Low-cost and energy-efficient hybrid Photonic integrated circuits for fiber- optic, free-space optical and mmWave communication systems supporting Time critical networking in industrial Environments

# Deliverable D2.1

## Definition of application scenarios, system requirements and specifications at the network, module, and component level

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# List of abbreviations

| | |
|---|---|
| **3G/4G/5G /6G** | Second/third/fourth/fifth generation mobile communication networks |
| **3GPP** | Third Generation Partnership Project |
| **5GC** | 5G Core |
| **AI** | Artificial Intelligence |
| **BPP** | Bits per Pixel |
| **C2** | Command and Control |
| **cAWG** | cyclic Arrayed Waveguide Gratings |
| **CA** | Consortium Agreement |
| **COTS** | Commercial off the Shelf |
| **CP** | Control Plane |
| **CPU** | Central Processing Unit |
| **CRI** | Carrier Re-Insertion |
| **CTLE** | Continuous Time Linear Equalization |
| **dB** | Decibel |
| **dBi** | Decibels with respect to an isotropic antenna reference |
| **DC** | Direct Current |
| **DMZ** | Demilitarized Zone |
| **DL** | Downlink |
| **DU** | Distributed unit |
| **E2E** | End to End |
| **ECL** | External Cavity Laser |
| **EIRP** | Equivalent Isotropic Radiated Power |
| **eMBB** | Enhanced Mobile Broadband |
| **eNB** | Enhanced Node B (4G base station) |
| **EU** | European Union |
| **FH** | Fronthaul |
| **FN** | Fixed Node |
| **FPS** | Frames per Second |
| **FSO** | Free Space Optical |
| **GaAs** | Gallium Arsenide |
| **GB** | Gigabyte |
| **Gbps** | Gigabits per second |
| **GDP** | Gross domestic product |
| **GHz** | Gigahertz |
| **gPTP** | Generic Precision time Protocl |
| **IMT** | International Mobile Telecommunications |
| **IF** | Intermediate Frequency |
| **IIoT** | Industrial Internet of Things |
| **InP** | Indium Phosphide |
| **ITU** | International Telecommunications Union |
| **LNOI** | Lithium Niobate On Insulator |
| **LO** | Local Oscillator |
| **LOS** | Line of Sight |
| **MCF** | Multicore Fiber |
| **MEC** | Mobile Edge Computing |

| | |
|---|---|
| **MH** | Midhaul |
| **MHz** | Megahertz |
| **MIMO** | Multiple Input Multiple Output |
| **mMIMO** | massive MIMO |
| **MMI** | Multi-Mode Interference |
| **MP** | Mega Pixel |
| **MPO** | Multi-fiber Push On |
| **mMTC** | Massive Machine Type Communications |
| **mmWave** | Millimeter Wave |
| **MN** | Mobile Node |
| **MZM** | Mach-Zehnder modulator |
| **MW** | Microwave |
| **NC** | Numerical Control |
| **NCU** | Numerical Control Unit |
| **NETCONF** | Network Configuration Protocol |
| **NIC** | Network Interface Card |
| **NLOS** | Non-Line of Sight |
| **NR** | New Radio |
| **NSA/SA** | Non-Standalone / Standalone (5G implementation options) |
| **OBFN** | Optical Beamforming Network |
| **OTT** | Over the Top |
| **ORAN** | Open RAN |
| **PCA** | Photoconductive Antenna |
| **PIC** | Photonic Integrated Circuit |
| **PLC** | Programmable Logic Computer |
| **PLO** | Phased Lock Oscillator |
| **PoP** | Point of Presence |
| **PTP** | Precision Time Protocol |
| **PZT** | Depositing lead zirconate titanite |
| **QoS** | Quality of Service |
| **QSFP** | Quad Small Form-factor Pluggable |
| **RAN** | Radio Access Network |
| **RAT** | Radio Access Technology |
| **RF** | Radio Frequency |
| **ROADM** | Reconfigurable Optical Add-drop Multiplexer |
| **RSOA** | Reflective Semiconductor Optical Amplifier |
| **RRH** | Radio Remote Head |
| **SDN** | Software Defined Network |
| **SDO** | Standard Developing Organization |
| **SFP** | Small Form-factor Pluggable |
| **SM** | Single Mode |
| **SMF** | Single Mode Fiber |
| **SOA** | Semiconductor Optical Amplifier |
| **srsLTE** | Software Radio Systems LTE implementation (open source) |
| **TDD** | Time Division Duplex |
| **THz** | Terahertz |
| **TIA** | Transimpedance Amplifier |

| | |
|---|---|
| **TRx** | Transceiver |
| **TSN** | Time Sensitive Networking |
| **TT** | TSN Translation |
| **UHD** | Ultra-High Definition |
| **UP** | User Plane |
| **UL** | Uplink |
| **uRLLC** | Ultra-Reliable Low Latency Communications |
| **VCSEL** | Vertical-Cavity Surface-Emitting Laser |
| **vEPC** | Virtual Evolved Packet Core |
| **VPN** | Virtual Private Network |
| **VR/AR/xR** | Virtual Reality / Augmented Reality *(Note: xR applies to both)* |
| **WPx** | Work Package #x |
| **WPAN** | Wireless Personal Area Network |

# Executive Summary

SPRINTER main objective is to develop a set of low-cost, energy-efficient, and ultra-dynamic optical transceivers and an optical switching solution to cope with the diverse needs of the industrial networks and expedite their truly digital transformation. In order to showcase SPRINTER's full potential, the developed technology will be evaluated within application scenarios that will be deployed in a relevant industrial environment incorporating a fully operational closed-loop control system.

This deliverable aims at:

i) describing the application scenarios that will serve as a guide for the design and development of SPRINTER technology demonstrators,

ii) identifying a first set of the system specifications and requirements.

iii) specifying - at high-level - SPRINTER network architecture and demonstration scenario.

The deliverable starts with an overview of Industrial Communication Networks - Industry 4.0 and identifies two groups of Use Cases (UC) relevant to SPRINTER proposition:

**UC1: Advanced operations** that essentially refers to industrial processes and operations automation

**UC2: Unlock Intelligence** that refers to employment of AI algorithms for optimizing industrial production.

From these two groups of Use Cases the SPRINTER Application Scenarios are deduced:

**Application Scenario 1** - Robotics motions accuracy and

**Application Scenario 2** - Visual inspection for Quality Assurance.

A typical industrial automation network comprises three main network segments: *the central room/edge cloud, the backbone, and the local machine cells*. SPRINTER architecture employs a hybrid electrical-optical configuration and proposes the full adoption of Time Sensitive Networking (TSN) on all the three network sectors. The TSN-compatible switches and Network Interface Cards (NICs) enhanced with high-performance optical transceivers will enable the connectivity between the different nodes (i.e., PLCs and field devices), and ensure that time-critical traffic is delivered reliably, and within a specific time across the whole network.

In the backbone segment, the legacy electrical switches are replaced by TSN switches, supporting 50 Gb/s throughput per port. In order to address the high-capacity needs of this segment, SPRINTER will develop two high-performance optical transceivers, **Module-1a** and **Module-1b**,

In the same segment, SPRINTER will introduce an 8-core fiber ring topology to facilitate the interconnection of the TSN switches as well as their connection with the nodes deployed in the other segments. The key component in this architecture is the active SDM-ROADM (**Module-3**).

Regarding the local machine cells, SPRINTER will introduce an all-optical switching system for the connectivity of the distributed controllers with the field devices, as well as for the connectivity between the different field devices, guaranteeing the reliability and time determinism required for time critical communication. To this end, multiple stages of electronic switches, that typically introduce ms scale latency in each stage will be avoided. The proposed architecture is based on passive cAWGs, and novel 10Gb/s ultra-fast tunable optical transceivers (**Module-2a, Module-2b**) that exhibit switching time in μs scale.

Finally, SPRINTER will provide a set of novel photonics-enabled free space optics FSO/mmWave transceivers (**Module-4**), that will enable seamless interconnection between the distributed PLCs and remote field devices. Leveraging the unique complementary characteristics of the FSO and mmWave systems with respect to the atmospheric conditions, the developed transceivers will be able to provide PtP 10 Gb/s links with high reliability. The FSO link will act as a virtual fiber extender of the all-optical network, providing connectivity to remote nodes with zero added latency. On the other hand, the mmWave system will be able to serve moving nodes, thanks to the integrated ultra-fast OBFN that can accurately steer the direction of the emitted beam.

**Keywords:** Industrial communication requirements, industrial communication network, use case, application scenarios, optical communications, Industry 4.0, system requirements, AI, process automation, quality assurance, cobots, mmWave, FSO, local machine cell.

# 1 INTRODUCTION

SPRINTER solution is designed to address applications of Industrial Communication Networks i.e. applications of factory automation, process automation, logistics, warehousing, monitoring, and maintenance. Industrial communication networks play a vital role in the implementation of Industry 4.0 technologies in manufacturing cells, especially those that involve robotics. In this context, industrial communication networks refer to the technologies and protocols used to transmit data and control signals between different components within a manufacturing cell, such as robots, sensors, controllers, and other devices.

The present document, Deliverable - D2.1 "*Definition of application scenarios, system requirements and specifications at the network, module and component level*" is devoted to the description of the application scenarios that will serve as a guide for the design and development of SPRINTER technology demonstrators and identifies a first set of the system specifications and requirements. It starts with positioning SPRINTER proposition in the context of Industry 4.0, presents the use cases it addresses and it identifies the application scenarios that will form the canvas on which the SPRINTER solution will be developed. SPRINTER system first set of requirements and specifications that will drive the SPRINTER industrial communication network design, at system and component level, is also described.

This deliverable is a *public report* and consists of the basis for the work to be carried out in the rest of the work packages, mainly *WP7 – System integration and testing of SPRINTER prototypes*.

Following this introduction, the document comprises three more sections:

Section 2 that gives an overview of the Industrial Communication Network technology as of today, refer to the Use Cases relevant to SPRINTER proposition and describes the SPRINTER applications scenarios.

Section 3 sums up the system requirements that will drive the design and development of SPRINTER network components and modules.

Section 4 presents the system design & system specification at network, component and module level.

A brief description and overview of the project is published on its website https://horizon-de-sprinter.eu/.

# 2 SPRINTER USE CASES AND APPLICATION SCENARIOS

## 2.1 Overview of Industrial Communication Networks –Industry 4.0

Manufacturing, according to the World Bank, accounts for roughly 16% of the world's gross domestic product (GDP), so remains one of the foundations of our global economy. Industry 4.0 is the subset of digital transformation that pertains to manufacturing; it can be defined in accordance to [1]: "the comprehensive transformation of the whole sphere of industrial production through the merging of digital technology and the internet with conventional industry"

Industry 4.0 describes the blending of traditional manufacturing practices with new technologies, increasing performance with lower costs, improved safety, higher efficiency, better customer retention, and improved quality and consistency. Such technologies include BDA (big data and analytics), IIoT (industrial internet of things), cloud computing, additive manufacturing (3D printing), and AR (augmented reality).

The challenges that are the actors of the manufacturing sector are called to face, are flexible production lines to satisfy customers' expectations of faster delivery and swift customization of products as well as increased profitability through process automation and digitization.

Ways to address those challenges are investigated in Smarter, swifter, safer: The future of work in manufacturing with technology – Ericsson Blog – April 2022[2] Ericsson's report, on the basis of interviews to 8,000 respondents working within the manufacturing industry; the result is shown in Figure 1 that illustrates the nine areas where digitalization and ICT-enabled production tools will play the most important role, in the next five years. In all cases a wide increase in ICT-enabled production tools is expected: to help redistribute production employees' work, improve employee's senses and make possible to reduce human intervention in production phases.

The two most important areas of digitalization expansion are i) **AI software** followed by ii) **video recognition and analytics**. Both areas will be addressed by SPRINTER project. Application scenario UC1.a capture from motion and UC2.c quality inspection, are located in these areas. Rank three is held by **remote control of machines**, **robots and vehicles** which is also covered by both application scenarios. Demonstrations will be given by the application scenarios also for augmented reality, digital twins and collaborative robots.

**Augmented reality** (AR), can visualize a mix of data with reality to provide a better understanding of what an employee is seeing, easy to follow instructions, increased understanding, immersive training and interactions, improved safety and more.

Video recognition and remote control of machines can then be used to reduce dull duties like surveillance, counting and continuous tracking as well as keep employee far from potentially harmful or dangerous environments.

In These are all examples on how increasing digitalization helps to stay competitive, factories and warehouses leveraging on all Industry 4.0 technologies.

Industry 4.0 potentialities rely not only on sensors deployed in factory environment and UCs enabled by them, but also by centralization of computational resources. This is a key factor because it enables quickly and cost-efficiently rearrangement of production, e.g., scaling up and down computational resources depending on production needs. Moreover, centralization of computational resources is important for easy upgradability.

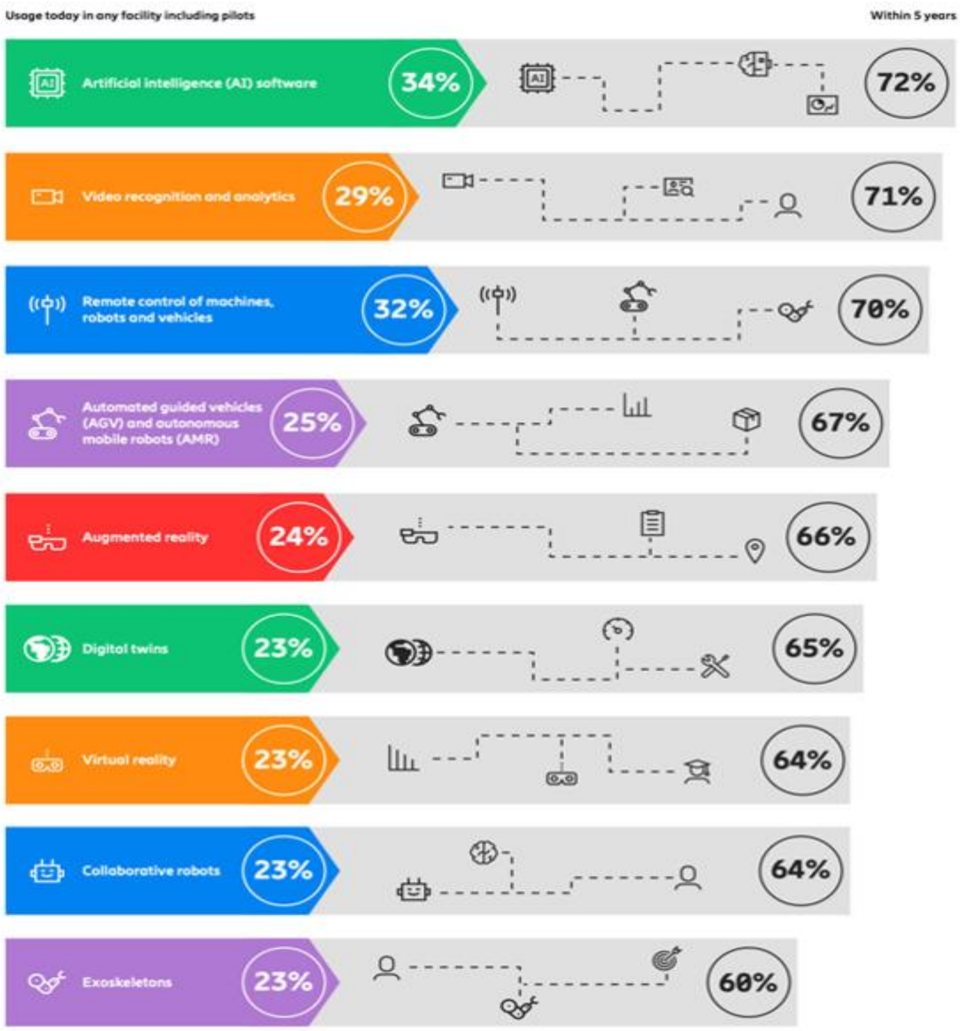

**Figure 1: Current and expected future usage of ICT-enabled production tools**

All the Industry 4.0 production tools when deployed with centralized computational resources, requires connectivity with characteristics of reliability, bandwidth reservation, latency, and security, tailored to each type of application. And the same characteristics of connectivity must be replicated across a plurality of sensors distributed on the production lines.

To achieve that it is necessary to overcome the plurality of connectivity protocols that for years characterized a fragmented Operational Technology (OT) (e.g., PROFIBUS, PROFINET, EtherCAT and others wired connectivity protocols) requiring GateWays (GW) to interface different connectivity technology domains. This is possible through bandwidth reservation to applications and guaranteed by low latency, both key parameters of industrial networks, which are well explained in [3], modernizing connectivity between Manufacturing execution system (MES) and field level as shown in Figure 2.

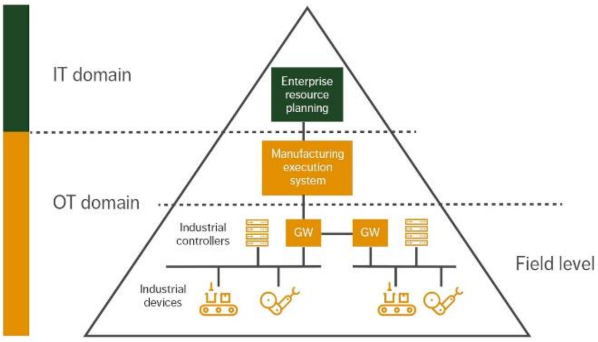

Figure 2: Hierarchical network design based on the industrial automation pyramid

In this way it is possible to guarantee real-time communication between humans, robots, factory logistics and products realizing a fundamental prerequisite of the Industry 4.0 concept, where real-time data will generate transparency and actionable insights, while edge analytics will help reap maximum machine value and optimize production, making possible to progress towards higher level of digitalization solution maturity [4].

