Private 5G Networks for Connected Industries

Deliverable D6.3

Final Report on Dissemination and Standardization

Co-funded by the Horizon 2020 programme
of the European Union in collaboration with Taiwan

Date of Delivery: 30.12.2022
Project Start Date: 01.10.2019 **Duration:** 36 Months

Document Information

Project Number:	861459
Project Name:	Private 5G Networks for Connected Industries

Document Number:	D6.3
Document Title:	Final Report on Dissemination and Standardization
Editor:	Mathis Schmieder (HHI)
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Dissemination Level:	Public
Contractual Date of Delivery:	31.12.2022
Work Package	WP6
File Name:	861469-5G CONNI-D6.3-Final Report on Dissemination and Standardization-v1.0.docx

Revision History

Version	Date	Comment
0.1	02.12.2022	Skeleton document
0.2	15.12.2022	Consolidated input from ATH, Bosch, CEA, CHT, III, ITRI, SAP
0.3	16.12.2022	Input from ANI
0.4	21.12.2022	Further work on report and exploitation plan
0.5	23.12.2022	Cleaned up document, finalization for submission
1.0	30.12.2022	Version for submission

Executive Summary

This deliverable has been written as part of the work in the project Work Package (WP) 6 “Dissemination”, and reports on the 5G CONNI project dissemination and standardization activities achieved during the second half of the project. The deliverable also gives an updated exploitation plan for each project member.

Table of Contents

List of Figures

List of Acronyms

3GPP	3rd Generation Partnership Project
5G CONNI	5G for Connected Industries
ANI	Alpha Networks
AP	Access Point
API	Application Programming Interface
ATH	Athonet
BNetzA	Bundesnetzagentur, German Telecommunication Regulation Agency
CAE	Convolutional Auto-Encoder
CEA	Commissariat à l'énergie atomique et aux énergies alternatives
CHT	Chunghwa Telecom
COVID-19	Corona Virus Disease 2019
CPE	Customer Premise Equipment
CU	Central Unit
DisCO	Discontinuous Computation Offloading
DU	Distributed Unit
EML	Edge Machine Learning
ES	Edge Server
ETSI	European Telecommunications Standards Institute
HARQ	Hybrid Automatic Repeat Request
HHI	Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute
IB	Information Bottleneck
IEEE	Institute of Electrical and Electronics Engineers
III	Institute for Information Industry
IMTC	Intelligent Machine Tool Center
IoT	Internet of Things
ITRI	Industrial Technology Research Institute
ITU	International Telecommunication Union
LMS	Least Mean Squares
MADDPG	Multi-Agent Deep Deterministic Policy Gradient
MADQL	Multi-Agent Deep Q-Learning
MANO	Management and Orchestration
MEC	Multi-Access Edge Computing
MOEA	Ministry of Economic Affairs
MQTT	MQ Telemetry Transport
Mu-MERAS	Multi-User Minimum Energy Resource Allocation Strategy
RAN	Radio Access Network
RMS	Root Mean Square
RU	Radio Unit
SIMO	Single In Multiple Out
SNS	Smart Network and Services
UE	User Equipment
URLLC	Ultra-Reliable and Low-Latency Communications
WP	Work Package

1 Introduction

The main objective of this deliverable is to report on the achieved dissemination, standardization, and exploitation activities with main focus on the second half of the 5G CONNI project. The information presented in this deliverable can be seen as an addition to what was compiled previously in Deliverable D6.1, “Dissemination Plan & Project Website”, and Deliverable D6.2, “Intermediate Report on Dissemination and Standardization”, where the activities during the first half of the project were presented.

A comprehensive list of all the achievements in the second half of the project, both in terms of dissemination of project results to academic and non-academic audiences, and standardization in related fora, is given in this deliverable. Furthermore, an updated exploitation plan for the period after the conclusion of the project is presented.

The second half of the project was still overshadowed by restrictions due to the COVID-19 pandemic, especially on international travel. Nevertheless, the 5G CONNI consortium managed to successfully disseminate project results, both through in-person events, and through alternative means like online conferences, special sessions and webinars.

