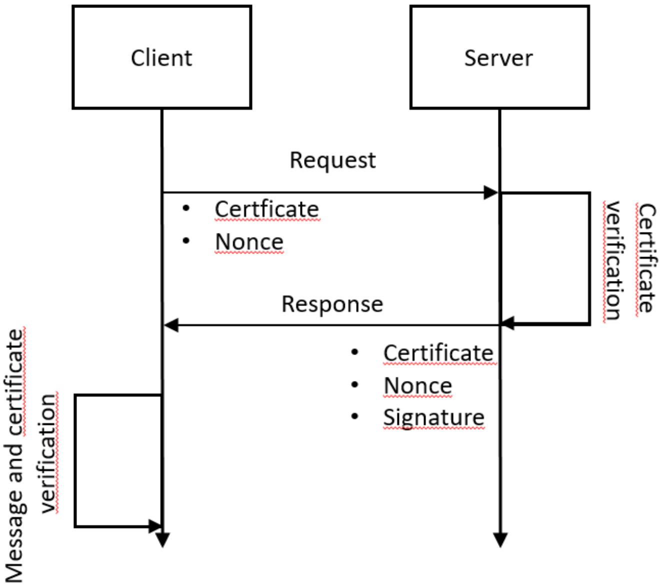


Figure 13 Challenge/Response Authentication

Figure 13 depicts the process of the Challenge/Response authentication. If the client wants to be authenticated by the server, the client sends the Certificate of the commonly trusted CA and a Nonce (number used once). A nonce is a newly generated number. The server verifies the certificate issued by the CA and sends his certificate, nonce and additionally a signature. If the client is able to verify the issuer of the certificate and the signature, both parties will trust each other and continue with the session establishment.

So far, this process does not include the authentication of a user. The user is identified by a token, which is send during the activation process of the session. OPC UA defines the following identity tokens for the user:

Token Type	Description
AnonymousIdentityToken	No user information
UserNameIdentityToken	Identification by an user name and a password
X509IdentityToken	Identification by an X.509 v3 Certficate
IssuedIdentityToken	Identification by a token issued by an external Authorization Service

Table 5 User Identity Tokens

For the secure communication in the PubSub model, the publisher and subscriber request a common secret from the central entity Security Key Server (SKS). This has to be requested with the traditional Client/Server model. Figure 14 shows the handshake of the SKS.

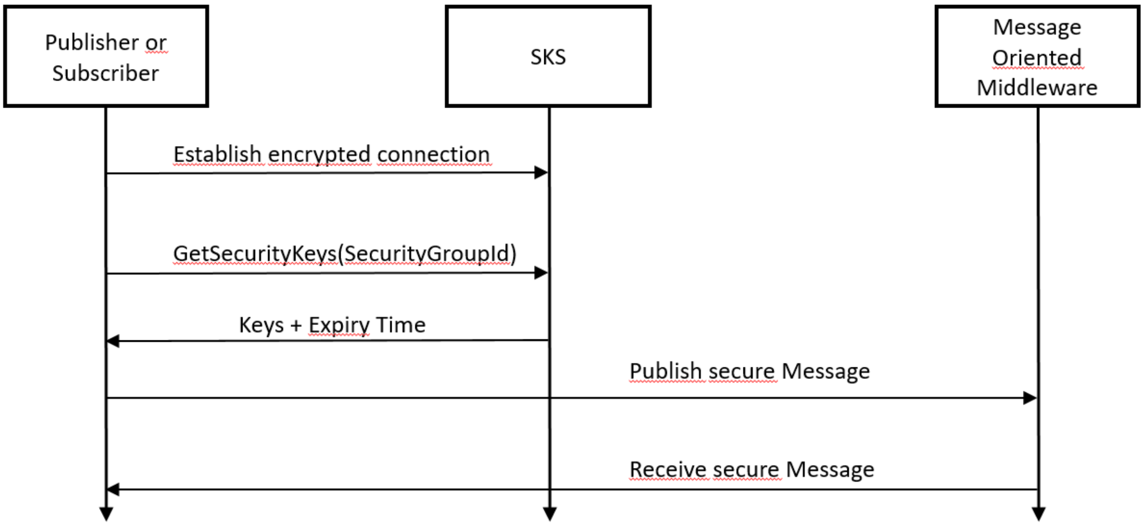


Figure 14 Security Key Service Handshake

For a secure communication, the publisher and subscriber must have a common key. Instead of deriving it directly, a SKS is responsible for the key distribution. This needs to be requested initially and after the expiry time. Since the publisher a subscriber retrieved the key from a common entity, to which they authenticated themselves, they are considering themselves as trustworthy.

Other mechanisms that do not include cryptographic functions, but are still important to fulfill the security objectives are the logging mechanisms, to identify uncommon behavior, the restriction of the number of sessions and the limitation of sensitive data to certain groups, which are assigned through roles.

4.4. WP4 Experimental quantification at system level

4.4.1. Integration of components into systems

4.4.1.1. SPE: 100Base-T1

Used equipment (Figure 15, Figure 16 Figure 17):

- 1x Tektronix MSO 5054B
- 2x Texas Instruments DP83TC811EVM (media converter)
- 1x Rohde & Schwarz RT-ZF7 Automotive Ethernet T&D Fixture
- 2x Rohde & Schwarz RT-ZF7A SMA adapters
- 1x Siemens CPU 1512SP F-1 PN (IO-Controller)
- 1x Siemens ET200SP (Distributed IO)

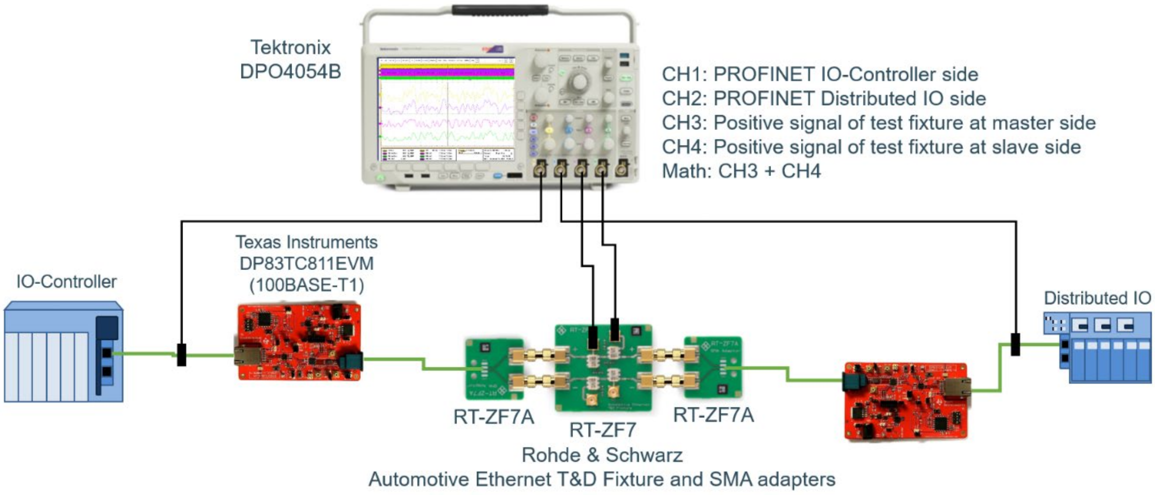
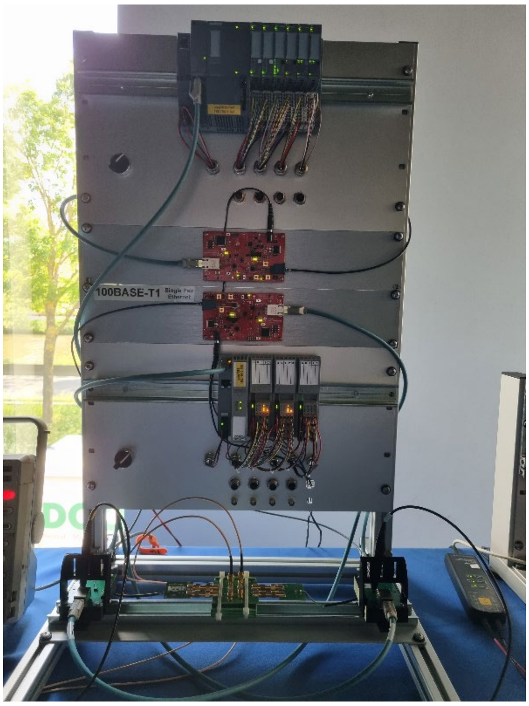


Figure 15 Schematic of the 100BASE-T1 setup



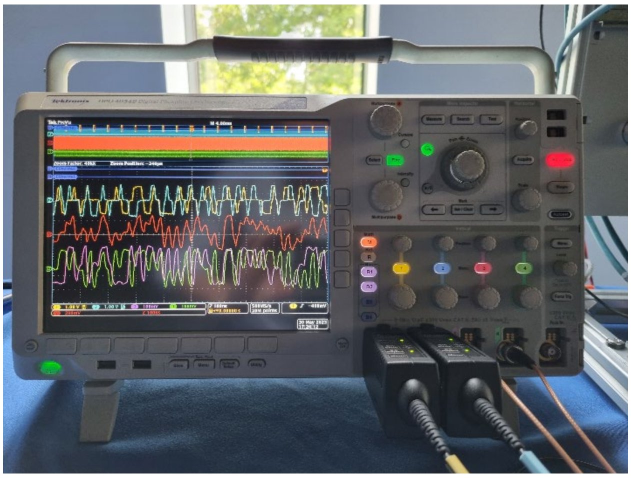


Figure 16 100BASE-T1 setup

Figure 17 Tektronix MSO 5054B connected to 100BASE-T1 setup

4.4.1.2. SPE: 10BASE-T1L

The 10BASE-T1L setup is combined with the EMI setup (see III for more information). There are two 10BASE-T1L links in this setup, one with the Analog Devices media converters (EVAL-ADIN1100) and one with Phoenix Contact switches (FL SWITCH 2303-8SP1).

The Analog Devices media converters are connected using a PROFIBUS PA cable, as example of implementing SPE in a brownfield environment (Figure 18). The media converters support both transmit level amplitudes (2,4 V and 1,0 V).

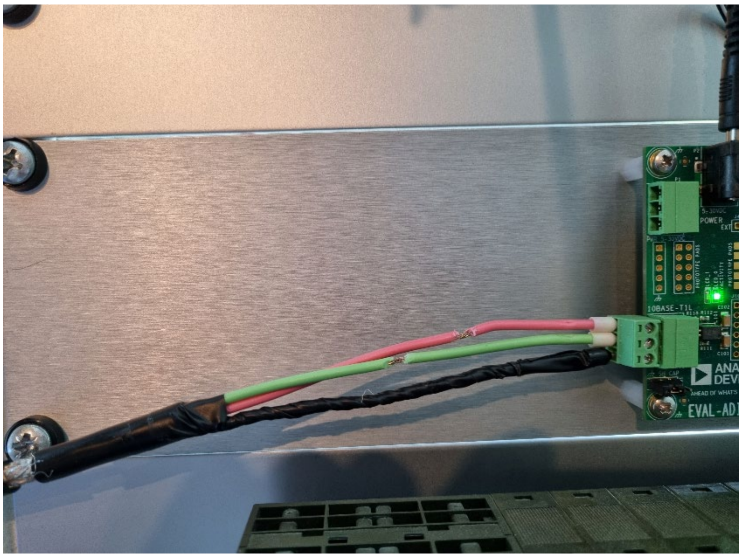


Figure 18 PROFIBUS PA cable connected to an Analog Device 10BASE-T1L media converter

The Phoenix Contact switches (Figure 19) are connected using two Phoenix Contact SPE cables of 5 meters, these switches and cables use the IEC 63171-2 connectors. The switches only support the 2,4 V transmit level amplitude. The signal levels are measured using in-house developed PCBs with correct characteristic impedance, and allow for direct connection of oscilloscope probes and SPE and Ethernet cabling (Figure 20).

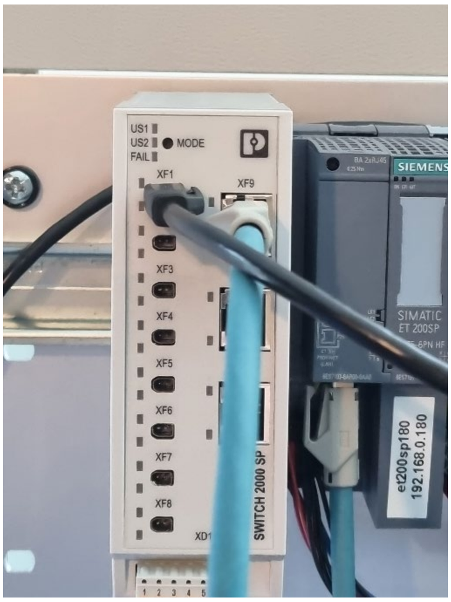


Figure 19 Phoenix Contact FL SWITCH 2303-8SP1

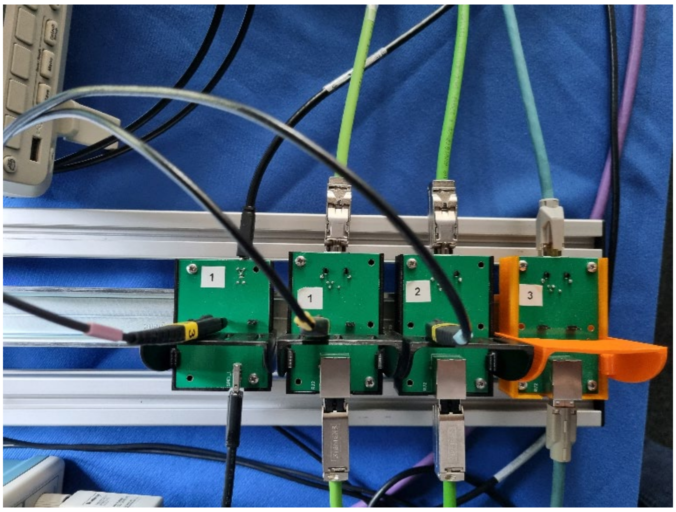


Figure 20 Measurement boards for SPE (one on the left) and Ethernet (three on the right)

4.4.1.3. TSN Setups

This setup (Figure 21 and Figure 22) is a comparison between “legacy” PN RT and PN RT over TSN network.

Implemented TSN features:

- 802.1AS – Synchronization
- 802.1Qbu + 802.3Qbr – Frame preemption

Best-effort traffic is injected into the network, which consists of Phoenix Contact FL SWITCH 2316 TSN switches.