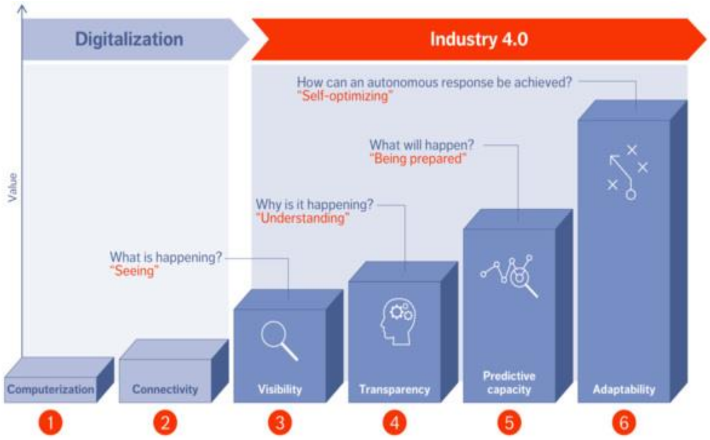

Figure 3: The Industry 4.0 maturity index

Figure 3 shows the evolution path towards Industry 4.0 transformation and its value chain; connectivity is identified as the second and necessary step to move from simple digitalization (here "computerization") to more enhanced functionalities and UCs.

Industrial Communication networks are the backbone of any system which provides connectivity between devices with exchange of information for various tasks. It has conventional wired systems with use of various protocols including a variety of industry standards. With automation and open standards replacing the traditional ones, the process of data exchange becomes easier, posing the basis to step up in the maturity index stairs.

Communication happens at the most elementary levels with sensors, actuators and so on. The information is then needed to be transmitted utilizing serial communication standards such as field buses to facilitate various activities. Activities are included but not limited to configuration, loading and supervising of various parameters. To include the activities on various devices and levels on the system local/wide area networks adopting Profibus, Control net, Ethernet and a multitude of other standards are used.

The ethernet standards are serving today a few hundred Mb/s up to one Gb/s speed. In the future, we look forward to having speeds of thousands of Mb/s (at least tens of Gb/s) with improved network hardware, adoption of new standards and technologies as photonics and fiber connectivity on the field level. The use of 5G systems can provide an alternative connectivity method to drive the innovation briskly to accommodate remote machines.

Both wireless and wired systems in future will use methods such as IIoT (Industrial Internet of things) and M2M (Machine to Machine Communications) which would lead to reduced human interaction improving user experience, speed, automation and various other factors such as QoS (Quality of Service), QoE (Quality of Experience). It will be bound to decentralized scenarios with more information available at the hands. This information could leverage the creativity of human experts in collaboration with efficient, intelligent, and accurate machines. This in turn obtained resource-efficient and user-preferred manufacturing solutions which drove open source, open interface, and open innovations.

With the advent of automation, cobots (collaborative robots), use of AI/ML (Artificial intelligence/Machine Learning), intelligence for productions systems is unleashed and technology is transformed to improve processes for efficient systems. This can be regarded not as the final goal but as an intermediate step in manufacturing evolution since it is a system approach where the human contribution is not accounted for. In addition, purposefulness of the activity beyond producing services must be considered. Finally, an account of robustness must be achieved in case of disruptions to provide security. These would lead to the establishment of a new industry standard called Industry 5.0. It is defined by the European Union as "Industry 5.0 recognizes the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity, by making production respect the boundaries of our planet and placing the wellbeing of the industry worker at the center of the production process" [7].

### 2.1.1 Industrial Communication networks - Use Cases

Many examples can be provided of industrial applications that, leveraging on real-time communications, can effectively bring huge benefit for manufacturing. Two main groups of Use Cases (UCs) [5] relevant to SPRINTER proposition are identified and will be the canvas for the SPRINTER Application Scenarios and SPRINTER System design. Build on this industrial communication networks SPRINTER will develop a new disruptive generation of low-cost, energy-efficient, and ultra-dynamic optical transceivers as well as switching solutions that will cope with the diverse needs of the industrial networks.

**UC1: Advanced operations**

By automating operations, manufacturers can establish a more efficient production process that increases yields, improves product quality, and reduces waste. A good level of automation requires robust connectivity. Private networks are supplying the reliability and security needed to realize connected manufacturing. These smarter factories offer productivity-boosting technologies such as robotic assistance, visualization tools, and augmented reality. In addition to the financial benefit, smarter manufacturing systems create a substantial triple bottom line improvement in particular achievement of the Sustainable Development Goals (SDGs) - with an increase in safety for workers, plus a kinder environmental impact through reduced scrap and emissions.

Here are reported a few subcases:

- **UC 1.a Digital Twin**
  By creating a digital replica of physical assets, digital twins let manufacturers streamline the production environment without physically changing anything. Manufacturers can produce useable insights for both process and factory, letting them plan for future states with "what-if" scenarios, while giving them the full control to plan and implement change. The digital twin offers the possibility for optimization. Capture from motion of robotic cells expands the data acquisition and is pathing the way for calibrated digital twins. In summary, the combination of a digital twin and capture from motion enables the simulation and testing of a robot's behavior and performance using captured motion data, which can help improve the efficiency and accuracy of the robot's control algorithms and behavior.
- **UC 1.b Operators interacting with Cobots**
  Collaborative robots, or cobots, can work side by side with human operators to conduct both manufacturing tasks and quality inspections. Flexible production cells with human-robot interaction becomes an essential resource in future assisting human operators working side-by-side with robots. Reliable sensors such as cameras for operator`s safety and the control of

safety functions is extremely important. High data rates with low latency are important and crucial for establishing robotic cells with human interaction.

- **UC 1.c AR applications: inspection and maintenance**
  AR for maintenance is a concept that uses AR technology to provide maintenance technicians visual information and instructions in real-time, enhancing the accuracy and speed of maintenance tasks and reducing the risk of errors and safety hazards. AR for maintenance has many applications in various industries and is a promising technology for improving the efficiency and effectiveness of maintenance and repair processes.

**UC2: Unlock Intelligence**

Data-driven means efficiency-driven: operations become more digitalized and data-driven, Manufacturers will be able to use this data to optimize production and deploying AI algorithm while decreasing their expenses. Connectivity in the production plant empowers manufacturers to capture, collect, and evaluate a mountain of data that can unlock actionable insights.

These insights can be used to make more informed decisions in particular based on AI and data analytics, make the workplace safer, train employees better, and increase sustainability; three examples:

- **UC 2.a Energy consumption and environmental condition real time monitoring**
  Availability of real time data on energy consumption and environmental conditions inside the production plant allow to take immediate actions to enforce application of procedures designed to optimization as to minimize energy consumption and to set the most ideal working conditions for workers, equipment and the whole production process
- **UC 2.b Empower predictive maintenance**
  Asset condition monitoring allows predictive maintenance, which uses data collected by sensors to reveal exactly when maintenance is needed. This intelligent tracking of machines reduces factory downtime and enables a more sustainable use of machinery by expanding their lifespan.
- **UC 2.c Speed-up quality inspection**
  Manufacturing of parts are causing deviations which needs to be measured and characterized. Performing high-speed quality inspection in-line during the manufacturing process increases the production speed, decreases delays and space requirements.

To provide numerical examples about network requirements to enable the UCs listed above facts and figures for specifications can be taken as an example from the activity done in the 5GROWTH project by Ericsson, TIM and Comau.

**Figure 4: 5GROWTH Use Cases**

Definition of UC shown in Figure 4 is provided on [6] and consists in:

- a robotic manufacturing cell “Factory of the Future” which replaced the wired LAN with 4G/5G connections and demonstrated the control logic in the cloud (vPLC);
- an “Digital Twin and Monitoring” use case demonstrating a virtual-reality digital twin running on an Oculus VR glass and an augmented reality digital twin on an AR HoloLens

- an "Automated Mobile Robot" use case demonstrating 5G connected vehicles and the visual navigation in the remote server.

All the three cases used 5G NSA and network architecture shown in Figure 5.

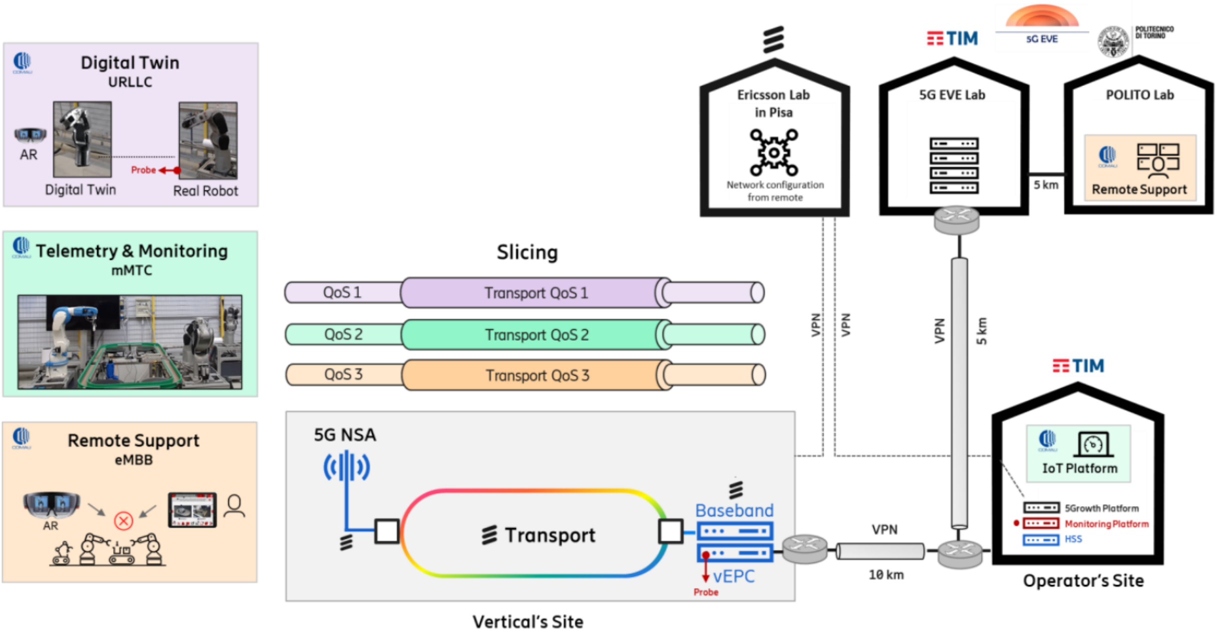

Figure 5: 5GROWTH industrial Use Cases pilot architecture [6].

Within the demonstration in the project 5GROWTH for the industrial use cases the numerical results for latency are reported in [7] and are 18.23ms round trip time with a packet loss <2 $10^{-6}$.

At the physical layer SPRINTER adopts the Ethernet Electrical standard for all wired connections. Bit error rate (BER) after Forward Error Correction will be less than $10^{-12}$ that roughly translates to an Ethernet packet Error rate (assuming 1512 byte packet size) of $1.2 * 10^{-7}$, which is within the Industrial use case requirements. At the transport layer, where packets can be dropped due to congestion (e.g. switch queue overflow) SPRINTER leverages the TSN-based traffic scheduling that effectively reserves resources along the communication path and assigns them to specific network flows, which completely eliminates the possibility of packet loss due to congestion.

Table 1 sums up the latency, reliability and bandwidth data rates needed by different industrial use cases. While process automation in industry has the widest and highest range of latency, the more precise processes in automation as machining on machine tools, (including milling, waterjet and laser cutting, 3D printing) and advanced robotic processes already deploy numerical control systems (CNC) with low latency to realize precise process controls and have the need for a high reliability of the communication network. Bandwidth data rates are stated with medium due to the limitation of existing ethernet standards (<1 Gb/s).

**Table 1: Industrial Use cases and characteristics for network latency figures [16].**

| Industrial Use case | Latency | Reliability (%) | Bandwidth data rate | Max Packet loss |
|---|---|---|---|---|
| Factory Automation | 1-10 ms | 99.9999 | Low | $1.2 * 10^{-7}$ (1512 byte packets) |
| Process Automation | 100 ms – 1 s | 99.9999999 | Low | $1.2 * 10^{-7}$ (1512 byte packets) |
| Machine tools control (CNC) | 1-5 ms | 99.99999999[1] | Medium | $1.2 * 10^{-7}$ (1512 byte packets) |
| Advanced robotic process control (CNC) | 1-5 ms | 99.9999999 | Medium | $1.2 * 10^{-7}$ (1512 byte packets) |
| Tele-operations of equipment | 10-40 ms | 99.9999 | Medium | $1.2 * 10^{-7}$ (1512 byte packets) |

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[1] [17] (see page18 compare table II-1)

| | | | | |
|---|---|---|---|---|
| Virtual / Augmented Reality | 1 ms | High | High | 1.2 *$10^{-7}$ (1512 byte packets) |
| Automated guided vehicle | few ms | 99.99999 | High | 1.2 *$10^{-7}$ (1512 byte packets) |
| Workers connected 5G glasses | 5-10ms | High | High | 1.2 *$10^{-7}$ (1512 byte packets) |

As a general statement, it is possible to define real-time communication in industrial environment the communications that can guarantee network parameters (latency, bandwidth, reliability, etc.), sensors/actuators and computing resources where application software is running, that make remotization of control operations, not affecting functionalities, no matter which physical media is used (e.g., wired or wireless connectivity). Only for reference some typical values of those parameters for UCs from industry for use of 5G are reported in Table 1 and are valid for SPRINTER too.

Other figures to consider in order to understand the suitability of the communication network to provide real time connectivity are the ones coming from PLC control cycle latency for process automation, in that case PLC cycle time of industrial manufacturing cells span between 1-6000ms. The cycle time of Siemens S7-1500, if not redundant, is set by default to 150ms, from practical use the cycle times are in between 50-150 ms. The latency of the communication system shall be much lower than the data processing time.

With the growing use of algorithms and software for data processing the use of powerful computational devices in process automation as edge computing devices also grows. The process automation which requires PLCs depends on low latency and high data rates communication for receiving processed signals within the cycle time of PLCs. For more accurate process automation, the numerical control NC systems are applied more often, those NC systems have cycle times down to 1ms. Data communication in industrial communication networks therefore becomes challenging. Industrial PCs used as an edge device are getting more performance and cloud computation is growing.

Industrial communication network as defined so far shall be designed to serve modern computational systems where the “brain” (deploying machine learning and data analytics on powerful industrial PCs as edge computing or accessing cloud computing resources) for the industry 4.0 UCs is realized.

An accelerated system is the next phase in the evolution of computers. Just like how all smartphones today have processors for graphics and AI, so too will every server and workstation have computational accelerators to power today’s modern applications, including AI, visualization, and autonomous machines. Many of these systems will also have data processing units, which accelerate the network, storage and security services that are central to cloud native and cloud computing frameworks [10].

The traditional paradigm of CPU-only computing is shifting. GPUs have eclipsed their initial role of accelerating graphics-related processes such as rendering and ray tracing and are now being used to deliver revolutionary speedups to a wide range of compute algorithms in areas such as machine learning, deep learning, high-performance computing (HPC), and data analytics. In fact, GPUs are now the leading compute accelerator, and provide better performance than any other technology for both training and inference of AI algorithms. Especially the use of GPUs in edge computing devices on shopfloors are causing network traffic to bring augmented reality services on AR devices (e.g., Hololens) to fulfill the need for low latency <1-2 ms.

The digital transformation of the modern age has dramatically increased the volume of data available for developing above mentioned actionable insights. Additionally, as cameras and other data hungry remote sensors proliferate in industrial applications, secure, reliable, and high-speed networking is essential for moving the large amounts of data generated by these devices to processing centralized computational resources. To run these modern applications, enterprises need an easy way to deploy accelerated infrastructure. When a particular line of business is investing in an accelerated server or workstation, they care about the factors that directly impact user productivity and immediate business needs. These factors include performance and the ability to use a large set of developer tools and frameworks.

The team who's responsible for taking care of these systems cares about management, security, and how to scale out as demand grows. One of their biggest challenges is to ensure the systems are configured optimally while delivering performance. Some customers simply want to deploy an accelerate scalability, and security so they can get up and running quickly, without additional tuning. Other administrators want to adjust the configuration for their specific use case in a manner that's consistent with best practices.

Server-class systems are tested to ensure remote data access and multi-node scalability by running workloads that involve coordination and data transfer between hosts. The use of these devices provides key benefits for customers in performance, manageability, scalability, and security.