2 Report on dissemination activities

As in the first reporting period, the information about the 5G CONNI project was shared both through internal and external dissemination:

- *Internal dissemination*: The main *intra*-project results were continued to be shared with all involved partners through email distribution lists and a file sharing repository server. Due to the ongoing COVID-19 situation, these online resources were as necessary as ever to enable active discussion between the project partners.
- *External dissemination*: Following the status quo established in the first project period, the consortium continued to participate in international private and public events. Wherever the COVID-19 situation allowed it, partners participated in in-person events, but continued to leverage alternative dissemination means like online conferences or webinars. The project web site, https://5g-conni.eu, was kept up to date with press releases and other dissemination results.

In the following sections, the specific dissemination activities during the last project period are described.

2.1 Internal dissemination

The resources established by Fraunhofer HHI as project coordinator for internal dissemination were further used in the second half of the project. The set of mailing lists, both for each WP and a general project-wide list, were vital for reporting the status of the WP, arranging conference calls and for discussions on important issues.

Each member of the project was provided with individual accounts for the internal, members-only file sharing repository server hosted at Fraunhofer (https://owncloud.fraunhofer.de), which was used to store all information, such as documents, deliverables, software, publications, research activity, obtained results and meeting minutes.

For all work packages active in the second project period, either bi-weekly or monthly calls among the WP participants were held to organize the work and to monitor the status of both technical and non-technical aspects. Minutes of these calls and main information relevant to all project participants were made available on the mailing lists and stored on the repository. In addition to the WP calls, a monthly call including all project partners were organized for exchanging the most important information. A regular monthly management call between the Taiwanese and European coordinators ITRI and Fraunhofer HHI was held.

As international travel and in-person meetings in general were still heavily restricted in 2021 and 2022, most of the bi-annually general assemblies were still held as online-only events. Due to the time difference between Taiwan and Europe, the meetings were limited to half-day events, but with stringent scheduling and good cooperation between all partners, both meetings were successful, and all aspects could be discussed. The final general assembly in December 2022 could be held as a hybrid event with the European partners meeting at BOSCH and the Taiwanese partners meeting at IMTC.

Besides internal dissemination between the project partners, the project results were also shared internally at the project partners. For example, BOSCH has held various presentations and has given continuous updates to different business divisions. Results have been transferred into these divisions on a regular basis, in particular, the use cases and demonstrators are being considered for further experimentations, lab activities and possible future product concepts. In addition, multiple other BOSCH plants have been supported with regards to individual 5G activities based on the 5G CONNI results. At Fraunhofer HHI, the work conducted

during the 5G CONNI project serves as basis for further analysis and evaluation by PhD students.

2.2 External dissemination

External dissemination of the main project results was still impacted by the COVID-19 situation as it was originally planned to share the results not only through (academic) publications and via the project web site, but also through exhibitions and industry events. Most of the planned in-person events, like the Mobile World Congress or 5G/6G Global Event, were cancelled throughout the span of the project. Nevertheless, the project consortium leveraged online and hybrid meetings to share the project results with both scientific and non-scientific audiences, besides regular means of dissemination through press releases and conference and journal papers. Details on the specific external dissemination activities are provided in the following subsections.

2.2.1 5G CONNI web site

A public web site was set up at the beginning of the project under the domain https://5g-conni.eu in order to obtain the broadest possible impact of the project results. Active during the whole lifetime of the project, this site contains general information on the consortium, all public deliverables, as well as accepted project-related conference and journal papers, invited talks and other presentations held by the consortium partners. In addition, news entries and press statements related to the project were published on the web site. Fraunhofer HHI is hosting the web site and is planning on keeping it open at least three years after the project end. A screenshot of the project web site can be seen in Figure 1.

