Project number: 826276

CPS4EU

Cyber Physical Systems for Europe

D2.1 – Specification and architecture of the communication modules

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EXECUTIVE SUMMARY

In recent years, Cyber Physical Systems (CPS) technologies have become a game changer in strategic sectors such as Automotive, Energy and Industry Automation, where Europe is a world leader. CPS4EU is an European project, aiming at developing enabling technologies for CPS, encompassing various vertical uses cases.

The Work-package 2 of CPS4EU deals with the communication aspects of the CPS: how a physical system can be connected efficiently and securely to a network, in the context of emerging technologies, as Internet of Things (IoT) and 5G.

This report is the first report of WP2, task 2.1, dealing with the specification and architecture of the communication modules. Part of these communications modules will be developed in WP2 and later integrated into WP6 into the pre-integrated communication platform. However, CPS communications may request tough characteristics that cannot be served with nowadays communications systems. As a result, the WP2 has also the mandate to studies innovative solutions to meet these tough requirements, in line with 5G development in 3GPP.

Consequently, this report presents on one hand the requirements captured from “use cases” work package, at least the one available at the time of this document; then it summarizes what could be done with nowadays technologies (4G or early 5G solutions). In addition, it presents the assumptions and initial ideas of the work undergone in task 2.2, dealing with these prospective studies, including an introduction to the DSP framework that could support the prototyping of some of these prospective ideas within task 2.3.

From the early requirements collected from other work-packages, we derived the high-level requirements of the communication modules to serve a maximum of use cases. It appears that a single radio modem cannot meet all the requirements. For instance, depending on use cases, very low data rate could be good enough, while for others, high data rate is a must. As a result, a CPS communication system has to address multiple modems, that could be then integrated into a pre-integrated architecture board, which is the objective of WP6.

The report performed a quick survey of existing technologies. It appears that 4G is a good starting point since it proposes a framework meeting most of the requirements, thanks to the various LTE categories. However, for most stringent requirements, such as low latency, time deterministic communication, 4G is somehow limited and WP2 has to work on building blocks, enabled by 5G to fulfil the complete set of requirements expressed by verticals. This report proposes three axis of research for WP2, investigating Time Sensitive Networking, URLLC, and a DSP framework and development flow that could combine communication and AI processing.

This report has therefore set the scene for WP2, highlighting early requirements from verticals about communication, proposing short term solution to meet most of these requirements and long term research activities to propose solution for tightest requirements.

Update of the report will be provided in Q4 2020 to better capture requirements from vertical (coming from WP6, WP7, WP8, WP9, since these requirements elicitation is still work in progress at the time of this deliverable) and status from 5G development in the standardization forum.

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Table of content

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

Tables

Figures

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1 INTRODUCTION

1.1 PURPOSE

This report is the first report of WP2, task 2.1, dealing with the specification and architecture of the communication modules. Part of these communications modules will be developed in WP2 and later integrated into WP6 into the pre-integrated communication platform. However, CPS communications may request tough characteristics that cannot be served with nowadays communications systems. As a result, the WP2 has also the mandate to studies innovative solutions to meet these tough requirements, in line with 5G development in 3GPP.

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1.2 DEFINITIONS, ACRONYMS, AND ABBREVIATIONS

Acronym / abbreviation	Description
3GPP	3rd Generation Partnership Project
ADC	Analog to Digital Converter
AI	Artificial Intelligence
API	Application Programming Interface
CCSK	Cyclic Code Shift Keying
CoMP	Coordinated Multipoint
CPS	Cyber Physical System
CSI	Channel State Information
D2D	Device to Device
DSP	Digital Signal Processor
EPC	Evolves Packet Core
FEC	Forward Error Correction
FPGA	Field-Programmable Gate Array
gNB	Next Generation Node B
HSS	Home Subscriber Server
IoT	Internet of Things
LDPC	Low Density Parity Check (codes)
LTE	Long Term Evolution
LTE-M	Long Term Evolution – Machine Type Communication
MAC	Medium Access Control
MME	Mobility Management Entity
NAS	Non Access Stratum
NB (codes)	Non-Binary codes
NB-IoT	Narrow Band IoT
OAI	Open Air Interface
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PIARCH	Pre-Integrated Architectures
QoS	Quality of Service
RLC	Radio Link Control
RRC	Radio Resource Control
S+P-GW	Serving/Packet GateWay
SCTP	Streal Control Transmission Protocol
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver-Transmitter
UE	User Equipment

URLLC	Ultra Reliable and Low Latency Communications
USB	Universal Serial Bus
UTRA	Universal Terrestrial Access Network
V2I	Vehicle to Infrastructure
V2X	Vehicle to Everything
X2AP	X2 Application Protocol
TSN	Time Sensitive Networking

2 REQUIREMENTS FROM VERTICAL

This section captures the high-level requirements with respect to communication aspects coming from other WPs, mostly WP6, WP7 and WP8. In the CPS4EU project plan, the first delivery of use case work-packages is planned for February. This deliverable captures the available requirements at Q4 2019, if new requirements arise, they will be captured in a updated version of this report.

2.1 REQUIREMENT FROM WP6 AND WP7

2.1.1 High-level needs from the automotive use case (WP7)

WP7, the automotive use case, aims to demonstrate several features and technologies for next generation cars, mainly:

- Autonomous driving level 4 and the related technologies for perception, localization and human-machine interfacing,
- Added value of secure V2X communications,
- Digital twin simulation for validation.

This section will focus on the "secure V2X communications" part of this automotive use case. The objective is to demonstrate the added value provided by secure V2I (Vehicle to Infrastructure) communications, for functional chains such as Health and Usage Monitoring Systems, Over-the-Air updates and interaction with IoT objects. These demonstrations require a connectivity subsystem (Figure 1) providing the following features:

- Various LTE communication capabilities (LTE-M, NB-IoT, Cat. 4), for the communication between the vehicle and either the cloud or nearby IoT objects. 5G could also be considered during the second step of the project,
- Wi-Fi and Bluetooth connectivity, for multimedia applications,
- Access to the embedded network of the vehicle, in this case an Ethernet backbone,
- A secure gateway for the communications between the trusted embedded network and the non-trusted infrastructure.

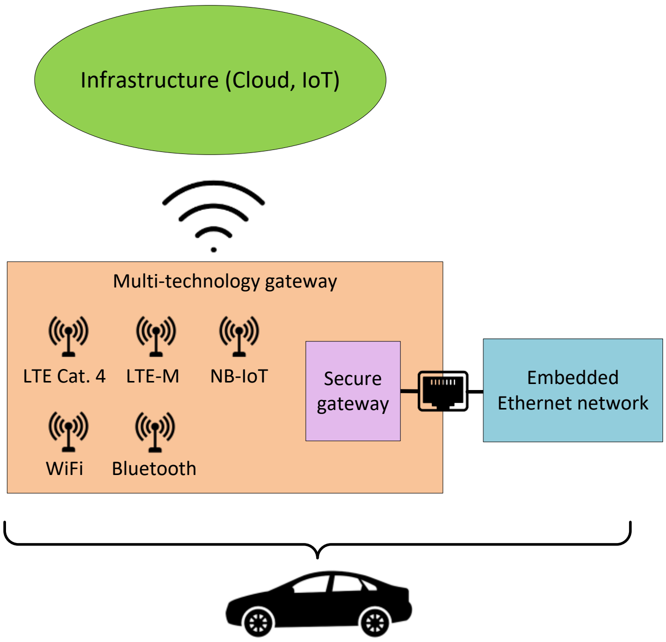

Figure 1. Connectivity subsystem of the automotive use case

This connectivity subsystem will be integrated using the "Connectivity Pre-Integrated Architecture" developed in WP6.

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2.1.2 Connectivity Pre-Integrated Architecture (WP6)

The purpose of Pre-Integrated Architectures (hereinafter PIARCH) proposed in CPS4EU is to facilitate the integration of CPS building blocks into final systems.

The first objective is to help technology providers having a better understanding of industrial integration contexts. To this end, PIARCHs will propose an abstraction of these contexts, such as required interfaces, security features, mechanical constraints, etc.

The second objective is to enable a reusability of the integration work, by separating the integration work specific to a building block, to the integration work specific to the final system or application. This intermediary integration work, which we call pre-integration, will be associated with tools for the integration, configuration, and validation of the PIARCH.

The Connectivity PIARCH led by Thales Research & Technology focuses on the integration of connectivity and security modules. It will address the needs of WP7 but is meant to be usable for other projects as well. It will be composed of:

- A central board with Wi-Fi and Bluetooth connectivity and a general-purpose OS
- A high-performance LTE module (Cat. 4) from WP2,
- A low-power LTE module (Cat. M1, Cat. NB1) from WP2, that would ideally make use of low-power processors such as ARM Cortex-M4,
- During the second step of the project, a 5G/URLLC module could be added,
- A secure OS (Trusted Execution Environment) for cyber-critical services, such as a gateway between an embedded Ethernet network and a non-trusted wireless environment,
- Tools for utilizing the PIARCH, e.g. a tool for configuring network parameters from a high-level model.

The integration work performed for each module can be used separately, or the PIARCH can be used as a pre-integrated subsystem.

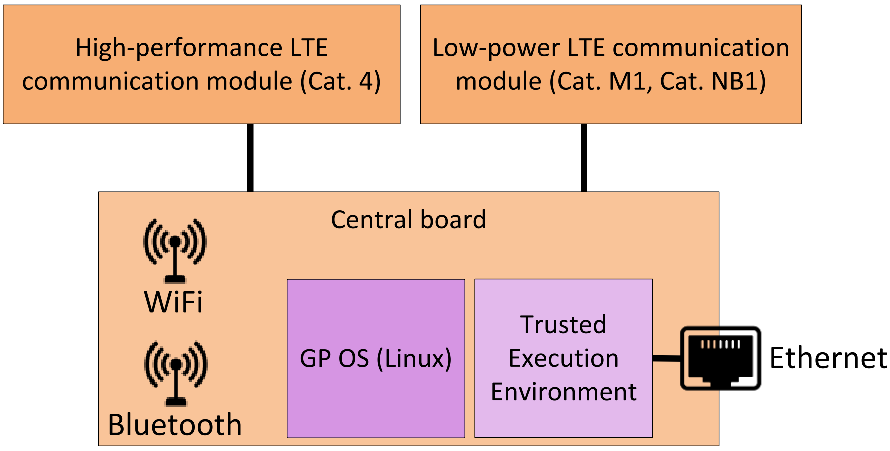

Figure 2. A representation of the connectivity PIARCH

2.1.3 Requirements for WP2

As was described above, there is a need in WP6 for two different communication modules, one for high-performance applications, and the other for low-power applications. Each has different interface requirements. In Figure 2, we represented them as two physically separated modules, but they could be aggregated into one communication module (one board), as long as they can be accessed separately. If no dedicated board is provided by WP2, we at least need an evaluation board for the pre-integration.

In the following subsections, we give the current requirements for the connectivity PIARCH of WP6.

2.1.4 High-performance module

	Required	Preferable	Nice to have in addition
Supported technologies	Cat. 4		
Interfaces	At least UART interface	Ethernet interface	USB and UART interfaces in addition to Ethernet
Drivers	Linux drivers		

2.1.5 Low-power module

	Required	Preferable	Nice to have in addition
Supported technologies	Cat. M1, Cat. NB1		
Interfaces	At least UART interface	SPI interface	UART and USB interfaces in addition to SPI
Drivers	Linux drivers		Cortex-M4 drivers with C API

2.2 REQUIREMENTS FROM INDUSTRIAL MANUFACTURING

The requirements of this section come from CPS4EU WP8.

2.2.1 Use Cases communication needs

Leonardo is a partner of major civil aircraft programs in Europe and in North America, manufactures for world players such as Boeing, Airbus, Bombardier, ATR, Lockheed Martin. As a Boeing strategic partner, Leonardo's Aerostructure Division develops and manufactures about 14% of the 787's airframe.