- Speeds of up to 200Gb/s and the option to use InfiniBand provides the accelerated networking that technologies like GPU Direct allows efficient, zero-copy data transfer between GPUs and increased transfer capacity to storage, unlocking high-throughput, low-latency network connectivity and alleviating data bottlenecks in data center-scale computing clusters.
- Transport Layer Security (TLS) and Internet Protocol Security (IPsec) in-line cryptography are offloaded from the CPU, allowing these operations to be accelerated without impacting the high-bandwidth and low-latency communications needed for data-intensive workloads.
- Hardware root of trust enables security at the platform layer with secure boot and secure firmware updates. Such frameworks handle a large portion of the packet.
- processing operations in hardware, freeing up and providing high-throughput connectivity. Connection tracking offload capability enables stateful connection-based filtering thus enhancing performance, scale, and efficiency of the overall system.

Summing up this section, the industry needs are well identified. SPRINTER will address the two main use cases and two detailed applications of industrial communication. In those industrial applications, such as factory automation and process control, reliable and high-speed communication is essential for ensuring efficient operation of the system. SPRINTER will help to provide this level of communication by offering high-speed data transfer, immunity to interference, and physical robustness, making it an important component of industrial network architecture. The future way forward in the most important areas of digitalization expansion within next five years based on growth on data rates and need for low latency.

### 2.1.2 Industrial Communication Networks Typical Architectures

There are several industrial network architectures and communication protocols in use today, and while there are standards that apply to some of them, there is no one-size-fits-all standard for industrial networks. The architecture can be hierarchical on layered levels, ring, star, mesh and bus architectures.

Each of these architectures can be implemented using various connectivity media (e.g., wireline copper or fiber, wireless, hybrid) and protocols such as Ethernet, 5G, Wi-Fi, Bluetooth, or fieldbus protocols like PROFIBUS or Modbus. Therefore, they are not necessarily connectivity agnostic, as the choice of connectivity options can affect the performance, reliability, and cost of the network. The selection of the network architecture and connectivity options will depend on factors such as the specific application, the type of devices used, the required data transfer rates, the distance between devices, and the level of reliability and security required for the system.

Some of the most common industrial network architectures include:

- Ethernet-based architectures: These architectures use Ethernet as the primary communication protocol and are typically used for high-speed data transfer in factory automation and process control applications.
- Fieldbus-based architectures: These architectures use specialized communication protocols, such as PROFIBUS or DeviceNet, to connect field devices to control systems. They are typically used in discrete manufacturing applications, such as automotive assembly lines.
- Wireless-based architectures: These architectures use wireless communication technologies, such as Wi-Fi or 4G/5G, to connect devices in industrial settings. They are typically used in applications where wired networks are impractical (e.g., high number of endpoints, wide area to cover, indoor and outdoor operations) or where mobility is required.
- Hybrid architectures: These architectures combine elements of Ethernet, fieldbus, and wireless technologies to create customized solutions that meet the specific needs of a particular application.

There are several standards that apply to industrial networks, such as the IEC 61158 and IEC 61784 standards for fieldbus communication, and the IEEE 802.3 and IEEE 802.11 standards for Ethernet and wireless communication, respectively. However, these standards focus mainly on protocols and do not dictate a specific architecture for industrial networks, and different industries and applications may require different network architectures to meet their unique needs.

The industrial communication network architecture of process automation varies depending on the specific automation solution and manufacturer. Some examples of manufacturers of process automation systems and their communication network architectures include:

- Siemens: Siemens offers several communication protocols for its process automation systems, including PROFIBUS, PROFINET, and OPC UA.[2]
- B&R: B&R uses its proprietary POWERLINK protocol for communication between its devices, as well as other protocols such as OPC UA and Modbus.[3]
- Fanuc: Fanuc uses its proprietary FANUC FIELD system for communication between its various devices, including its CNC controllers, robots, and sensors.[4]

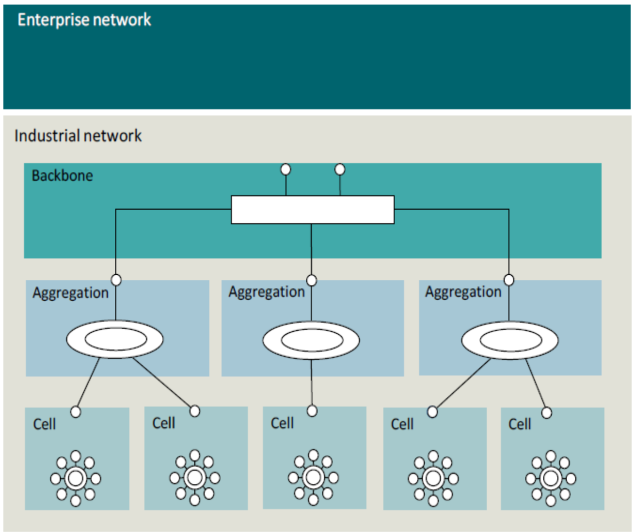

Figure 6: Architecture of manufacturing network [14]

A standard state of the art industrial network using a Siemens S7-1500/ET200MP PLC which is e.g. a delivery specification to be used in process automation by several well-known OEMs and TIER-1 in Europe and worldwide is built up on cells communicating with the aggregation layer and are connected to the backbone which interacts with industrial data centers (e.g. MES, WinCC,…) and separated by a firewall with other IT systems. The industrial communication network within Siemens is based on SIMATIC NET: Industrial Ethernet/PROFINET Industrial Ethernet using SIMATIC NET: Industrial Ethernet switches can be SCALANCE XC-200.

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[2] Connectivity solutions for Siemens networks and systems (anybus.com) [February 2023]
[3] Networks and fieldbus modules | B&R Industrial Automation (br-automation.com) [February 2023]
[4] FIELD system – Data On Premise - Fanuc [February 2023]

Siemens provides a detailed description on network concepts for factory automation. [14]. A summary is given on the support portall[5]. The most important advantages are described there, and they are quoted here in italics. Figure 6, 7, 8, 9 are also quoted from [14].

**Error! Reference source not found.** shows a generic structure of a company network. Typically, networks within production facilities can be divided into the three areas of cell, aggregation and backbone.

### Industrial backbone

The backbone is implemented as the central data communication layer. It bundles the communication from all lower levels and combines datacenters and the demilitarized zone (DMZ).

### Aggregation

The aggregation layers are added to combine various production cells and implement load distribution and network segmentation based on communication relationships.

### Automation cells

The cells are separate network spaces for various assembly lines, automation cells or machines. They are grouped within the factory according to safety standards, communication relationships, production-specific layouts or the delivery contents of various OEMs.

Figure 7 illustrates an enterprise network architecture with a schematic representation of traditional IT infrastructure with intranet, internet and datacenter as well as the link to the industrial infrastructure and presents a solution in the form of a physically separated industrial network in order to deliver a structured, reliable platform that supports various communication requirements while also meeting the current security requirements (> Security Level 1).

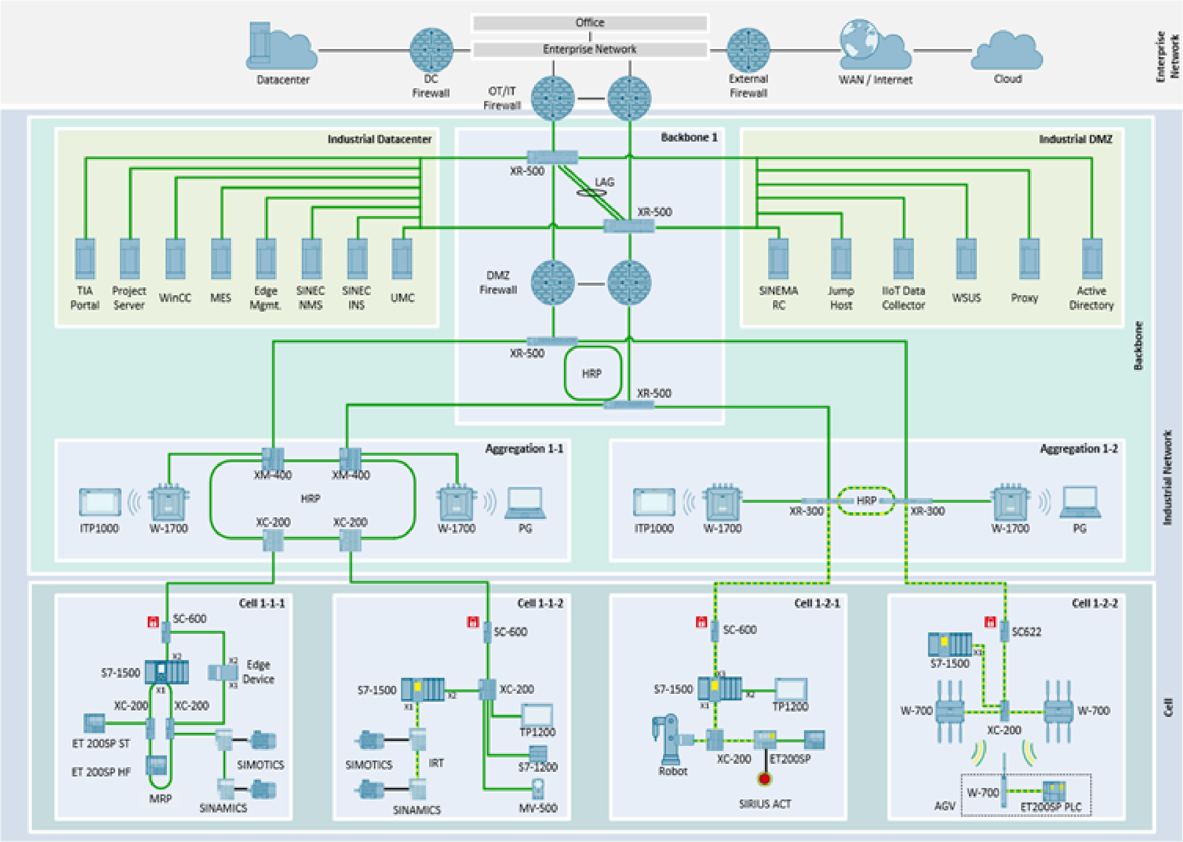

Figure 7. Siemens architecture of Enterprise Network Layer 2 [14, p.19]

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[5] Network concepts for factory automation - ID: 109802750 - Industry Support Siemens [February 2023]

Cell 1-2-1 is a typical architecture for a CPU based robotic cell. In this cell shown in Figure 8 (left), the CPU represents the central network node. The uplink here is a gigabit uplink via the CPU. This architecture is especially suited for applications with high data load between the CPU and higher-level systems.

Cell 1-1-2 is shown in Figure 8 (right) Camera-based monitoring necessitates higher bandwidth in this cell. Therefore, the SCALANCE SC600 series with 1 Gbit/s interfaces is used as a firewall. The CPU is used for network isolation between the cell network and PROFINET. No realtime communication is necessary for the HMI here. Thus, a clear separation is possible here between the realtime network (PROFINET 1 Cell1-1-2) and non-realtime network (VLAN 1020 Automation Cell1-1-2).

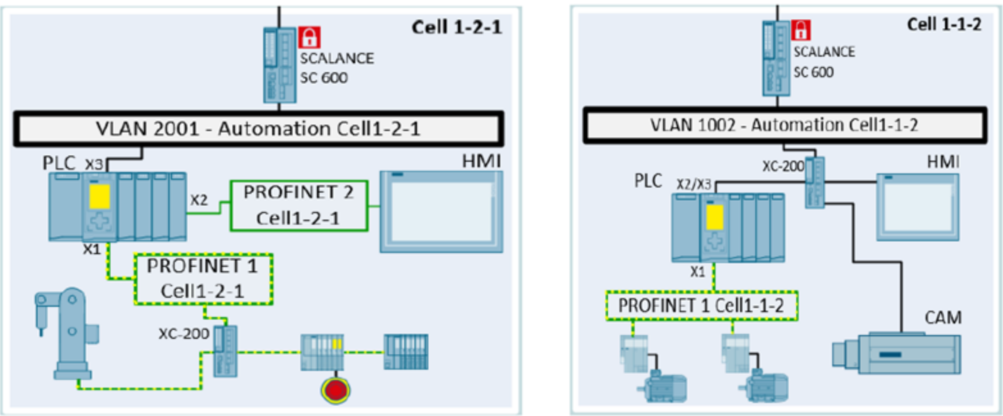

**Figure 8: (Left) Cell 1-2-1 detail from Siemens architecture [14, p.28], and (right) Cell 1-1-2 detail from Siemens architecture [14, p.27]**

The HMI is decoupled from the rest of the application through network isolation. Access to I/O devices and the HMI is possible with IP forwarding. In this case, too, the PROFIsafe domain terminates at the CPU.

The cornerstone of secure network design begins with choosing the solution approach. In this implementation of a factory automation network concept, we present a cell security concept that relies on a layer-3-based isolation of the cells.

The key points of this approach are:

- network segmentation
- protection of zone boundaries
- securing the communication between the security zones

**Time-Sensitive Networking (TSN) communication networks**

Time-Sensitive Networking is a set of standards developed by the IEEE 802.1 task group to provide deterministic, low-latency communication over Ethernet networks. TSN can be used in a variety of industrial applications, such as factory automation, transportation systems, and power grids.

In a TSN industrial communication network, the switches and endpoints (such as sensors, actuators, and controllers) are equipped with TSN-enabled Ethernet interfaces that support specific TSN standards. These standards include:

- Time synchronization: TSN requires that all devices on the network be synchronized to a common clock source with sub-microsecond accuracy. This is achieved using the Precision Time Protocol (PTP) standard defined in IEEE 1588.
- Quality of Service (QoS): TSN allows the network administrator to prioritize traffic according to its importance, ensuring that critical messages are delivered with low latency and high

reliability. TSN uses a variety of QoS mechanisms, such as traffic shaping, traffic policing, and traffic scheduling.

- Stream reservation: TSN allows devices to reserve bandwidth on the network for specific streams of data. This ensures that critical data is not delayed or dropped due to congestion on the network.
- Path redundancy: TSN allows for redundant paths to be set up between devices on the network, ensuring that critical data can be delivered even if a network link fails.

Overall, TSN provides a highly reliable and deterministic communication infrastructure for industrial applications that require low-latency and high-reliability networking.

As described in  Figure 2 the OT domain is including MES but not ERP system. The TSN for industrial applications and usecase scenarios are compared with Figure 6, covering the field level, the control level and the supervisory level.

- **Field level:** This layer includes sensors and actuators that are responsible for monitoring and controlling physical processes. TSN can be used to provide real-time communication between sensors and actuators and the controllers in the next layer of the pyramid. For example, TSN can be used to provide low-latency and highly reliable communication between a sensor that measures temperature and a controller that adjusts the temperature of a furnace.
- **Control level:** This layer includes programmable logic controllers (PLCs) that are responsible for processing data from sensors and actuators and issuing control commands. TSN can be used to provide deterministic communication between PLCs and other controllers in the same or higher layers of the pyramid. For example, TSN can be used to provide low-latency and highly reliable communication between two PLCs that are responsible for controlling different parts of a production line.
- **Supervisory level:** This layer includes human-machine interfaces (HMIs) that allow human operators to monitor and control industrial processes. TSN can be used to provide low-latency communication between HMIs and the controllers in the lower layers of the pyramid. For example, TSN can be used to provide real-time data to an HMI that displays the status of a production line.
- **Enterprise level:** This layer includes enterprise resource planning (ERP) systems that are responsible for managing the business processes of an industrial organization. TSN can be used to provide low-latency communication between ERP systems and other systems in the lower layers of the pyramid. For example, TSN can be used to provide real-time data to an ERP system that manages inventory levels in a warehouse.

So, for a central room with a centralized control (C2C) to communicate via a TSN backbone with distributed controls of machine/cell/line as shown in Figure 9 it is mandatory to fulfill the needs of security and standards by fieldbus devices.

5G ACIA is giving a brief description on TSN communication networks in its white paper. The following description of TSN is mandatory for SPRINTER to allow shifting of control functions to a central room to exploit edge and cloud computing and their advantages vs distributed control architecture.

“Time-sensitive networking (TSN)… is a set of novel open standards that provide deterministic, reliable, high-bandwidth, low-latency communication; it is envisioned as the future-proof wired technology for convergent industrial communication, e. g., for Industry 4.0 and smart factories.” [9][5G ACIA, p.4.]

Figure 9 below is an example of a system architecture which includes 5GS and TSN. Existing vendor-specific industrial Ethernet solutions (brown circles) are typically used inside a machine. The green blocks denote various types of field-level devices, e.g., sensors, actuators, i.e., input and output (I/O) devices. Brown circles denote industrial Ethernet or fieldbus devices, e.g., Profinet bridges. The PLC is located inside a machine (yellow circles), production cell or production line, and it controls field-level devices (i. e., C2D communication) through existing industrial Ethernet or fieldbus solutions. Field-level devices react to the control data received from the PLCs, and subsequently send their feedback to the PLCs via the same link. In an Industry 4.0 production environment with a converged network infrastructure enabled by TSN, applications can be located anywhere and do not need to be physically close to the field-level applications. This is represented in greenfield scenario of [8]. This solution offers far greater flexibility and allows some control functions to be moved from field level to centralized management level]. It also allows the exploitation of technological advances typical of edge cloud computing (scalability, upgradability, fast reconfigurability, etc.).