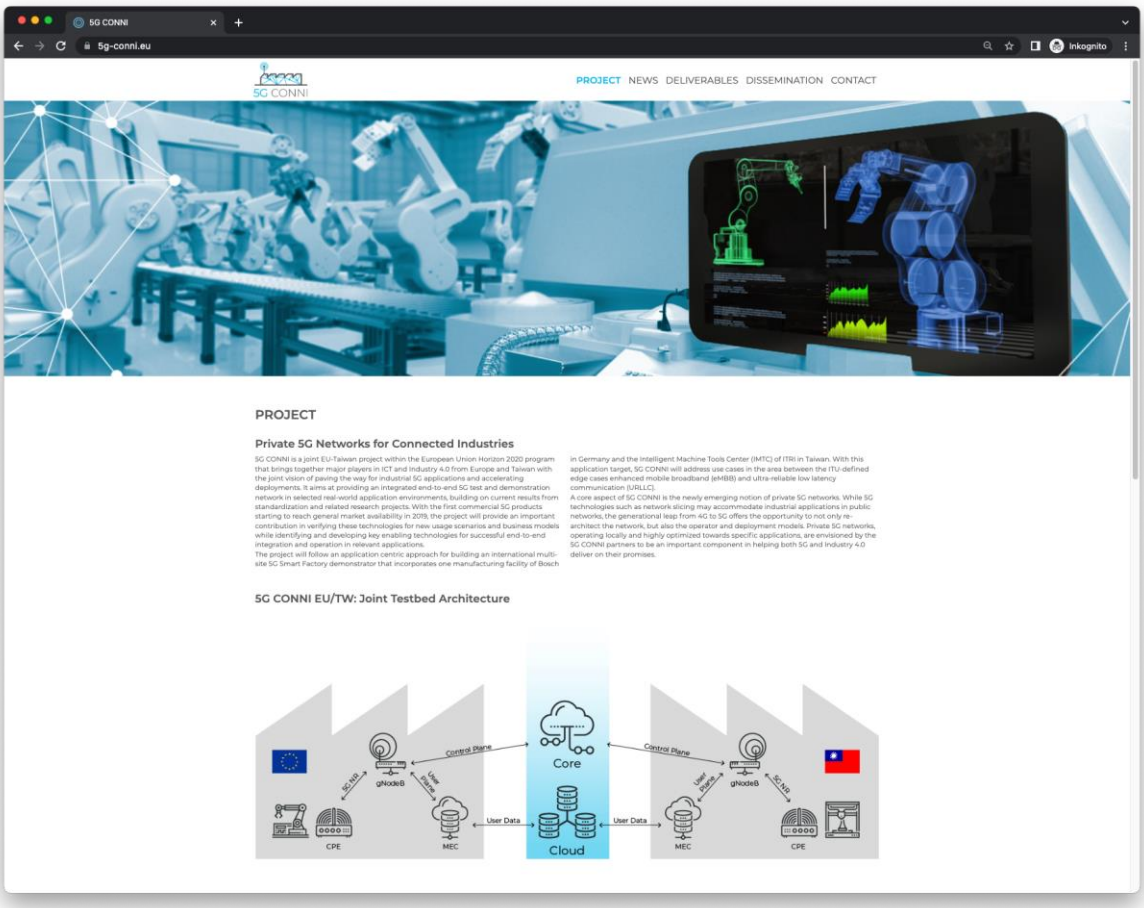

Figure 1: Screenshot of the project website

2.2.2 Articles and Press Releases

The 5G CONNI consortium has undertaken several activities to promote the awareness of the project in academic and industrial ecosystems, and to ensure that its results were adequately advertised to the broadest possible audience during and beyond its lifetime. For example, project flyers were distributed by Athonet at the 5G World event, held in London (UK) from September 21st to 23rd, 2021.

During the last year of the project, the 5G CONNI project coordinator was interviewed for an article on the Fraunhofer InnoVisions platform ((https://www.fraunhofer-innovisions.de/iot-und-sensorik/funkfertigung/). In this German-only article, project results were shared with a wider public audience within Germany.

2.2.3 Other external dissemination

As in the first project period, Athonet organized and hosted the 2022 UPTIME conference, held on January 26 and 27 at Villa Marconi, Bologna, Italy, and with remote connection of participants from all over the world. Every year at UPTIME, tier-1 operators, vendors, end users, and academics meet for discussing the evolution of private mobile networks. In its 2022 edition, a dedicated session was hosted for European funded projects, and 5G CONNI was presented and discussed. Please refer to following link for more information: https://athonet.com/uptime-2022/

Furthermore, 5G CONNI project partner Athonet presented some of the project's activities at the following seminars and webinars:

- Dec. 20th, 2021: "5G Network Slicing: Athonet's Perspective and Testing Tools," organized by the Bicocca University of Milan (Italy).
- May 11th, 2022: "5G Networks in Action – The Private Mobile Era," organized by the Federico II University of Naples (Italy) as part of the 5G Academy.
- May 13th, 2022: "5G Networks in Action – The Private Mobile Era," webinar organized by the Bicocca University of Milan (Italy).