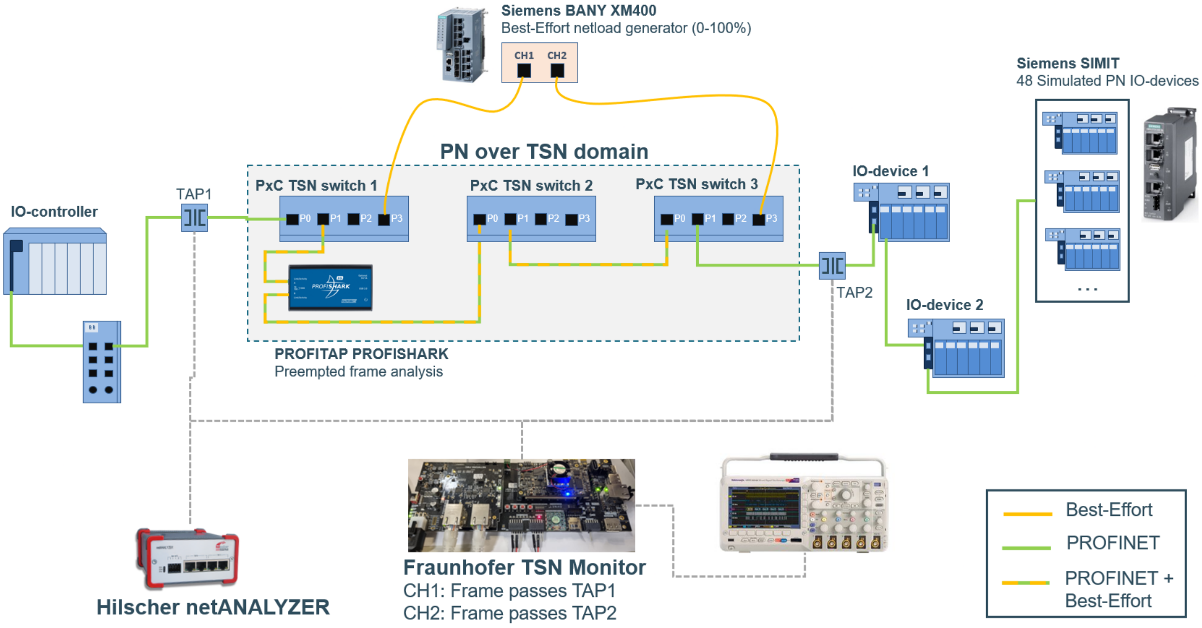


Figure 21 Schematic overview of the end-to-end delay measurement

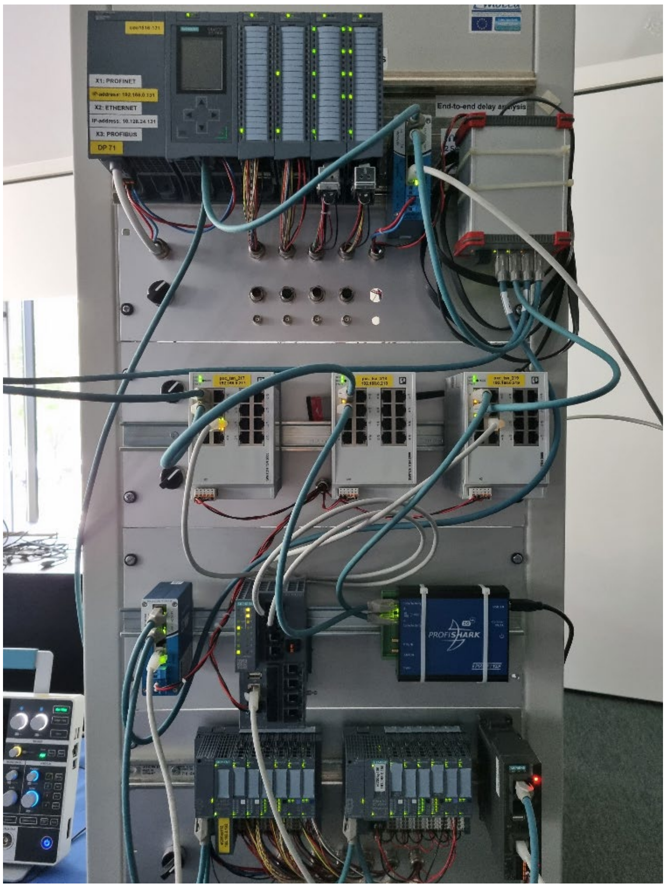


Figure 22 End-to-end delay measurement setup

4.4.1.4. Converged network

Technologies used in this network (Figure 23, Figure 24, Figure 25 and Figure 26):

- TSN
- PLC-PLC I-device communication
- IP camera
- Data-acquisition
- MQTT

TSN configuration (using Relyum RELY-TSN-BRIDGE switches):

1) TAS Configuration
    2) 125 Mbps reserved for PROFINET
        3) 12,5 µs = 12500 ns
    4) 875 Mbps PROFINET + BE
        5) 87,5 µs = 87500 ns
6) Preemption enabled in TSN domain

Components of User Committee members Siemens, Phoenix Contact, Indu-Sol, Prokorment, iba Benelux and Perinet are used. Relyum TSN bridges have been used extensively in KU Leuven. NXP and Phoenix Contact switches have been used by Fraunhofer and TH Lemgo.

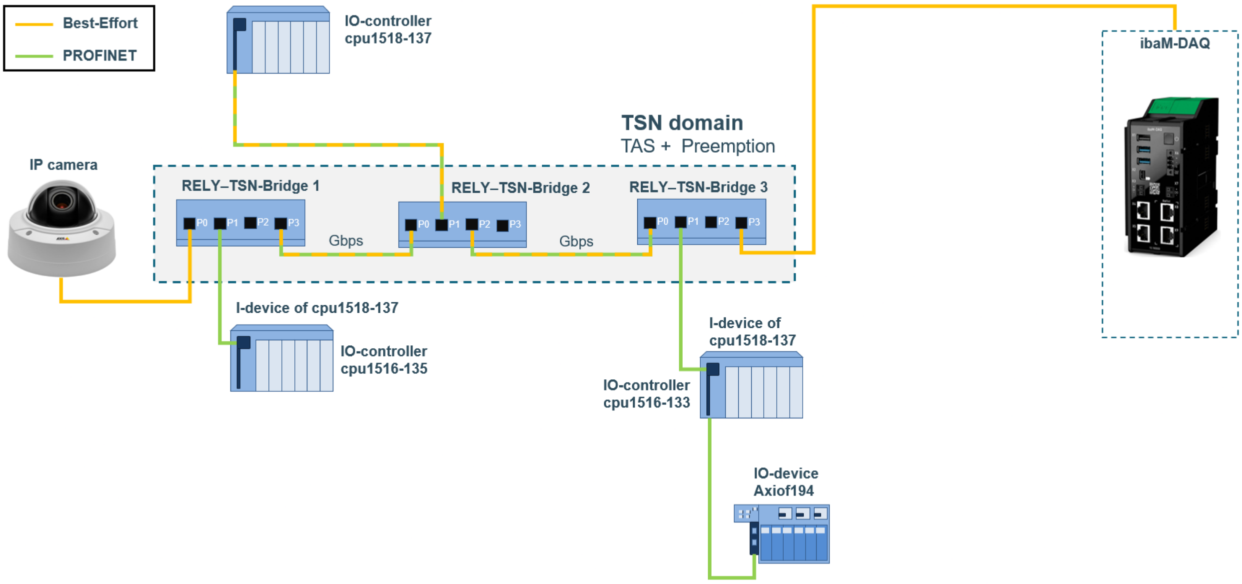


Figure 23 Simple converged network

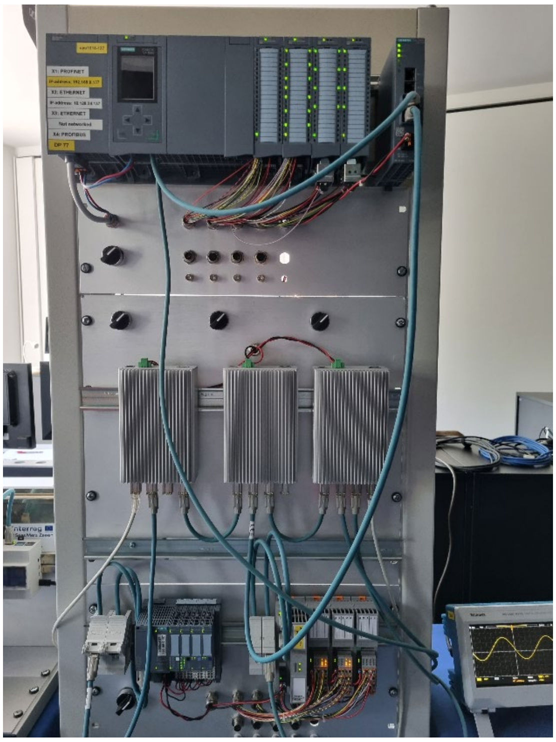


Figure 24 Converged network (part 1)

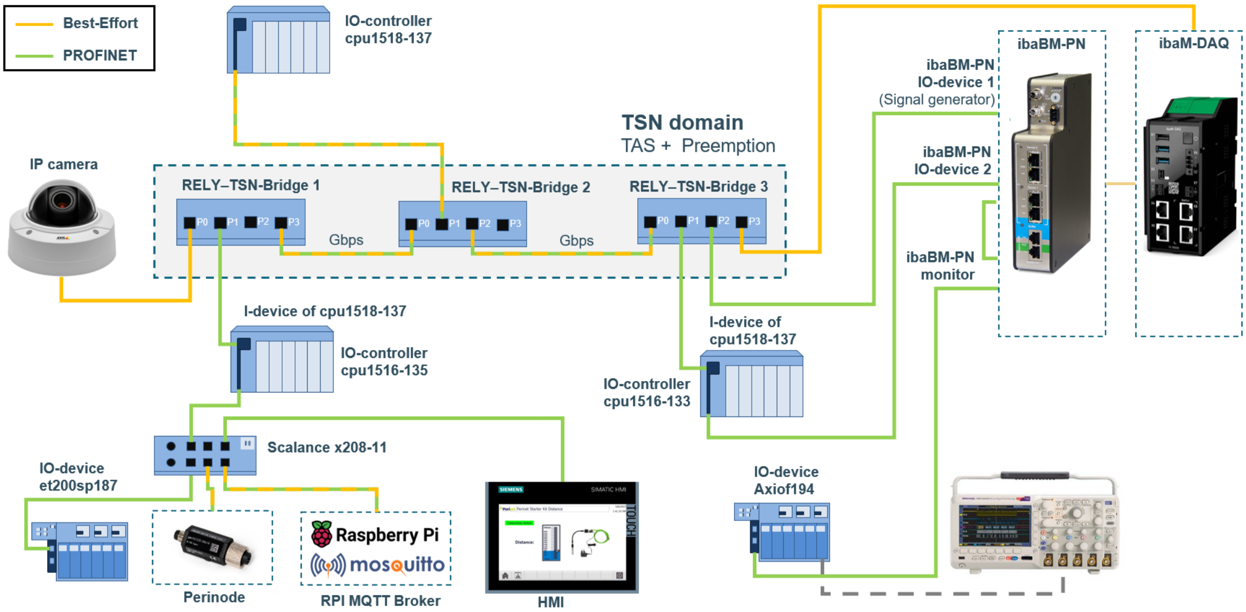


Figure 25 Extended converged network

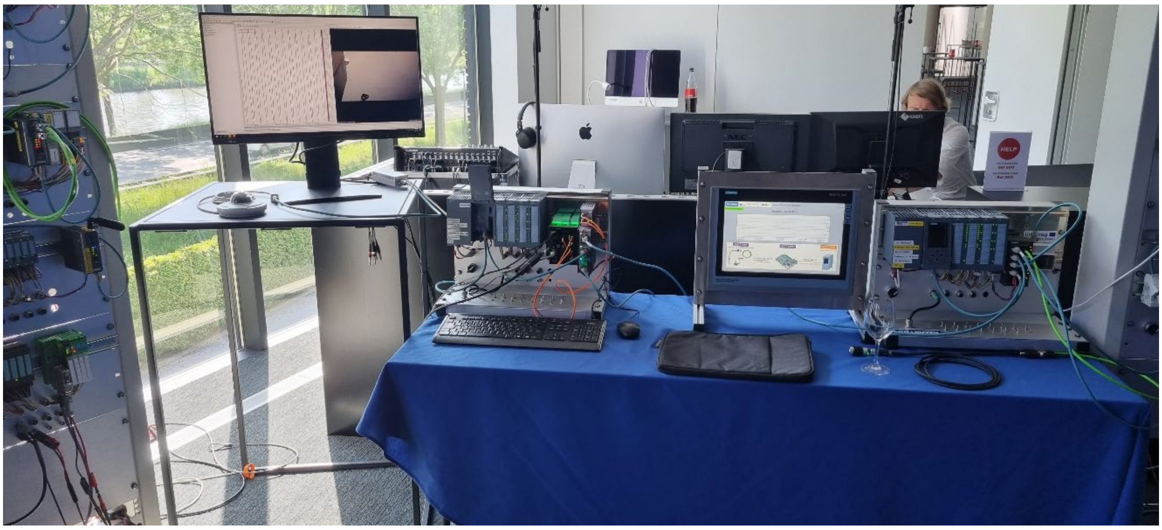


Figure 26 Converged network setup (part 2)

4.4.1.5. EMI Setup

Different experimental setups were created to test robustness of communication. The influence of the measurement setup on the measurements was also examined. For the first part of the measurements, measurements were mainly made using the RF Clamp. Here, an inductive coupling was created to inject the interference. Differential probes (M1, M2) and an oscilloscope were used to visualise the signals.

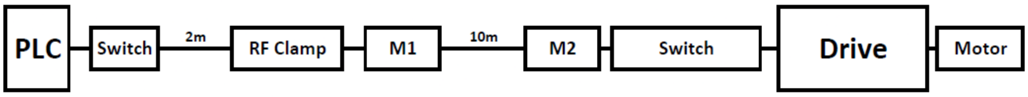


Figure 27 Schematic representation of the EMI measurement setup

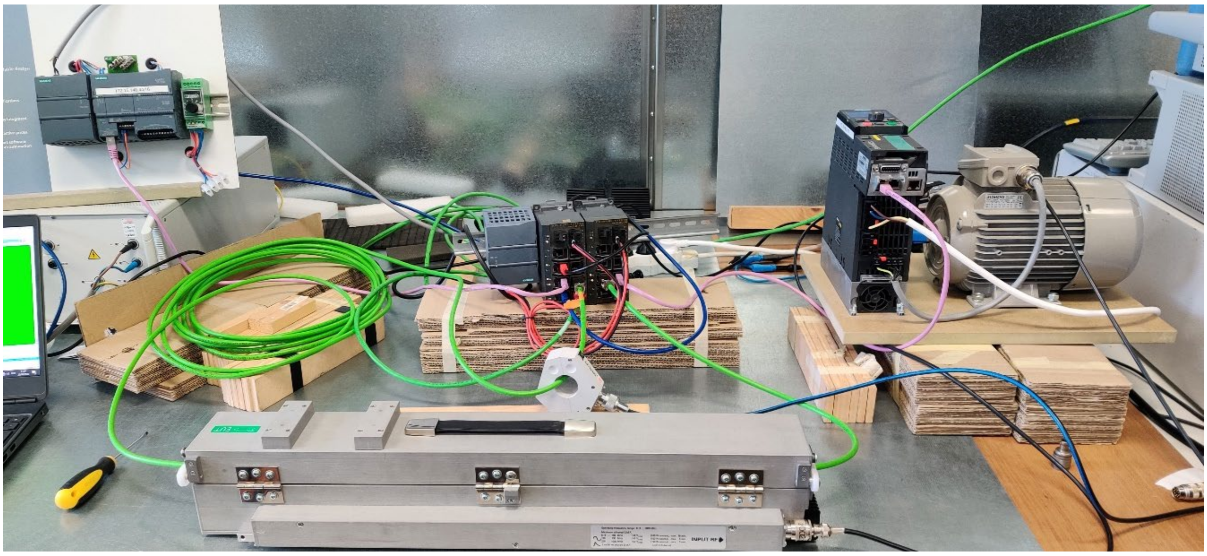
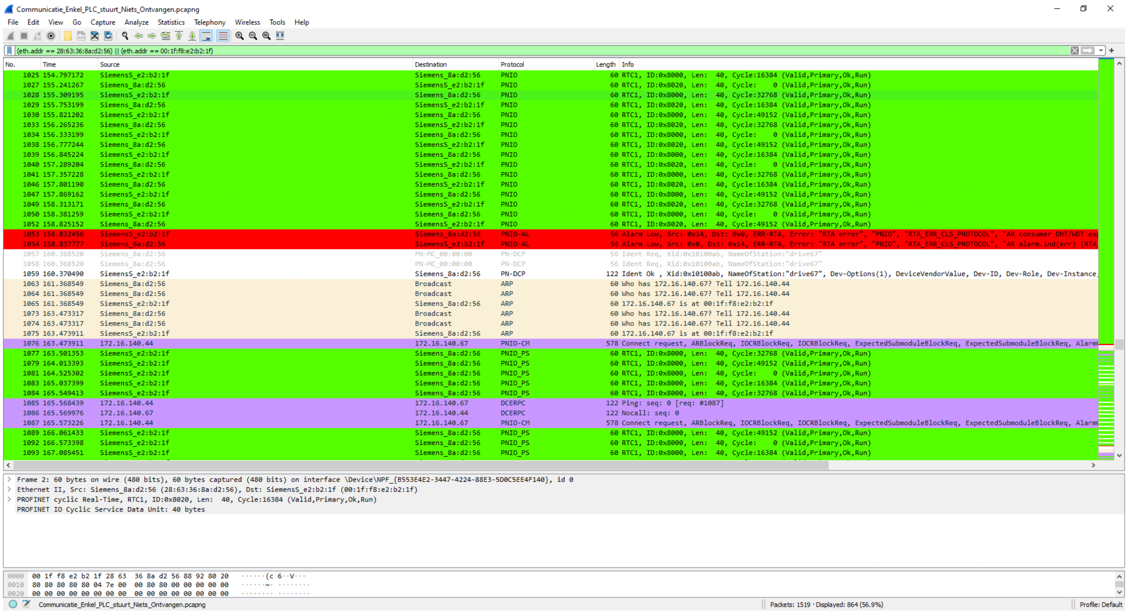