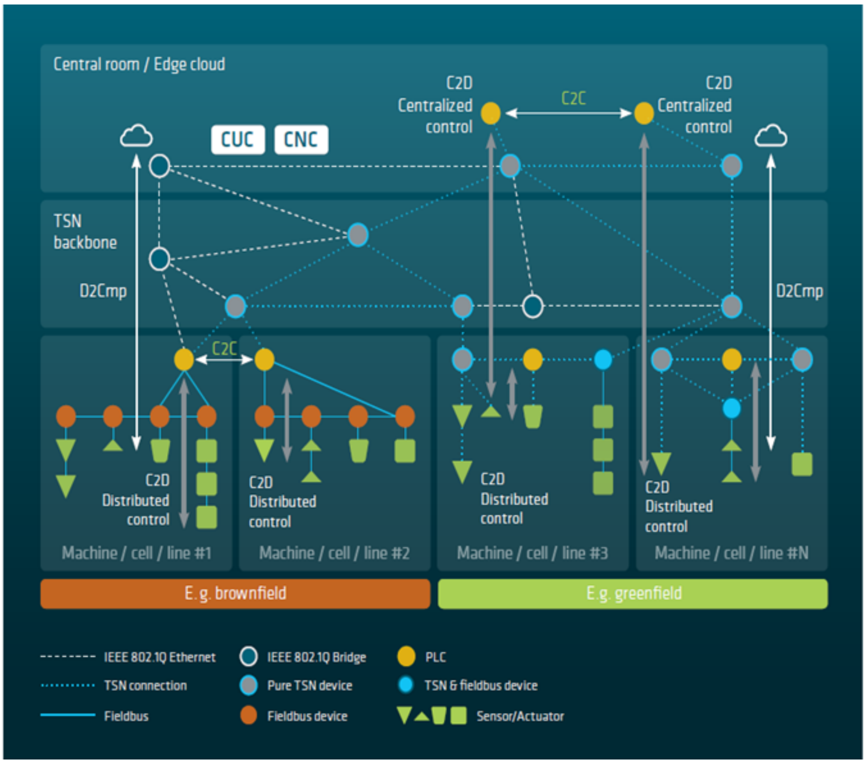

**Figure 9: Example of the Introduction of TSN for industrial automation [9, 5G ACIA]**

The described industrial communication network architectures above can be merged in a common legacy system architecture. Figure 10 is showing the legacy system architecture which SPRINTER is based on. The local machine cells will have a distributed PLC which is computing basic programs. Parts of the computational performance needed to compute data at higher band width can be shifted to the centralized PLC which can be also a VM virtual machine/PLC. Thus, with SPRINTER the industrial PCs at local machine cells can be reduced. This architecture is extended by the items Central Network Configuration (CNC) and Central User Configuration (CUC) which is described in the following.

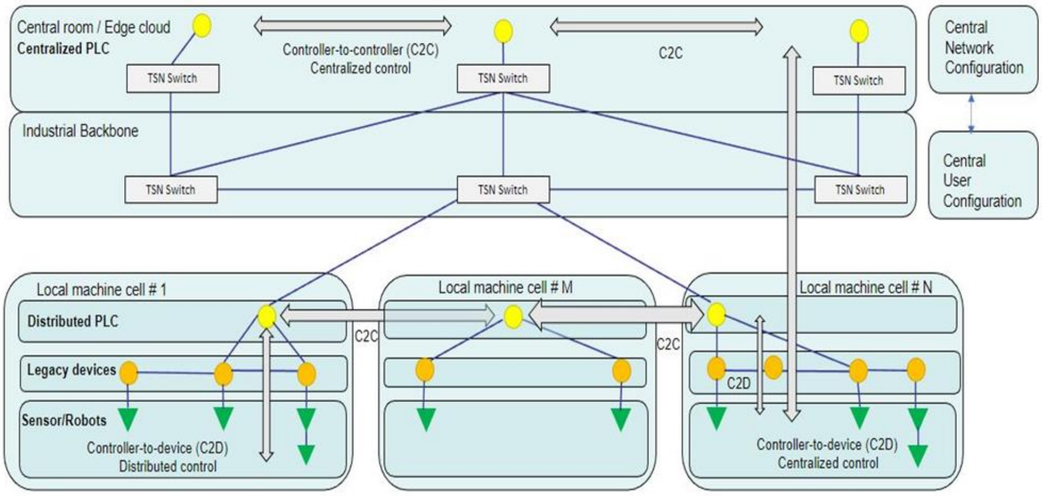

**Figure 10: System Architecture adopted by SPRINTER**

To run the data processing in the central PLC within the latency needed to be integrated in the local machine cell PLC, Time Sensitive Networks (TSN) infrastructure is mandatory for industrial application, Central Network Configuration (CNC) and Central User Configuration (CUC) are two important components that help simplify network management centrally and ensure required configurations across all network components of the architecture topology.

CUC, a part of the control plane in TSN, is responsible for managing the network topology, routing protocols, and other network-level functions. CNC which works with the data plane of TSN is responsible for forwarding data packets between network devices with low latency, high reliability, and determinism.

The purpose of CNC is to provide a centralized mechanism for managing network-level configurations such as switches and end devices. It allows administrators to configure network-wide settings, such as time synchronization parameters, traffic shaping policies and Quality of Service (QoS) settings. When network devices are configured consistently with the required features and capabilities it simplifies network management enabling deterministic communication.

The objective of CUC is to be responsible for managing user-level configurations. It grants administrators to manage user profiles, permissions, and settings from a centralized location. In addition, it controls users' access to resources, actions and priority of traffic for communication.

Summing up a future proof industrial communication architecture connects local machine cells with an industrial backbone and a central room where centralized PLC are deployed on edge cloud computing infrastructure; to make possible to realize low latency, high throughput, service separation and high reliability connectivity between local machine cells and centralized control function is based on TSN capable infrastructure.

Physical connectivity between local machines and switches can be realized with different technologies e.g., fiber, FSO/Microwave, 5G and WIFi6 that can all replace old copper lines.

These four technologies have different characteristics that can be summarized below:

- **Fiber**
  Extremely wide bandwidth (ideally tens of Tb/s scaling up transceiver data rate and using Wavelength Division Multiplexing) and low latency defined by light transmission over glass (speed of light in glass is 2/3 of light speed in vacuum, typical latency value is 5µs/km). Distances from tens of meters to tens of Km without optical amplification required. It needs cabling of all local machine cells. No fees shall be paid for spectrum usage.
- **FSO/Microwave**
  Free Space Optics (FSO) require line of sight with no obstacles to establish connectivity,

bandwidth can be extremely high (like fiber) and latency even lower since speed of light in air is equal to the one in vacuum but higher attenuation limits distances to some kms or hundreds of meters, it suffers moisture, fog and smoke that reduce maximum distance even further. To overcome this, it can be complemented by microwave connectivity that is not affected by the above impairments, but it has lower bandwidth (tens of Gb/s). Suitable for point-to-point connection with precise alignment between endpoints.

- **5G**
  When operating on licensed spectrum, 5G offers superior reliability and better predictability to meet critical communication needs than any other wireless connectivity method. 5G is designed to fulfill QoS requirements for much broader range of use cases than Wi-Fi (5G has full support for massive MTC, eMBB, critical IoT, TSN). A 5G system can also use unlicensed spectrum to offload non-critical traffic. (Known as New Radio Unlicensed or NR-U, this version of NR is part of 3GPP Release 16). 5G provides both wide-area and local coverage with full mobility, while Wi-Fi 6 is limited to local coverage and more basic mobility. 5G has end-to-end specifications covering a complete system architecture, whereas Wi-Fi specifies primarily layer 1 and layer 2. 5G offers the combined merits of the mid-band and low-band for good coverage, and high-band in mmWave for extremely high capacity, low predictive latency, and highly accurate positioning. Wi-Fi 6 is limited to the mid-band and finite bandwidth per access point or device. Unlike Wi-Fi 6, 5G provides end-to-end security and global identity management. Latency for Ultra Low Latency UCs can be around 1ms.
- **WiFi6**
  As a technology option, Wi-Fi has been far more widely adopted by non-smartphone device manufacturers and is established in more ecosystems than 5G. Wi-Fi 6 modems are less expensive than their 5G counterparts. Deployment is often easy and requires limited technical competence (users can establish one or a few access points themselves). Available to all, Wi-Fi 6 (and NR-U) operates on unlicensed spectrum. Usage rights are limited with 5G NR, which operates on licensed spectrum. Typical latency for limited number of users is around 10ms.

Note: full comparison between 5G and WiFi 6 can be found in [15].

SPRINTER project will mainly be focusing on optical connectivity because:

- Immunity to interference: Optical systems are immune to electromagnetic interference (EMI) and radio frequency interference (RFI), which can disrupt the transmission of data over copper-based cables. This makes it particularly useful in industrial environments where EMI and RFI are common, such as in manufacturing plants and power plants.
- Robustness: Fiber communications are physically robust and resistant to corrosion, moisture, and temperature extremes, making it ideal for use in harsh industrial environments.
- Security: Optical communications is difficult to tap or intercept, making it more secure than copper-based cables for transmitting sensitive data.
- Scalability: Optical technology is scalable, meaning that it can be easily expanded to accommodate additional network nodes or to increase bandwidth as network traffic grows.
- Latency: Optical communications provides extremely low latency

### 2.1.3 Industrial Communication Network - System Requirements

Industrial communication networks must guarantee high availability, high throughput, real-time transmission, low jitter and low latency. In addition to the specified KPis, the data needs to be delivered without fail, must have high tolerance to jitter and loss. In the white paper of 5G ACIA “Integration of 5G with Time-Sensitive Networking for Industrial Communications” a brief current description is given.

Effective values to be considered as KPI are dependent from the UC requirement, Table 1 provides some examples based on 5G industrial UC. In general, on the same industrial network many UCs shall run one independently from the others; the network shall guarantee services independency and separation and satisfy specific requirements of each UC, this is clearly stated in the definition of TSN industrial network: "*A TSN-based industrial communication network is a converged network that allows a mix of various traffic types. Service requirements range from best-effort traffic to critical real-time traffic. Several organizations (e. g., 3GPP [3], IEC/ IEEE [33], IEEE [18], IIC [14]) have defined traffic types and corresponding requirements of relevance to industrial automation, and these are summarized in [9]*" [5G-ACIA, p.13]

**Table 2: Industrial automation traffic types of service requirements and related TSN features**

| Traffic types | Periodic Sporadic | Typical period | Data delivery guarantee | Tolerance to jitter | Tolerance to loss | Typical data size (Bytes) | Criticality |
|---|---|---|---|---|---|---|---|
| **Isocronous** | P | 100 µs-2 ms | Deadline | 0 | None | Fixed: 30-100 | High |
| **Cyclic-Synchronous** | P | 500 µs-1 ms | Latency bound (τ) | ≤ \| 2µs \| | 1 frame | Fixed: 50-1000 | High |
| **Cyclic-Asynchronous** | P | 2 ms-20 ms | Latency bound (τ) | ≤ 2µs | 1-4 frames | Fixed: 50-1000 | High |
| **Events: control** | S | 10 ms-50 ms | Latency bound (τ) | n.a. | Yes | Variable: 100-200 | High |
| **Events: alarms and operator commands** | S | 2s | Latency bound (τ) | n.a. | Yes | Variable: 100-1500 | Medium |
| **Network control** | P | 50 ms-1 s | Throughput | n.a. | Yes | Variable: 50-500 | High |
| **Configuration and diagnostics** | S | n.a. | Throughput | n.a. | Yes | Variable: 500-1500 | Medium |
| **Video** | P | Frame Rate | Throughput | n.a. | Yes | Variable: 1000-1500 | Low |
| **Audio/Voice** | P | Sample rate | Throughput | n.a. | Yes | Variable: 1000-1500 | Low |
| **Best Effort** | S | n.a. | None | n.a. | Yes | Variable: 30-1500 | Low |

To meet these requirements, different industry standards and protocols were developed in the past which were compatible only at the physical layer. This made interoperability with different protocols and hardware difficult. To overcome this, Time Sensitive Network (TSN) systems were introduced. They enabled compatibility not only at the physical layer but also at higher layers. Thus, various types of traffic can coexist.

Nowadays several powerful PCs are installed locally at the production cells to allow computing devices to handle the fast data rates. With each powerful PC for every cell there is a higher investment for the shopfloor needed. Alsoforreplacing and maintaining those PCs for upgrading to new hardware as CPUs, RAM, etc. and to upscale them width higher data rates from new sensors it is more labour-intensive. Acentralized computing device is advantageous. Furthermore in a central concept, the software update is also easier than on local PCs. For deploying new functionalities, e.g. running ML algorithm which are released more often then hardware changes are needed, ther centralized solutions have a high benefit.

## 2.2 SPRINTER Application Scenarios

### 2.2.1 Applicability of Photonic Technology in Industrial Communications Network

In order to achieve the required automation in the prescribed use cases, the connections must be reliable. The data from the sensors/PLCs needs to be transmitted to the control/application layer via the backbone of the industrial network. This information is time critical which is passed by the legacy electrical switches. Information might be delayed or lost. SPRINTER introduces TSN-compatible optical switches to ensure that time-critical traffic is delivered reliably, and within a specific time across the whole network. TSN switches support the operation with 50 Gb/s throughput per port.

Sensors/PLCs also produce information related to the maintenance or analysis of data which is not time critical. TSN-compatible switches and Network Interface Cards NICs enhanced with high-performance optical transceivers are also introduced in SPRINTER to facilitate the connectivity between the different nodes. SPRINTER will also introduce an 8-core fiber ring topology to facilitate the interconnection of the TSN switches, and their interconnection with nodes deployed in the other segments. The ring will provide an alternative path for the transmission of elephant or best-effort data flows that otherwise would clog the electrical switches, causing significant queuing delays and packet loss.

Figure 11 shows methods for robot accuracy improvement achieved by additional joint encoders. The system architecture in Figure 14 already combines the use of advanced robotic control using a numerical control based on Siemens Sinumerik (CNC).

Thus, SPRINTER architecture follows a hybrid electrical-optical configuration to combine the benefits of both technologies.

In the following paragraphs, the SPRINTER application scenarios are presented, following the concepts of the UCs described in Section 2.2.1.

### 2.2.2 Application Scenario 1 - Robotics motions accuracy

The first application scenario is connected to **UC *1.a Digital Twin*** and focuses on robotics motion accuracy. Currently, standard industrial robots achieve a positional accuracy of 1 mm as Figure 11 shows. Using additional joint encoders as a measuring system an accuracy of 0.3 mm can be achieved. In addition, the kinematics are optimized with complex models. To achieve even higher positional accuracies and to avoid the use of additional joint encoders, motion tracking can be used.

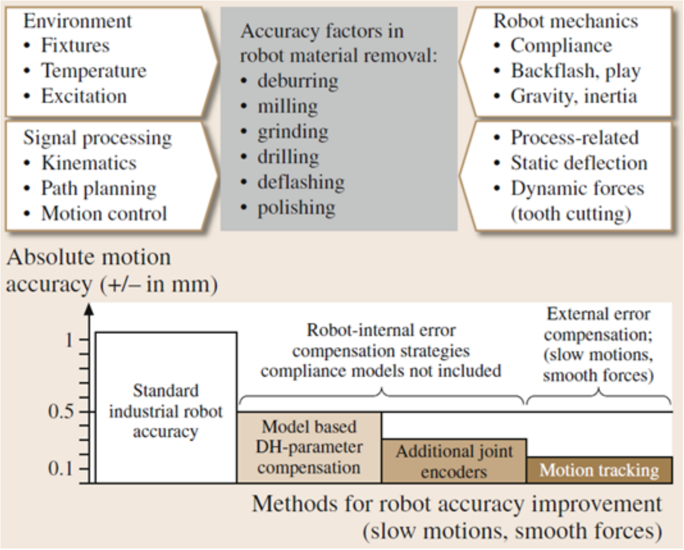

Figure 11: Influences on accuracy of IR during machining and methods for increasing accuracy [13].

Using stereovision instead of additional joint encoders, the real position of the end effector can be determined. Comparing with the target position of control of the robot, the compensation values can be derived and send to the NC to adjust the position and minimize the position error. This is illustrated in Figure 12 and Figure 13, giving an overview of a robotic system equipped with additional encoders.

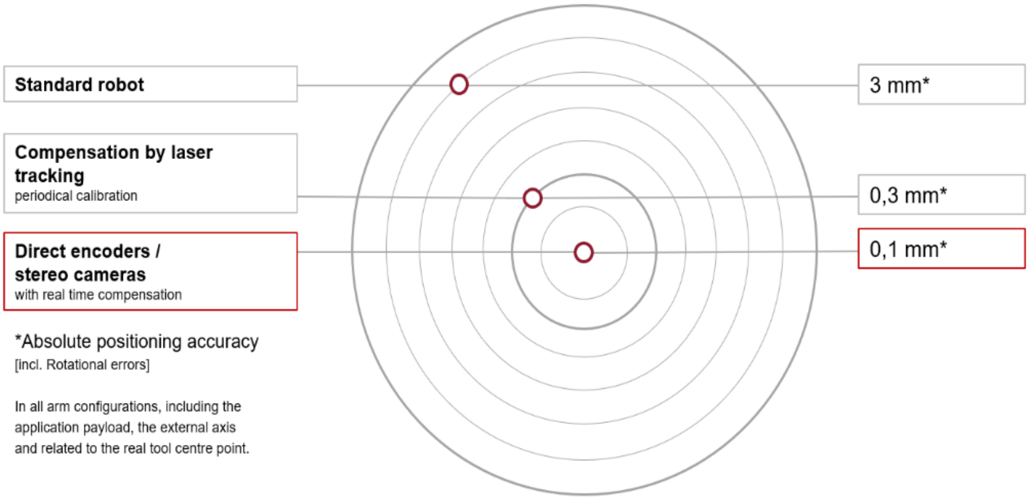

Figure 12: Direct encoders and stereo cameras for high accuracy.