Figure 2: Title slides of Athonet presentations

ITRI has worked with Small Cell Forum and the consortium members to organize the dissemination activity at Small Cell World Summit 2021 to promote project results. In particular, an online virtual booth has been setup to display project achievements, which is shown in Figure 3. Moreover, ITRI has organized a speaking slot in the session "Industry 4.0 and Private Networks, Edge Computing", which was presented by Athonet from the perspective of 5G CONNI project.

Furthermore, ITRI has worked with Ministry of Economic Affairs (MOEA) to organize the dissemination activity at EU-Taiwan Joint 6G SNS Workshop held in Taiwan on Nov. 15 2022.

(https://www.eu-taiwanjoint6gsnsworkshop.tw/) In particular, a dedicated booth, displayed in Figure 4, has been setup to display the inter-site use case (Remote Expert Support for Process Diagnosis). The on-site machine operator at IMTC can interact with a remote expert at the venue to resolve the problem of the milling process. The 5G CONNI consortium presented the results of three years of work at the EU-Taiwan Joint 6G SNS Workshop held in Taipei with an invited talk by Thomas Haustein (Fraunhofer HHI) and a demonstration by ITRI.

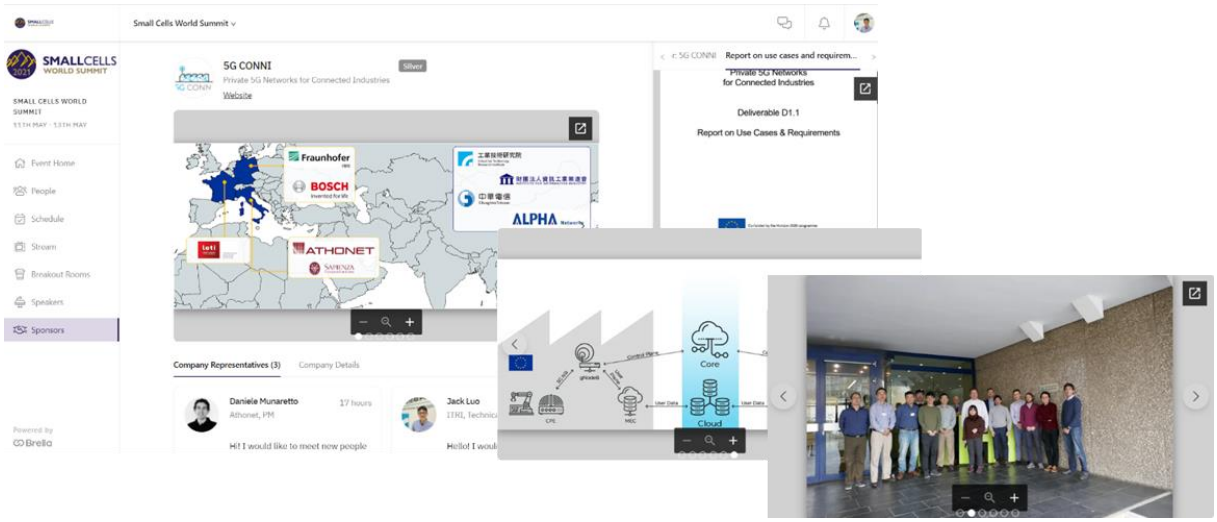

Figure 3: Online virtual booth at SCWS 2021

Figure 4: Demonstration of inter-site use case at EU-Taiwan Joint 6G SNS Workshop.

During the final demonstration workshop held in Stuttgart, Germany, and Taoyuan, Taiwan, on December 12, 2022, a professional film crew accompanied the project consortium in order to produce high quality audiovisual material suitable for presenting the project results to a wider audience. At the time of writing of this report, the demonstration films are still in post-production. As soon as the final cut is available, the content will be disseminated via the project's website, as well as internal and external social media channels of the project partners. The targeted time frame for this is January 2023.

2.3 Scientific publications

The 5G CONNI consortium has the ambition to generate a highly visible and impacting footprint of their research outcome in the scientific community. To achieve this, high profile conferences and fora, mainly in the communication and networking domain, were primarily targeted. In the second project half, the 5G CONNI partners have published twelve scientific international conference papers and seven scientific journal papers, bringing up the total number to eighteen conference and thirteen journal papers. Furthermore, the consortium also participated in several keynotes, invited talks and tutorials, and co-organized several workshops. The details are provided in the following subsections.