Figure 28 EMI measurement setup

To easily see if Profinet communication is still present, a visual indication was set up in Wireshark using port mirroring on switch 1.



```
(eth.addr == 28:63:36:8a:d2:56) || (eth.addr == 00:1f:f8:e2:b2:1f)
```

```
No.   Time        Source            Destination       Protocol  Length Info
1025 154.797172  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:16384 (Valid,Primary,Ok,Run)
1027 155.241267  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:    0 (Valid,Primary,Ok,Run)
1028 155.309195  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:32768 (Valid,Primary,Ok,Run)
1029 155.753199  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:16384 (Valid,Primary,Ok,Run)
1030 155.821202  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:49152 (Valid,Primary,Ok,Run)
1033 156.265236  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:32768 (Valid,Primary,Ok,Run)
1034 156.333199  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:    0 (Valid,Primary,Ok,Run)
1038 156.777244  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:49152 (Valid,Primary,Ok,Run)
1039 156.845224  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:16384 (Valid,Primary,Ok,Run)
1040 157.289204  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:    0 (Valid,Primary,Ok,Run)
1041 157.357228  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:32768 (Valid,Primary,Ok,Run)
1046 157.801190  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:16384 (Valid,Primary,Ok,Run)
1047 157.869162  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:49152 (Valid,Primary,Ok,Run)
1049 158.313171  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:32768 (Valid,Primary,Ok,Run)
1050 158.381259  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO        60 RTC1, ID:0x8000, Len:  40, Cycle:    0 (Valid,Primary,Ok,Run)
1052 158.825152  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO        60 RTC1, ID:0x8020, Len:  40, Cycle:49152 (Valid,Primary,Ok,Run)
1053 158.832456  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO-AL     56 Alarm Low, Src: 0x14, Dst: 0x0, ERR-RTA, Error: "RTA error", "PNIO", "RTA_ERR_CLS_PROTOCOL", "AR consumer DHT/WDT ex
1054 158.837777  Siemens_8a:d2:56   SiemensS_e2:b2:1f PNIO-AL     56 Alarm Low, Src: 0x0, Dst: 0x14, ERR-RTA, Error: "RTA error", "PNIO", "RTA_ERR_CLS_PROTOCOL", "AR alarm.ind(err) (RTA
1057 160.368520  Siemens_8a:d2:56   PN-MC_00:00:00    PN-DCP      56 Ident Req, Xid:0x10100ab, NameOfStation:"drive67"
1058 160.368520  Siemens_8a:d2:56   PN-MC_00:00:00    PN-DCP      56 Ident Req, Xid:0x10100ab, NameOfStation:"drive67"
1059 160.370490  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PN-DCP     122 Ident Ok , Xid:0x10100ab, NameOfStation:"drive67", Dev-Options(1), DeviceVendorValue, Dev-ID, Dev-Role, Dev-Instance
1063 161.368549  Siemens_8a:d2:56   Broadcast         ARP         60 Who has 172.16.140.67? Tell 172.16.140.44
1064 161.368549  Siemens_8a:d2:56   Broadcast         ARP         60 Who has 172.16.140.67? Tell 172.16.140.44
1065 161.368549  SiemensS_e2:b2:1f  Siemens_8a:d2:56  ARP         60 172.16.140.67 is at 00:1f:f8:e2:b2:1f
1073 163.473317  Siemens_8a:d2:56   Broadcast         ARP         60 Who has 172.16.140.67? Tell 172.16.140.44
1074 163.473317  Siemens_8a:d2:56   Broadcast         ARP         60 Who has 172.16.140.67? Tell 172.16.140.44
1075 163.473911  SiemensS_e2:b2:1f  Siemens_8a:d2:56  ARP         60 172.16.140.67 is at 00:1f:f8:e2:b2:1f
1076 163.473911  172.16.140.44      172.16.140.67     PNIO-CM    578 Connect request, ARBlockReq, IOCRBlockReq, IOCRBlockReq, ExpectedSubmoduleBlockReq, ExpectedSubmoduleBlockReq, Alarm
1077 163.501353  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:32768 (Valid,Primary,Ok,Run)
1079 164.013393  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:49152 (Valid,Primary,Ok,Run)
1081 164.525302  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:    0 (Valid,Primary,Ok,Run)
1083 165.037399  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:16384 (Valid,Primary,Ok,Run)
1084 165.549413  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:32768 (Valid,Primary,Ok,Run)
1085 165.568439  172.16.140.44      172.16.140.67     DCERPC     122 Ping: seq: 0 [req: #1087]
1086 165.569976  172.16.140.67      172.16.140.44     DCERPC     122 Nocall: seq: 0
1087 165.573226  172.16.140.44      172.16.140.67     PNIO-CM    578 Connect request, ARBlockReq, IOCRBlockReq, IOCRBlockReq, ExpectedSubmoduleBlockReq, ExpectedSubmoduleBlockReq, Alarm
1089 166.061433  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:49152 (Valid,Primary,Ok,Run)
1092 166.573398  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:    0 (Valid,Primary,Ok,Run)
1093 167.085451  SiemensS_e2:b2:1f  Siemens_8a:d2:56  PNIO_PS     60 RTC1, ID:0x8000, Len:  40, Cycle:16384 (Valid,Primary,Ok,Run)
```

```
> Frame 2: 60 bytes on wire (480 bits), 60 bytes captured (480 bits) on interface \Device\NPF_{B553E4E2-3447-4224-88E3-5D0C5EE4F140}, id 0
> Ethernet II, Src: Siemens_8a:d2:56 (28:63:36:8a:d2:56), Dst: SiemensS_e2:b2:1f (00:1f:f8:e2:b2:1f)
> PROFINET cyclic Real-Time, RTC1, ID:0x8020, Len:  40, Cycle:16384 (Valid,Primary,Ok,Run)
  PROFINET IO Cyclic Service Data Unit: 40 bytes
```

```
0000  00 1f f8 e2 b2 1f 28 63  36 8a d2 56 88 92 80 20   ······(c 6··V···
0010  80 80 80 80 80 04 7e 00  00 80 80 00 00 00 00 00   ······~· ········
0020  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00   ········ ········
```

Figure 29 Wireshark capture of the EMI measurement setup

Setup for measuring the impact of shield currents. A frequency drive was added and the shield current was forced through the PNshield. The shield current was measured by a current clamp.

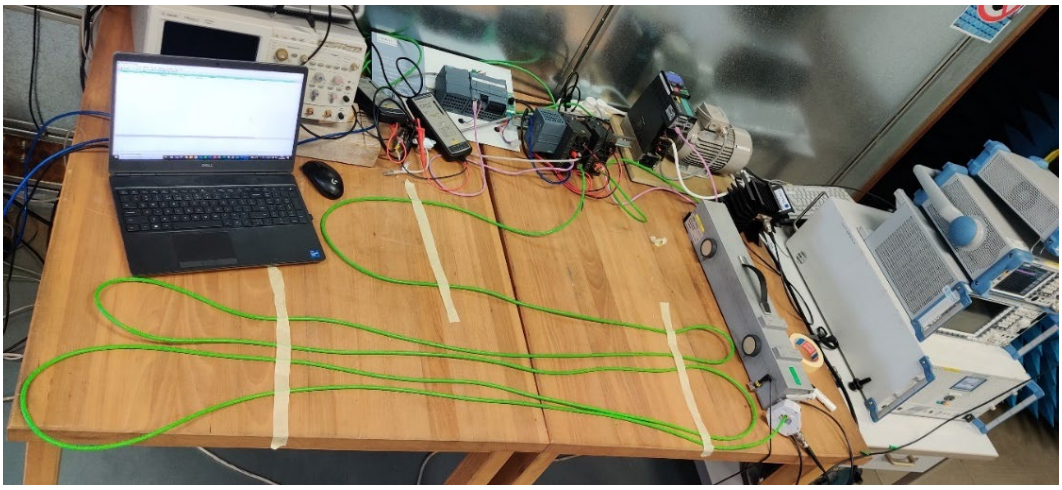


Figure 30 Impact of shield current

4.4.1.6. Joint UGent – KU Leuven EMI Measurement setup

This setup consists of an IO-controller and several remote IO devices, which are connected via multiple technologies like top-to-bottom SPE, SPE over brownfield PA cable, Ethernet CAT 6A and 5e, and PROFIBUS DP. Using an EMI amplifier and EMI clamp, the communication between the PLC and the IO devices can be disturbed.

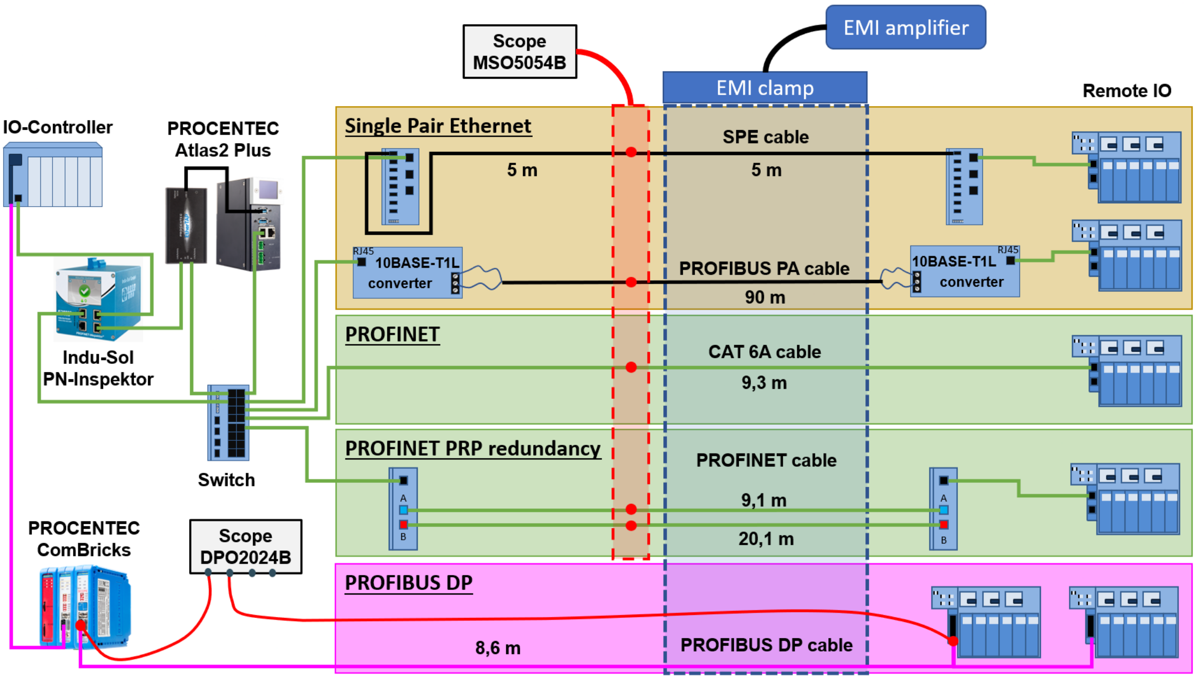


Figure 31 Schematic of the joint EMI setup

Figure 32 Pictures of the joint EMI seutp

Figure 33 Close up view of the EMI clamp and amplifier

4.4.1.7. OPC UA TSN Setup

The exhibit demonstrates the interoperability of OPC UA and TSN in a completely heterogeneous network. A host is continuously sending messages using the OPC UA PubSub protocol over a TSN capable network. The topology is depicted below:

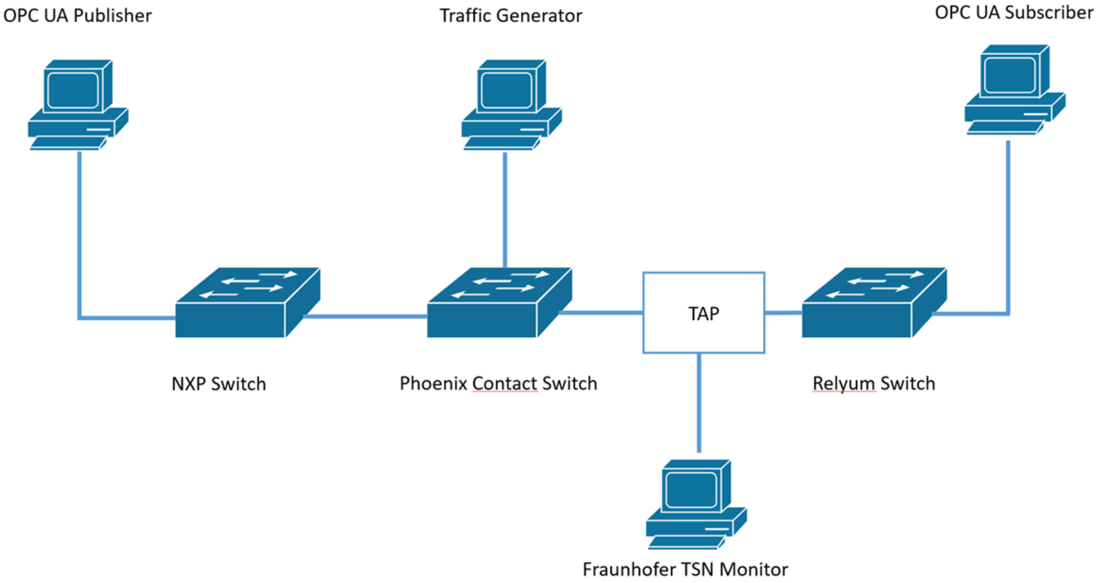


Figure 34 Schematic overview of the OPC UA TSN setup

A netX-development board from Hilscher is configured as an OPC UA Publisher. Every two milliseconds a VLAN-tagged message is send over three TSN-enabled switches to an OPC UA Subscriber executed on a Raspberry Pi. Additionally, a traffic generator is sending additional untagged messages over the same network as the OPC UA Publisher. The switches are configured to prioritize tagged messages using the Frame Preemption feature according to IEEE802.1 Qbu. This results in stable latency and jitter for the prioritized messages although the network load is increased. For the visualization of this feature, a custom FPGA-based measurement device from Fraunhofer IOSB-INA is connected to this network, the Fraunhofer TSN-Monitor. The TSN-Monitor is capable of visualizing and filtering the Ethernet Traffic. In this specific case, it visualizes the preemption effect on the non-prioritized Ethernet traffic, such that the OPC-UA frame is capable of reaching the OPC-UA Subscriber with the required bounded latency.

Figure 35 shows the real setup in more detail.