Three Use Cases will be developed in Leonardo's plant in Grottaglie where we manufacture the largest composite "one piece barrel" fuselage, a large and complex carbon fibre structure built with unique and innovative technologies.

Leonardo will use its own ICT platform to support the development of use cases (ie. for storing data collected from sensors/machines, dashboards, user interfaces, etc.). Through the CPS4EU project, such platform will be enriched and complemented by modules, tools and architectures coming from the CPS4EU project.

In those Industrial automation use cases we have communication scenarios:

- **Device-to device** (e.g. UC3: vacuum and drill need to exchange information on their position)
- **Device to Data Center** (e.g UC5: monitoring of process parameters i.e Pressure, durations, temperatures, humidity, geometry of the product; data collection from field for later analysis; analysis of big amount of data and the statistical correlations between variables need to be performed in real time are to be monitored in order to take control decisions and correctly stamp form the part; UC4: feeding of sensor data into the prediction model (for the entire trimming duration)
- **Data Center to device** (e.g UC4: real time application of the quality prediction model and the setting of tool parameters, with the aim to reach the best final quality trimming;)

2.2.2 Communication requirements

To this extent, we envisage the need of a communication gateway to address the following needs:

- Monitoring
- Data collection
- Supervision and control.

The communication gateway should satisfy the following requirements:

- Security: support for mutual authentication (also for the communication device-to-device), data integrity and confidentiality, intrusion protection from cyber attacks, anti-tampering.
- Throughput/bandwidth: ability to support high rate transmission of large amount of data at for monitoring purposes (including images).
- Low latency: support for real-time control of production machines.
- Interoperability: ability to work with different infrastructure and devices supporting various protocols and interfaces providing an abstraction from the adopted device/infrastructure.
- Remote Management: possibility to configure the devices and gateways and to manage remote updates of firmware and business logic.
- Reliability: ensure delivery and quality of data transmission against interferences (e.g. noise, disturbances and/or frequency constraints on plant).

2.3 OTHER REQUIREMENTS FROM VERTICAL

Eurotech is a cyber-physical systems manufacturer and an industrial IoT solution provider. Eurotech is involved in the industrial use cases lead by Leonardo and, in these use cases, it will be responsible for the IoT-based infrastructure devoted to edge computing, data collection, systems and enterprise software (e.g. cloud platform) integration. In addition, Eurotech is exposed to other industrial use cases whose requirements are summarized hereafter.

The IoT based integration solution that should be adopted in the industrial use case requires a communication gateway capable to monitor the infrastructure, ensure continuous, secure and reliable data collection and to provide remote management functionalities. The communication gateway should satisfy the following hardware and software high level requirements:

- Rich set of hardware interfaces to provide connectivity between local devices & sensors and the communication gateway.
- Several OT Communication Technology options, to ensure the interoperations of the two parts of the software framework, the one on the edge and the one on the enterprise side.
- M2M/IoT communication protocols support, to ensure unattended, geographically dispersed and mobile devices connectivity, with a message oriented, publish & subscribe, hierarchically structured and standardized model.
- Communication security, providing support for mutual authentication (also for the communication device-to-device), data integrity and confidentiality. Hardware support for security (e.g. TPM) might improve the adopted solution.
- For data collection and command/control activities the communication gateway should support high transmission rate with low latency and near real-time capabilities.
- Provide a solution for command and control activities with a specific protocol capable to support the gateway remote management for its entire lifecycle.
- Ensure reliable communications in an industrial environment.

It has to be noted that part of the requirements expressed here are similar to the one seen in section 2.1 (requirements coming from the automotive sector)

2.4 SYNTHESIS OF REQUIREMENTS

One characteristic of the CPS4EU project is to combine many use cases from various vertical industries. Each vertical has its own set of requirements that may lead to completely different solutions. The previous sections illustrate somehow this variety. In this section we try to summarize – and synthetize – these requirements to define theoretically a unified communication solution that could suit all needs.

The Table 1 summarizes the requirements expressed previously.

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Table 1. Summary of high level requirements

Requirement	**Exemple**	**Comments**
Long-range communication capability – low data rate	Cat-M or Nb-IoT	Low power is a key requirement here
Long range communication capability – high data rate	LTE Cat-4 or LTE Cat-6	Depending of the application, higher data rates (up to few Gbits) may be required. However, 150 to 300Mbits DL seems to be a nice sweet spot. UL to be addressed too, for new set of applications.
Short range communication capability	Wi-Fi, Bluetooth, Zigbee and alike	Could be interesting to have mesh capability too
Wired communication	Ethernet	To connect "old" non wireless objects; for transition purpose as well as future application (e.g. automotive embedded network).
Security	Capability to define a secure / non secure zones in the device	Private 4G or 5G deployment is also a mean to ensure end-to-end security to the vertical
Device Management capability	Example: LWM2M, OMA based Should enable secure over-the-air upgrade	
Unified Software environment	Ideally, applications should be able to interface with modems in a unified manner	The standard for M2M is to use AT command based interface. It would be better to get more modern interface such as C-API
Low latency, high reliability	The level of requirements directly depends on the use case.	4G may be limited here. 5G, with URLLC and TSN can fit the requirements. Requirement on latency is not only to get low latency, it is also to have deterministic latency
On-board processing capability	Ability to process data locally for faster analysis and limit communication burden	It is not directly a requirement for communication module, rather for the complete device

The first conclusion is that a single solution to fit all needs is not realistic, at least from modem perspective! However, it seems possible to define a kind of pre-integrated platform, integrating multiple communication systems, but leveraging possibly unified interface to ease its final use. This is indeed the target of WP6 and of the already mentioned PIARCH.

Moreover, it seems feasible to meet most of the requirements expressed in this initial phase of CPS4EU project with 4G technology, except possibly the low latency / high reliability ones that have to wait for 5G.

As a result, the next section proposes some building blocks for the communication module that could be considered into the WP6 PIARCH.

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3 COMMUNICATION MODULES – LEGACY PART

3.1 4G BASED SOLUTIONS

3GPP is the body of standardization of cellular technology since 3G. Although 3GPP did not change its name, it has standardized 4G (also known as LTE) and is now addressing 5G (the radio part is known as “NR” New Radio).

LTE was introduced with Rel. 8 of 3GPP, around year 2009. Rel. 13 was completed early 2013. In this release, LTE cat-M (also known as LTE-M) and NB-IoT were introduced as technologies for LPWA systems (Low Power Wide Area) as the answer of cellular systems camp to (semi) proprietary solutions such as LoRA or Sigfox.

Hence, LTE offer a complete set of solutions, from very low end to high-end, to connect devices of various capabilities and demands, with a unified network. 5G is completing this trend – single wireless system to cover all needs – bringing into the picture even higher data rates, lower latencies, higher reliability and techniques to support this flexibility, such as network slicing.

The Table 2 represents the typical data rate that could be obtained with various LTE categories of devices and exemplifies some objects from day-to-day life that could be connected with a given categories. Definitely, in industrial context, similar split can be imagined.

Table 2. Illustration of IoT that could be served with LTE based technologies

Throughput	Category	Applications
1Gbps	LTE Cat-4 (and higher)	Routers network bridges, High-res video, A/R devices
100 Mbps		Video surveillance, In-car hotspot, Infotainment, Digital signage
10 Mbps	LTE Cat-1	Telematics, Predictive maintenance
1 Mbps		Smart watches, Point of sales terminals,
100 kbps	LTE Cat-M	Patient monitor, Alarm panels, Wearables
10 kbps		Fitness devices, Trackers, Gas/water meters
1 kbps	NB-IoT	Waste management, Smoke detector
Few messages		Parking control, Smart agriculture

The next sections illustrate some of LTE modules designed by Sequans that could meet part of the requirements expressed in section 2.

3.1.1 Examples of Sequans solutions

The GM01Q EZLinkLTE module is the first, all-in-one, single-mode LTE category M1 (Cat M1) module with worldwide deployment and roaming capability. GM01Q is based on Sequans’ Monarch LTE Cat M1/NB1 platform, a member of Sequans’ StreamliteLTE™ family of LTE chip products for the Internet of Things. GM01Q comprises Sequans’ Monarch LTE Platform and all other elements necessary for a complete LTE modem system. These include an LTE-optimized transceiver, a complete Single SKU™ RF front-end to support LTE bands worldwide, and key interfaces, all in a single compact LGA package. GM01Q also includes Sequans’ carrier-proven LTE protocol stack and a comprehensive software package for over-the-air device management and packet routing. GM01Q is compatible with any host running Linux, Windows and a wide range of embedded and real-time operating systems. It is an ultra-compact, high performance solution, delivering a perfect blend of LTE features and ultra-low power consumption ideal for the design of cellular devices including sensors, meters, buttons, and trackers of all kinds.

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Obviously, Sequans is not the only LTE module vendor. Similar modules can be purchased from Gemalto (Thales), Sierra Wireless, Telit, Quectel, Simcom etc. Sequans offer is optimized for 4G systems and provides most often lower cost, lower power consumption and lower size than its competitor. Moreover, it can allow more customization to fit very specific needs of end customers, thanks e.g. to an advanced debug and monitoring tool providing deep information on the modem and the system.