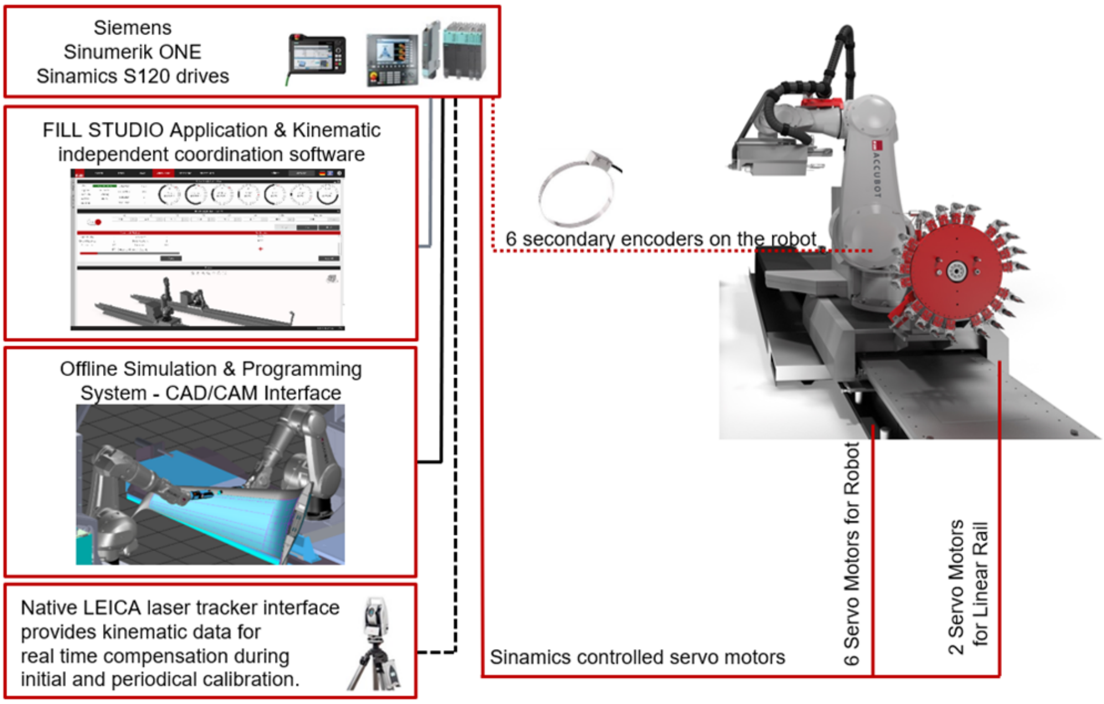

**Figure 13: Advanced robotic control (CNC).**

### 2.2.3 Capture of Motion

In this regard, first studies were made in the paper "Localization of distinctive features of a robot end effector for tracking of a 3D structured light sensor" [9]. This new concept was tested using two stereo cameras, a Fill Accubot[6] and a measurement object with markers. All results are verified with a Leica Lasertracker. (see Figure 14) Using the position of the markers in Figure 15. the compensation of the position is determined as described before. This refers to UC1.a, in Section 2.2.1. Currently, using image processing, only the information of the markers can be used as the other information in the image exceeds data transfer limits. Using the remaining information in the image, the UC can be improved, e.g. by detecting humans in the safety area or detecting deviations in the cable positions due to wear, etc.

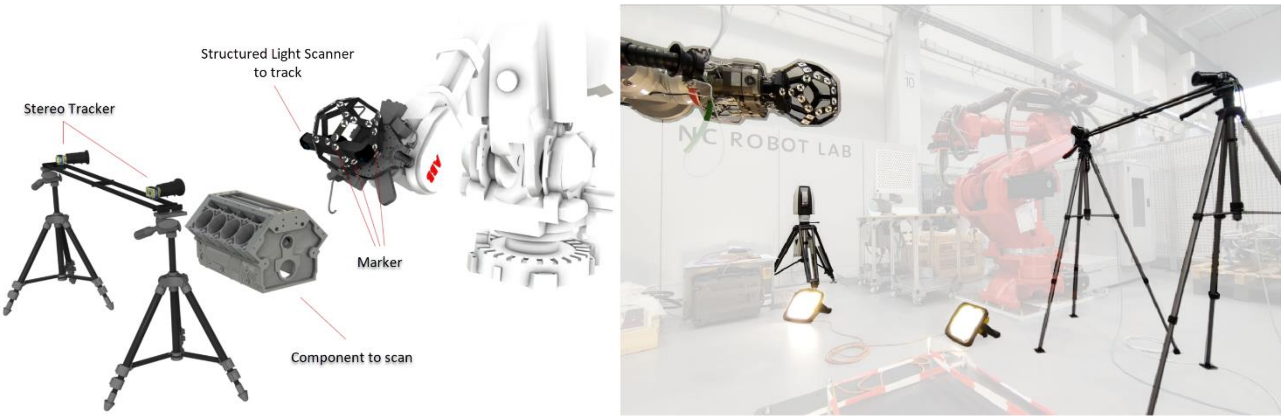

**Figure 14: Experimental setup for stationary pose estimation and compensation with stereo cameras**

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[6] ACCUBOT DRILLING | Fill [February 2023]

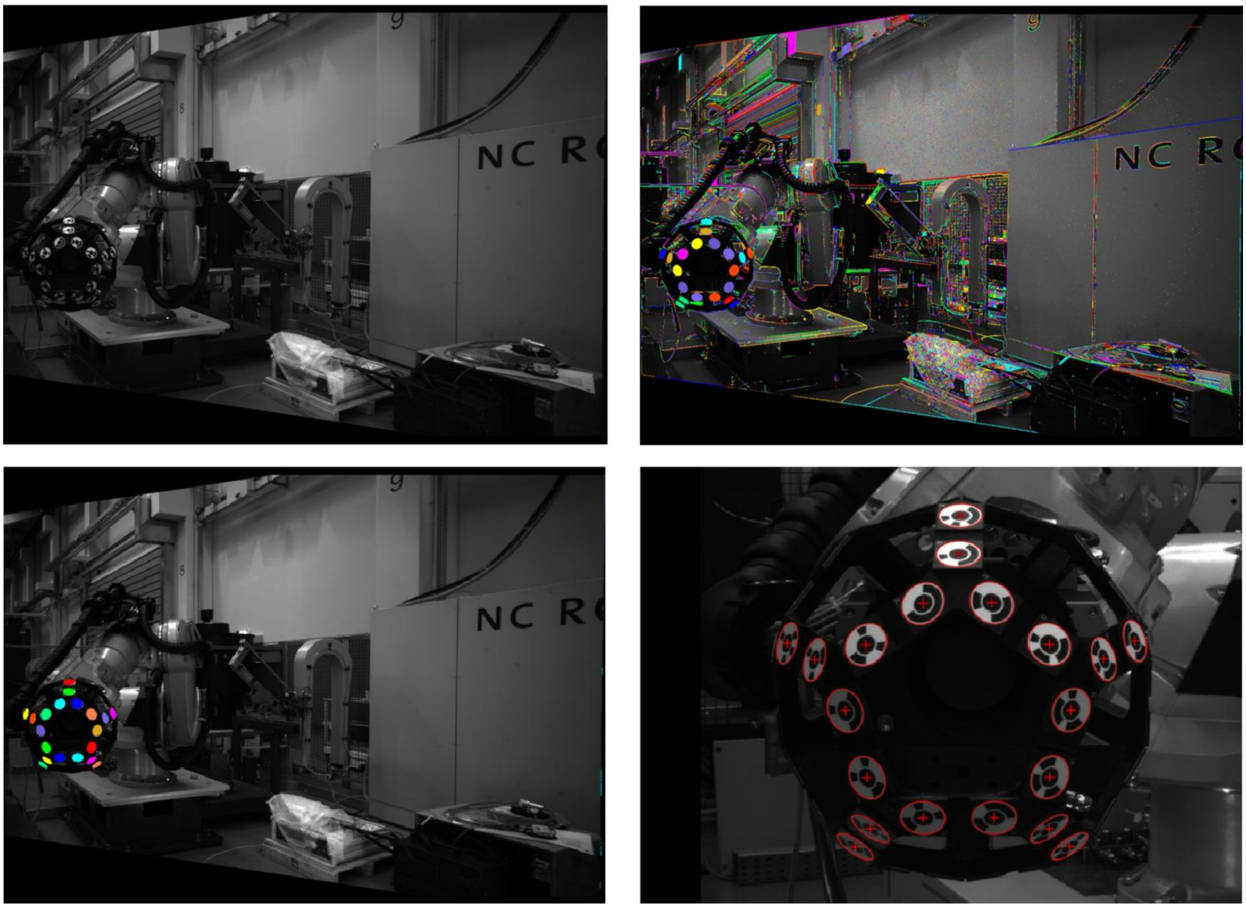

**Figure 15: Image Processing to extract marker positions from stereo cameras**

This additional information can be gathered using an enlarged view of the stereo cameras on the whole scenery. Figure 16 shows the robot in the blue circle, whereas the cables are highlighted in the yellow one. Using this information, the safety of human operators can be increased, too. This refers to UC1.b in Section 2.2.1.

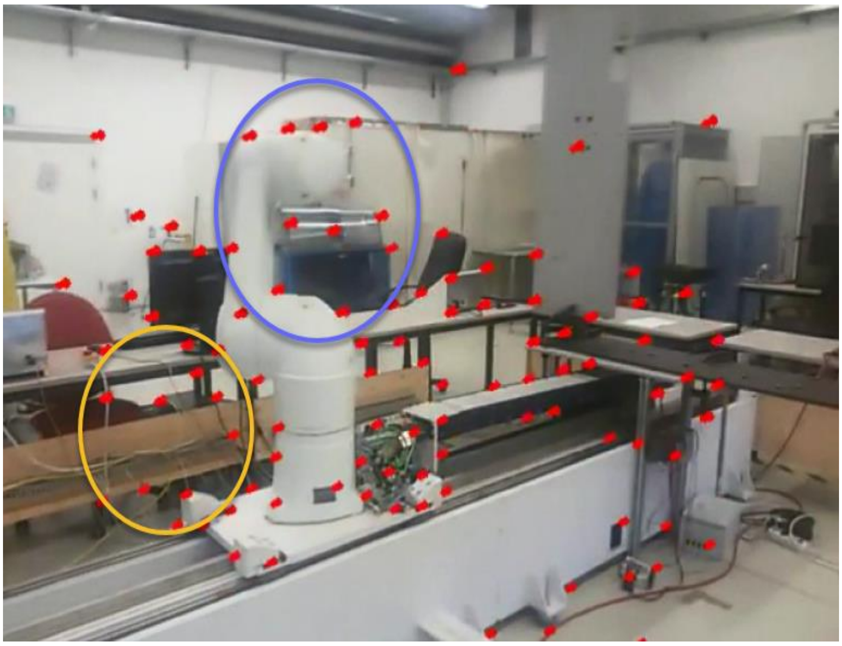

**Figure 16: Motion tracking of additional references in stereo view.**

This UC can be even taken further by giving additional guidance for the operator on how to proceed, like checking the condition of the cable. This refers to UC1.c in Section 2.2.1.

In all three application scenarios described above, the stereo camera enables the extension of the use case by not only improving the accuracy, but also considering relevant information in the surroundings of the robot. However, to make use of this information, the transfer and processing of high amounts of data with low latency is necessary. SPRINTER technology can help bridging the gap in data transfer limits and processing of higher data amounts guaranteing the cycle times currently achieved.

### 2.2.4 Hardware components and experimental setup available

For the experimental setup summed up in Table 3, the hardware components and specifications for Capture the motion are basically defined, two Dalsa Genie Nano 12MP cameras are directly connected to a high-performance computer. To avoid issues sending raw image data, every camera has its own network card on the computer. At 9.7 fps a data rate of 177 Mb/s is reached.

For the evaluation of the system, the deviation of real pose to the pose captured by the cameras is taken. This depends mainly on the resolution of the camera as well as the distance from camera to robot endeffector. At 1.5 m the mean positioning error is 0.172 mm and at 2.5 m already 1.046 mm.

**Table 3: Hardware components and specifications for Capture for Motion.**

| Hardware components | Specifications |
|---|---|
| **Accubot** | Stäubli TX200L<br>extended with Absolute Encoder on axes<br>Absolute Position Accuracy < 0.15mm |
| **Stereo Cameras** | Dalsa Genie Nano M4020 Monochrome Camera<br>Pixel: 4112 x 3008 BPP: 8/12 bits Focal length: 1.5m<br>fps: 9.7 |
| **Lens** | Kowa LM12XC |
| **Lasertracker** | Leica AT960<br>Accuracy: 0.025mm |
| **Computer** | Supermicro X12SPA-TF<br>Intel® Xeon® Silver 4310/2,1GHz BD<br>DDR4-RAM 16GB/KSM32RS8/16MER (2x)<br>Adlink Framegrabber PCIe-GIE74P (2x) |

### 2.2.5 Future Concept and Requirements

An improved future concept of this system requires that a low positioning error is achieved, as well as that it is extendable to the full working space of the robot and that the robot will be correct in the NC cycle time. Therefore, a higher frame rate is required, which, as a result, has a very high data volume. With a 250 fps stereo vision system, the position of the endeffector of the robot could be tracked and compensation values for the position send to the NC within its 4 ms cycle time. Furthermore, with a lower framerate of 5 fps, the 200 ms cycle-time of the PLC could be matched. In addition, for safety control, at least 5 cameras, from each spatial direction, must be used to cover the full workspace and to capture each pose with at least 3 cameras. With increasing robot accuracy, a higher resolution is required. To realize such a system, high-speed and high-resolution cameras are needed. These in turn generate a high volume of data that must be sent to further processing components in the shortest possible time.

On the one hand, this creates general image processing challenges, such as synchronization of the cameras as well as very short exposure times, which can be solved with skillfull image processing. On the other hand, the vast amount of generated data creates a more complex problem.

The emerging data volume will be compared briefly below (Table 4). With a 12 MP camera and a frame rate of 60 fps, the datarate of 1 Gbyte/s is already reached. If the ARAMIS stereo cameras from Gom are used for application scenario, a data rate of 6 Gbyte/s per camera is achieved with 12 MP resolution (12 BPP) and 335 fps for possible future scenarios [11].

**Table 4 : latency and data rate for application scenario UC1**

| Capture for motion | Requirements |
|---|---|
| Latency | Max. 5ms including image processing algorithm for TCP |
| Cameras | 5 / robot |
| Datarate / camera 60 fps application scenario | 8 Gb/s |
| Datarate / camera 335 fps future scenario | 48 Gb/s |

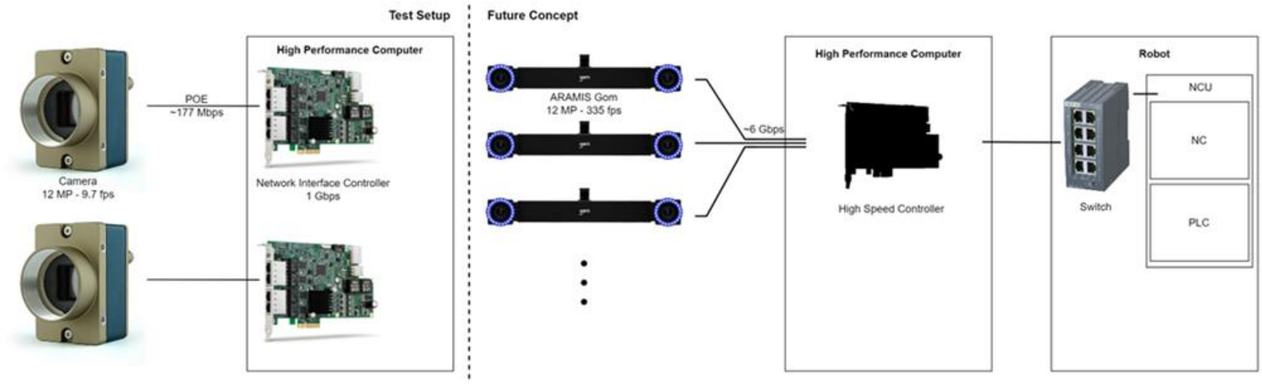

**Figure 17: Schematic Setup for the current Test Setup and a Future Concept for Capture for Motion.**

Figure 18 below shows the Accubot system of Fill for demonstration of the application scenario.

**Figure 18: Accubot in the Fill NC Robot Lab and Dual Robot NDT cell.**

### 2.2.6 Application Scenario 2 - Visual inspection for Quality Assurance

In this section, the application scenario 2 is introduced referring to UC 2.c.

The unique combination of highspeed series production machines focus on innovation solutions for highspeed scanning and processing of wooden products like PARQUET, SOLID WOOD BOARDS, and SOLID WOOD COMPONENTS, as well as surface repairs of PLYWOOD and 3-LAYER BOARDS. Figure 19 is showing a core layer production machine for parquet. Ever increasing quality requirements and the necessity for 100% inspection in production call for INNOVATIVE IMAGE PROCESSING SOLUTIONS. State-of-the-art camera systems and powerful algorithms of machine learning - e.g., for POSITION

DETECTION, TYPE RECOGNITION, COMPLETENESS CHECK, and QUALITY CONTROL - make complex and highly flexible automation processes possible.