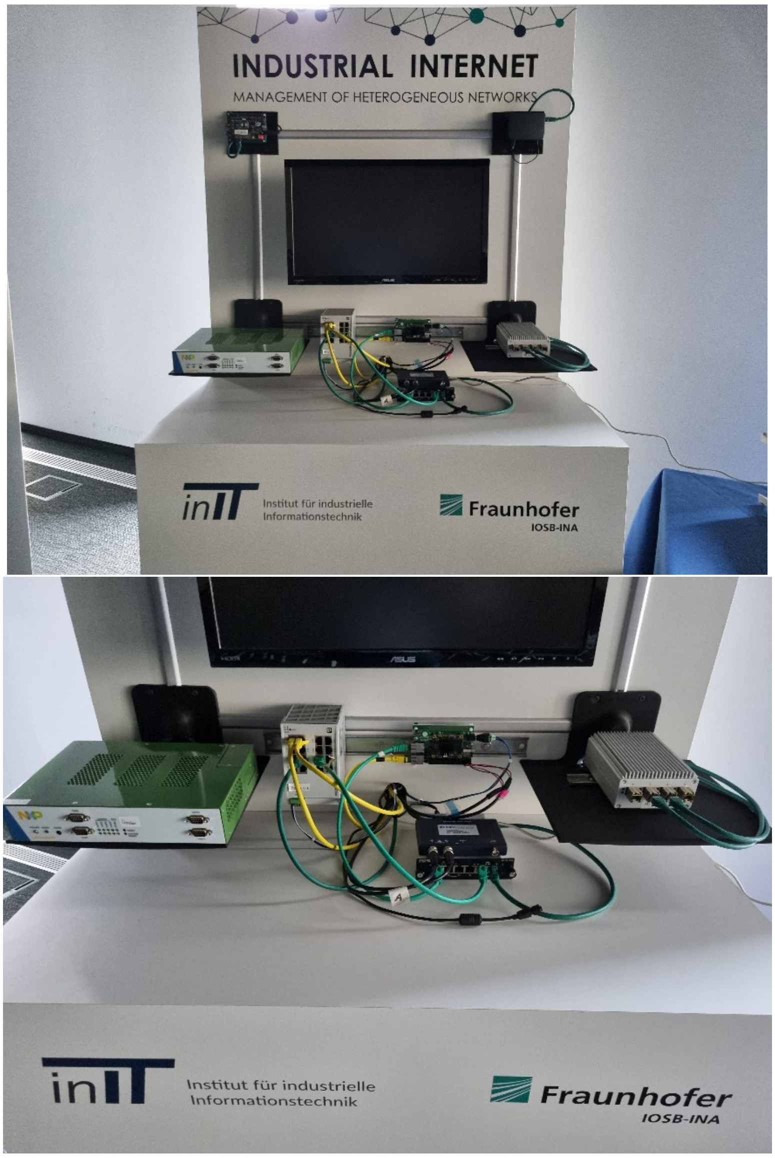


Figure 35 OPC UA TSN setup

4.4.2. Measuring operational properties

At the moment, proposed industrial Ethernet TSN solutions mainly focus on a greenfield implementation with only TSN capable components. Backward compatibility with legacy brownfield devices is provided, as is the case with PN V2.4 [11]. However, brownfield PN RT traffic does not really benefit from the TSN domain. In this report, some benefits of providing additional real-time capabilities using TSN features to brownfield PN RT traffic in the TSN domain are investigated. This remains relevant given the very large installed base and the long lifecycle of legacy devices, and the state of play of the industrial implementation of PN V2.4.

The performance of a brownfield PN over TSN network with legacy industrial PN devices and industrial TSN bridges on 100BASE-TX and 1000BASE-T physical layers is evaluated in this work. The main indicators are end-to-end delay and end-to-end delay jitter. These indicators guarantee timely delivery of frames and deterministic communication, even in a converged network with a high netload of combined OT and IT traffic. This results in the formulation of an optimal configuration of a TSN backbone based on 802.1AS, 802.1Qbv and 802.1Qbu for a brownfield PN over TSN network.

4.4.2.1. PROFINET and Best Effort Traffic

The deterministic behavior of standard PN RT is obtained by assigning a priority of 6 in the 802.1p Quality of Service (QoS) strict prioritization field [12]. This allows PN RT frames to overtake lower priority frames in the switch egress buffer. Furthermore, PN messages are typically short, reducing forwarding delay in store-and-forward switches, which are commonly used in PN RT networks. In addition, bandwidth use is restricted by the network design rules: the PN Commissioning Guideline sets a limit of 50%. However, it recommends a netload under 20% [13]. In practice, a PN RT network cannot (or only to a very limited extend) be converged with BE (IT) communication as this undermines the real-time behavior of PN RT frames.

A test network consists of 1 IO-controller, 3 TSN bridges and 50 IO-devices with an update time of 1 ms. A single physical IO-device is used, the other 49 IO-devices are simulated with a Siemens SIMIT Unit. An overview is given in Figure 36 and Figure 37, Table 6 lists the network components. The PN frames have a length of 88 bytes, each IO-device creates 0.704% netload on a 100BASE-TX link. The total PN netload is 35.2%.

BE traffic is artificially generated with a Siemens BANY XM400: unicast messages with a priority of 0 and a length of 1538 bytes are used, as this is the limit of the load generator. The generated BE netload is set to 35 Mbps on 100BASE-TX links and 350 Mbps – or in some cases 700 Mbps – on 1000BASE-T links.

The TSN domain consists of 3 TSN bridges in a line topology. Three types of TSN bridges are investigated: the Relyum RELY-TSN-BRIDGE, Phoenix Contact FL SWITCH 2316 TSN and the NXP LS1028A; the supported TSN features are found in Table 7 Supported TSN standards for each device. The network is evaluated under steady-state (but high netload) conditions without network traffic bursts. All measurements are carried out with this topology, unless stated otherwise.

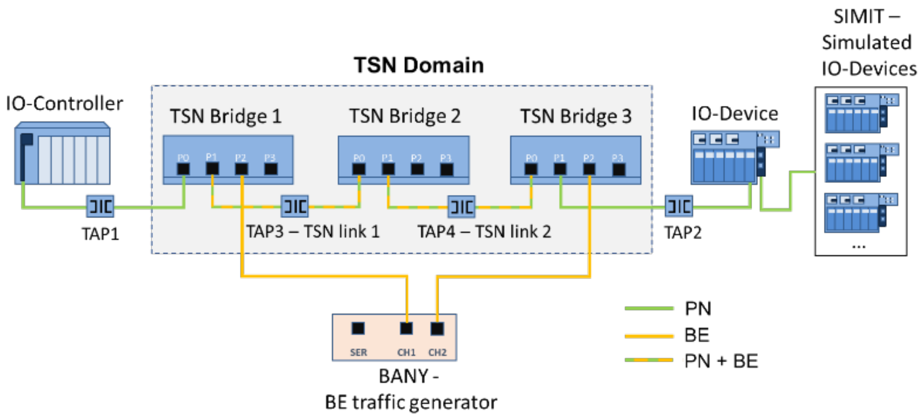


Figure 36 Schematic overview of the PN TSN setup

Figure 37 The PN TSN test bed: (moddle, top to bottom) 3 Relyum, 3 Phoenix Contact and 3 NXP TSN bridges; (left and on the table) measurement tools and PN devices

Brownfield PROFINET over TSN network		
Name	***Art. Nr.***	***FW***
CPU S7-1516-3PN/DP	6ES7 516-3FN01-0AB0	V2.1.0
ET200SP HS	6ES7 155-6AU00-0DN0	V4.0.0
Siemens SIMIT UNIT PN 128	9AE4120-2AA00	2.1.00.14-128
Siemens BANY XM400	9AE4140-2AA00	1.05.09
Relyum RELY-TSN-BRIDGE	/	22.1.0
NXP LS1028A	/	/
Phoenix Contact FL SWITCH 2316 TSN	1232304	V3.10.0

Table 6 PN TSN test network components

Supported standards in TSN bridges					
IEEE Standard (IEEE802)	***Name***	***Used in PN V2.4***	***RELY-TSN-BRIDGE***	***PxC FL SWITCH 2316 TSN***	***NXP LS 1028***
.1AS	Timing and Synchronization	x	x	x	x
.1Qbv	Enhancements for Scheduled Traffic	x	x		x
.1Qav	Forwarding and Queuing Enhancements for Time-Sensitive Streams		x		
.1Qcc	Enhancements for Stream Reservation Protocol		x		
.1CB	Frame Replication and Elimination for Reliability	x	x		
.1Qbu	Frame Preemption	x	x	x (1000BASE-T)	x
.3br	Interspersing Express Traffic	x	x	x (1000BASE-T)	x
.1Qci	Per-Stream Filtering and Policing	x			

Table 7 Supported TSN standards for each device [11], [13]

As stated in I.C, the main performance indicators are end-to-end delay and end-to-end delay jitter. The end-to-end delay of a PN RT frame over the TSN domain is defined as the time between the start of the preamble measured at TAP1 and at TAP2, the boundary ports of the TSN domain. For a more detailed discussion on this definition, refer to [14]. The delay can be split up in 3 main parts: forwarding delays, switch egress buffer delays and propagation delays. Forwarding delay is the time it takes a switch to receive and retransmit a frame, it is dependent on hardware and switching mode. Cut-through switching provides a constant forwarding delay. Forwarding delay of store-and-forward switches is dependent on frame length. Egress buffer delays exist if a PN RT frame has to wait while another frame is being transmitted; it is dependent on other netload and the network topology. Propagation delay is the time it takes for the signal to propagate over the copper cable. In this setup, it is kept constant by using cables of 1 m. Phoenix Contact VS-OE-OE-94F cables are used which account for an additional delay of 20.46 ns on the end-to-end delay measurements and 10.23 ns on the forwarding delay measurements.

4.4.2.2. Measurement results

The measurements are summarized in Table 8 and Table 9, and discussed in detail underneath these tables. All repeated end-to-end delay measurements on 802.1p QoS (PN RT) and 802.1p QoS + preemption stand alone returned practically identical results. Therefore, only the highest min and max99.7 value is given in Table 8 Forwarding delay TSN bridges. In Table 9 End-to-end delay results for 802.P QoS ("PN RT") and preemption, for 3 TSN bridges in line, the results for 802.1p QoS + TAS are given. As the repeated measurements sometimes returned varying results, all repeated measurements are included.

The “Meas. Jitter” columns presents the maximum difference between obtained results over the 5 measurements, both for the “min” and “max99.7” results. The “Extreme Values” column gives the minimum resp. maximum value out of the 5 “min” and “max99.7” measurement results.

First, baseline measurements are carried out on a legacy converged PN network. The TSN bridges are configured as regular Ethernet switches that support 802.1p QoS, identical to PN switches. The results are stated in Table 10 in the “PN RT” rows. Figure 38 shows end-to-end delay results for the RELY-TSN-BRIDGE, without and with BE traffic. Then, the line topology is extended to 4 RELY-TSN-BRIDGES and 3 NXP LS1028A bridges. This increases the number of converged links from 2 to 6, with the max99.7 delay value going from 265.7 µs to 768.92 µs. It is clear that increased line depth leads to a buildup of end-to-end delay.

The maximum end-to-end (E2E) delay is approximated as the number of converged links times the maximum length of a BE frame, augmented with the bridge’s forwarding delay (FW). This approximation assumes that no non-PN traffic exists in the non-converged links.

	100BASE-TX (µs)		1000BASE-T (µs)	
	Min	$\text{Max}_{99.7}$	Min	$\text{Max}_{99.7}$
RELY-TSN-BRIDGE	8.78	8.93	1.72	2.20
NXP LS1028A	10.03	10.74	2.05	2.68
Phoenix Contact FL SWITCH 2316 TSN	10.92	11.87	4.11	5.30

Table 8 Forwarding delay TSN bridges

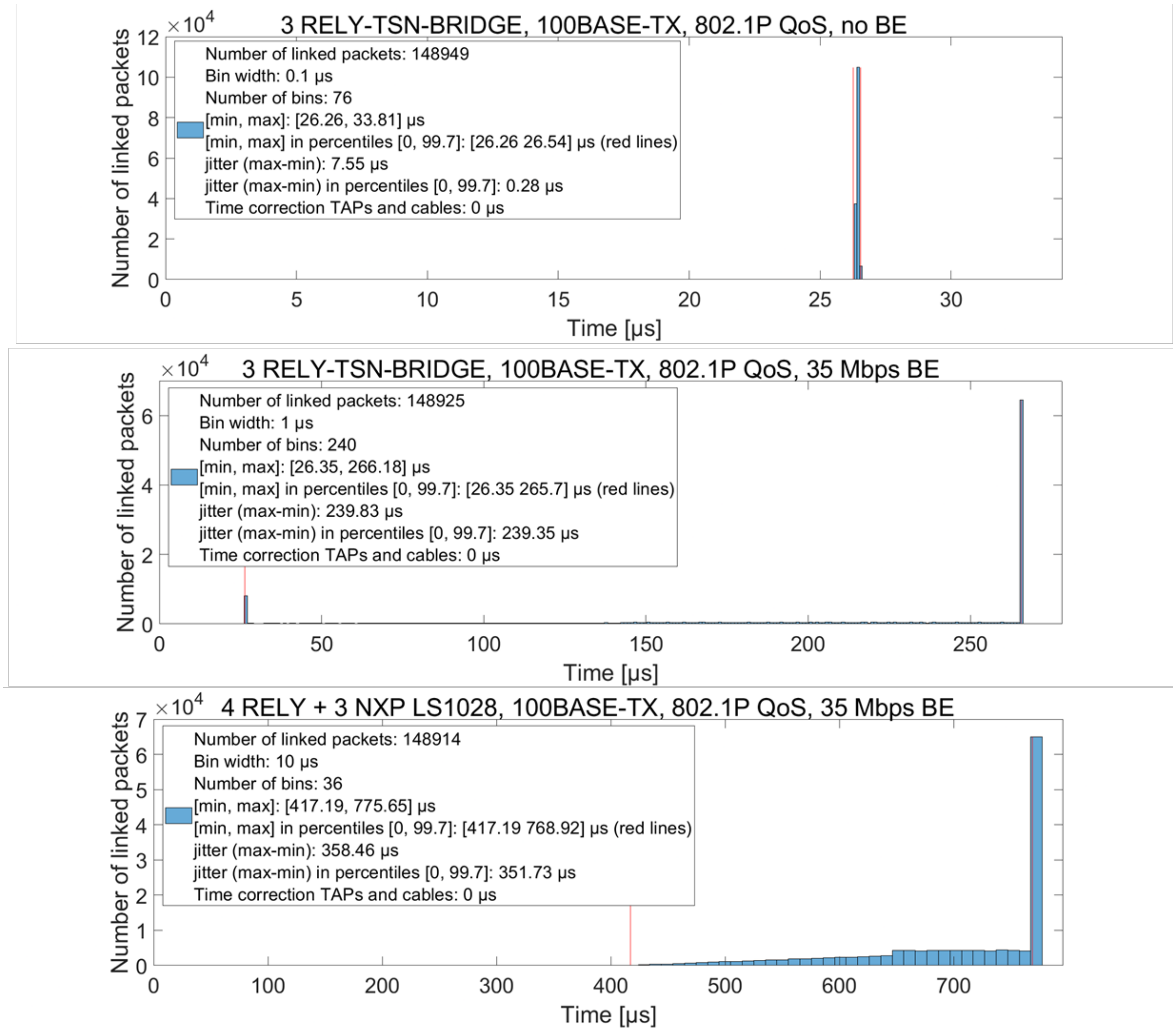
Measurement conditions			**RELY-TSN-BRIDGE**		**Phoenix Contact FL SWITCH 2316 TSN**		**NXP LS1028A**	
Speed (Mbps)	***TSN Domain config.***	***BE (Mbps)***	***min (μs)***	***max*$_{99.7}$ *(μs)***	***min (μs)***	***max*$_{99.7}$ *(μs)***	***min (μs)***	***max*$_{99.7}$ *(μs)***
100	PN RT	0	26.26	26.55	33.02	35.43	29.41	30.14
100	PN RT	35	26.35	265.70	33.16	319.46	29.44	288.37
100	Preemption	0	26.31	26.60	n/a	n/a	29.38	30.16
100	Preemption	35	26.31	50.01	n/a	n/a	29.39	101.75
1000	PN RT	0	12.73	12.87	19.86	21.93	14.52	15.07
1000	PN RT	350	12.77	37.70	19.77	46.87	14.52	38.77
1000	PN RT	700	20.02	37.64	27.27	46.53	20.95	38.82
1000	Preemption	0	12.72	12.87	19.73	21.95	14.51	15.07
1000	Preemption	350	14.80	29.48	19.79	22.94	14.53	21.74
1000	Preemption	700	15.02	35.14	20.01	23.66	17.46	21.91