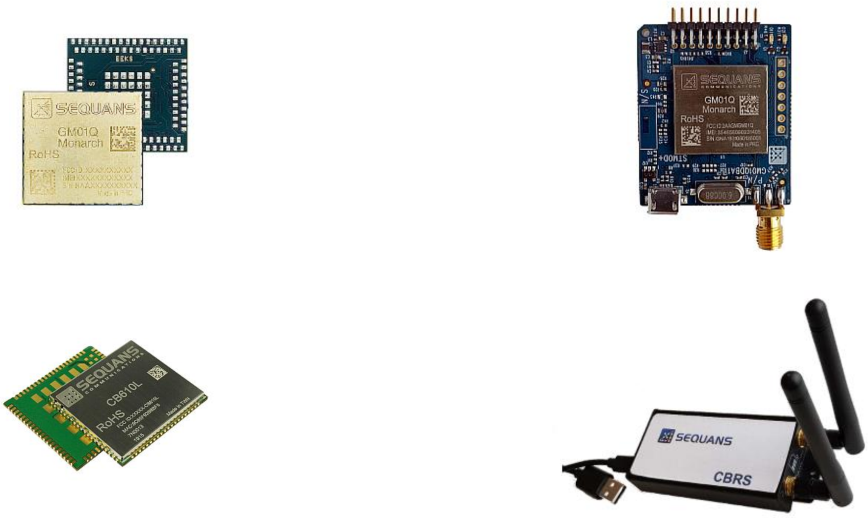

Figure 3. Examples of Sequans modules and EVK

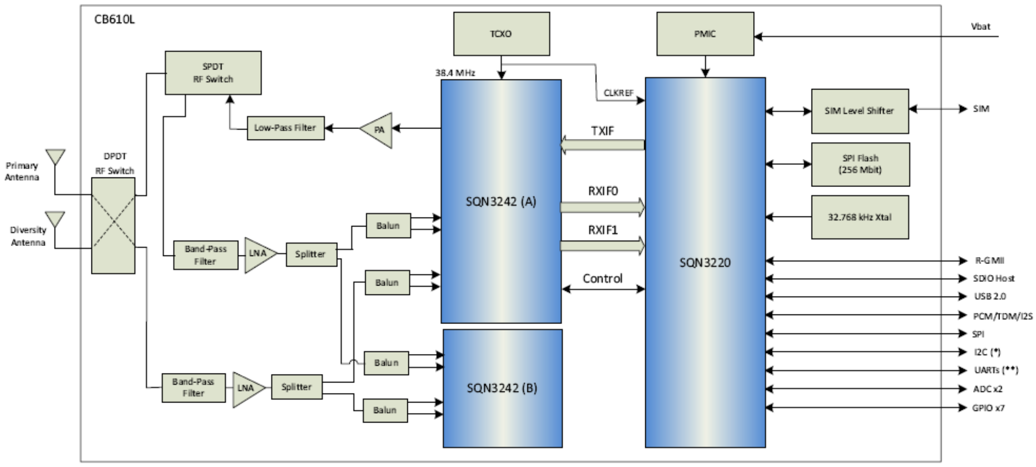

Figure 4. Examples of architecture of a LTE cat-6 Sequans module

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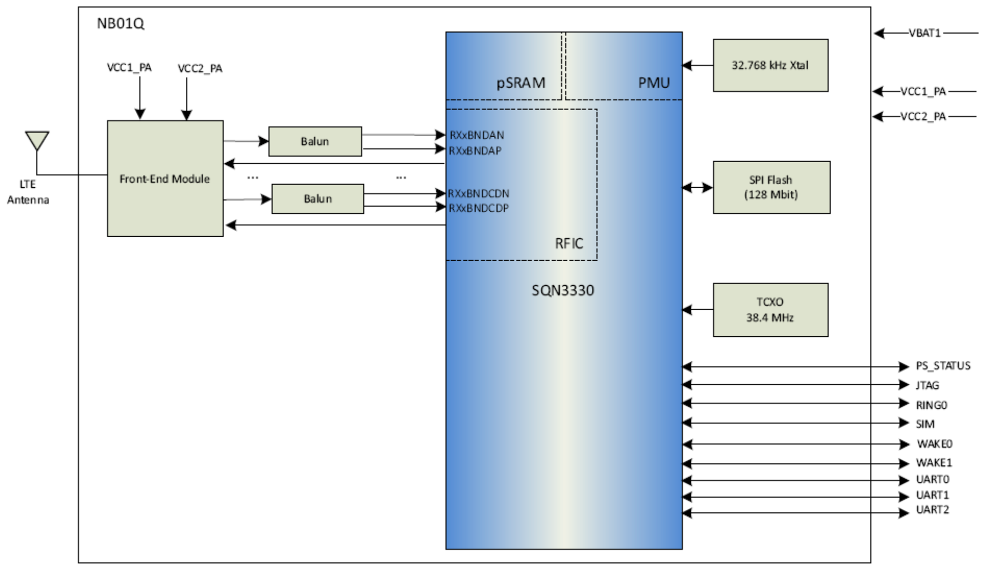

Figure 5. Examples of architecture of a NB-IoT Sequans module

Though these modules address different market, they present similar software interface: an user application can be quickly adapted from one module to the other, though in practice it is unlikely that the same application is defined for either low-end or high-end communications modules.

The next section introduces an IoT gateway from Eurotech, being developed in context of CPS4EU, based on a new hardware platform leveraging legacy communication components.

3.2 AN IOT GATEWAY FOR INDUSTRIAL CONNECTIVITY

Eurotech is developing a solution to support IoT communications in industrial context.

The IoT-based infrastructure is composed of a hardware platform conceived for edge computing and a software framework for hardware abstraction, data collection, edge processing, devices remote control, fleet management and systems integration. The gateway will provide not only communication support (WP2) but also all these latter functions in relation with WP1, WP6, and WP8. It also provides a complete and developers-friendly environment for the implementation of the business logic, that is, the use case specific application that partially runs on the edge and partially on the enterprise side.

Both components of the infrastructure, that conceptually compose a communication gateway, are application independent and could become Pre-Integrated Architectures.

The hardware platform provides all the functionalities of an edge controller/multiservice gateway in a small and rugged format factor, specifically conceived for industrial application. The platform will provide the computing power and the hardware resources required to host the IoT software framework and the business logic of the industrial use cases (e.g. intel Atom or AMD processor starting from 1GHz, 8 GB eMMC and several storage media). It will also provide a rich set of communication interfaces, in order to guarantee a high level of connectivity, both on the field for the integration with the manufacturing plant and with the enterprise IT infrastructure (e.g. cloud platforms, data centers, etc.). Typically, the communication interfaces include multiple Ethernet, USB, RS-232/RS-422/RS-485, digital I/O ports, a CAN bus port, a mini display port, an LTE internal cellular and several internal interfaces for further expansions.

The software framework will be based on Eclipse Kura and Kapua, the open source community version of Eurotech ESF and EC. From the connectivity perspective, the framework is responsible for:

- Communication channel abstraction: developing and maintaining the business logic on the field is a challenging task, specifically when the integration with legacy systems is required. The complexity of the communication protocols represents an obstacle both for the development of the business logic and for its maintenance. The framework offers an abstraction layer that hides the technological details of the communication protocols, with a unified and service-oriented interface that simplifies and speeds-up the development process. The interface provides specific services for field communication,

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for the interaction with sensors/actuators and more complex devices, but also for the interaction with cloud platforms or enterprise software.

- Field communications (e.g. Zigbee / 802.14, Serial, Bluetooth, Ethernet, Wi-Fi, RFID, but also Field Bus technology like ModBus, CAN, etc.):
    - o with low level support for wireless and wired interaction with sensors/actuator;
    - o with low level support for machine to machine communications (e.g. industrial use case UC3: vacuum and drill need to exchange information on their position).
- LAN and WAN communications and Internet connectivity (OSI Model Layer 1 & 2), including Cellular Networks, Satellite, Ethernet, Wi-Fi, xDSL, etc., and M2M/IoT Communication (OSI Model Layer 5) through MQTT layered on top of TCP/IP (e.g. data collection in industrial use cases).
- Command and control communications required to manage the fleet of edge controller/multiservice gateways deployed in the manufacturing plants (e.g. industrial use case UC3 and UC4).

3.3 SYNTHESIS OF EXISTING COMMUNICATION SOLUTIONS

From the quick review of existing communication modules or more advanced solutions from Eurotech, it appears that most of the requirement expressed in section 2 can be fulfilled with existing solutions. However, some of the requirements, especially on latency cannot be met with 4G technologies and it is important to work on future building blocks to enable communication modules able to support the more demanding use cases from industry.

In practice, WP2 will deliver for short term (~1 year time frame):

- Communication modules to be integrated into the PIARCH (WP2)
- Field protocols to interface the industrial gateway with the manufacturing infrastructure (WP8)
- Wide area network support for the integration of the industrial gateway with the existing IT infrastructure (enterprise level as defined in WP8)

The next section discusses two main axis of work, that will be tackled in WP2 with longer term deliveries.

4 COMMUNICATION MODULE – AXIS OF IMPROVEMENT

In the previous sections we have seen on one hand the early requirements expressed by the verticals through the various use cases investigated in the CPS4EU project and on the other hand the capability offered by nowadays communication modules. On the requirements side, several aspects that are not fully supported by legacy IoT systems, can be highlighted. For instance:

- The need to combine intimately communication and AI based data processing functionalities supported within the same hardware system.
- The need for low latency and ultra-reliable communications;
- The need for time deterministic communication;

WP2 is aiming to propose innovative solutions to fil these gaps. The next sections propose axis of improvement on these topics that will be investigated within the project.

4.1 TOWARDS A UNIFIED FRAMEWORK COMBINING COMMUNICATION AND ARTIFICIAL INTELLIGENCE

4.1.1 Main goal, scope of the project

The main goal is to develop a 5G system (reception) supporting the URLLC feature defined in the standard or to investigate new protocol and approach (prospective study; see paragraph 4.2: 5G enhancements for CPS communication modules at the physical layer) The system will deal with the part between the output of the ADC (reception of the digitalized signal from the antenna) and the entry of the channel decoding module. We call this part here "baseband" (also mentioned as *BB*).

Actually, a complete chipset as presented in Figure 4 or Figure 5 is a collection of many IPs. Among these IPs, for a communication system we generally find:

- A RF module, including various low noise amplifiers (LNA), splitters, filters, switches, etc …
- Oscillators for clock generation
- Some interfaces modules (usb, uart, AXI, DMA …)
- Functional modules IPs

VSORA's DSP is one of these IPs and must be associated to a channel decoding module (code correction) to be fully functional (for instance to be plugged to a video decoder) as summarized in Figure 6.

Figure 6. Representative high-level architecture

VSORA's DSP is dedicated to the signal synchronisation and channel equalization. These operations require a lot of computations with an exponential increase for the 5G standard compared to older standards due new features (for instance beamforming) and new technics to increase the quality of reception (mimo 4x4, 8x8 and higher).

Traditional IPs doing this functionality are based on DSPs with many hardwired co-processors. VSORA's strength is to be a solution relying on 100% software development: there is no need of additional co-processors. This approach is new in this field and opens up a broad range of capacities linked to the software flexibility: we can now imagine having a single DSP for 3G, 4G and 5G, wifi transmission, performing smooth handover from one standard to the other; controlling the quality of reception; adjusting the processing for power saving. Finally it will easier to follow the evolution of the standard, requiring just an update of the embedded code.

Thanks to the high frequency of processing, it will be also possible to control the latency and to meet the requirements for the URRLC feature.

During the project, VSORA framework can be used by CEA LETI to develop and prototype advanced algorithms with the help of VSORA. These algorithms must be written using the VSORA's dev-platform and library (delivery of a free license).

Overall, the advantage of the proposed architecture is to provide enhanced flexibility with respect to the standard solution and functionalities. This flexibility targets to meet the heterogeneous requirements of CPSs, which can be contradictory for different services. To achieve the required flexibility, this architecture adapts its parameters to trade-off latency, reliability, spectral efficiency, and complexity depending on the specific service.

4.1.2 Software Architecture

The methodology proposed by VSORA includes several steps. Each step is associated with a different development platform:

- The "native" platform
- The "high level" platform
- The "RTL" platform
- The "cloud" platform

All phases of development share the same code and we can go through one model to the following by refining it. In the CPS project, we will focus on the "native", "high level" and "cloud" platforms: the RTL model is dedicated to the physical implementation which is out of the scope of the project.

The first step is a research approach ("native" model): VSORA's library (called *vslib*) is a C++ library defining containers as the standard library does and which are basically matrices with a set of operators and functions. This library is very similar to the matlab tool which allows to try various designs/strategies. In addition, the *vslib* defines also base objects like *module, port, channel* which follow the same concepts as those used in systemC or in other system languages. In this phase, there is no constraints about the hardware architecture.

The second step is to compile this system for the VSORA's DSP target using VSORA's compiler ("high level" model). During this step, we can evaluate the load of the DSP (in term of memory footprint and number of cycles to execute the code) for a given architecture and choose the one which is required to meet the real time constraint. We can easily and quickly re-run this sequence (step1/step2) during the whole project. This way of development is a breakthrough compared to the state of the art, since it reduces dramatically the time to market and allows to the signal processing engineer's team to measure directly the consequences of their choice without waiting for a complete integration of their work on the final target.

The choice of the final software architecture will be made through this iterative process.

4.1.3 Host processor, OS

In a commercial project, the host processor is chosen by the customer who purchases it from an IP provider. (for instance an ARM processor, RISC V, etc …). This aspect causes additional work (and costs) which are pure constraint of code porting without true interest for the project. Thus, we decide to model the host processor with user's PC (x86) and the operating system will be linux with Ubuntu as preferred distribution. The simulation in the *high level* platform provides also estimation of the load for a real host processor.

4.1.4 Introduction of the Artificial Intelligence (AI)

CEA-LETI has expressed his interest to introduce artificial intelligence in the baseband's algorithm (prospective study). Although this possibility was not mentioned in the early stage of the project, it is be possible to use another line of product proposed by VSORA targeting AI.