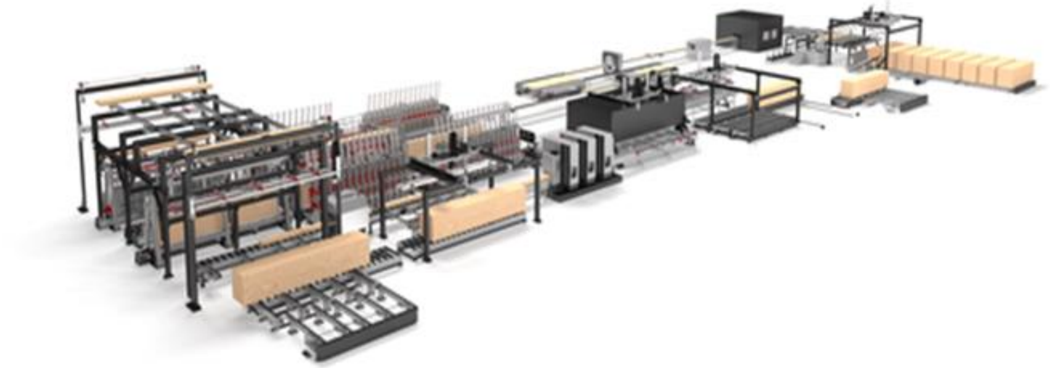

**Figure 19: Core layer production, www.fill.co.at CORE LAYER PRODUCTION | Fill.**

Currently, cameras and scanners (laserlines) with high resolutions are used to detect quality deviations, e.g., Linea HS as illustrated in Figure 21. These cameras can be aligned also 2-6 cameras in a row. The layout for manufacturing lines is oriented on the processing time of the data derived from cameras to decide on next steps for further processing e.g., sorting or repairing. Wooden structures are naturally inhomogeneous and sorting the different quality issues for further processing is needed. To ensure the throughput rate, conveying speeds of scanning lines are enormous high. Therefore, also the postprocessing and assigning the quality label needs to be of high speed. For defect correction the corrections mechanism path planning also needs to be processed with low latency to save space or to reduce waiting times. To give an example, woodenboard with 6 m length is moved at conveying speed of 40m/min, i.e., 0.66 m/s. Therefore, 4 s max. can be used for the sorting including conveying.

Figure 19 shows an example for core layer production. For sorting the wooden boards in quality labels A/B/C the scanning is done at 1.7 seconds per 6 m length. Table 5 gives an overview of achievable scantimes and impact with higher data rates. Figure 20 shows examples of wooden defects to be scanned and processed and sorted.

**Table 5: Requirements highspeed detection of wooden boards**

| | State-of-the-art | Unit |
|---|---|---|
| Takt time / board 6m | 1,7 | sec |
| Conveying speed | 300 | m/min |
| Production volume | 7 | $m^2$/year |
| Detection time and postprocessing(Scanner) | 1,7 | sec |

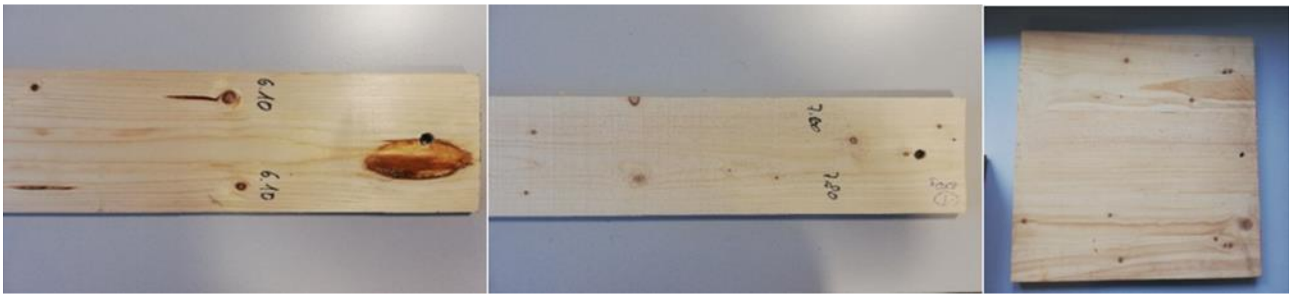
Figure 20: Wooden defects examples for scan.

### 2.2.6.1 Hardware components and experimental setup available


**Figure 21: Linea HS Camera**

The Linea HS camera which is illustrated in Figure 21 is used for detection in wood industry. The specification is given in Table 6. By using such high-performance scanning devices, the manufacturing lines can be more productive by less space for conveying systems. In addition, there are further technical advantages for the customer, which can be explained by the reduced cycle time and optimal transport and loading units, and which are particularly effective in combination with other systems. With 3-shift operation and a technical availability of 80%, approx. 2.7 million more lamellas can be inspected and processed per year (compared to the state of the art, due to the reduced cycle time and the increased speed of the lamella transport, as well as the reduced scrap). The scanners detect defects, knots, cracks, resin pockets, discoloration, dimensional tolerances according to certain quality criteria (e.g., 3 categories A/B/C + rejects - individual customer requirement).

Table 6: Specification for Linea HS camera.

| Linea™HS CMOS TDI Camera systems | Specification application scenario 16k camera | Specifications future scenario 32k camera |
|---|---|---|
| Resolution | 16,384 x 192 pixels | 32,768 x 64 pixels |
| Line rate | 70 kHz | 400 kHz maximum |
| Pixel Size | 5 x 5 µm / 2.5 x 2.5 µm | 5 x 5 µm / 2.5 x 2.5 µm |
| Bit depth | 8 bit | 8 bit – 12 bit |
| Data rate | 9.17 Gb/s | 67.2 Gb/s. |

# 3 REQUIREMENTS

Section 3 sums up the system requirements that will drive the design and development of SPRINTER network components and modules. In the second column the requirement is briefly named. The two application scenarios are giving the baseline requirements for SPRINTER modules.

**Table 7 Application scenarios requirements**

| No. | Requirements | Robots motion accuracy (2.2.2) Application Scenario 1 | Visual inspection for Quality Assurance (2.2.3) Application Scenario 2 | Comment |
|---|---|---|---|---|
| 1 | **Latency** | 1-4 ms | 5 ms | 5 ms standard NC cycletime, Quality Inspection default 20-50ms, parallel processing in use for reduction in processing time,<br>B&R robotic cycletimes <400µs in the case of longer computation times up to 1ms |
| 2 | **Data rate (Gb/s)** | <10 Gb/s | <10 Gb/s | |
| 3 | **Number of local machine cells x TSN aggregation switch** | 2 | 2 | Depends on aggregated bandwidth of machine cells connected to the switch upper limit is 100 Gb/s, 2 cells with each 50 Gb/s, 4 cells with each 25Gb/s |
| 5 | **Number of switches in TSN backbone** | 2 | 2 | Each switching layer introduces an overhead of 5µs drift, 20µs is seen as the limit for TSN setup |
| 6 | **Temperature range** | 4°C to 40°C | 4°C to 40°C | Advanced robotic cells in foundry for machining hot parts heat up the cell Siemens XC200 switch altidute max. 2000m above sea level (NN) -40°C to +60°C |
| 7 | **Transmission path fiber** | Max. 100 m | Max. 100 m | Distance from devices to computation PCs and PLC/NC |
| 8 | **Bending radius fix** | 100mm | 100mm | Reference SINAMICS S120 ethernet topology for drives communication >100mm |
| 9 | **Bending radius flexible** | 200  mm | none | In advanced robotic cells the industrial robot can be moving on an addional 7th axis to increase workspace, therefore the fiber needs to be installed in moving energy chains |
| 10 | **Transmission path FSO** | Max 70 m | Max 70 m | Indoor, straight transmission paths in layouts may replace fiber |

Standards and norms applied to SPRINTER project:

- Reference for the implementation of time protocol is based on IEEE 1588-2008: "IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control".
- Time Sensitive Network is based on IEEE Std 802.1AS-Rev/D7.3, August 2018: "IEEE Standard for Local and metropolitan area networks--Timing and Synchronization for Time-Sensitive Applications".

- Machinery Directive (2006/42/EC): Explicitly tackles aspects which are intended to limit environmental impacts (such as safety integration, materials and products and related design measures must not endanger persons safety or health, airborne noise and other emissions, such as vibrations, radiation has to be minimized, and emissions of hazardous materials and substances have to be reduced through design and construction).
- Industrial communication networks – Network and system security, IEC 62443, is an international series of standards that address cybersecurity for operational technology in automation and control systems.

- Electromagnetic Compatibility (EMC) Directive (2004/108/EC): Lays down requirements in order to prevent electrical and electronic equipment from generating or being affected by electromagnetic disturbances.
- 5GS system is referenced from the document 3GPP TS 23.501: "System Architecture for the 5G System; Stage 2".

# 4 SYSTEM DESIGN & SYSTEM SPECIFICATIONS

## 4.1 SPRINTER Network Architecture for Industrial automation – Demonstration Scenario

As described in Section 2, a typical industrial automation network comprises three main connectivity segments: the central room/edge cloud, the backbone, and the local machine cells.

SPRINTER architecture follows a hybrid electrical-optical configuration to combine the benefits of both technologies, and proposes the full adoption of TSN on all the three connectivity segments, deploying TSN-compatible switches and NICs enhanced with high-performance optical transceivers to facilitate the connectivity between the different nodes (i.e., PLCs and field devices), and TSN-compatible optical switches to ensure that time-critical traffic is delivered reliably, and within a specific time across the whole network. Figure 22 presents the overall SPRINTER architecture, indicating the role of each prototype within it.

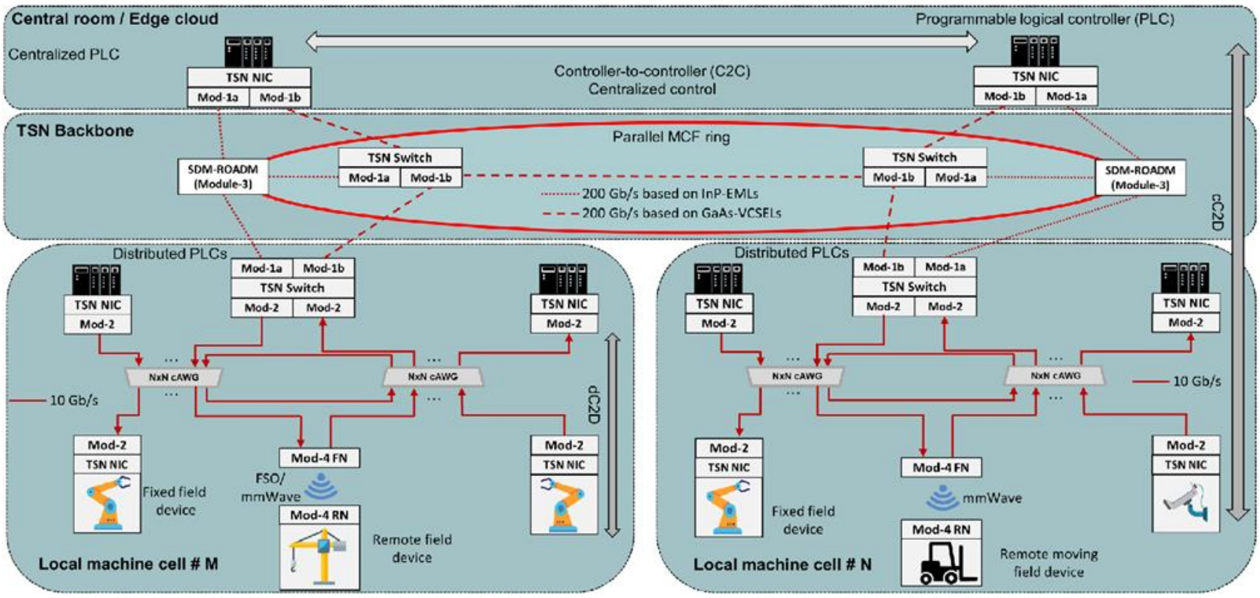

**Figure 22: SPRINTER architecture.**

In the backbone segment, the underlying legacy electrical switches are replaced by TSN switches, supporting operation with 50 Gb/s throughput per port. In order to address the high-capacity needs of this segment, SPRINTER proposes two high-performance optical transceivers, Module-1a and Module-1b, to be deployed. The prototypes will operate with a four parallel single-mode (PSM-4) configuration, at 50Gb/s with on-off keying (OOK) non return to zero (NRZ) for each lane and aggregated capacity of 200Gb/s, also reducing the power consumption since there will be no need for power hungry digital to analog converters (DACs), analog to digital converters (ADCs) and DSP blocks on the transmitter and receiver side respectively.

In parallel, in this segment, SPRINTER will introduce an 8-core fiber ring topology to facilitate the interconnection of the TSN switches, and their interconnection with nodes deployed in the other segments. The ring will provide an alternative path for the transmission of elephant or best-effort data flows that are not time critical, that otherwise would clog the electrical switches, causing significant queuing delays and packet loss. The key component in this architecture is the active SDM-ROADM (Module-3) that will be developed within SPRINTER and will provide interfaces toward the 8-core ring, and the TSN switches and network interface cards (NICs) utilizing Module-1a. Module-1b will be responsible for the PtP interconnection of the TSN-compatible switches, serving only time critical data flows.

Regarding the local machine cells, SPRINTER will introduce an all-optical switching system for the connectivity of the distributed controllers with the field devices, as well as for the connectivity between the different field devices, guaranteeing the reliability and time determinism required for time critical communication. To this end, multiple stages of electronic switches, which can introduce ms scale latency in each stage will be avoided. The proposed architecture is based on passive cAWGs, and novel 10Gb/s ultra-fast tunable optical transceivers (Module-2a, Module-2b) that exhibit switching time in µs scale.

Finally, SPRINTER will provide a set of novel photonics-enabled free space optics FSO/mmWave transceivers (Module-4), that will enable seamless interconnection between the distributed PLCs and remote field devices. Leveraging the unique complementary characteristics of the FSO and mmWave systems with respect to the atmospheric conditions, the developed transceivers will be able to provide PtP 10 Gb/s links with high reliability. The FSO link will act as a virtual fiber extender of the all-optical network, providing connectivity to remote nodes with zero added latency. On the other hand, the mmWave system will be able to serve moving nodes, thanks to the integrated ultra-fast OBFN that can accurately steer the direction of the emitted beam.

## 4.2 SPRINTER Network Components

SPRINTER network includes sensors and robots at the lowest layer of the system architecture which are interconnected and controlled by legacy devices and PLCs. The data is transmitted in a robust and reliable manner. In order to achieve this, system must ensure there is time synchronization (deterministic communication). The higher levels of the industrial backbone are connected by legacy switches/devices. These legacy switches/devices in the system have different clocks or time is often drifted with respect to each other. In order to achieve time synchronization, Time Sensitive Networks are introduced.

As defined in Section 2 (Sub Section- Industrial Communication Networks Typical Architectures) "Time Sensitive Networking (TSN) is a set of standards for enabling deterministic communication over Ethernet networks". TSN devices (which includes switches) are also time-aware, which means they are capable of accurately measuring and predicting network delays and jitters. This allows them to make real-time decisions about how to transmit and receive data.

In order to achieve time synchronization among components in the system, SPRINTER introduces Clocks (often referred to as Grand Master Clocks and Secondary Clocks). Grand Master Clocks are based on the IEEE 802.1AS-2011 standard which includes the Generic Precision Time Protocol (gPTP) to establish hierarchy and synchronize with other nodes in gPTP domain by exchanging information. Grand Master is the source of the clock signal in the backbone network and the components have the information via dedicated messages in the gPTP protocol. Secondary clocks are installed in subnetworks and separate domains can be established on these nodes (local machine cells). In SPRINTER, independent topologies can be contemplated based on the installation requirements.

3GPP also introduces new architecture where the mobile network is considered as a virtual bridge, which is connected to a TSN bridge (Illustrated in the following figure). SPRINTER will also investigate mechanisms to achieve time-synchronization between nodes that are connected to a wired network and nodes that are connected to the same network but wirelessly. Network elements/agents interconnect the mobile system to external networks. In this case, a TSN network. A PTP profile (defined in ITU-T Recommendation G.8275.1) is used for synchronizing time in wired mobile backhaul networks. This mechanism assists in achieving synchronicity for mobile industrial networks, where the timing from the wired backhaul is transported and distributed to the industrial network.

These components are leveraged in SPRINTER to integrate FSO and mmWave end points as part of the time-aware system as per IEEE 802.1AS. Thus, SPRINTER will contribute with innovation where 3GPP design could be enhanced to introduce new entities at both edges of the FSO and mmWave devices to provide TSN Translation (TT) functionalities.

In addition to the characteristics of the system mentioned above, the network entails the physical components such as: TSN Switches which includes Network Interface Cards (NICs) designed by SPRINTER, TSN bridges (wired/wireless networks), TSN controllers (Centralized Network and User Configurations), TSN agents (listeners, talkers). The below figure illustrates the network topology and components in particular.