Table 9 End-to-end delay results for 802.P QoS ("PN RT") and preemption, for 3 TSN bridges in line

End-to-end delay results for TAS implemented in RELY-TSN-BRIDGE								
TSN config.		**meas. 1**	**meas. 2**	**meas. 3**	**meas. 4**	**meas. 5**	**Meas. jitter**	**Extreme values**
100BASE-TX links with 35 Mbps of BE traffic								
TAS, 125 μs slots	***min (us)***	27.22	27.20	27.22	27.23	27.20	0.03	**27.20**
	max*$_{99.7}$ *(μs)	273.50	273.55	273.56	273.56	273.58	0.08	**273.58**
TAS, 250 μs slots	***min (us)***	26.34	26.30	47.75	86.72	26.28	60.44	**26.28**
	max*$_{99.7}$ *(μs)	272.32	265.57	233.63	213.81	265.57	58.51	**272.32**
TAS, 500 μs slots	***min (us)***	223.47	26.32	26.36	26.31	26.33	197.16	**26.31**
	max*$_{99.7}$ *(μs)	228.08	171.34	191.65	28.03	272.64	244.61	**272.64**
TAS, 15.625 μs slots + preemption	***min (us)***	26.28	26.27	26.28	26.26	26.28	0.02	**26.26**
	max*$_{99.7}$ *(μs)	51.74	51.95	52.18	51.49	50.73	1.45	**52.18**
TAS, 125 μs slots + preemption	***min (us)***	26.26	26.27	26.27	26.25	26.28	0.03	**26.25**
	max*$_{99.7}$ *(μs)	51.36	52.20	51.19	51.30	53.00	1.81	**53.00**
TAS, 250 μs slots + preemption	***min (us)***	26.27	26.28	26.27	26.27	26.28	0.01	**26.27**
	max*$_{99.7}$ *(μs)	51.29	50.96	51.87	51.87	50.92	0.95	**51.87**
TAS, 500 μs slots + preemption	***min (us)***	26.27	26.27	26.28	26.26	26.26	0.02	**26.26**
	max*$_{99.7}$ *(μs)	50.69	50.30	49.91	49.35	49.48	1.34	**50.69**
1000BASE-T links with 350 Mbps of BE traffic								
TAS, 15.625 μs slots	***min (us)***	12.77	12.78	12.78	12.78	12.78	0.01	**12.77**
	max*$_{99.7}$ *(μs)	27.24	27.26	27.32	27.31	27.35	0.11	**27.35**
TAS, 125 μs slots	***min (us)***	25.36	12.78	12.77	12.78	25.35	12.59	**12.77**
	max*$_{99.7}$ *(μs)	38.73	38.69	38.55	38.71	38.76	0.21	**38.76**
	min (us)	12.77	12.75	12.77	12.76	12.76	0.02	**12.75**

TAS, 15.625 µs slots + preemption	***max$_{99.7}$ (µs)***	39.66	39.37	39.29	39.59	39.42	0.37	**39.66**
TAS, 125 µs slots + preemption	***min (us)***	12.76	12.76	12.76	12.75	12.75	0.01	**12.75**
	max$_{99.7}$ (µs)	39.29	39.34	39.32	39.33	39.39	0.10	**39.39**

Table 10 End-to-end delay results for TAS, for 3 TSN bridges in line


3 RELY-TSN-BRIDGE, 100BASE-TX, 802.1P QoS, no BE

3 RELY-TSN-BRIDGE, 100BASE-TX, 802.1P QoS, 35 Mbps BE

4 RELY + 3 NXP LS1028, 100BASE-TX, 802.1P QoS, 35 Mbps BE

Figure 38 End-to-end delay results for 802.P QoS with 3 and 7 TSN bridges

The repeated TAS measurements return varying results. This is explained by the random offset between the PLC send clock and the TAS cycle. Every time the setup is restarted, the offset differs. The larger the TAS cycle, the greater the variability. When the BE slot is active, the network functions as a legacy PN RT network in which delay can build up. Therefore, the TAS time slots should be as small as possible. In this 100BASE-TX network, 125 µs is optimal as it is a multiple of 31.25 µs and greater than the maximum frame length on 100BASE-TX.

On 100BASE-TX, TAS does not result in a lower end-to-end delay compared to the regular PN RT network. As the PLC send clock and TAS cycle are not synchronized, there is no guarantee that PN RT frames are transmitted in the PN RT TAS slot. However, as soon as PN RT frames are within the RT slot, they will not experience further delay by BE frames. This can occasionally lead to a very low end-to-end delay, e.g. meas. 4 on TAS time slots of 500 µs. Figure 39 also illustrates this: it shows end-to-end delay histograms with TAS slots of 125 and 500 µs. In this example, the TAS slot of 500 µs provides a shorter end-to-end delay.

The other measurements, on exactly the same setup and configuration, returned completely different results. A high jitter is present in these results, making it unsuitable for an industrial network. In terms of worst case end-to-end delay (max99.7), the results are similar to 802.1p QoS PN RT.

The worst-case scenario is that a part of the PN frames are spread out over only the PN RT TAS slots, which means that they can only be held up by an equal number of BE slots.

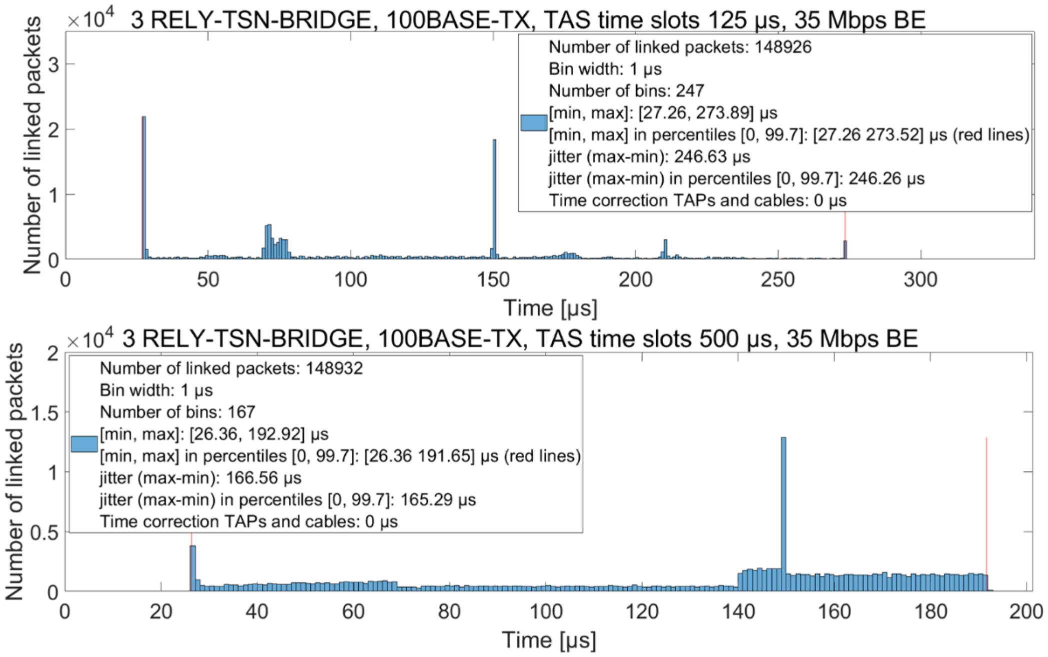


Figure 39 End-to-end delay results with TAS windows of 125 and 500 µs

While TAS does not guarantee a low end-to-end delay, it does provide bandwidth protection for PN RT frames. This is essential in a converged network, as BE traffic load is usually not predictable.

End-to-end delay measurements are performed with preemption in isolation and preemption combined with TAS (Table 9 and Table 10). Both configurations provide a large timing improvement over legacy PROFINET RT. The performance improvement is practically identical for both configurations, the TAS window size does not influence the result. It can be concluded that preemption, whether or not it is combined with TAS, provides a huge end-to-end timing improvement for brownfield PN RT.

At 100 Mbps, implementing preemption in isolation provides a reduction in max99.7 end-to-end delay from 265.7 to 50.01 µs compared to “legacy” PN under converged network conditions with an OT + IT netload of 70%. This is far higher than the suggested netload of 20% and maximum netload of 50% stated by [15]. This reduction in end-to-end delay provides for a faster and more deterministic industrial network. Comparing the reduction in end-to-end delay to the PN cycle time of 1 ms, we can state that deterministic PN RT communication is achieved over a brownfield PN over TSN network under converged OT/IT conditions with high netload.

At 1000 Mbps, implementing preemption in isolation can result in a jitter of only a couple of µs under converged OT/IT conditions. This is illustrated with the measurements on 1000BASE-T with Phoenix Contact FL SWITCH 2316 TSN bridges. This makes the PN RT communication running over the TSN domain practically immune from delay caused by BE frames, resulting in a highly deterministic network, independent of BE traffic.

TAS in itself does not guarantee a reduced end-to-end delay as the legacy IO-controller send clock is not synchronized with the TAS cycle. It does provide reserved bandwidth for PN RT frames, which protects it from excessive netload. Ideally, TAS windows are as small as possible to increase the chance that at least a part of the PN RT frames is transmitted during the Real-Time TAS slot. To optimize BE bandwidth utilization, TAS windows should be larger than the maximum size Ethernet II frame to avoid unnecessary preemption of BE frames, as this does create overhead. For 100BASE-TX, the suggested TAS time slot size is 125 µs. For 1000BASE-T, it is 15.625 µs. To guarantee availability of PN RT frames, the time percentage in which the Real-Time queue is active should exceed the PN RT netload.

Independent of preemption and TAS, 1 Gbps link speed provides further timing improvements and large additional bandwidth for RT and BE traffic. Converged OT/IT networks with high BE (IT) throughput can be set up, upholding robust brownfield PROFINET communication at high OT netload scenarios.

4.4.3. Designing for robustness at system level

In the domain of digital communications and control systems, the delineation of cable specifications and design principles constitutes a pivotal aspect of ensuring system integrity and performance. The International Electrotechnical Commission's (IEC) 11801 series serves as a cornerstone in this regard, providing a framework for information technology cabling within various customer premises. This series is characterized by its application-agnostic approach, thereby facilitating its implementation across a diverse array of environments, ranging from extensive campus networks to specific device connections.

A critical element in cable design is the selection between various configurations of twisted pair cabling, such as quad pair and star quad pair designs. These configurations offer distinct advantages, notably in terms of minimizing cable dimensions and optimizing electromagnetic compatibility (EMC).

Further, the IEC 61156 series offers detailed specifications for multicore and symmetrical pair/quad cables utilized in digital communications. This series delineates specific parts catering to different application scenarios, for instance, horizontal floor wiring versus work area wiring, thus addressing the unique demands of each setting.

The Telecommunications Industry Association’s (TIA) 568 standard plays a significant role in defining the requirements for cable categories. This standard articulates key performance metrics such as maximum bandwidth, data rate, and transmission distance, covering a spectrum of categories from Cat 5e to Cat 8.2. These specifications are instrumental in guiding the selection process for cabling solutions tailored to specific application requirements.

In the context of EMC, the EN61000 series of standards elucidates the criteria for EMC testing. These standards encompass a comprehensive range of EMC-related aspects, including but not limited to, radiated field immunity and power frequency magnetic field immunity tests, thereby ensuring cable resilience to electromagnetic disturbances.

In industrial network applications, particularly PROFINET cabling, adherence to specific IEC standards such as IEC 61156-2, IEC 61156-3, and IEC 61935-1 is paramount. These standards encompass guidelines for balanced cable testing and installation, underscoring their criticality in industrial settings where reliability and precision are non-negotiable.

The design of cables necessitates a multifaceted approach, considering variables such as physical cable parameters informed by impedance measurements, signal characteristics, and environmental influences. Factors such as surface transfer impedance, the impact of twisted pairs on interference and crosstalk, and the effects of installation methodologies on cable performance are integral to the design process.

The categorization of cables into shielded, unshielded, and foiled variants, each with distinct properties and intended applications, is another crucial consideration. The distinction between balanced and unbalanced circuits, particularly regarding impedance and noise handling, informs the selection process for appropriate cabling based on specific application needs.

Assessing cable performance through various testing methods and parameters – including return loss, insertion loss, crosstalk, and environmental condition impacts – is essential for quality assurance and functional validation of cabling systems.

Additionally, understanding the interactions of shielded cables with nearby capacitive and inductive coupling, and developing strategies to mitigate potential issues such as ground loop currents and interference, are critical for maintaining the overall reliability and efficiency of the system.

In conclusion, the specification and design of cables in the context of digital communications and control systems involve a comprehensive integration of international standards, detailed design principles, and pragmatic application considerations. This integration ensures that cabling systems meet the rigorous demands of modern electronic and industrial environments, in terms of performance, reliability and robustness.

4.4.4. Intensive technical exchange days

4.4.4.1. Exchange week in Gent

1) Measurements overview (also see measurement files):

a) Shield current measurements: discussion of setup and status (UGent & KU Leuven).

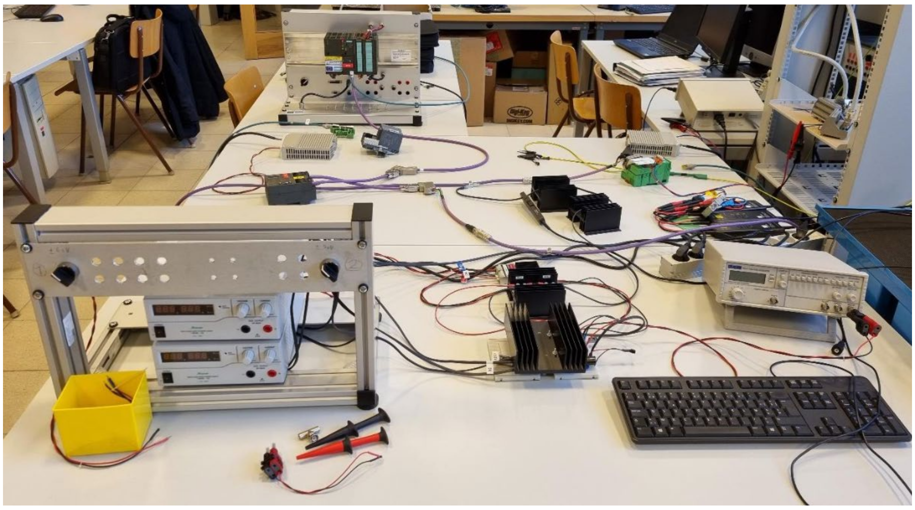


Figure 40 Shield current measurements

   a) Discussion on the measurement results of the Plugfest, especially the Keysight histograms
      i) Extra equipment from Lemgo: TSN monitor, Keysight oscilloscope for doublechecking.
      ii) Installation of the sent TSN monitor; it's confirmed that it can stay a while in Gent.
      iii) Conclusions:
         (1) Histograms by Keysight confirmed to be not good.
         (2) Check on Tektronix 5054B with current software: time measurement as such ok (edge detection, also not for all frames); histogram not found during the session, will be checked once more as one of the TSN monitors remain in Gent.
   b) Repeating/adding a few measurements that was not done previously in Lemgo.
      i) Extra equipment from Lemgo: 3 NXPs; one of the items to complete is a large network @100 Mbps, but without preemption
   c) The TSN Systems TSN Test box.
      i) We have confirmed that following features work, based on initial measurements
      ii) Capture of Ethernet frames on multiple TAPs, including combined 1000/100BASE-TX (2 TAPs) and 100BASE-T1 (2 TAPs)
      iii) Capturing preempted frames on 1000BASE-T: on initial fragments of preemptable frames, the preamble seems to be 1 byte short.
      iv) Some programming options, not yet clear what are the possibilities.