4.1.4.1 AI in digital communication devices

Nowadays AI is a hot topic overwhelming many areas: it is well known for speech recognition, computer vision, natural language, etc. Its popularity relies on significant performance improvement but requires a lot computation. Most of AI applications we use daily are performed on data-centers without tight time constraint but more and more, it is used in end-user devices (for instance most of smartphone now embed AI engines for face/image recognition, or simply to enhance picture quality). In addition, AI is nowadays considered to support communication receiver algorithms. For instance the following articles exactly address the topic:

- *Power of Deep Learning for Channel Estimation and Signal Detection in OFDM Systems,* Hao Ye, Geoffrey Ye Li, Fellow IEEE, and Biing-Hwang Fred Juang, fellow IEEE, 28 august 2017
- *Deep Learning-Based Channel Estimation for High-Dimensional Signals,* Eren Balevi and Jeffrey G. Andrews, 19 april 2019
- *Artificial Intelligence-Aided Receiver for a CP-Free OFDM System: Design, Simulation, and Experimental Test*, Jing Zhang ; Chao-Kai Wen ; Shi Jin ; Geoffrey Ye Li, 06 May 2019

This use of AI to support communication receiver is particularly relevant for non linear part of the receiver chain, to replace complex algorithms (when facing NP problems). It is for instance used in channel prediction for measurement reporting, and could be considered for MIMO or channel decoder, especially in context of 5G.

Another use of AI in end-user device is to support local processing of data, somehow referred to Mobile Edge Computing. Such local processing allows very fast decision loop or help to reduce the communication load.

VSORA's approach is to embed the AI on the device to support the two above mentioned application: to replace complex receiver algorithms and to support local data processing. Having both functionalities (AI processing and communication) gathered within a single framework, combined with the flexibility of the full software processing will multiply the opportunities to have very efficient systems.

4.1.4.2 VSORA approach for AI

The Artificial Intelligence is a blooming topic and all major actors are defining their own framework. Among most popular frameworks we find tensorflow, caffe, pytorch …. VSORA's approach is to be fully agnostic of these frameworks and to accept all of them. For this purpose VSORA has developed a graph compiler and according to the framework which will be used, some adaptations should be required (adding features in the graph compilation flow to support new networks).

VSORA's dsp are dedicated to the inference process. This means that the training phase of the network should be done separately and the result ("weights") are inputs of the system.

Up to now, VSORA has never mixed AI dsp and BB dsp. Both dsps have the same architecture: a host processor controls a VPU (vectorial processor unit). The goal of this part of the project is to achieve the integration of both architectures using the same host processor and to allow communication between the cores.

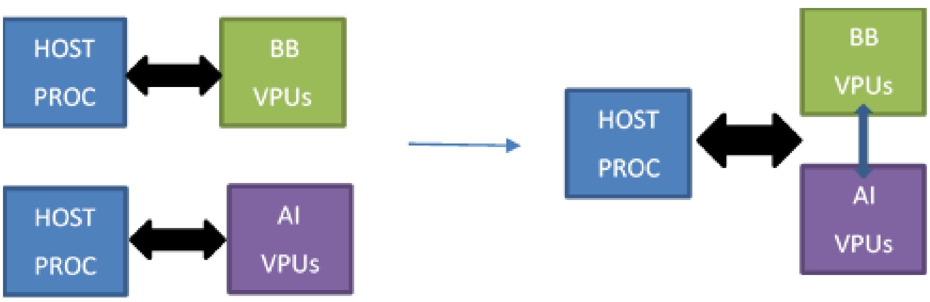

Figure 7. Integration of the AI and BB part using the same host processor

The code executing the AI processing and the code executing the baseband processing will be run on separated cores but controlled by the same host processor. VSORA's work consists in:

- Defining a methodology
- Developing a unified framework (compilation tool chain)

- Developing software modules (including communication modules between AI core and BB core)

This functionality is optional and will depend on the conclusion of the prospective study.

4.1.5 Prototyping

The prototyping on remote FPGA may be used to validate the algorithms (long simulations) and / or to run live scenarios but with potential limitations (the output bitrate can be limited).

The prototyping of the system will be done on remote FPGA (cloud). VSORA uses Amazon's platform for this purpose.

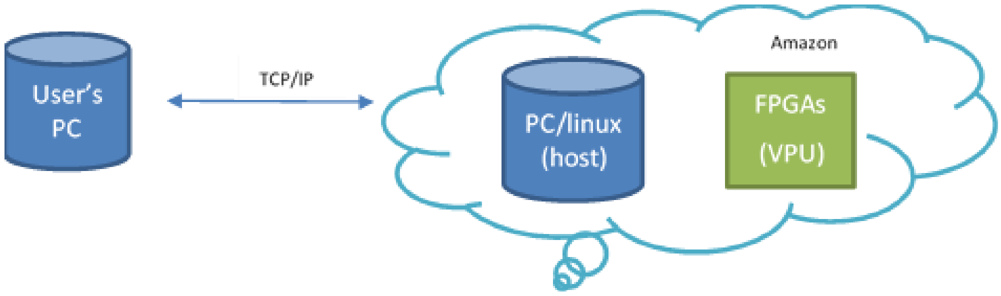

Figure 8. Remote FPGA infrastructure

Due to the capacity of the FPGA, the DSP architecture (number of ALUs, quantization) implemented may differ from the one derived from the conclusion of the study (number of ALU per core, communication between cores). The system is still functional but the real time aspect could be altered.

There are many possibilities to feed the system with input data (simulating the output ADC):

- Use equipment on user's side: in this case data are send through the TCP protocol which becomes a bottleneck
- Export the generator of data on PC next to the FPGA boards (compiled executable).
- Read pattern files stored on the PC next to the FPGA boards.

In the same way, the output stream can be processed on the remote PC or on the user's PC through messages sent via TCP/IP.

4.2 5G ENHANCEMENTS FOR CPS COMMUNICATION MODULES

In this Section, we will present the studies under investigation to extend 5G mobile communication capabilities in order to deal with the CPS requirements, i.e., limited latency, high-energy efficiency, and ultra-reliability. Specifically, in Section 4.2.1 we will introduce physical layer solutions and in Section 4.2.2 we will discuss MAC layer mechanisms. In the first group of studies, we will investigate precoding schemes for cooperative communication in the context of non-ideal backhaul, non-binary (NB) channel codes for massive and critical IoT, and channel codes for multi-link communications. In the second group of studies, we will study the trade-off between reliability and low latency and we design MAC solutions to deal with this trade-off. In this context, Artificial Intelligence algorithms may be efficiently applied to optimize these functionalities and conduct to reduced complexity compared to existing approaches based on classical heuristics or optimization framework.

In the next deliverable, we plan to provide a detailed description of the specific problems under investigation and define the potential solutions to solve them.

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 826276

4.2.1 5G PHY Enhancements for CPS communication modules

4.2.1.1 Link reliability enhancement and cooperative networks

State-of-the-art researches allow wireless Ultra Reliable Low Latency Communications (URLCC) networks to ensure Quality of Service currently only satisfied by specialized wired networks such as PROFINET [KJG2019]. Ensuring wireless but reliable communications proves to be appealing as it improves network flexibility, e.g. straightforward management of connected nodes, and it allows the support use cases implying mobility, e.g. guided vehicles.

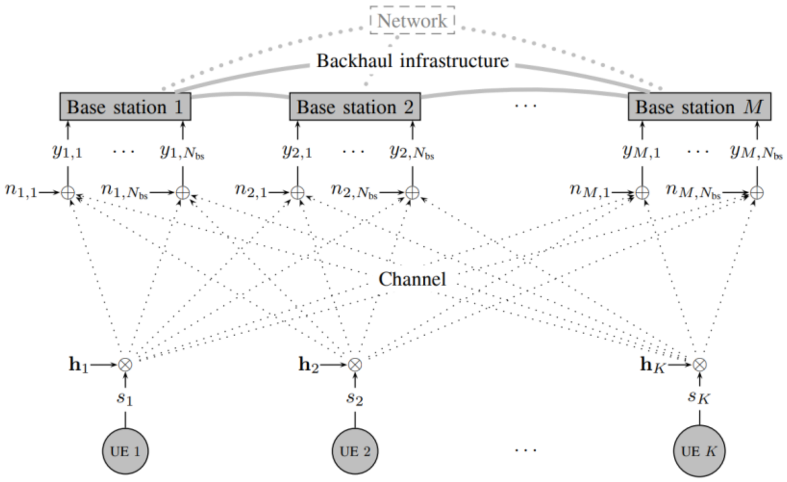

Figure 9 Example of an uplink transmission via a CoMP network with M base stations and K served users [MF2011].

A pragmatic approach is to deploy dedicated networks, integrated but independent to public ones. Such networks are fully adapted to industrial systems requirements and ensure straightforward maintenance and data privacy. However when mobile industrial systems are involved, shadowing and path loss are likely to occur which hinders the transmission/reception of connected nodes. Extending the service coverage can be achieved by considering multiple coordinated base stations. This technique is known as Coordinated MultiPoint (CoMP) [MF2011] and inherently provides spatial diversity to cope with the two aforementioned impairments (see Figure 9).

However, because of the limited capacity of the backhaul links and the mobility of nodes it is infeasible to obtain a centralized global channel state information (i.e. shared by all coordinated base stations). Therefore, determining ideal cooperatively joint-transmission (downlink) or joint-detection (uplink) strategies is challenging. In practice, the channel state informations (CSI) of other base stations are imperfectly known because of quantized and/or outdated feedbacks (in addition to inaccurate channel state estimation). A few results are available on scenarios with decentralized channel state information [AG2018]. In the framework of this study, we propose to investigate new precoding techniques to fulfil reliability requirements with constrained backhauls link (quantization, imperfect CSI, etc…). Coding schemes (e.g., space time block coding [BRL2019] and rate splitting coding [SSP2009] will be addressed as well to benefit from the diversity gain they offer.

4.2.1.2 Design of optimized modulation and coding schemes for IoT

The publication of 3GPP Release 15 in June 2018 paved the way for the new 5G air interface, making a new step towards the new generation of mobile networks. The work on the development of a new radio interface dedicated to Internet of Things (IoT) connectivity should then start in 2020. It is expected to replace or to complete the Narrow Band-IoT and LTE-M interfaces originally specified in Release 13 [3GPPTS38.212] in order to achieve the multi-service capability of 5G. Actually, IoT use cases can be divided into two categories (Figure 10): “massive” applications (smart buildings, transport logistics …) and “critical” applications (traffic safety, automated vehicles…). Massive applications are characterized by high density of connected devices, small data payloads, as well as stringent constraints on the device energy consumption and cost. Maximizing the spectral efficiency of an IoT network is a key pre-requisite for providing massive connectivity. Critical IoT applications are characterized by ultra-reliability and very low latency requirements.

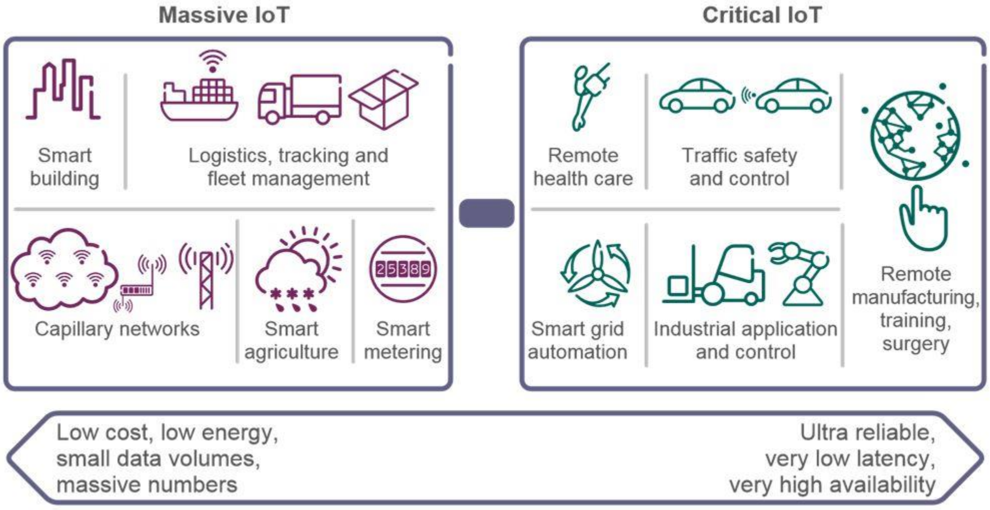

Figure 10: Requirements for massive and critical IoT applications

The first wave of IoT standards are far from achieving the reliability and spectral efficiency targets: they implement sub-optimal Forward Error Correction (FEC) schemes such as convolutional or Turbo codes combined with repetition codes (EC-GSM [GSM], Narrow Band-IoT and LTE-M [3GPP]), simple Hamming codes (LoRa [LORA]), or simply omit any FEC capability (SigFox [SIGFOX]).