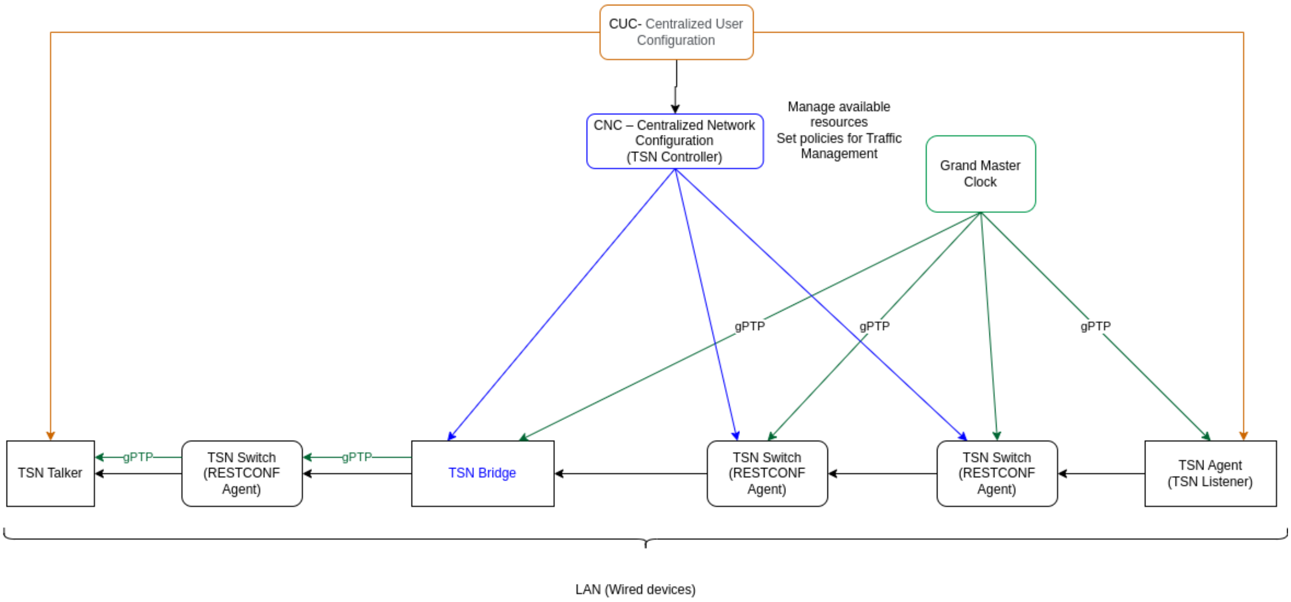

**Figure 23: Network Components with respect to TSN architecture.**

Network components are described in list below:

1. Ethernet switches support the TSN standards which cater features such as the time synchronization, traffic shaping, and stream reservation. In accordance with the SPRINTER project, the Ethernet switches are modified to optical switches to deliver time critical traffic. They also include NICs enhanced with high-performance optical transceivers that facilitate the connectivity between the different nodes to serve best effort data flows shortening queuing delays and packet loss.
2. TSN network controllers include the Central Network Configuration and Central User Configuration which are responsible for managing the network and user configurations. Required agents(software) are to be integrated into the switches to achieve time synchronization and have predefined policies to control the resource management. This is implemented by utilizing RESTCONF (which is similar to the NETCONF and OpenFlow) technology.
3. TSN agents include the talkers and listeners which are essentially end points used to send and receive the time synchronized signals.
4. TSN bridges include wired network components. Sometimes, these bridges could include a wireless system which would appear to the network as a wired network component. This helps in maintaining wireless connectivity, if required by the system.
5. TSN networks support redundancy mechanisms to ensure high availability.

Overall, the physical network components required for TSN support the TSN standards for time-sensitive and deterministic communication.

The TSN switches will receive the priority for different flows from the CNC and when receiving the traffic each flow will be allocated to different queues according to the priority. The CNC has to calculate what is the gate opening/closing for each queue to ensure the flows are transmitted along the path between TSN endpoints (talker and listener).

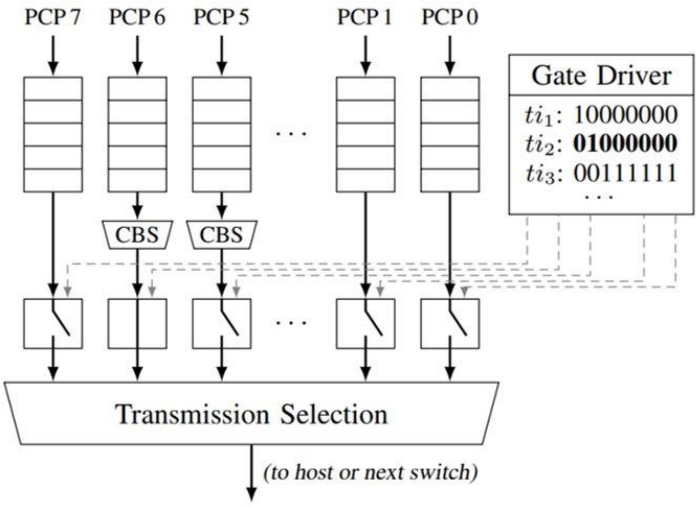

**Figure 24: Selection of Priority flows in the SPRINTER switches.**

Time Sensitive Networking (TSN) which communicates over Ethernet networks has several effects on edge cloud and local machine cells. These are enumerated below:

- **Determinism**: TSN provides deterministic communication which ensures data is transmitted with required latency and jitter. This results in improved performance of edge cloud and local machine cells by enabling real-time applications such as industrial control systems, robotics, and autonomous vehicles.
- **Reliability**: To guarantee critical data communication during network failures, TSN systems are fault tolerant with redundancy built in multi layered architecture. In regard to the SPRINTER project, an 8-core fiber ring topology is present which facilitates alternative paths for transmission. Thus, these can be deployed in harsh environments which improve reliability.
- **Simplified network architecture**: Legacy Industrial networks included multitude of protocols and networks. By introducing TSN, the system was simplified to use ethernet standards resulting in a unified deterministic communication with real time performance. This resulted in reduced cost and complexity for deploying/managing edge cloud and machine cells.
- **Edge computing**: Enabling real-time processing of data at the edge of the network can be supported by TSN networks, this lowers data transmission to the cloud thereby enhancing network efficiency and reducing latency.

The usage of edge computing where some of the endpoints will be deployed will help in the scheduling of TSN communications. If either talker or listener is located in edge computing where the number of hops/ports is reduced then it is easier to guarantee deterministic communications. The gate opening time for forwarding operation $O(i,j)$ to send the data stream i at j-th port is calculated by adding the cumulative network delay in each of the hops/ports between the talker and listener. Thus, when reducing the number of ports, it is easier to optimize the scheduling.

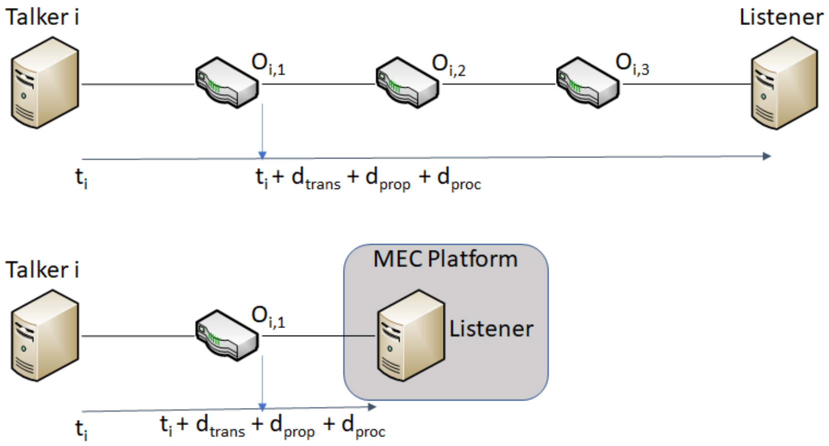

Figure 25: Edge Computing in Time Sensitive Networks

In conclusion, use of TSN network for edge computing/edge cloud and local machine cells are practical enabling improved communication, reliability and simplified network architecture. These enable the accelerated adoption of technologies in a wide range of applications.

## 4.3 SPRINTER Modules

### 4.3.1 Module 1: PSM-4 200Gbps optical transceivers

**Module 1** prototypes will operate with a four parallel single-mode (PSM-4) configuration, where each lane will be accommodating 50 Gb/s data rate transmission by means of OOK-NRZ modulation, leading to a total of 200 Gb/s aggregated capacity per transceiver. SPRINTER's ambition is to provide ultra-low power consuming transceivers, targeting maximum energy efficiency. The OOK modulation scheme is preferred, reducing the complexity, and eliminating the need for power-consuming analog-to-digital and digital-to-analog converters, and complex DSP chips. In this direction SPRINTER will develop two kinds of transceivers (Module-1a and Module-1b)

For **Module-1a** SPRINTER will invest on the use of 4-fold indium phosphide (InP) electro-absorption modulated laser (EML) and InP photodiode (PD) arrays for on-off keying non-return-to-zero (OOK-NRZ) operation at 50 Gb/s per lane in the O-band (1260 nm-1360 nm), for distances up to 2 km. Each lane will operate at the same wavelength at 1310 nm.

For **Module-1b** SPRINTER will invest on the use of 4-fold single-mode (SM) gallium arsenide (GaAs) vertical-cavity surface-emitting laser (VCSEL) and InP-PD arrays supporting OOK-NRZ operation at 50 Gb/s per lane at 1060 nm for distances up to 500m.

For both prototypes SPRINTER will rely on SiGe BiCMOS circuits to develop high-bandwidth transmitter and receiver electronics for 50 Gb/s with OOK-NRZ modulation scheme. A co-design methodology will be developed, targeting optimization of the interfaces of all electronics and optoelectronic components, minimizing the losses and maximizing the energy efficiency.

Figure 26 presents the artistic layout of both prototypes while Table 8 presents the initial specifications of Module-1a and Table 9 for Module-1b.

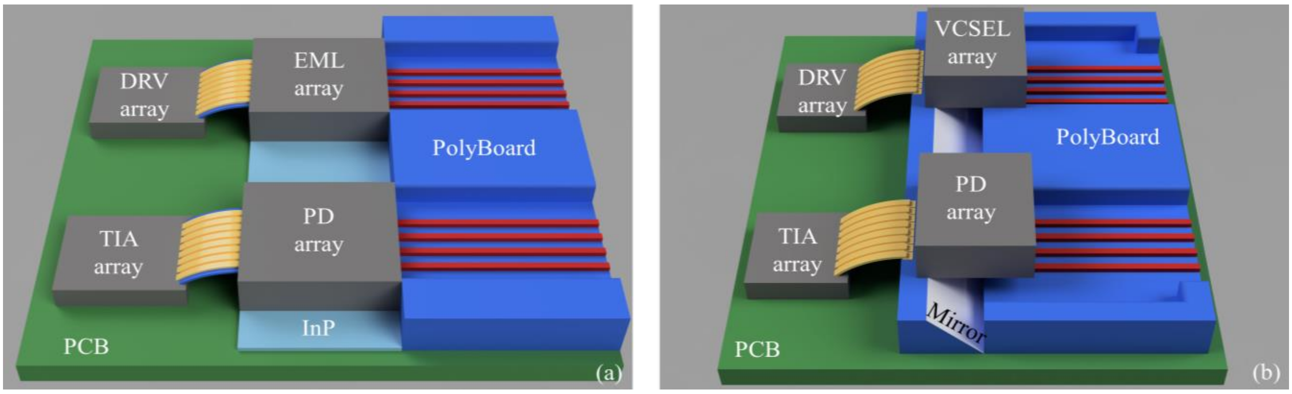

**Figure 26: Artistic layouts of (a) Module-1a EML-based and (b) Module-1b VCSEL-based 200 Gb/s optical transceivers**

**Table 8 Specifications of Module-1a.**

| **Parameters** | **Module-1a** |
|---|---|
| **EMLS** | |
| Length of laser array | 1x4 EML |
| Bit Rate per lane (Gb/s) | 50 |
| Modulation format | OOK NRZ |
| EO Bandwidth (GHz) | >35 |
| Output optical power (dBm) | > 5 |
| Operating wavelength (nm) | 1310 |
| Driving requirements | <1.5 Vpp |
| Integration method | Edge-coupling |
| EML array Footprint: | 1.2 mm x 0.3 mm |
| **PDs** | |
| Length of PD array | 1x4 pin PD |
| EO Bandwidth (GHz) | >35 GHz |
| Responsivity (A/W) | >0.6 |
| PD array pitch | 350μm |
| | |
| Thermal operation | Uncooled |
| **DRVs** | |
| Bit rate per DRV (Gb/s) | 50 |
| Technology | SiGe BiCMOS |
| Driving swing | Up to 1.5 Vpp |
| CTLE | optional |
| **TIAs** | |
| TIA array length | 1x4 |
| Gain (dBΩ) | >65 |
| Output voltage (Vpp) | >0.4 |
| **Input current noise (μArms)** | **<3** |
| **Power Consumption** | **Module-1a** |
| InP EML array (W) | 4x0.15 |
| InP PD array (W) | 4x0.001 |
| BiCMOS Drivers (W) | 4x0.15 for differential operation, 4x0.3 for single-ended drive |
| BiCMOS TIAs (W) | 4x0.12 |
| Energy efficiency (pj/bit) | 8.4 - 11.4 |

**Table 9: Specifications of Module-1b.**

| **Parameters** | **Module-1b** |
|---|---|
| Length of VCSEL, PD, DRV and TIA arrays | 1x4 |
| VCSEL/PD-Polyboard integration method | Flip-chip |
| DRV-VCSEL, PD-TIA integration method | FlexLine or bond wires |
| Bit rate per lane (Gb/s) | 50 |
| Modulation format | OOK NRZ |
| Transmission distance (m) | ≤ 500 |
| Operating wavelength (nm) | 1060 |
| Thermal operation | Uncooled |
| **VCSELs** | |
| Bandwidth, electrical (GHz) | > 25 |
| Threshold current (mA) | < 1 |
| Slope efficiency (W/A) | ~0.7 |
| Output optical power (dBm) | ~5 |
| Beam divergence (1/$e^2$FW) | < 18 |
| Differential resistance (Ω) | < 100 |
| **PDs** | |
| Bandwidth, electrical (GHz) | > 30 |
| Responsivity (A/W) | ≥ 0.55 |
| Dark current (μA) | < 1 |
| Aperture diameter (μm) | 20 |
| **DRV** | |
| DRV technology | CMOS or SiGe BiCMOS |
| Bit rate per DRV (Gb/s) | 50 |
| Driving swing | up to 10 mApp |
| CTLE or pre-emphasis | optional |
| **TIA** | |
| TIA technology | SiGe BiCMOS |
| TIA Bandwidth (GHz) | >30 |
| Gain (dBΩ) | >65 |
| Output voltage (Vpp) | >0.4 |
| Input current noise (μArms) | <3 |
| **Power Consumption** | **Module-1b** |
| GaAs VCSEL array (W) | 4x0.015 |
| PD array (W) | 4x0.001 |
| Drivers (W) | 4x0.060 |
| TIAs (W) | 4x0.120 |
| Energy efficiency (pj/bit) | 3.9 |

### 4.3.2 Module 2: Ultra-fast tunable 10 Gb/s optical transceivers

SPRINTER will develop a set of ultra-fast ECL-based tunable transceivers, Module 2a and Module 2b, leveraging the low propagation losses of the TriPleX platform for the implementation of an ultra-narrow linewidth ECL that will act as the optical source for both versions of Module 2. The tuning of the ECLs will be facilitated by PZT phase actuators combining fast tuning performance and low power consumption. Module-2a will host a Mach-Zehnder Modulator (MZM) implemented in the LNOI platform based on a symmetric push-pull configuration targeting low driving requirements and power consumption. Module-2b will also host an MZM based on the InP platform. Both modulators will be driven without any electronic units due to the low Vπ requirements, supporting 10 Gb/s OOK-NRZ traffic. At the receiver part both modules will accommodate C-band InP PDs and an intermediate PolyBoard part responsible for the routing of the input signal from the fiber array to the PDs, leveraging PolyBoard's polarization insensitivity. Finally, both modules will host a 10 Gb/s Burst-Mode Receiver (BM-Rx) based on the SiGe platform providing offset compensation and automatic gain control mechanisms. Figure 27 presents an artistic layout of the modules, whereas

Table 10 describes the targeted high-level requirements and components specifications for both versions of Module 2.