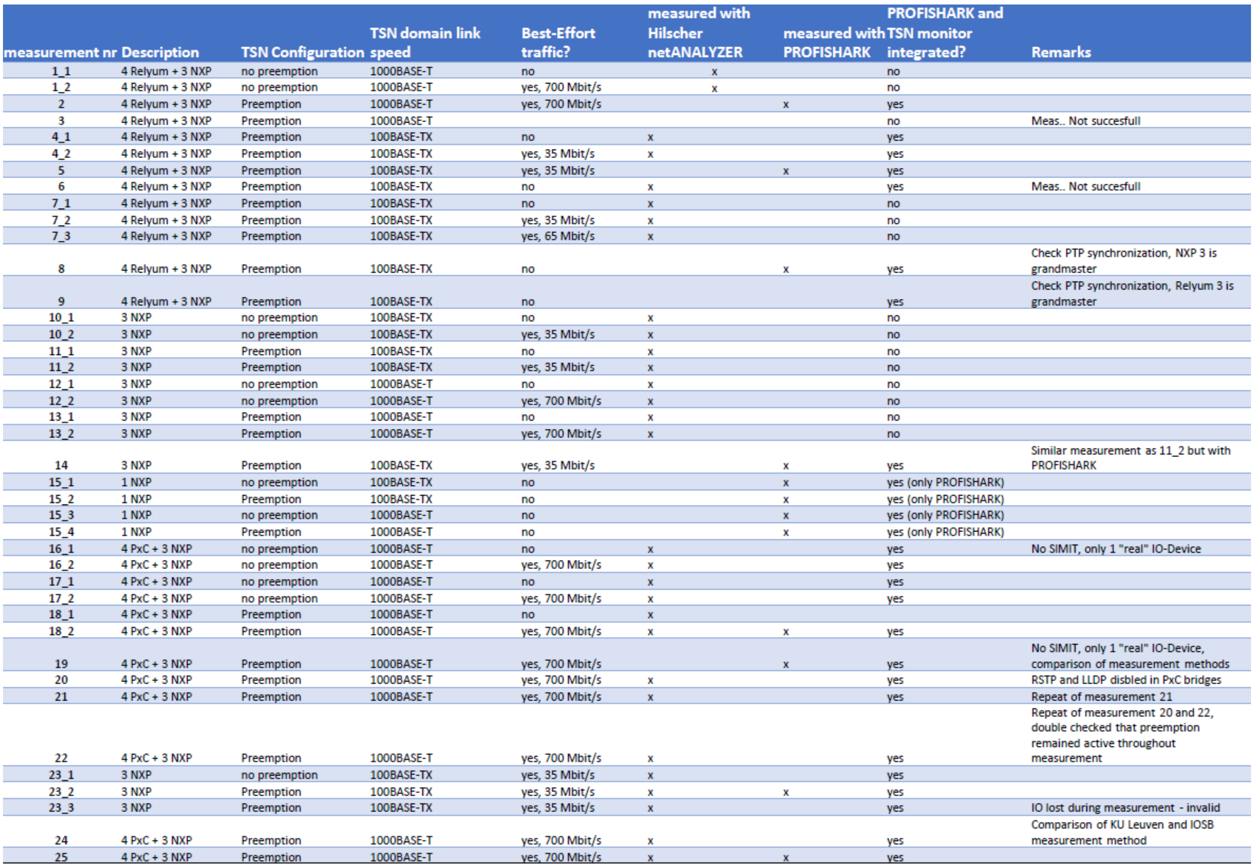
Figure 41 Measurement setup in the lab of KU Leuven

2) Short project management meeting
   a) Discussion of upcoming events (WFCS, INDIN, ETFA, Conference day in Gent)
   b) Discussion of upcoming paper submissions
   c) Preperation for the next user committee meeting
   d) Discussion on the possibilities of a setup for signal measurements on SPE

4.4.4.2. Exchange week in Lemgo, Germany

<u>CINI 4.0 TSN Plugfest 14-16/11/2022 Smartfactory TH-OWL, Lemgo</u>

This week was used to combine multiple TSN bridges in various topologies and measure them using different measurement methods. The objectives were to compare measurement method, perform interoperability tests and measure TSN networks on a large scale. The following spreadsheet provides an overview of the performed measurements, variations and provide remarks.



measurement nr	Description	TSN Configuration	TSN domain link speed	Best-Effort traffic?	measured with Hilscher netANALYZER	measured with PROFISHARK	PROFISHARK and TSN monitor integrated?	Remarks
1_1	4 Relyum + 3 NXP	no preemption	1000BASE-T	no	x		no	
1_2	4 Relyum + 3 NXP	no preemption	1000BASE-T	yes, 700 Mbit/s	x		no	
2	4 Relyum + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s		x	yes	
3	4 Relyum + 3 NXP	Preemption	1000BASE-T				no	Meas.. Not succesfull
4_1	4 Relyum + 3 NXP	Preemption	100BASE-TX	no	x		yes	
4_2	4 Relyum + 3 NXP	Preemption	100BASE-TX	yes, 35 Mbit/s	x		yes	
5	4 Relyum + 3 NXP	Preemption	100BASE-TX	yes, 35 Mbit/s		x	yes	
6	4 Relyum + 3 NXP	Preemption	100BASE-TX	no	x		yes	Meas.. Not succesfull
7_1	4 Relyum + 3 NXP	Preemption	100BASE-TX	no	x		no	
7_2	4 Relyum + 3 NXP	Preemption	100BASE-TX	yes, 35 Mbit/s	x		no	
7_3	4 Relyum + 3 NXP	Preemption	100BASE-TX	yes, 65 Mbit/s	x		no	
8	4 Relyum + 3 NXP	Preemption	100BASE-TX	no		x	yes	Check PTP synchronization, NXP 3 is grandmaster
9	4 Relyum + 3 NXP	Preemption	100BASE-TX	no			yes	Check PTP synchronization, Relyum 3 is grandmaster
10_1	3 NXP	no preemption	100BASE-TX	no	x		no	
10_2	3 NXP	no preemption	100BASE-TX	yes, 35 Mbit/s	x		no	
11_1	3 NXP	Preemption	100BASE-TX	no	x		no	
11_2	3 NXP	Preemption	100BASE-TX	yes, 35 Mbit/s	x		no	
12_1	3 NXP	no preemption	1000BASE-T	no	x		no	
12_2	3 NXP	no preemption	1000BASE-T	yes, 700 Mbit/s	x		no	
13_1	3 NXP	Preemption	1000BASE-T	no	x		no	
13_2	3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s	x		no	
14	3 NXP	Preemption	100BASE-TX	yes, 35 Mbit/s		x	yes	Similar measurement as 11_2 but with PROFISHARK
15_1	1 NXP	no preemption	100BASE-TX	no		x	yes (only PROFISHARK)	
15_2	1 NXP	Preemption	100BASE-TX	no		x	yes (only PROFISHARK)	
15_3	1 NXP	no preemption	1000BASE-T	no		x	yes (only PROFISHARK)	
15_4	1 NXP	Preemption	1000BASE-T	no		x	yes (only PROFISHARK)	
16_1	4 PxC + 3 NXP	no preemption	1000BASE-T	no	x		yes	No SIMIT, only 1 "real" IO-Device
16_2	4 PxC + 3 NXP	no preemption	1000BASE-T	yes, 700 Mbit/s	x		yes	
17_1	4 PxC + 3 NXP	no preemption	1000BASE-T	no	x		yes	
17_2	4 PxC + 3 NXP	no preemption	1000BASE-T	yes, 700 Mbit/s	x		yes	
18_1	4 PxC + 3 NXP	Preemption	1000BASE-T	no	x			
18_2	4 PxC + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s	x	x	yes	
19	4 PxC + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s		x	yes	No SIMIT, only 1 "real" IO-Device, comparison of measurement methods
20	4 PxC + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s	x		yes	RSTP and LLDP disbled in PxC bridges
21	4 PxC + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s	x		yes	Repeat of measurement 21
22	4 PxC + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s	x		yes	Repeat of measurement 20 and 22, double checked that preemption remained active throughout measurement
23_1	3 NXP	no preemption	100BASE-TX	yes, 35 Mbit/s	x		yes	
23_2	3 NXP	Preemption	100BASE-TX	yes, 35 Mbit/s	x	x	yes	
23_3	3 NXP	Preemption	100BASE-TX	yes, 35 Mbit/s	x		yes	IO lost during measurement - invalid
24	4 PxC + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s	x		yes	Comparison of KU Leuven and IOSB measurement method
25	4 PxC + 3 NXP	Preemption	1000BASE-T	yes, 700 Mbit/s	x	x	yes	

Figure 42 Spreadsheet of the performed measurements

Preemption interoperability has been successfully achieved through the integration of the RELY-TSN-BRIDGE, PxC FL Switch 2316, and NXP LS1028, with the caveat that preemption must be manually enabled on the PxC FL Switch 2316. Comprehensive network performance analyses conducted on 100BASE-TX and 1000BASE-T configurations demonstrate significant timing benefits of preemption. Additionally, a comparative study of the measurement methodologies of KU Leuven and Fraunhofer IOSB-INA provides valuable insights into varying analytical approaches within the field.

<u>Technical exchange week in Flanders – 14-17/03/2022</u>

(Participants: De Schuyter Dimitri, Knockaert Jos, Konradi Oliver, Saey Philippe, Troch Mathieu, Verhoeven Arne, Wisniewski Lukasz.)

15.03.2022:

The working day at KU Leuven Technology Campus Gent, Lab B124 "Regeltechniek en Automatisering," commenced with a planning session at 8:30 AM. Activities included hands-on sessions with Single Pair Ethernet (SPE) measuring tools, component discussions, and documenting findings until 4 PM. A shield currents set-up was also addressed. Post-4 PM, preparations for Hirschmann-Belden TSN switch setup began, covering documentation, power supply, and configurations. Amidst these activities, a sandwich lunch was provided, and the day concluded with a wrap-up at 5:30 PM. Discussions revolved around SPE measurements, MATLAB analysis of PCAP captures for Ethernet signals, CINI4.0 project administration, and constructing a multivendor TSN network, detailed in the appendix "2022_03_18_TSN_Interop_V1."

16.03.2022:

The focus remained on Building B, Lab B124, where discussions began at 8:30 AM, covering topics like SPE, shield currents, and TSN until 10 AM. A brief lab tour with Lukasz followed. Later, at 11:15 AM, they traveled to UGent Campus Kortrijk for a working lunch at "Au Casino" and a visit to the EMC lab, continuing meetings until 4:30 PM.

The meeting covered future agendas, including NXP-Relyum integration, attendance at upcoming events like Hannover Messe and Indumation, and arrangements for the CINI4.0 Conference Day. Discussions ensued on scheduling, papers for ETFA, a proposed workshop agenda, including lectures, demos, and speakers. Topics spanned EMC, SPE, TSN, OPC UA pub/sub, and a panel discussion. Preparing a joint paper for Komma involving multiple vendors was also planned. The day concluded with plans to return to Gent for further discussions.

17.03.2022:

The working day commenced with planning at 8:30 AM. The focus centered on TSN-related activities, including utilizing measurement tools, exploring various TSN devices, assessing the Belden switch for potential integration, and documenting the week's progress. The day concluded with a wrap-up at 5:30 PM. The interoperability measurements between Relyum and Hirschmann TSN switches concluded, and the detailed report is available in "2022_03_18_TSN_Interop_V1."

4.5. WP5 Validation using large lab setups or industrial use cases

4.5.1. Validation of design methods on industrial grade use cases

For this task, an extensive report was created as “Best Practices Part 1" (Appendix B). The key aspects of this document are as follows:

I. Introduction

An overview of the CINI4.0 project and its focus on investigating emerging technologies for robust Industrial Internet of Things (IIoT) applications.

II. Line Depth

Discusses the impact of switches on data transfer delays, emphasizing the importance of considering line depth in network topology planning. It delves into the influence of line depth on different data rates, packet lengths, and the utilization of Cut Through or Store-and-Forward switches.

III. Integrating Legacy Devices

Provides examples and strategies for integrating legacy PROFIBUS DP networks into modern systems, detailing scenarios involving DP slaves, DP masters, and various approaches like IE/PB LINKs, PN/PB Proxies, and Interface PLCs.

IV. Inserting 100 and 1000 Mbps TAPs in Industrial Ethernet

Explores the use of Test Access Points (TAPs) for diagnostic purposes in larger networks, discussing their principles, physical layers (100BASE-TX, 1000BASE-T), and examples of TAPs with varying speeds and functionalities.

V. Planning Tools

Describes planning tools like PROnetplan V2, Siemens SINETPLAN, and the PI Network Load Calculation Tool for network planning and traffic analysis in the context of OT and IT networks.

VI. Single Pair Ethernet over Brownfield Cabling

Details the cabling requirements and testing considerations for 100BASE-T1, 1000BASE-T1, and 10BASE-T1L technologies, highlighting the feasibility of using brownfield cabling for 10BASE-T1L with certain limitations and considerations.

The document provides in-depth insights into various technological aspects and best practices for designing, integrating, and analyzing industrial networks, offering comprehensive guidance for Industry 4.0 network implementations.

4.5.2. Migration and implementation aspects in brownfield installations

The document “Best practices part 2” (Appendix C) provides a comprehensive overview of various industrial network evaluations and analyses conducted in different settings. The contents are structured into several sections:

I. Introduction

- TSN Brownfield PROFINET Evaluation
- AMG WWA Mill Maintenance Hall Analysis
- EMC AMG SDG
- EMC Prolink-engineering (Renson)
- Historically grown converged OT/IT networks at Barry Callebaut
- ArcelorMittal Gent – Steel Shop

II. TSN Brownfield PROFINET Evaluation

- Analysis of a large 100BASE-TX network
- Analysis of a large 1000BASE-T network

III. AMG WWA Mill Maintenance Hall Analysis

- Wired network problem – Lathe (draaibank)
- Wireless/wired network problem – LK372 (overhead traveling crane)
- Analysis

IV. EMC

- AMG SDG

- Prolink-engineering (Renson)

V. Historically grown converged OT/IT networks at Barry Callebaut

VI. ArcelorMittal Gent – Steel Shop

Each section delves into specific network evaluations, analyzing problems encountered, whether wired or wireless, and includes detailed analyses of various networks' configurations and challenges faced. The document appears to offer insights into troubleshooting, assessing, and potentially optimizing these networks within industrial settings for improved efficiency and reliability.

4.5.3. M. Sc. Thesis projects

Analyse en optimalisatie van industriële netwerken in Barry-Callebaut Halle (Klaas BARBÉ)

The Barry-Callebaut plant in Halle occasionally encounters issues in their Ethernet networks. The objective of this master's thesis is to conduct a thorough and systematic analysis of both the OT and IT networks, and to identify the requirements and issues. The primary aim is to gain an understanding of the existing network within the plant; a custom dashboard developed by Barry-Callebaut and a SINEC NMS server are used for this purpose. For in-line measurements PROFITAPs, mirror ports, etc., were installed, along with an Allegro device and ProfiShark as measuring devices. The obtained results were analyzed using Wireshark and the Allegro Packets Multimeter software. These analyses allow the protocols present in the network to be identified, as well as the establishment of timing requirements, priorities and network errors. The presence of critical points (such as the IT switches and the core IT switch) and the lack of a redundant network in general, combined with the convergence of the OT and IT networks, the use of VLANs without priority assignment, and the absence of continuous monitoring, are among the identified areas for improvement. These lead to increased robustness, throughput and determinism. In the test laboratory in Wieze, the use of a redundant network and the separation of the OT and IT networks have been implemented and tested.