Our contribution aims at optimizing both the reliability and spectral efficiency of IoT networks, by defining new coded modulation schemes to address IoT-specific requirements. To this end, our contribution will build upon the emergence of NB codes, combined with a Cyclic Code Shift Keying (CCSK) modulation. Powerful NB codes will be investigated, such as NB Low-Density Parity Check (LDPC), and NB-Polar codes.

NB codes are known to provide increased error correction performance at short block lengths, which makes them excellent candidates for addressing critical-IoT ultra-reliability and low latency requirements. While decoding algorithms for NB-LDPC codes have been intensively investigated by various authors [SAV2014], decoding algorithms for NB-Polar codes have practically not been investigated in the literature. We aim at investigating different solutions for decoding NB-Polar codes, including Successive-Cancellation (SC) decoding with min-sum or min-max approximations [SAV2008], or the generalization to the NB case of more powerful SC-List and D-SC-Flip decoding algorithms [CSD2018].

To address massive-IoT requirements, such as long-range connectivity and low levels of sensitivity, NB codes will be combined with CCSK modulation. This new coded modulation scheme, referred to as CCSK-NB-code, can be easily implemented in a cost efficient way at the device side. CCSK-NB-code provides several advantages compared to state of the art waveforms: it offers self-synchronization and self-identification capabilities, and is able to operate at ultra-low Signal-to-Noise Ratios (SNR). Our objective is twofold: (1) the design and the optimization of low coding rate CCSK-NB-codes, and (2) the definition of efficient detection and synchronization algorithms, by considering the whole frame itself as a preamble thanks to the particular structure of CCSK-NB-code frame.

4.2.1.3 URLLC based on coded multi-connectivity

The interaction of Cyber Physical Systems (CPSs) with the surrounding world and with other connected and intelligent systems will strongly rely on the powerful and revolutionary features of the fifth generation (5G) of mobile communications. 5G will benefit from (massive) MIMO communications, from a dense deployment of small cell base stations, and from larger bandwidths [ABC14]. These three technological developments are possible also thanks to millimetre wave (mmWave) communications for radio access in mobile environments [RSM13], [SHB17], because mmWaves have short wavelengths and allow many antenna elements to be packed together into well-performing and highly directional MIMO systems. Going beyond the enhancement of the physical layer, 5G networks are foreseen to enable several new services for different sectors (verticals), such as Internet of Things (IoT), industry 4.0, autonomous vehicles, remote surgery, etc., in which CPSs will be integrated

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and play crucial roles. Many of these services will be characterized by strict requirements in terms of latency and reliability, for which a flexible design of the network and new communication techniques are needed. In particular, Ultra-Reliable and Low-Latency Communications (URLLC) have to be guaranteed for mission-critical applications that are especially delay-sensitive. The performance goals of URLLC are sub-millisecond over-the-air latencies, packet error rates of less than 10^{-5}, and low to medium data rates achievable also in scenarios with high-speed users' mobility. Such challenging performance can be attained via the combination of several different techniques and enablers, including new communication protocols for uplink access, flexible scheduling of physical resources, novel error-correcting codes for short blocks, and reliability through spatial, temporal, or frequential diversity. In such a context, our work will focus on solutions for joint multi-connectivity (spatial diversity) and mmWave communications as enablers of URLLC.

The major drawback of mmWave communications is their vulnerability to blocking events due to obstacles or beam collisions [AC13], [SMM11], [JKP19]. When a blocking event occurs, the attenuation is so high that the communication is interrupted. The passage of obstacles between the transmitter and the receiver causes a certain "intermittency" of the channel that may lead to losses of information. Then, the latter has to be either retransmitted or recovered via suitably designed error-correcting coding schemes. In URLLC scenarios, there may be no time to retransmit the information bits, since blocking events can last longer than the maximum allowed offloading latency; moreover, retransmissions can lead to a high additional power consumption, which is not suitable to some applications. Then, different countermeasures can be taken to deal with blocking events. [BCM17] and [BCMC17] propose anti-blockage solutions in the context of computation offloading and edge cloud networks. These solutions exploit multi-link communications and overprovisioning of radio and computation resources, taking into account a priori knowledge (estimation) of the blocking probabilities. In these works, a resource allocation problem is formulated as the minimization of the power consumption to guarantee an average bit rate above a certain threshold, in spite of blocking events. In [OAN+15], the authors perform a proactive access point (AP) selection based on prediction of human blocking events. In [GMRZ16], uplink channel measurements are used for the selection of the best AP and to select a new AP in case a blocking event occurs. In [OSF14], the authors investigate the problem of achieving high availability in wireless networks exploiting an optimal number of Rayleigh fading links. In addition, the temporary failure of intermittent mmWave channels can be overcome via multi-connectivity [RRM16], [WSD19], which refers to several different techniques to leverage diversity. The idea is that, through diversity, messages can be delivered from the users to the network and vice versa even when not all wireless connections allow effective communication due to temporary blockages. Through Coordinated Multi-Point (CoMP), for instance, a number of network APs collaborate and coordinate with each other to both reduce inter-cell interference, to optimize their beamforming, and to deliver messages to users avoiding beam collisions and losses due to blocking [3GPPTR36.819]. Carrier aggregation [3GPPTR36.823] and dual connectivity [GMRZ16], [PGM+17], instead, are other forms of multi-connectivity based on inter-frequency communications.

We will investigate scenarios in which CPSs communicate with the network via mmWave communications. We will focus on uplink communications between CPSs and the network's APs, especially in delay-constrained or rate-constrained scenarios. As illustrated in Figure 11, the CPSs are supposed to be able to exploit multi-beamforming techniques to send information to several APs at the same time. The information sent over different links is then collected by one the APs, which transfers it via backhaul communications to a processing unit or to further nodes in the network, depending on use cases. The concurrent exploitation of different communication links has two advantages: i) it allows reducing the uplink transmission power [dMCB19], [BCMC17] at the user's side; ii) it enhances the communication reliability through diversity, since the information transmission remains active even when some of the single links between the CPS and one AP are temporary unavailable due to blocking events. Our goal is to investigate the problems of beamforming, link selection, power optimization, and blockage counteracting in such scenarios. Moreover, we will propose novel solutions to the problem of long-term blocking events that interrupt the communication over one (or more) links and cause the partial loss of the transmitted data. Sensors on CPSs linked to digital maps can help to determine if blockages due to static obstacles occur. Therefore, their effect can be alleviated, e.g., by optimizing accordingly the resource allocation. However, managing dynamic blockages, due to moving obstacles, is an open challenge.

We propose to make the communications ultra-reliable by exploiting spatial error-correcting coding: the information sent over different mmWave links can be jointly encoded and protected against partial losses via ad-hoc erasure correction schemes. New coding techniques have to be developed in this scenario, due to its "asymmetricity" (the erasure probability on each block is different) and due to the overall requirements of the problem (low latency, power optimization, etc.). Our goal is to find analytical performance bounds and trade-

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offs and to design codes for multi-link communications that both guarantee a good outage probability and reduced power consumptions at the transmitter's side.

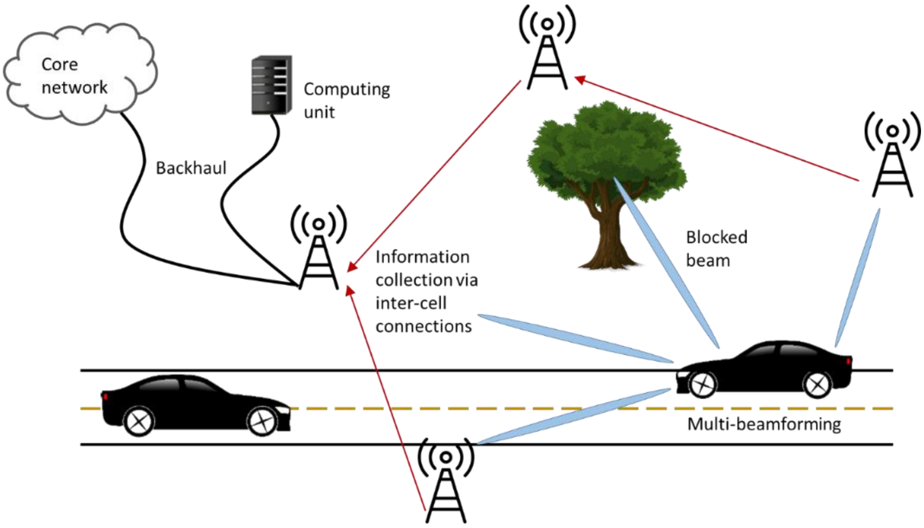

Figure 11: Multi-connectivity uplink communications exploiting spatial diversity.

4.2.2 5G MAC Enhancements for CPS communication modules

4.2.2.1 Stochastic Geometry Framework for Ultra-Reliable Cooperative Communications with Random Blockages

Traditionally, control/command applications in industrial environment such as automated manufacturing, packaging, and on-field process monitoring are realized through wired communications, e.g., using Ethernet based solutions [CVV2008]. These solutions can be expensive to deploy and cumbersome to maintain. Additionally, several of these applications require a highly flexible and dynamic communication infrastructure so as to support mobility. As a result, there is an increased interest to replace wired communication systems with wireless alternatives to reduce bulk as well as installation and maintenance costs [GH2009].

On the downside, the presence of physical blockages or unfavorable channel conditions in factory environment, can severely degrade the transmissions signal strength when using wireless communication technology. This may be detrimental, especially for Ultra-Reliable Low Latency Communication (URLLC) applications. To address this issue, multi-hop transmission with cooperative relaying is proposed in [SSR2015], where the devices with good channel conditions cooperate to provide a reliable communication link to devices in poor channel conditions. Here we extend this work by assessing this cooperative communication protocol in realistic industrial propagation environment, considering the effect of random blockages to the system performance (see Figure 12).

Specifically, we assess multi-device cooperation for reliable industrial wireless control while taking into account the effect of channel blockages. We model the location of the devices and the blockages as random processes, and use tools from stochastic geometry [GDC2018] to analytically characterize the probability of a typical node to be under coverage with and without cooperation.

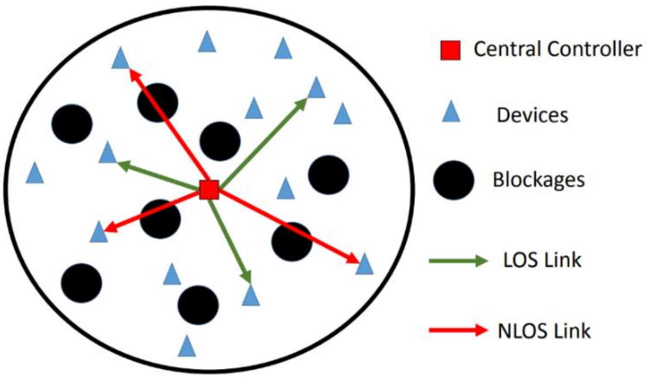

Figure 12. System model under investigation.