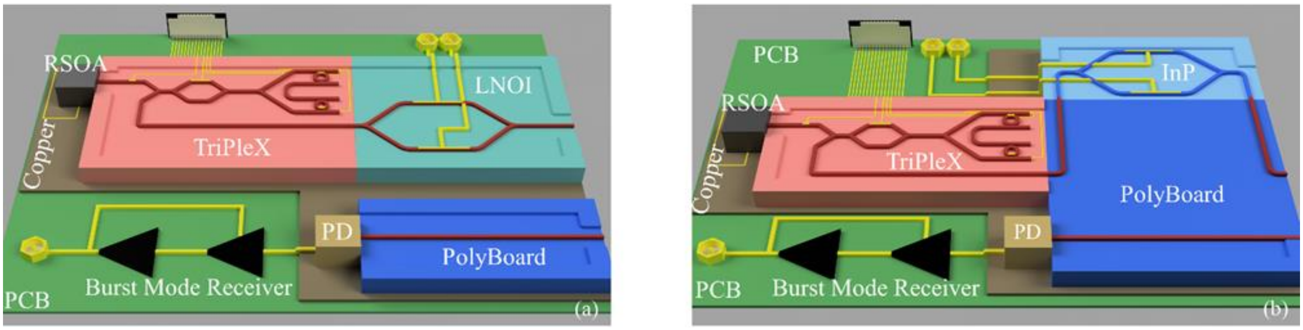

**Figure 27: Artistic layout of (a) Module-2a and (b) Module-2b ultra-fast tunable 10 Gb/s optical transceivers.**

**Table 10: Specifications of Module 2.**

| Parameters | Module 2 |
|---|---|
| **ECL** | |
| Wavelength band | C-band |
| ECL tunability (nm) | >105 |
| ECL output power (mW) | >100 |
| Linewidth (Hz) | <300 |
| SMSR (dB) | >60 |
| RIN (dB/Hz) | <-170 |
| Wavelength drift (MHz) | <100 |
| Phase actuation | PZT-based |
| Tuning speed (MHz) | >10 |
| PZT Vπ (V) | <40 |
| **PD** | |
| PD technology | pin-PD |
| Responsivity (A/W) | 0.8 |
| Integration method | Edge-coupling |
| **Electrical Parameters** | |
| Driving unit | N/A |
| Burst-Mode Receiver (BM-Rx) | YES |
| BM-Rx technology | SiGe |

| | |
|---|---|
| BM-Rx settling time (ns) | 83 ns |
| BM-Rx dyn. range (dBΩ) | >20 |
| **Parameters** | **Module-2a** |
| **Modulator** | |
| Modulator technology | LNOI |
| Modulation scheme | OOK-NRZ |
| Bit rate (Gb/s) | 10 |
| Driving scheme | Push-pull |
| Vπ (V) | <0.9 |
| EO Bandwidth (GHz) | >30 |
| Integration method | butt-end |
| Optical loss (dB) | <1 |
| **Parameters** | **Module-2b** |
| **Modulator** | |
| Modulator technology | InP |
| Modulation scheme | OOK-NRZ |
| Bit rate (Gb/s) | 10 |
| Driving scheme | Push-pull |
| Vπ (V) | <1.5 |
| EO Bandwidth (GHz) | >20 |
| Integration method | butt-end |
| Optical loss (dB) | <3 |
| **Power Consumption** | **Module-2a** |
| InP gain chip (W) | 0.15 |
| TriPleX cavity (W) | $10^{-5}$ |
| LNOI-MZM (W) | 0.01 |
| InP PD plus PolyBoard (W) | 0.001 |
| SiGe Burst-mode Rx (W) | 0.28 |
| TEC unit (W) | 1.5 |
| Total (W) | 1.95 |
| Energy efficiency (pJ/bit) | 195 |
| **Power Consumption** | **Module-2b** |
| InP gain chip (W) | 0.15 |
| TriPleX cavity (W) | $10^{-5}$ |
| InP-MZM (W) | 0.015 |
| InP PD plus PolyBoard (W) | 0.001 |
| SiGe Burst-mode Rx (W) | 0.28 |
| TEC unit (W) | 1.5 |
| Total (W) | 1.96 |
| Energy efficiency (pJ/bit) | 196 |

### 4.3.3 Module 3: SDM-ROADM

Module 3 will be an active 3D PolyBoard 32x32 space-division multiplexing (SDM) active reconfigurable optical add-drop multiplexer (ROADM)-SDM-ROADM. The ROADM will operate in the O-band supporting operation within SDM networks, featuring polarization-independent operation, and low power consumption and cost. The circuit will consist of two 3D PolyBoard multicore fiber (MCF) interposers and a 32×32 3D PolyBoard active optical switch based on the Benes non-blocking and fully reconfigurable architecture. The artistic layout of the proposed SDM-ROADM is presented in Figure 28 and the initial specifications in Table 11.

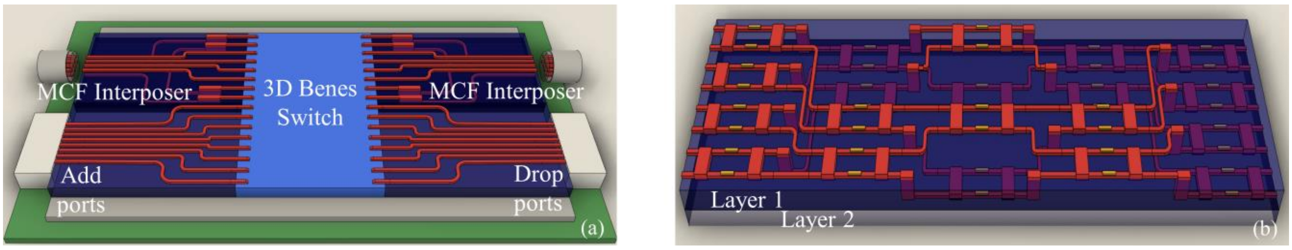

**Figure 28: (a) Artistic layout of the 3D PolyBoard SDM-ROADM (16x16 shown for simplicity) and (b) an 8×8 3D Benes switch monolithically integrated on the 3D PolyBoard platform (8x8 shown for simplicity).**

**Table 11: Module-3 Specifications.**

| **Parameters** | **Module 3** |
|---|---|
| Operating wavelength | 1310 |
| Size | 32 x 32 |
| Add/Drop ports (#) | 26 |
| MCF cores (#) | 6 |
| Reconfiguration time (ms) | <10 |
| Crossbar switches (#) | 144 |
| Power for π phase shift (mW) | <10 |
| SMF/MCF core coupling losses (dB) | <1 |
| Crosstalk between ports (dB) | <-30 |
| worst-case path loss (dB) | <10 |
| Power consumption (W) | <2 |

### 4.3.4 Module 4: Hybrid FSO/mmWave transceivers

SPRINTER Module 4 consists of a set of novel photonics-enabled FSO/mmWave transceivers enabling the seamless interconnection between the distributed PLCs and remote field devices. These innovative transceivers will be able to provide ptp 10Gbit/sec links with high reliability, leveraging the complementary characteristics of the FSO and mmWave systems with respect to the atmospheric conditions. The FSO link will act as a fiber extender of the all-optical network, providing connectivity to remote nodes with zero added latency. On the other hand, the mmWave system will be able to serve moving nodes, thanks to the integrated ultra-fast OBFN that can accurately steer the direction of the emitted beam.

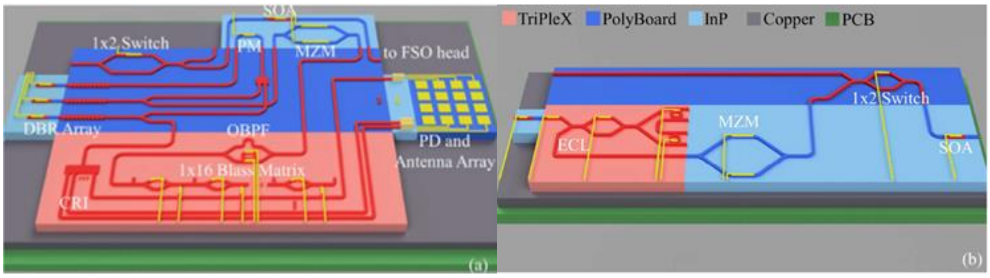

**Figure 29: Artistic layout of the (a) transmitter part and (b) receiver part, of the hybrid FSO/mmWave transceiver**

Figure 29 shows the functional layout of the Tx and Rx parts of Module-4 Fixed Node (FN) transceiver. The three technologies InP, PolyBoard and Triplex technologies will be combined under the hybrid integration to host all the required elements for processing the FSO and the mmWave signals.

For operation with the FSO system, the main units are the crossbar switch, the optical signal amplification unit based on the semiconductor optical amplifier (SOA) on the InP platform, an attached fiber on the PolyBoard connected to a fiber-pigtailed telescopic lens system, based on commercially available off-the-shelf (COTS) components that facilitate the optical signal's transmission toward the remote node.

The five main units of the FN transmitter enabling the generation, processing and transmission of the mmWave signals are the followings:

1. Optical carrier generation unit based of two distributed Bragg reflector (DBR) lasers.
2. Optical frequency comb generation unit including an InP phase modulator (PM) and a DBR laser.
3. The modulation unit consists of an InP MZM driven by the IF waveform generated by the BBU/IFU unit.
4. The optical beamforming unit based on Triplex platform including an optical bandpass filter and 1x16 OBFN based on Blass matrix architecture.
5. The unit which will be responsible for the actual generation and emission of the wireless beam to the air.

Table 12 and Table 13 summarize the specifications for the Tx/Rx parts of the Fixed Node.

**Table 12: Module-4 FN Tx specifications.**

| Parameters | Module 4 FN Tx |
|---|---|
| Input signal Bit Rate (Gb/s) | 10 |
| Input signal Mod. scheme | OOK-NRZ |
| SOA gain (dB) | 10 |
| Transmission distance (km) | >0.5 |
| FSO head | COTS based |
| Central frequency (GHz) | 71 – 76    81 - 86 |
| Baud Rate (Gbaud) | 1.6 |
| Mod. format | Up to 256-QAM |
| IF (GHz) | Up to 10 |
| Power per laser (dBm) | >10 |
| Wavelength tuning (nm) | >10 |
| Type of modulator | SD MZM |
| Vπ (V) | <1.5 |
| Optical filtering scheme | SSB-SC |
| OBFN architecture | 1x16 Blass Matrix |
| Phase actuation | PZT based |
| SOAs gain (dB) | 10 dB |
| PD bandwidth (GHz) | TBD (70 to 90 GHz) |
| PD responsivity (A/W) | >0.35 |
| Tx Antenna type, gain | 4x4 planar slot, 16 dBi |

**Table 13: Module-4 FN Rx specifications.**

| Optical Parameters | Module 4 FN Rx |
|---|---|
| **FSO path** | |
| FSO head | COTS based |
| Amplification stage | YES |
| SOA gain (dB) | 10 |
| **mmWave path** | |
| Rx antenna type | Horn antenna |
| Demodulation unit | RF/BBU (ICOM) |
| ECL characteristics | (see Module 2) |
| Type of modulator | MZM (DD/SD) |
| Modulation format | OOK-NRZ |
| Bit Rate (Gb/s) | 10 |
| SOA gain (dB) | 10 |

In Figure 30 is shown the layout of the Tx part of the hybrid FSO/mmWave of the Remote Node (RN) transceiver.

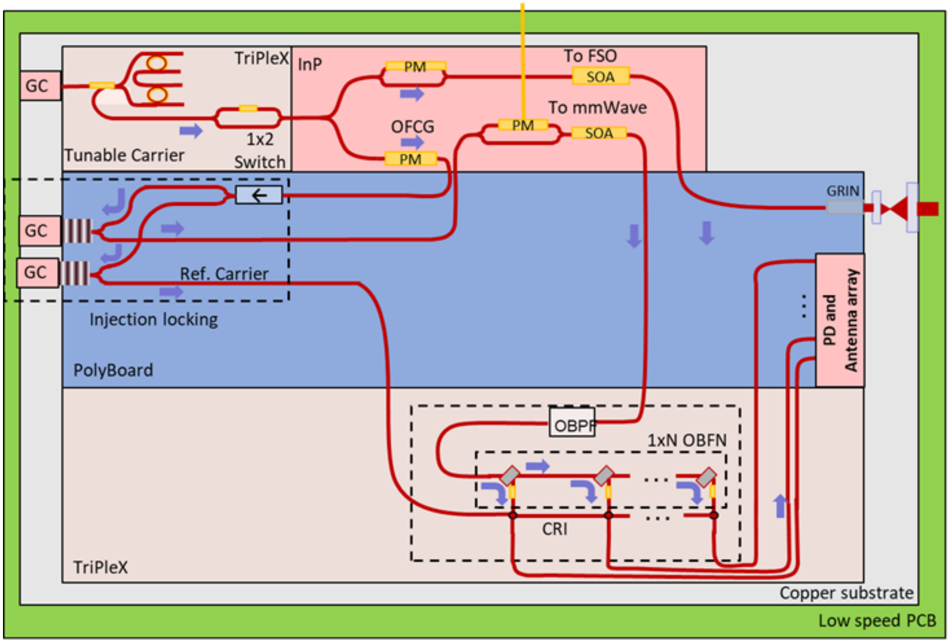

**Figure 30: Layout of the Tx part of the hybrid FSO/mmWave of the Remote Node (RN) transceiver**

The Tx part of the RN will be based on the hybrid PolyBoard/InP/TriPleX platform allowing the generation, processing and transmission of the mmWave and FSO signals. For the operation of the mmWave signals, the optical carrier will be routed to the lower port of the MZI and it will be used to generate an optical frequency comb. Then, by following the exact approach and same optical units as in the FN-transmitter, the PIC will facilitate the transmission of the mmWave signal.

**Table 14 : Module-4 RN Tx specifications**

| Optical Parameters | Module 4 RN Tx |
|---|---|
| Mod. Scheme | OOK-NRZ |
| Bit rate (Gb/s) | 10 |
| SOA gain (dB) | 10 |
| Transmission distance (km) | >0.5 |
| FSO head | COTS based |
| Type of modulator | InP MZM (DD/SD) |
| ECL characteristics | *(see Module 2)* |
| Central frequency (GHz) | 71 – 76<br>81 - 86 |
| Baud Rate (Gbaud) | 1.6 |
| Mod. Format | Up to 256-QAM |
| IF (GHz) | Up to 10 |
| Power per laser (dBm) | >10 |
| Type of modulator | SD MZM |
| Vπ (V) | <1.5 |
| Optical filtering scheme | SSB-SC |
| OBFN architecture | 1x16 Blass Matrix |
| Phase actuation | PZT based |
| SOA gain (dB) | 10 dB |
| PD bandwidth (GHz) | TBD (70 to 90 GHz) |
| PD responsivity (A/W) | >0.35 |

| | |
|---|---|
| Tx Antenna type | 4x4 planar slot |

Table 14 summarizes the specifications of the Tx part of Module-4 RN. When operating with the FSO system, the optical carrier will be routed to the upper port of the MZI crossbar switch and will be connected to an InP-MZM followed by an InP-SOA. After the amplification, the optical signal will be coupled to a fiber-pigtailed telescopic lens system, as in the FN-transmitter.

The Rx part of Module-4 RN will be based solely on COTS components. A fiber-pigtailed telescopic lens system together with a 10 GHz photoreceiver, coupled to a TSN NIC will be deployed for the detection and demodulation of the FSO signals. For the mmWave signals, a horn antenna combined with an RF/baseband units will be deployed for the detection and demodulation of these mmWave signals. The demodulated electrical signals will be forwarded to the field device via an Ethernet switch.

### 4.3.5 Module 4: Baseband unit and IF/RF units

ICOMs baseband unit (BBU) will implement all the required functions at the physical layer for operation in real-time with symbol rates up to ~1.6Gbaud/sec as part of Module-4. The produced baseband QAM signals will be up-converted to an intermediate frequency through the Intermediate Frequency (IF) unit. This IF signal will modulate the optical carrier at the Tx part of the Module-4 FN. At the receiver side of the Module-4 FN, the mmWave signals will be received by the horn antenna and will be down-converted to the baseband signals through the ICOM's E-Band RF downconverter unit. Then, ICOMs BBU will compensate for the induced impairments and demodulate the baseband signals. A similar approach will be applied in the case of the remote Node (RN).

The following table shows the parameters of the baseband, intermediate and radio frequency units.

**Table 15 BBU/IF unit specifications**

| **Baseband & IF/RF units** | |
|---|---|
| **Parameter** | **Values** |
| Channel bandwidth | Up to 2GHz |
| Intermediate frequency | Up to 10GHz |
| Symbol Rate | Up to 1.6Gbaud |
| QAM constellation size | Up to 256 |
| E-band Radio Frequency (RF) | 71 – 86 GHz |

# 5 CONCLUSIONS

This deliverable is the outcome of the initial work carried out in the framework of WP2. Combines the results of the project effort in T2.1 -SPRINTER technology: application scenarios and analysis of system requirements, T2.2-SPRINTER network architecture: System design and specifications and T2.3 -Module design and component specifications.

The two SPRINTER application scenarios with commercial interest that are identified: **Application Scenario 1- Robotics motions accuracy** and **Application Scenario 2- Visual inspection for Quality Assurance,** have led to the initial architectural design of the SPRINTER system and its specifications (see sections 4.1 & 4.2 ) and next to a preliminary description of the SPRINTER modules (see section 4.3).

Following, and in the framework of T2.2, the network topology, and the interfaces within the application scenarios, as well as the architecture of the SDN platform for the optimization of the network topology and allocation of the system resources will be further analyzed and refined. The system designs of SPRINTER prototypes – part of the work in T2.3 - will provide guidance to the activities in WP3, WP4 and WP5 that deal with the development of the individual network modules and components, as well as WP6 that develops the network management system.

Ultimately the work summarized in this deliverable will form the basis for the development of SPRINTER technology demonstrators and to the realization of the two application scenarios that will take place in the industrial premises of FILL (WP7- System integration and testing of SPRINTER prototypes).

# List of Figures

## List of Tables

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