Strategie voor permanente monitoring en foutzoeken in PROFINET (Dion Derycke)

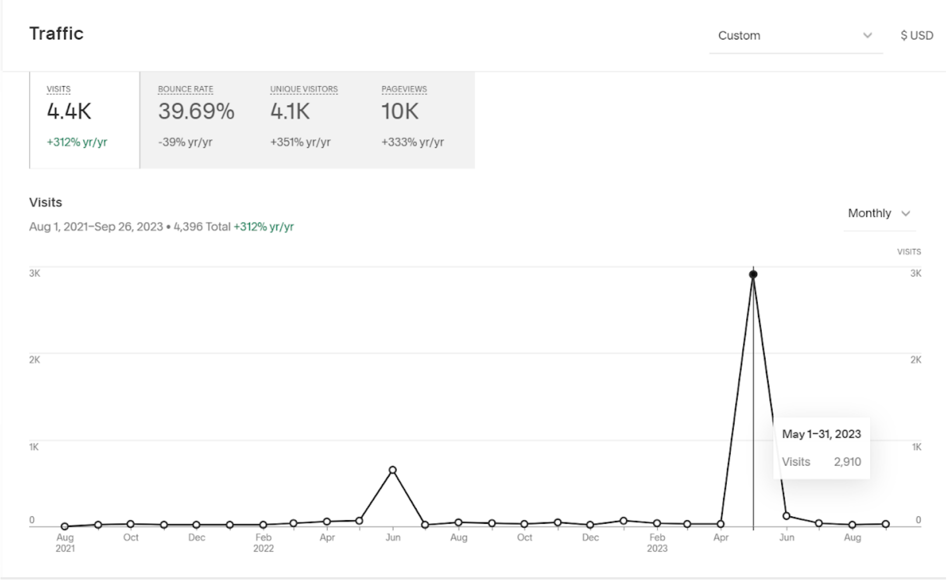
The steel shop of ArcelorMittal Gent has, next to their PROFIBUS networks, also implemented a number of PROFINET installations. Because a downtime of these processes could cost up to thousands of EURO's per minute, a strategy for efficient and effective troubleshooting and permanent monitoring of PROFINET networks is needed, to prevent unnecessary losses. The design of such a strategy is the subject of this MSc thesis. The first goal was to evaluate a number of tools to permanently monitor and troubleshoot PROFINET. Some of these tools and the necessary devices/connections (to create certain types of fault situations) where available in the control and automation lab of KU Leuven within the framework of the CINI4.0 project. A limited number of tools and systems were selected for further research and evaluation: the webpage of the PROFINET switches, Proneta, TH-link & TH-scope, PN-Inspektor, SINEC NMS and an advanced cable tester. SNMP-Traps have also been evaluated; using this protocol, monitored devices can notify the network supervisor. The Traps are researched and tested for the switches and IO-controllers, to notify e.g. SINEC NMS in the event of certain errors.

The second goal of this MSc thesis was to design and test flowcharts for troubleshooting. The main purpose of these flowcharts is to eliminate network faults as quickly as possible with the use of the above mentioned tools. These flowcharts are designed for – but not limited to – "first line" troubleshooting. Seven relevant error situations were created in the lab for flowchart design and testing purposes, and afterwards recreated during a standstill in the steel shop for final testing.

4.6. WP6 Knowledge transfer

4.6.1. Website Design

For promotional activities, providing contact information and providing additional material for a broad audience, the website www.cini40.eu was created. This website was continuously promoted during the project period. The traffic over the project period is shown in the graph below:



The two peak moments occurred during the CINI conference days. The first event was in June 2022 with a total of 653 visits and the second event in May 2023 with a total number of visits of 2910.

4.6.2. Promotional activities

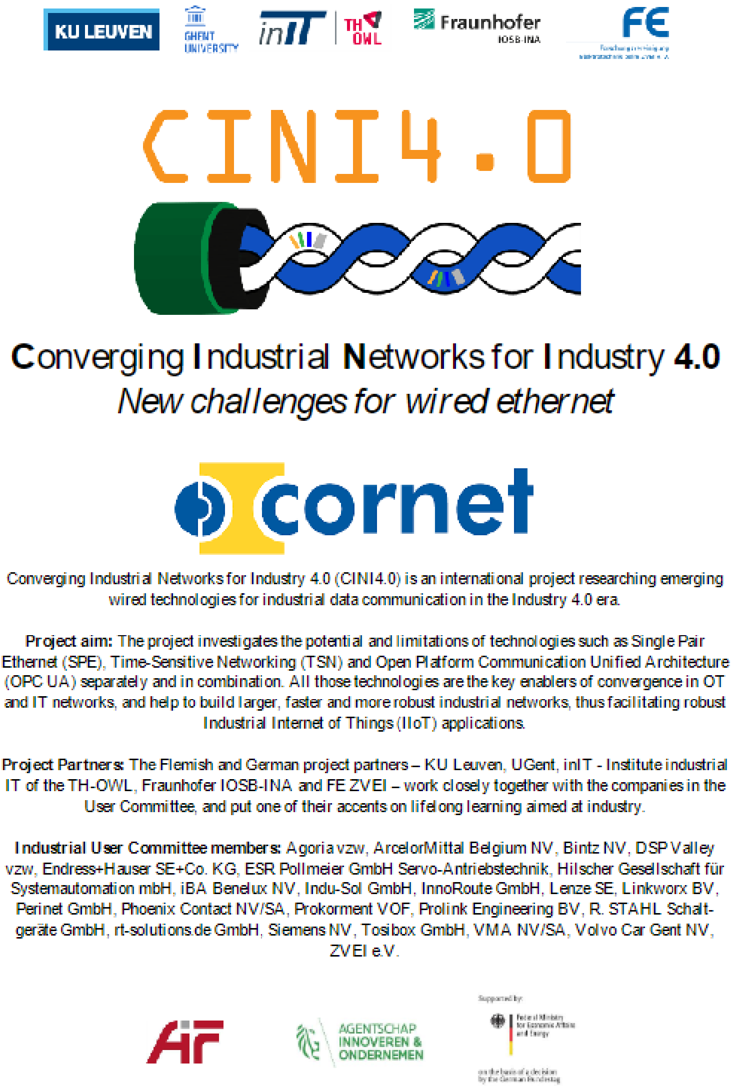
4.6.2.1. RollUp Banner

To promote the website and to present the participating institutions at fairs, workshops and other events, a banner was designed. The banner is depicted in Figure 43.

Figure 43 CINI4.0 RollUp Banner

4.6.2.2. Poster

Posters were designed and distributed at fairs, workshops and other events to clarify the objectives of CINI4.0. The poster is depicted in Figure 44.



CINI4.0

Converging **I**ndustrial **N**etworks for **I**ndustry **4.0**

New challenges for wired ethernet

Converging Industrial Networks for Industry 4.0 (CINI4.0) is an international project researching emerging wired technologies for industrial data communication in the Industry 4.0 era.

Project aim: The project investigates the potential and limitations of technologies such as Single Pair Ethernet (SPE), Time-Sensitive Networking (TSN) and Open Platform Communication Unified Architecture (OPC UA) separately and in combination. All those technologies are the key enablers of convergence in OT and IT networks, and help to build larger, faster and more robust industrial networks, thus facilitating robust Industrial Internet of Things (IIoT) applications.

Project Partners: The Flemish and German project partners – KU Leuven, UGent, inIT - Institute industrial IT of the TH-OWL, Fraunhofer IOSB-INA and FE ZVEI – work closely together with the companies in the User Committee, and put one of their accents on lifelong learning aimed at industry.

Industrial User Committee members: Agoria vzw, ArcelorMittal Belgium NV, Bintz NV, DSP Valley vzw, Endress+Hauser SE+Co. KG, ESR Pollmeier GmbH Servo-Antriebstechnik, Hilscher Gesellschaft für Systemautomation mbH, iBA Benelux NV, Indu-Sol GmbH, InnoRoute GmbH, Lenze SE, Linkworx BV, Perinet GmbH, Phoenix Contact NV/SA, Prokorment VOF, Prolink Engineering BV, R. STAHL Schaltgeräte GmbH, rt-solutions.de GmbH, Siemens NV, Tosibox GmbH, VMA NV/SA, Volvo Car Gent NV, ZVEI e.V.

Supported by:

Figure 44 CINI4.0 Poster

4.6.3. Conferences, fairs, seminars and workshops

4.6.3.1. Indumation 2022

Indumation is an industrial automation event at Kortrijk Xpo in Belgium. It is a fair for professionals in industrial automation and Industry 4.0. The event features exhibitions of the latest technologies in industrial equipment, control systems, software, and emerging areas like the Internet of Things and artificial intelligence. It provides a platform for industry professionals, academics, and students to engage in dialogue and stay abreast of advancements in industrial automation. The research project CINI 4.0 and the results were shown on a booth at this event.

4.6.3.2. Hannover Messe 2022

The Hannover Fair is an annual trade show focused on industrial technology, held in Hannover, Germany. It serves as a global platform for innovations and trends in the industrial sector, encompassing areas such as automation, robotics, industrial software, energy technologies, and more. The fair is also a venue for knowledge exchange, featuring forums, conferences, and networking opportunities that allow attendees to discuss current challenges, future directions, and collaborative opportunities in the field. The research project CINI 4.0 and the results were shown on a booth at this event.

4.6.3.3. ETFA 2022

The IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) is an academic and professional conference organized by the Institute of Electrical and Electronics Engineers (IEEE). It focuses on the latest developments and research in the realms of emerging technologies and factory automation. The conference serves as a forum for experts, researchers, and practitioners in the field to present and discuss advancements in areas such as automation systems, smart manufacturing, robotics, and industrial informatics. ETFA emphasizes the integration of cutting-edge technologies into factory settings, exploring how these innovations can enhance efficiency, productivity, and adaptability in industrial processes. The event also provides opportunities for networking and collaboration, fostering the exchange of ideas and knowledge between academia and industry.

In the context of CINI4.0, a full-day workshop was provided with more than 20 participants. The workshop was related to the relevant technologies. Additionally, a document with the title “Towards an Industrial Converged Network with OPC UA PubSub and TSN” (see Section 8) was published on that conference.

4.6.3.4. KommA 2022

The annual colloquium "Communication in Automation - KommA" is the forum for science and industry in the German-speaking region for all technical/scientific issues related to industrial communication. Key areas of interest include the development of reliable, efficient, and secure communication protocols and technologies that are vital for the smooth operation of automated processes. KommA may also delve into the integration of emerging technologies like the Internet of Things (IoT), wireless communication, and real-time data exchange, aiming to improve connectivity and interoperability in industrial settings.

In the course of this event, the publications “Practical investigation of an industrial converd network based on OPC UA PubSub and TSN” and “Investigation of Ethernet TSN Interoperability in Industrial Multi-Protocol Networks” (see Section 8) were submitted and presented.

4.6.3.5. WFCS 2022/2023

The IEEE International Conference on Factory Communication Systems (WFCS) is an established conference organized under the auspices of the IEEE, specifically dedicated to communication systems in industrial and factory environments. This event focuses on the exploration, development, and application of communication technologies in industrial automation. Key topics often include networked control systems, real-time communications, wireless communication technologies, and the integration of the Internet of Things (IoT) in factory settings. WFCS provides a platform for researchers, engineers, and industry professionals to share findings, advancements, and insights into the challenges and opportunities of communication technologies in industrial automation.

The TH-OWL was part of the organizational team and engaged with experts in that field to exchange the state-of-the-art knowledge in the relevant technologies.

4.6.3.6. Profinet Plugfest

The 10th official Profinet Plugfest of the PROFIBUS & PROFINET International (PI) organization took place on 24 and 25 May at the SmartFactoryOWL in Lemgo. The event was hosted by the Fraunhofer Institute in Lemgo. The tech event focused on the early testing of new communication standards in networked automation technology - more than 70 international representatives of leading manufacturers of automation devices from all over the world took part and once again marked Lemgo as a supra-regional center for intelligent automation and industrial networking. Representatives of CINI 4.0 were also present on both days.

4.6.3.7. CINI Conference Day 2022/2023

The CINI Conference Day was a specific event, dedicated to the topics of CINI4.0. It was planned and implementation of this event was carried out by KU Leuven and UGent and was held in Gent. Additional input and support in regards to the technical implementations was provided by TH-OWL and Fraunhofer IOSB-INA. State-of-the-art research results for the topics Single Pair Ethernet, Time Sensitive Networking and OPC UA were presented. The main audience consisted of representatives from the industry with about 100 visitors for both events (2022 and 2023). This event provided an opportunity to present our current measurement setups, demonstrators and provide a platform to exchange knowledge.

Figure 45 Impressions of the CINI Conference Day

4.6.3.8. INDIN 2023

The IEEE International Conference on Industrial Informatics (INDIN) is an annual event organized by the IEEE, focusing on the intersection of industrial information technologies and industrial automation. This conference covers a broad spectrum of topics related to industrial informatics, including but not limited to data processing, networked control systems, smart manufacturing, and the application of artificial intelligence in industrial environments. INDIN serves as a gathering for academics, researchers, and industry professionals to discuss and share developments, challenges, and emerging trends in the field of industrial informatics. The conference aims to foster innovation and collaboration, addressing how information technologies can improve efficiency, productivity, and adaptability in industrial systems.

The institutes TH-OWL and Fraunhofer IOSB-INA hosted this event at the university of TH-OWL in Lemgo. The research institutes of CINI4.0 presented demonstrators and engaged with experts and prospective experts in that field.

4.6.4. Closing event

The closing event was done in the course of the INDIN 2023. The created demonstrators were presented and the project partners got the opportunities to attend and exchange with each other.

4.7. WP7 Project management

4.7.1. Management Meetings

Over the project period, the research institutes organized meetings to discuss the current state of the project and upcoming events.

4.7.2. User Committee meetings

During the project period, in total eight meetings with the user committee meetings were performed. These meetings were particular useful to get feedback as early as possible from the user committee on the current results and the short term outlook.

User Committee meetings	Date
UC1	16.09.2021
UC2	14.12.2021
UC3	17.02.2022
UC4	22.06.2022
UC5	04.10.2022
UC6	31.01.2023
UC7	22.05.2023
UC8	04.07.2023

Table 11 User Committee Meetings

It was decided in the User Committee (UC) to systematically organize the Belgian and German UCs jointly after the joint start-up meeting, with a country-specific part at the end of the meeting if necessary.

5. Scientific-technical and economic benefits of the results obtained, especially for SMEs, as well as innovative contribution and industrial application possibilities.