4.2.2.2 *Enhancements of Deterministic Ultra-Reliable Low Latency Communication (URLLC) Protocols by opportunism*

The fifth-generation cellular mobile networks are expected to support ultra-reliable low latency communication (URLLC) services. The requirements of URLLC applications are:

- End-to-end latency down to 1ms
- Determinism (i.e. whether the latency is stable) down to 1µs
- Reliability (i.e. success probability of transmitting a certain number of bytes within a certain delay) between 99.999% and 1-10^-9
- Availability (i.e. percentage of time end-to-end communication service are delivered according to an agreed QoS) up to 99.99%
- Connection density (i.e. the number of devices fulfilling a target QoS per area) of 10^6/km² for massive deployment or 100/m² in certain area
- Lifetime up to 15 years

These goals are ambitious, but they are related to the 5G requirements for URLLC use cases and 3GPP is currently defining the functionalities that will enable 5G technology to meet them. Consider also that specific industrial applications can be characterized by (much) looser constraints and, in general, realistic use cases will not require those stringent constraints to be satisfied altogether.

As detailed in the survey [GJS2019] some mechanisms are proposed to exploit diversity in terms of time, frequency, space, antenna, interface to improve the latency/reliability limits. These mechanisms can address the PHY layer, the MAC layer or can be cross layer (Figure 13).

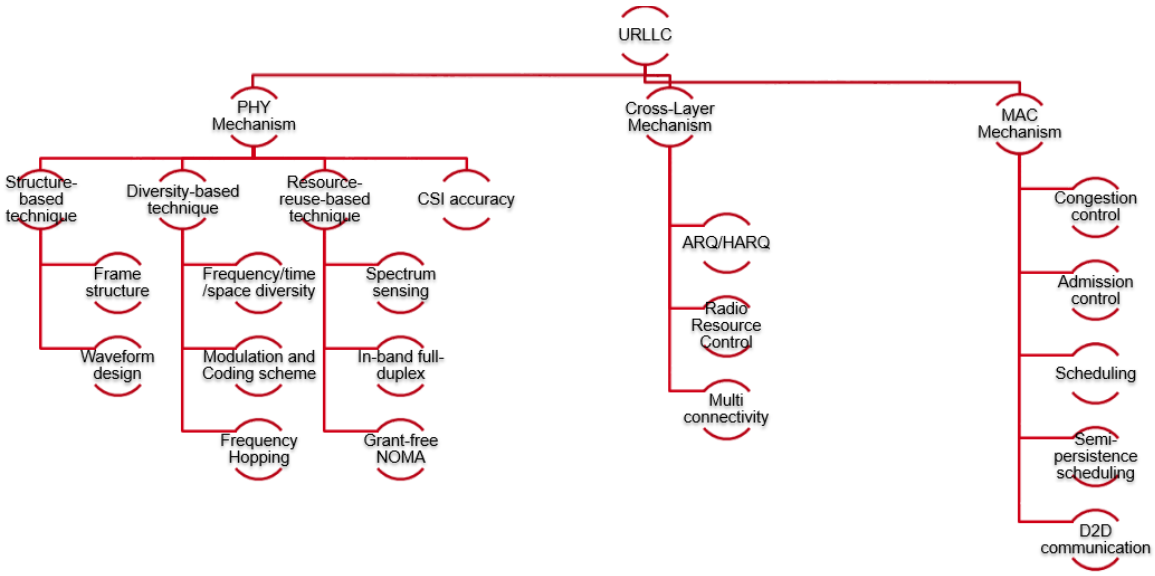

Figure 13: Mechanisms for URLLC communication in PHY/Cross/MAC Layer.

In 5G networks, for a UE to receive resources from eNB, the bearer needs to request access, be admitted and then have resources scheduled to it. A bearer requires a throughput, a delay and priority and fairness among users. Semi-persistent scheduling removes the delay for establishing each UL grant. The shorter the latency, the shorter the period, the more resources are wasted when intermittent use.

Then the main challenges that we will focus on, are: i) H*ow to achieve low latency and high reliability without wasting resources*? and ii) *How to support massive URLLC devices with limited resources*?

A simple observation can be made: All URLLC requirements can hardly be reached together. We need to make a tradeoff between reliability, latency, scalability and spectral efficiency. In this project, we propose to study a novel transmission and allocation (PHY/MAC) method providing a flexible tradeoff between reliability, latency, scalability and spectral efficiency. For that purpose, we propose to enhance URLLC deterministic protocols (providing the minimal QoS) by opportunism.

Taking into account that URLLC applications have a range of requirements (in terms of reliability and latency), our 5G URLLC building blocks will mix resource reservation and opportunistic use of the spectrum.

On the one hand, we will exploit existing or propose deterministic protocols to provide the minimal QoS requirements (e.g., minimal reliability, minimal availability, maximal latency without jitter) in order to ensure low latency and reliable communications. The aim of this protocol is to bound the performance. It could be based on dedicated semi persistent scheduling. However, resources can be reserved according to the bearer requirements but they are not expected to be always used. Thus, the cost of low latency is the potential high spectral inefficiency.

On the other hand, we will enhance the QoS (ultra-reliable or ultra-low latency) thanks to an opportunistic approach. This complementary protocol will share limited resources (shared/unused) for heterogeneous URLLC services and will improve the reliability by exploiting spatial and frequency diversity and propose a better latency (but with jitter). Thanks to this approach, we are allowed to overbook the shared resource and we can naturally provide heterogeneity management.

The design of our 5G URLLC building blocks taking into account the reliability and the latency requirements of CPS use cases will be validated in Open Air Interface (OAI) based platform (see Figure 14). OAI is open source software-based implementation starting from LTE and going on to 5G and includes the full protocol stack of 3GPP standard (E-UTRAN (eNB, gNB, UE), EPC (MME, S+P-GW, HSS))

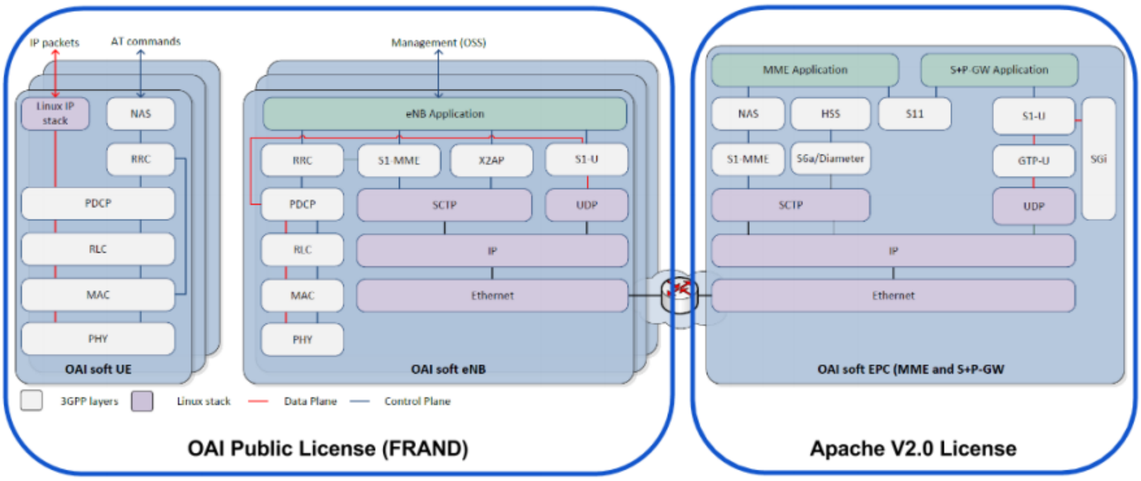

Figure 14: Architecture of OAI including RAN and core network

4.3 TSN ASPECTS

The move towards cloud manufacturing put a strain on networking technologies in order to ensure ubiquitous and seamless connectivity while meeting the stringent real-time requirements. An example of cloud manufacturing scenario is shown Figure 15 in where a PLC controller running on the cloud remotely control and monitor the I/O sources in the factory. Such critical communication will require high synchronicity in the order of 1 µs [3GPP22804] and presents stringent requirements on latency, communication service availability and determinism. Today, 5G networks are able to provide the ultra-reliable and low latency communications (URLLC) feature. Therefore, the integration of 5G networks with IEEE Ethernet Time Sensitive Networking (TSN) would make smart factories fully connected and enable the different communications to meet their requirements.

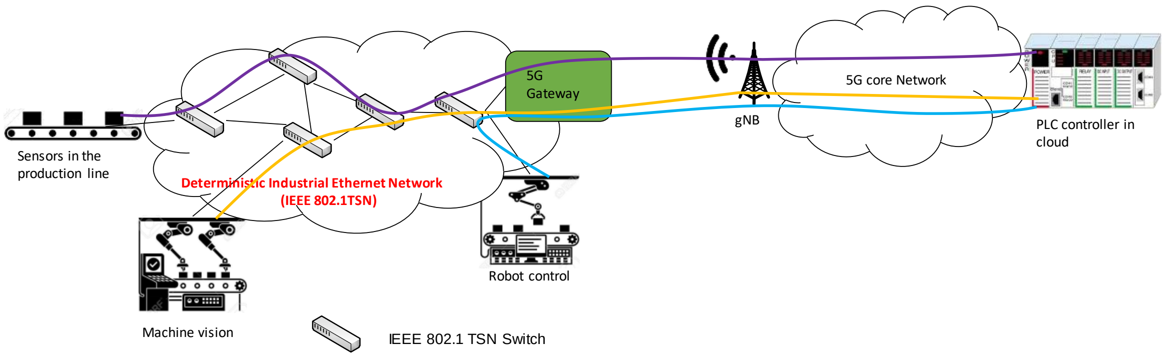

Figure 15: Cloud manufacturing use case (unified 5G-TSN architecture)

The goal of this study is to develop a solution capable to ensure an end-to-end determinism for critical flows that have to go through a hybrid architecture composed of Ethernet TSN and 5G networks. The first step for that is to establish a high synchronicity between the PLC controller and the I/O sources and to provide means to monitor and manage this synchronicity whenever it is needed.

Several techniques for improving the synchronization accuracy while minimizing the synchronization errors have been developed for TSN or 5G networks. However, considering the emerging heterogeneity of networks in industrial domain, a new ultra-tight synchronization architecture should provide the absolute synchronization among the networking devices.

Our aim is to provide a network configuration and management solution that will configure the time synchronization in networking devices, monitor the time accuracy and reconfigure the time synchronization when the high synchronicity requirement is no more satisfied. The proposed solution will rely on the protocol IEEE 802.1AS [802.1AS] to provide time synchronization between devices inside the Factory and the time synchronization feature in 5G networks in order to achieve the required synchronicity. The proposed solution will address how to ensure a global synchronization by mapping between the time synchronization naturally provided in 5G cellular radio and the time synchronization provided by IEEE 802.1AS in Ethernet TSN networks.

In the following, we provide an overview of the protocol IEEE 802.1AS as well as of time synchronisation in 5G networks. After that, we argue the need for a network configuration and management solution that will be in charge of configuring, monitoring and reconfiguring the time synchronization in the network.

4.3.1 Time synchronization in TSN networks (IEEE 802.1AS-2011)

IEEE 802.1AS (generalized Precision Time Protocol gPTP) [802.1AS] is a more “restrictive” profile of IEEE 1588-2008 (PTP) [IEEE1588] for LAN. The scope of this standard is to ensure that the synchronization requirements are met for time-sensitive applications, such as audio and video across bridged and virtual bridged local area networks consisting of LAN media where the transmission delays are fixed and symmetrical. This will allow multiple streams to be synchronized. It provides a common time base for sampling data streams at the source node and presenting those streams at the destination node with the same relative timing. The time-aware systems (i.e. Bridges and end stations) in the bridged LAN periodically exchange timing information that allows both ends of the link to synchronize their time base reference clock very precisely.

The rationale behind developing this standard was that the synchronization information provided to each network node will allow the jitter, wander, and time synchronization requirements of demanding applications, such as Audio/Video applications in a residential environment, to be met. In fact, existing time synchronization standards such as IEEE Std. 1588-2002 and RFC 1305 (NTP) operate at layer 3 and impose unacceptable operational complexity and implementation costs on a developer of residential AV equipment. Therefore, IEEE 802.1AS has defined a specific profile of IEEE 1588-2008 with additional timing features which greatly improve timing accuracy and lock time.

This standard provides precise time synchronization of the network nodes to a reference time with an accuracy of 1 μs (i.e. between pair of nodes separated by no more than 7 hops). In fact, all End stations and Bridges in the same LAN measure and exchange timing information such as link and residential delays leading to extremely accurate time, on the order of few hundreds of nanoseconds per hop, worst case. With such accurate time, streaming can be start immediately after system boot rather than waiting some milliseconds for the time

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reference to stabilize. Worst-case time synchronization accuracy degrades linearly beyond 7 hops [802.1AS] [BEL2004]

In the following, we provide details about 802.1AS architecture, Best Master Clock Algorithm and time synchronization mechanisms.

4.3.1.1 IEEE 802.1 AS Architecture

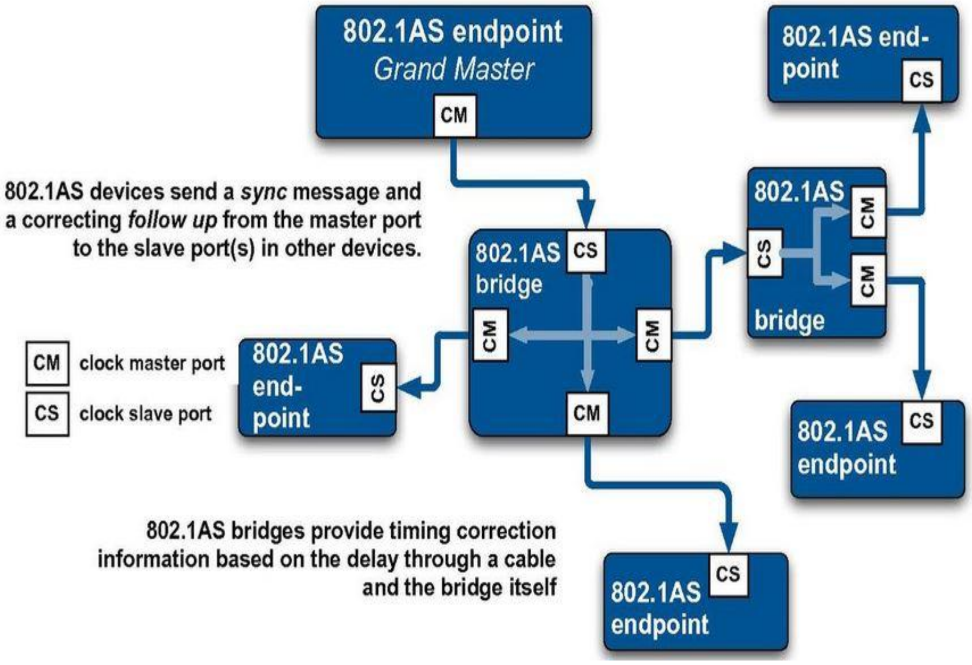

Figure 16: IEEE 802.1AS architecture

The IEEE 802.1AS architecture is depicted in Figure 16. A time-aware bridged LAN consist of two types of nodes:

- Time-aware end station: which if not grandmaster, is a recipient of time information
- Time-aware Bridge, which if not grandmaster, receives time information from the grandmaster(perhaps indirectly through other time-aware bridges), applies corrections to compensate for delays in the LAN and the bridge itself, and retransmits the corrected information

When a Bridge or end station is the grandmaster, all its ports are set on clock master mode. For two directly connected nodes, we cannot have both of their ports, at the same time, in clock master or in clock slave modes.

4.3.1.2 Best Master Clock Algorithm (BMCA)

All time-aware systems are required to participate in BMCA to determine the GM and construct a time-synchronization spanning tree with the GM as the root. This latter uses the spanning tree to spread the synchronized time to the other time-aware systems.

The GM-capable system announces its presence via ANNOUNCE messages. Each one of these messages contains the time-synchronization tree vector information where one time-aware system is the root of the tree. Each time-aware system in the network uses the information contained in the Announce messages along with its knowledge of itself, to compute the root of the spanning tree. If the root is GM-capable, it is considered the GM.

As part of constructing the time synchronization spanning tree, each port of each time-aware system is assigned a role namely *MasterPort*, *SlavePort*, *PassivePort* and *DisabledPort*. To decide the root for the spanning tree, all time-aware systems compare between the received ANNOUNCE messages using the *systemIdentity* parameter which is a concatenation of the following attributes: *priority1*, *clockClass*, *clockAccuracy*, *offsetScaledLogVariance*, *priority2*, *clockIdentity*.

The process is repeated until all time-aware systems converge for the best GM in the network. It can be reinitiated when a change happens in the network like the current GM fails or leaves the network, a time-aware system having access to better clock or a new suitable GM joining the network.

4.3.1.3 Time synchronization and correction

The grandmaster (GM) sends his current synchronized time to all directly attached time-aware nodes. Each one of these nodes must correct the received synchronized time by adding the propagation delay (i.e. the time needed for the information to transit the communication path between the grandmaster and the node).

Accurate local egress and ingress timestamps are required in the MAC/PHY to compute the following parameters:

- Propagation delay (per slave port): the computation depends on the link technology in use
- Next-neighbor rate ratio (PPM offset to link partner): to determine if the neighbor is running slower or faster than the current node

The time-aware Bridge must forward the corrected time information (including additional corrections for delays in the forwarding process, called residence time) to the other attached time-aware nodes. The residence time is local to the Bridge and easy to compute.

IEEE 802.1AS defines mechanisms for measuring propagation delay using standard-based procedures for the following media:

- IEEE 802.3 Ethernet using full-duplex point-to-point links
- IEEE 802.3 Ethernet using passive optical network (EPON) links
- IEEE 802.11 wireless
- Generic coordinated shared networks (CSNs)

In the following, we consider IEEE 802.3 Full-duplex point-to-point links in order to show how Bridges and endpoint in IEEE 802.1AS compute propagation delay and synchronize their clocks.

4.3.1.3.1 Propagation delay

The measurement of propagation delay on a full-duplex, point-to-point link uses the PTP peer delay mechanism described in IEEE 1588-2008 [IEEE1588]. Figure 17 shows the message exchanges between two time-aware systems in order to determine the propagation delay between them. The time-aware system 1 port is in master mode. The time-aware system 2 port is in slave mode.

1) Time-aware system1 schedules *Pdelay_Req* for transmission. As it passes out the PHY, the ingress timestamp t_1 is captured (using master clock).
2) The ingress timestamp of Pdelay_Req messame (t_2) is captured in time-aware system 2 as Pdelay_Req passes from PHY to MAC (using slave clock).
3) Time-aware system 2 schedules *Pdelay_Resp* for transmission. *Pdelay_Resp* carries t_2. The egress timestamp of *Pdelay_Resp* transmission (t_3) is captured.
4) The ingress timestamp of t_4 is captured in time-aware system 1.
5) Time-aware system 2 send *Pdelay_Resp_Follow_Up* message which carries t_3 to time-aware system 1

At the end of this exchange, the time-aware system 1 uses these four timestamps (i.e. t_1, t_2, t_3, and t_4) to compute the propagation delay. If link delay is fixed and symmetric, the propagation delay is calculated as follows:

$$D = \frac{(t_4 - t_3) + (t_2 - t_1)}{2}$$

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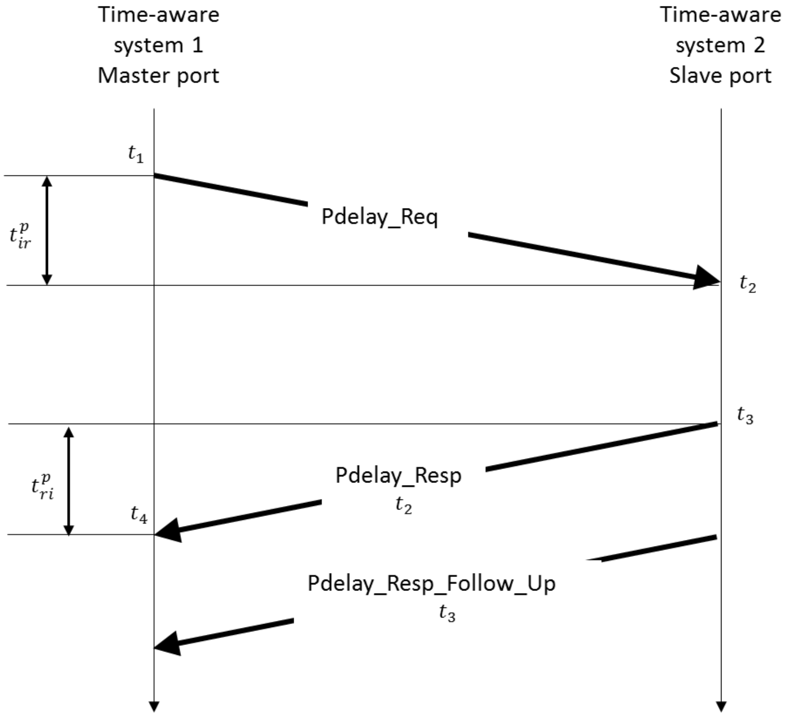

Figure 17: Propagation delay measurement using PTP peer delay protocol

Each port in the time-aware system is associated with several management parameters that defines the frequency with which messages are sent. For instance, The pdelayReqInterval defines the mean Pdelay_Req message generation interval for the port. The variable initialLogPdelayReqInterval controls the startup rate of pdelayReqInterval.

4.3.1.3.2 Clock synchronization

Figure 18 shows the clock synchronization mechanism.

1) The master port in time-aware system i-1 schedules a *Sync* message. Time-aware system i-1 captures the transmission timestamp $t_{s,i-1}$ using the master clock.
2) The slave port in time-aware system i captures the reception timestamp $t_{r,i}$ $t\_(r,i)$ as the *Sync* message passes from PHY to MAC layers using the slave clock.
3) The master port in time-aware system i-1 sends *Follow_Up* message that carries the $preciseOriginTimestamp$, the $\mathrm{correctionField}_{i-1}$ and $\mathrm{rateRatio}_{i-1}$. The $preciseOriginTimestamp$ contains the time of the GM when it originally sent this synchronization information. The field $\mathrm{correctionField}_{i-1}$ contains the difference between $t_{s,i-1}$ and $preciseOriginTimestamp$. The field $\mathrm{rateRatio}_{i-1}$ is the ratio of the GM frequency to the frequency of the LocalClock in time-aware system i-1. If link delay is fixed and symmetric, the slave clock offset is calculated as follows:
   - offset = $t_{r,i} - t_{s,i-1} - propagation\_delay$
4) The time-aware system i generates a new Sync message to be sent through its master port at time $t_{s,i}$. It computes the $\mathrm{correctionField}_i = (t_{s,i} - preciseOriginTimestamp)$. To do that, it computes the value of time interval between $t_{s,i-1}$ and $t_{s,i}$ expressed in the GM time base and added it to $\mathrm{correctionField}_{i-1}$. This interval is the sum of the propagation delay between time-aware system i-1 and i expressed in the GM base time and the residence time in time-aware system i (i.e. difference between $t_{s,i}$ and $t_{r,i}$ expressed in the GM base time. Upon receiving FOLLOW_UP message from time-aware system i-1, the time-aware system i creates new FOLLOW_UP message with the following fields: $preciseOriginTimestamp$, $\mathrm{correctionField}_i$, and $\mathrm{rateRatio}_i$ and send it to the time-aware system i+1.