5.1. Current Situation

The evolution toward Industry 4.0 (I4.0, "smart factories") is characterized, among other things, by the convergence (integration) of Information Technology (IT) and Operational Technology" (OT, industrial automation). As a result, industrial data communications - the backbone of modern "smart" machines and production facilities - faces a (partial) convergence of IT and OT data networks, adding new physical layers ("Single Pair Ethernet" (SPE), "Advanced Physical Layer" (APL)), "Time Sensitive Networking" (TSN), new needs for both network planning and maintenance, and the use of "middleware" such as OPC UA that brings together different protocols and data formats. Hence the urgent demand from SMEs and large companies in the manufacturing and automation industries for the developing knowledge about future physical layers (SPE, APL), TSN, middleware such as OPC UA, "information modeling," and to "best practices" and design methods for implementing new, robust network structures suitable for more performant and innovative applications. The goal of this project was to develop new innovative methodologies at the component and system level (WP2-4), and test their feasibility (WP4-5), for

- Designing robust high-performance networks and network structures, combined for OT and IT, and of migration paths for “brownfield” (legacy) machines and production lines.
- Integrating OPC UA into existing solutions, in which this acts as a link between IT and OT networks and software

This allows both SMEs and large companies to make forward-looking choices and gain a significant gain an edge over companies that continue to work with current concepts. The project - especially the German project partners - developed a proof of concept to embed OPC UA solutions into protocols of industrial networks, including the study of security aspects. In addition, the project - mainly the Flemish project partners - developed and implemented wired Ethernet (and wired "legacy" networks):

- a test platform to test and analyze new TSN and SPE networks
- test results clearly demonstrating the increased usage limits by TSN: nearly 100% netload compared to the current "maximum 20%" design rule, with very small jitter; possibility of (very) small cycle times
- test results confirming that SPE allows 10 to 20 times greater cable length (T1L, 10 Mbps to each individual network participants), and this with much faster and easier connector assembly and connectors, and with great robustness against EMI (Electromagnetic Interference).
- demonstration tools for best practices in permanent diagnosis and monitoring, and for network design (including mixed OT and IT traffic)
- test results for migration of existing networks to new technologies:
    - existing fieldbus cable (type A, e.g., PROFIBUS PA or Foundation Fieldbus) can be used for SPE/APL, allowing communication from sensor/actuator to controller entirely using Ethernet protocols
    - Legacy Ethernet networks (e.g. "brownfield PROFINET" can be integrated into new TSN networks

- Initial testing shows that TSN's built-in redundancy mechanisms are far superior to the currently standard built-in MRP (Media Redundancy Protocol) redundancy, and thus can compete with PRP and HSR redundancy.

In parallel, training courses, exercises and test setups - especially in Flanders – were developed for training courses and hands-on workshops, in order to achieve a broad technology transfer to the industry. After all, knowledge and know-how are of great importance to make future-oriented choices, rapid implementation and OT/IT integration, to get ahead of traditional legacy fieldbuses, and to enable increasing data graphs for condition monitoring, image processing and the like.

5.2 Potential economic impact

Added value with enterprises UC/target group.

The staff of the companies in the user committee, and at a later stage in (and after) the project also other companies from the broad target group, can make informed choices for new working methods and investments. This not only secures jobs, but also the competitive position of the companies.

After all, technology choices have medium-term consequences: choices made and investments in automation of machines and production lines last at least 10 years, and wrong choices have long-term consequences. The intensive hands-on technology transfer - courses of one or more days - ensure that knowledge is transferred in depth and permanently.

- The technological potential and current industrial implementability of the "emerging technologies" (TSN, SPE) has been demonstrated. I.e. important for both end-users, system integrators as well as suppliers/technology developers.
- This leads to a large number of "early adopters": 81 (out of 861) companies that have followed one or more dissemination activities followed indicate that they will use one or more of the technologies. For the full project (BE + GE) these are 107 out of 112, respectively.
- In-depth knowledge of network technology, continuous diagnosis capabilities and more robust network design lead to greater "uptime" of the industrial networks (productivity, competitiveness compared to foreign sites) and shorter commissioning times. I.e. important for end users and system integrators.
- Mainly for the guidance group - but also for a much broader group of Flemish companies for a specialized target group, 300+ FTE days of in-depth technical-scientific workshops and lectures were organized, each time including extensive demonstrations. A total of Flanders 338 participants (non-unique, there are those who participated in multiple activities have participated); for BE + GE, the number of participants is 553.

Economic value added

The technology transfer to end-users and system integrators, and the demonstrators who are demonstrating the feasibility and benefits of emerging technologies such as Single Pair Ethernet and Time-Sensitive Networking at this are already demonstrating, e.g., allow machine builders and other end users to make forward-looking choices and to implement them faster (and consequently build a better competitive position compared to users of traditional legacy fieldbuses). Investments in APL, for example, put the Antwerp chemical cluster in a better competitive position (maintaining of entrepreneurial activities): more diagnostic data is extracted from field instruments (predictive maintenance possibilities), Ethernet technology is used right into the field (one-time knowledge investment, data is available everywhere), and this with reuse of existing "brownfield" cabling (an economically feasible migration path). The degree of automation increases (mixed OT_IT networks, OPC UA as transparent middleware, etc.), leading to faster commissioning, collection of additional data from both process, sensors/actuators as well as the network itself (data analysis, machine learning, etc.), and ultimately results in higher competitiveness of Flemish and German companies. Faster diagnosis, preventive replacement by using permanent monitoring of the operation of the networks, etc. lead to a security of competitiveness and increase in competitiveness.

Accelerating innovation / international competitiveness

CINI4.0 has (partly) triggered new investments or interim upgrades of existing machines in determined a number of companies. Think e.g. of the above mentioned case "Design problem + migration/integration of legacy networks in new technology" in ArcelorMittal Gent - Cold rolling mills, or the preparatory study in BASF Antwerp on APL (Advanced Physical Layer, SPE for the process industry), the integration of permanent diagnosis in industrial networks (Volvo Cars Gent, Barry-Callebaut), or the lessons learned for Prolink Engineering in terms of layout and technology for EMC in electrical cabinets. This leads to acceleration of innovation, higher productivity (uptime networks), the availability of more data for e.g. predictive maintenance and machine learning, which of course benefits international competitiveness to the benefit of international competitiveness.

The combination of working demonstrators (demonstrating importance and state of the art of emerging technologies, including migration paths from brownfield installations) and the extensive (and in-depth) knowledge transfer to the companies in the guidance group and also externally (more than 300 FTE days of training and workshops, about 340 participants, 81 companies in Flanders indicating they will use these technologies) provide for a lasting impact on innovation and competitiveness of the companies. Integrating project results into courses and lab equipment, and involving students for their master's thesis obviously also has a lasting impact.

Notes on external circumstances

CoVid-19 had an influence on present meetings for the technical exchange weeks and partially on the organization of workshops. Due to the pandemic and restrictions, the user committee meetings had to be held online. Furthermore, the subsequent supply problem and chip shortage delayed most of our planned purchases and limited our selection for the technical devices.

6. Use of the appropriation

Technische Hochschule Ostwestfalen-Lippe

- Scientific and technical staff (A.1 of the financing plan)

HPA-Group A: 19,43 PM
HPA-Group B: 3,00 PM

- Devices (B of the financing plan)
    - None

- Third-party services (C of the financing plan)
    - None

Fraunhofer IOSB-INA

- Scientific and technical staff (A.1 of the financing plan)

HPA-Group A: 4,43 PM
HPA-Group B: 17,85 PM

- Devices (B of the financing plan)
    - None

- Third-party services (C of the financing plan)
    - none

7. Necessity and appropriateness of the work performed

The work performed was fully in line with the reviewed and approved application and was therefore necessary and appropriate for the implementation of the project.

8. Updated tabular plan for the transfer of results to the economy

Transfer of results during the project duration

Time period	Activity	Objective	Responsibility
16.09.2021 14.12.2021 17.02.2022 22.06.2022 04.10.2022 31.01.2023 22.05.2023 03.07.2023	Meeting of the user committee	Discussion and communication of work results, knowledge transfer and regular evaluation of practical relevance	All
Project duration	Short PowerPoint presentation of the project	The project was first recapped at the first user committee meeting with PowerPoint slides. The slides were reused at further events over the project duration	All
M3	Design of the Website	Provides an overview of current and planned events, contact information from the research institutes and a download area for various teaching materials	UGhent
M3	Banner and Poster for every partner	Promotional activity for the project	All
M5	KommA	Participation in a specialist conference for technical exchange	TH-OWL Fraunhofer
M10	Part of a booth for the Hanover Fair	Current results and demonstrators are presented to a wide audience	TH-OWL Fraunhofer
M10	Stand on Indumation fair (Kortrijk)	Present results and setups to a large audience	UGent

		building networks with experts	
M11	Conference Day	Lectures and stands for industry professionals, in cooperation with project partners, User Committee members, etc. Target = 80-100 participants from industry. Serves as closing event in Flanders	KU Leuven
M14	Project brochure	For distribution at fairs, workshops, courses, etc	KU Leuven
M14	All-day Workshop at the ETFA in Stuttgart	Knowledge transfer of the current results and establishment of a network with experts	All
M14	ETFA	Participation in specialist conference. Presentation of specialist literature and	KU Leuven TH-OWL
M16	KommA	Participation in a specialist conference for a technical exchange	TH-OWL Fraunhofer
M14 and M16	Papers on scientific conferences	Several scientific papers were published on dedicated conference (see chapter 9)	All
M16	PlugFest	System integration and testing of devices from different manufacturers	TH-OWL, Fraunhofer
M22	Conference Day	Lectures and stands for industry professionals, in cooperation with project partners, User Committee members, etc. Target = 80-100 participants from industry. Serves as closing event in Flanders	KU Leuven

Transfer of results beyond the project duration

Time period	Activity	Objective	Responsibility	Comment on Implementation
3 Years	Website	The website with content of the project will remain for 3 years	All	The website was already established at an early phase of the project and remained online over the project duration. It is planned to keep the website and its content online for additional three years.
Starting WS23/24	Additional chapter in courses for students	The technologies covered in CINI4.0 will be integrated into lectures for students. The practical structures created during the project will be reused and adapted so that students are able to analyze and evaluate the technologies	KU Leuven, UGhent, TH OWL	Additional chapters in courses for students were applied in WS23/24. It will remain a consistent part of these courses.
At least for 1 Year after project end	Publication of scientific papers at specialist conferences	Dissemination and publication at specialist conferences: ETFA, INDIN, IECON, WFCS	All	The topics that were part of CINI4.0, will continue to be part of further research. Future publications of scientific papers will be built upon the gained knowledge, published results and publications that were generated in CINI4.0
September 2023	Short articles in dedicated press	Project results in e.g. professional magazines or magazine of professional organizations in User Committee	All	Current results and the project itself was mentioned on social media platforms (LinkedIn), at the webpage of the inIT and TH OWL. Additionally, inIT published a year-end

				on September 2023 report with highlights of CINI4.0. There are no additional publications planned in magazines, as it was decided to reach a broader audience via more common media (social media, webpages).

9. Papers that have been published or are about to be published in relation with the project

Title: Towards an Industrial Converged Network with OPC UA PubSub and TSN

Authors: Oliver Konradi, André Mankowski, Lukasz Wisniewski, Henning Trsek

Published at: 2022 IEEE 27th International Conference on Emerging Technologies and Factory Automation (ETFA)

Abstract: Technologies such as TSN and OPC UA are enablers for converged networks in industrial applications. TSN enables the coexistence of network traffic with real-time requirements and best-effort requirements. On the other hand, OPC UA defines a common information model in addition to secure communication, scalability, and platform independence. The new specification of OPC UA PubSub enables the possibility of implementing OPC UA on the lower levels of the automation pyramid, the field level. Therefore, combining these two technologies can in principle be implemented for every vertical and horizontal communication. This document analyzes the state of the art of OPC UA over TSN and explains the first steps towards an easy to use proof-of-concept for a converged network that is also designed to be a testbed. The testbed will be used to evaluate the interoperability of TSN-capable devices from different vendors. In addition to that, different OPC UA PubSub implementations will be used and benchmarked. These future results will present an overview of the currently available products and provides hands-on experiences for practical implementations of converged networks.

(Translated from German to English)

Title: Practical investigation of an industrial converd network based on OPC UA PubSub and TSN

Authors: Oliver Konradi, Mario Schoppmeier, Lukasz Wiesniewski, Jürgen Jasperneite

Published at: Jahreskolloquium "Kommunikation in der Automation" 2022

Abstract: Convergent networks offer the flexibility that modern Industry 4.0-capable applications require. State-of-the-art technologies such as OPC UA and TSN have the potential to enable the convergence of information technology and operational technology. While TSN adds real-time capabilities to standard Ethernet and allows applications with real-time and non-real-time requirements to coexist on a single network, OPC UA flattens the standard automation pyramid. Although these technologies and the idea of combining these technologies (OPC UA TSN) exist, they are not yet widely used in the industrial environment. Therefore, a practical, heterogeneous setup is created that serves as a test environment and enables SMEs to gain initial practical experience. The practical realization of a network with OPC UA TSN is complicated by the limited number of available devices and the lack of available configuration and engineering tools.

Title: Investigation of Ethernet TSN Interoperability in Industrial Multi-Protocol Networks

Authors: Janis Albrecht, Tarek Schlabeck, Jürgen Jasperneite

Published at: Jahreskolloquium "Kommunikation in der Automation" 2022

Abstract: Ethernet TSN is adapted by the automation industry. Both standardization and prototyping progresses as TSN-mechanisms are integrated with various application protocols and network technologies. This work investigates the consequences of sharing Ethernet TSN-mechanisms in multi-protocol networks and the impact on interoperability. For example, PROFINET and CC-Link are not interoperable in an Ethernet TSN network today. A detailed examination of TSN-mechanisms configuration parameters reveals areas of possible conflict. An exemplary side-by-side comparison of PROFINET, CC-Link IE TSN and OPC UA Field eXchange specifications shows concrete interoperability issues on selected Ethernet TSN-mechanisms that can be produced and measured in an experimental test environment. Based on the findings of the analyses of this work a solution discussion is started.

Title: Increasing Ethernet TSN Multi-Protocol Interoperability by Algorithmic Configuration Merge

Authors: Janis Albrecht, Alexander Biendarra, Jürgen Jasperneite

Published at: 2023 IEEE 21st International Conference on Industrial Informatics (INDIN)

Abstract: Standardization and prototyping of Ethernet Time Sensitive Networking (TSN) makes progress and its mechanisms are utilized with various application protocols and technologies within the industrial automation domain. Sharing Ethernet TSN mechanisms in multi-protocol networks impacts interoperability. Although the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) attempt to unify Ethernet TSN utilization with the IEC/IEEE 60802 TSN Profile for Industrial Automation, Ethernet TSN devices already exists on the market by different vendors. An area of conflict is the egress configuration of a single Ethernet-Interface for TSN streams of different technologies, such as PROFINET, CC-Link IE TSN and OPC UA Field eXchange. A practical post processing solution can be to merge Ethernet TSN configurations for a single port. A concept for a Configuration Merge Algorithm (COMEA) is presented in this work. A test environment consisting of multiple industrial automation applications with an Ethernet TSN network infrastructure is used to demonstrate the result of application.

Title: Automated Root Cause Analysis in Time-Sensitive Networks based on Fault Models

Authors: Tobias Ferfers, Sebastian Schriegel, Jürgen Jasperneite

Published at: International IEEE Symposium on Precision Clock Synchronization for Measurement, Control and Communication ISPCS 2023

Abstract: Time-Sensitive networking plays a major role in the convergence of IT and OT in the use cases of Industry 4.0. The available mechanisms of TSN, such as Frame Preemption (IEEE 802.1Q), Time Synchronization (IEEE 802.1AS), and Enhancements for Scheduled Traffic (IEEE 802.1Q), make devices and networks more complex when they first start up, run, or fail. Fault detection and diagnosis require experience and expert knowledge to find the root cause of faults and troubleshoot them. However, unlike other communication technologies, there is no information about possible faults or errors, how to recognize errors, or how to handle errors in time-sensitive mechanisms. Therefore, a fully automated approach to identifying the underlying cause of a malfunction is required to aid network administrators in the event of a malfunction, thereby minimizing downtime. How can an automated root cause analysis system in time-sensitive networking be realized, and how can faulty configuration of scheduled traffic be automatically detected? This work describes a concept for automated root cause analysis in time-sensitive networks based on fault models (SARCAI-TSN), and investigates the possible symptoms of faulty

Frame Preemption and Scheduled Traffic configuration with a test setup. Furthermore, it presents a scheduled traffic anomaly detection algorithm for the detection of faulty scheduled traffic configurations. This research provides assistance to both vendors and users in fault detection and diagnosis (FDD) in Time-Sensitive Networking.

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