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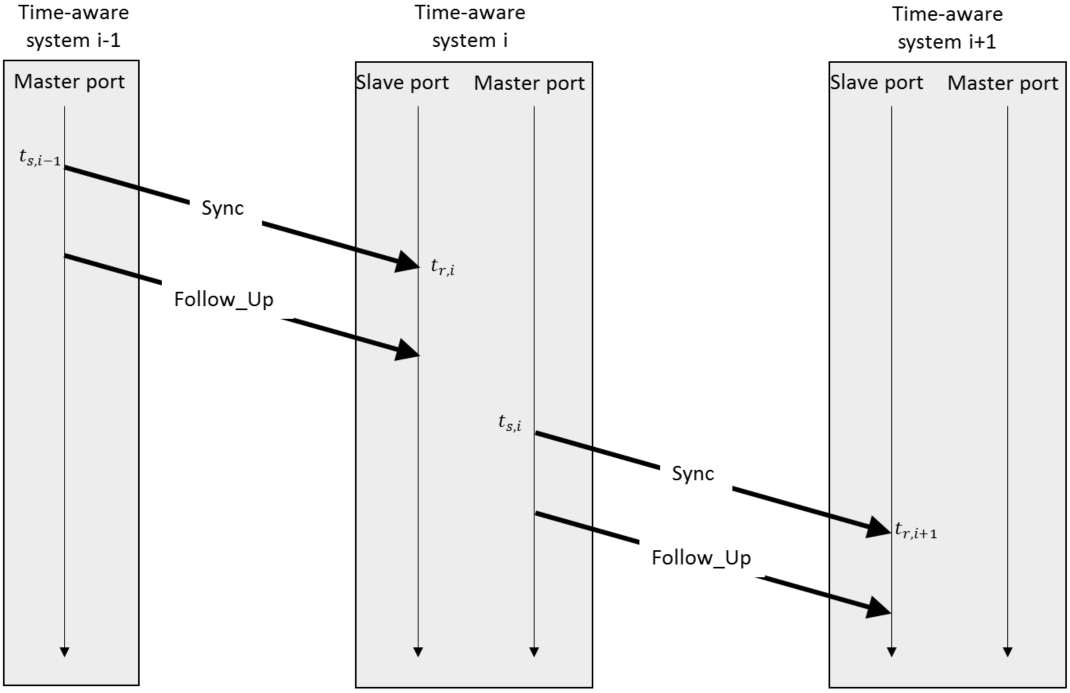

Figure 18: Clock synchronization

Each port in the time-aware system is associated with the SyncInterval parameter. It defines the mean time-synchronization event message generation interval for the port. The default value defined in this standard is 125ms. The SyncInterval has a direct impact on system synchronization time at startup as the time-aware system must receive a minimum of two Sync messages to obtain basic synchronization. After initial synchronization is achieved, synchronization can be maintained with a much larger SyncInterval, with the benefits of reduced CPU load and network overhead. The initial and operational sync intervals are set with the variables initialLogSyncInterval and operLogSyncInterval, respectively. The slave port may request that the SyncInterval be increased through the use of gPTP signaling message with the message interval request TLV.

4.3.2 Time synchronization in 5G networks

Time synchronization is an essential part of the 5G cellular radio systems operation. This has already been common practice for earlier cellular network generations. The fronthaul network provides connectivity between functional blocks of a cellular base station (BS). The fronthaul flows between these functional blocks have stringent quality of service requirements.

Recently, a collaborative work between Fronthaul experts of CPRI corporation and Ethernet networking experts of IEEE 802.1TSN Working Group led to producing IEEE 802.1CM specification. The purpose of this standard is to specify defaults and profiles that enable the transport of Time-sensitive fronthaul streams in Ethernet bridged networks.

4.3.2.1 Time synchronization 5G cellular radio

Since the earlier cellular radio systems, the time or frequency synchronization has been embedded into 5G cellular radio systems as an essential part of their operation. The purpose of synchronization in the context of cellular networks is to make sure that the relevant devices and base stations possess a common frequency, time and phase reference for data transmission. From Release 10 of LTE specification, advanced functionalities in LTE dealing with heterogeneous networks rely on a tight phase and time synchronization [KHA2010] Time synchronization in 5G cellular networks is not only censured between User Equipment (UE) and Base Station (BS) but also between neighboring Bases stations in order to synchronize their transmission and avoid any inter-cell interferences. Several work have been addressing how to achieve ultra-tight synchronization for URLLC. For instance, authors in [AAM2018] highlighted the potential of over-the-air synchronization mechanisms in 5G radio interface to satisfy the need for ultra-tight time synchronization in factory automation use case.

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In 5G cellular radio, a common base of time can be maintained by periodically broadcasting timestamps of reference time from master (i.e., gNB) to the slave devices. This information is transmitted by gNB over broadcast control channel (BCCH). The devices use the received timestamp information to synchronize their clocks after removing any time progress (i.e. the estimated propagation time of the message) from the reception timestamping of the message [AAM2018]. The synchronization period depends on the frequency and phase stability of the local oscillators in devices, causing clock skew and drift. Authors in [MAH2019] identified several factors that may impact the synchronization accuracy such as Time Alignment Error (TAE), propagation time and its variation (jitter), asymmetry of uplink and downlink propagation, time adjustment errors at devices.

4.3.2.2 Time synchronization in core network:

The standards IEEE 802.1CM and ITU-T G.8275.1 define how to ensure the time synchronization between radio network components. The standard IEEE 802.1CM provides the time synchronization requirements and solutions for fronthaul network. Whereas the standard ITU-T G.8275.1 is focusing in providing the Precision Time Protocol (PTP) telecom profile for phase/time synchronization with full timing support from the network.

4.3.3 Time synchronization configuration and management

The time synchronization for TSN networks has been specified in the standard IEEE 802.1AS. In order to ensure an accurate time synchronization, IEEE 802.1AS imposes several constraints such as:

- There is only one time domain and one GrandMaster in the network.
- IEEE 802.1AS messages are neither VLAN-tagged, nor priority-tagged
- All networking devices (End stations and Bridges) shall be IEEE 802.1AS capable. As a consequence, all networking devices shall implement the Best Master Clock Algorithm (BMCA). This algorithm will ensure that there is only one GrandMaster and that the rest of networking devices are slaves to this GrandMaster.
- All networking devices shall allow to configure 15 parameters [BHS-det2018]: parameters related to GrandMaster selection (priority1 and priority2), parameters related to propagation delay calculation (e.g. delayAsymmetry, initialLogPdelayReqInterval, etc.), parameters related to time synchronization (e.g. initialLogAnnounceInterval, initialLogSyncInterval, etc.)
- The frequency with which IEEE 802.1AS messages are sent shall be the same in the network (e.g. all networking devices shall send the Sync message each 125 µs).
- The network shall not include more than 7 hops (clocks are synchronized up to 1 µs over 7 hops).

From all these constraints, it is clear that IEEE Ethernet TSN networks required a centralized network configuration and management solution in order to support the time synchronization [BHS2018]. Such solution will be in charge of configuring, monitoring the time accuracy and reconfiguring the time synchronization when the required accuracy is no more satisfied. Furthermore, this solution will not only configure the time synchronization of the network interface in 5G gateway connected to IEEE Ethernet TSN network, but also it will address how to synchronize between Ethernet TSN and the 5G cellular radio in order to ensure the global synchronization. For real-time communication, each industrial device should maintain a local clock to execute received commands at deterministic instants. When multiple devices from different domains (i.e. device 1 in TSN network and device 2 in 5G domain) must coordinate or operate concurrently, an absolute time synchronization among the devices will be mandatory. Due to synchronization errors between the networking devices, the exchanged critical frames between these devices can miss the specific time slot that has been already scheduled by the time-aware shaper in TSN bridges.

Figure 19 shows an initial specification of the solution that we are targeting to provide the global time synchronization. The proposed solution will be in charge of managing the time synchronization software inside TSN bridges and 5G gateway. The 5G radio base station (gNB) can be used to provide time reference inside the URLLC domain. In this respect, the base station acts as a master clock while the 5G gateway as slave clocks. The 5G gateway acquire the reference time from the base station using the over-the-air time synchronization procedure. Then, the 5G gateway acts as a master clock to the TSN network domain and distributes time to the devices. This is will be a good basis to provide synchronization for time-critical applications. Clocks in Figure 19 illustrate a case where all TSN bridges, 5G gateway, 5G gNB and end devices (controller or I/O devices) are time synchronized.

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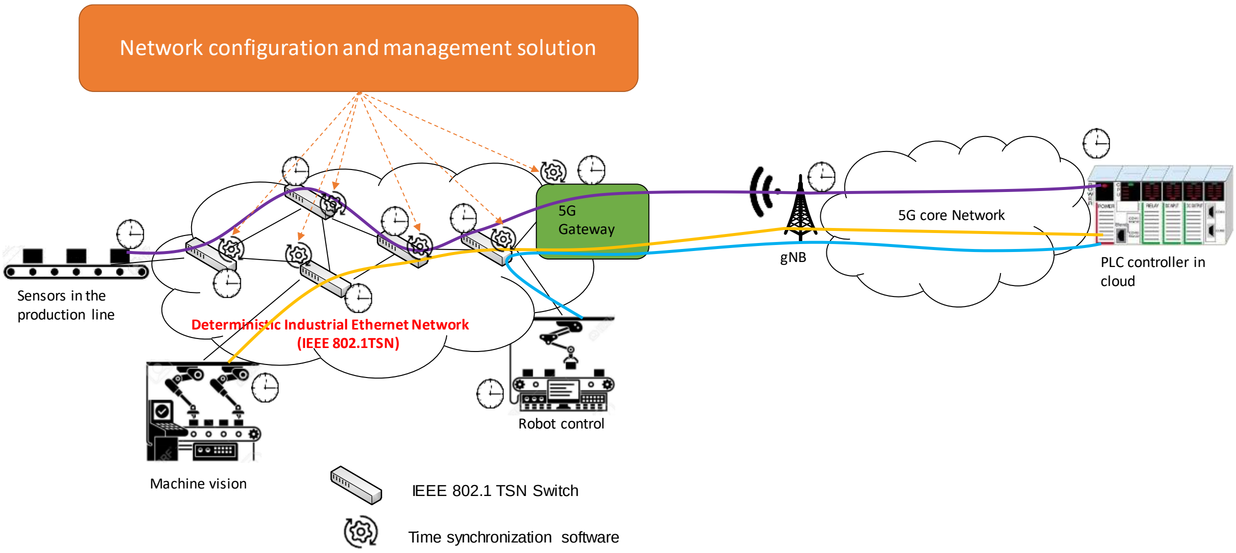

Figure 19: Global synchronization solution for a unified 5G-TSN networks

5 CONCLUSION

From the requirements expressed by the verticals or coming from other work-packages, we tried to derive the high-level requirements of the communication modules to serve a maximum of use cases. It appears that a single radio modem cannot meet all the requirements. For instance, depending on use cases, very low data rate could be good enough, while for others, high data rate is a must. As a result, WP2 has to address multiple modems, that could be then integrated into a pre-integrated architecture board, which is the objective of WP6.

We performed a quick survey of existing technologies. It appears that 4G is a good starting point since it proposes a framework meeting most of the requirements, thanks to the various LTE categories. However, for most stringent requirements, such as low latency, time deterministic communication, 4G is somehow limited and WP2 has to work on building blocks, enabled by 5G to fulfil the complete set of requirements expressed by verticals. This report proposes three axis of research for WP2, investigating Time Sensitive Networking, URLLC, and a DSP framework and development flow that could combine communication and AI processing.

This report has therefore set the scene for WP2, highlighting early requirements from verticals about communication, proposing short term solution to meet most of these requirements and long term research activities to propose solution for tightest requirements.

Update of the report will be provided in Q4 2020 to better capture requirements from vertical (coming from WP6, WP7, WP8, WP9, since these requirements elicitation is still work in progress at the time of this deliverable) and status from 5G development in the standardization forum.

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