2.3.1 Scientific conferences

The 5G CONNI consortium has actively disseminated project results at international conferences, workshops, and EU commission-specific events. The twelve scientific international conferences papers are:

1. S. Wittig, A. Schultze, M. Peter and W. Keusgen (HHI), **"Over-the-Air Verification of Angle-of-Arrival Estimation in Millimeter-Wave Channel Sounders,"** 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), 2021, pp. 1-5, doi: 10.1109/VTC2021-Fall52928.2021.9625085.

   Abstract

   In this paper, we discuss a controlled environment over-the-air verification approach for directional channel sounder receivers at millimeter-wave frequencies. The presented verification setup uses a benchtop compact antenna test range comprising two feed-reflector systems with overlapping quiet zones, thus creating two primary multipath components with well-defined angles of incidence at the receiver under test. We discuss possible verification scenarios and present initial measurement results for a virtual array/synthetic aperture-type SIMO channel sounder at 29 GHz.

2. M. Schmieder, H. Klessig, A. Schultze, S. Wittig, M. Peter and W. Keusgen (HHI), **"Channel Measurements and Large Scale Parameter Estimation in a Production Hall,"** 2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall), 2021, pp. 1-5, doi: 10.1109/VTC2021-Fall52928.2021.9625448.

   Abstract

   The integration of wireless communications into industrial production allows processes to be faster, more flexible and more cost effective. Fifth generation (5G) mobile networks are supposed to meet the requirements for ultra-reliable low latency communication, especially in non-public deployments. Already, spectrum around 3.7 GHz is reserved for such deployments and an expansion into millimeter wave range around 28 GHz is foreseeable. This paper presents a channel measurement campaign at both 3.7 and 28 GHz in an industrial production hall in three different relevant scenarios. Path loss, K-factor and RMS delay spread are evaluated.

3. Ming-Yen Wu, Jiun-Cheng Huang, Yuan-Mao Hung, Cheng-Yi Chien (CHT), Jack Shi–Jie Luo, Shuo-Peng Liang (ITRI), **"The Edge Cloud Implementation and Application of Transnational Smart Factory of 5G Private Network"**, 2022 23rd Asia-Pacific Network Operations and Management Symposium (APNOMS 2022), Japan, 2022, doi: 10.23919/APNOMS56106.2022.9919956.

Abstract

Smart factories enable the better deployment, operation, and flexible use of available resources and infrastructure through 5G and private networks. The 5G private network is the better solution for low latency, high reliability, and refactoring for smart manufacturing. However, many issues need to be resolved in terms of network architecture and operator model. We introduce the preliminary results of the 5G CONNI joint Europe-Taiwan collaborative project and provide an in-depth analysis of requirements, operator models, and network architectures. We propose that the operator model be applied to different network architecture options, as well as the choice of related use cases that provide hybrid private-public network operator governance and ownership. To this end, we implement related system platforms and application scenarios for smart manufacturing through cutting-edge technologies.

4. A. Ishaq et al. (ATH), **"Service-based management architecture for on-demand creation, configuration, and control of a network slice subnet,"** 2022 IEEE 8th International Conference on Network Softwarization (NetSoft), 2022, pp. 275-277, doi: 10.1109/NetSoft54395.2022.9844081.
This was a demo paper, and the corresponding proof-of-concept was presented at the conference on June 29th, 2022.

Abstract

The management of a 5G system comprises Operation and Management aspects defined by 3GPP, including Network Slicing, and the Management and Orchestration aspects specified in ETSI's Network Function Virtualization framework. Our Proof-of-Concept demonstrates the implementation of an on-demand provisioning procedure of a Network Slice Subnet composed of Virtual Network Functions from potentially different vendors. The demonstration includes a Network Management System conforming to the 3GPP Service-Based Management Architecture, an ETSI MANO orchestrator, and a Network Function Virtualization Infrastructure.

5. F Binucci, P Banelli, P Di Lorenzo, S Barbarossa (SAP), "**Dynamic Resource Allocation for Multi-User Goal-oriented Communications at the Wireless Edge**", 30th European Signal Processing Conference (EUSIPCO), 697-701, 2022

Abstract

This paper proposes a wireless, goal-oriented, multi-user communication system assisted by edge-computing, within the general framework of Edge Machine Learning (EML). Specifically, we consider a set of mobile devices that, exploiting convolutional encoders (CE), namely the encoder part of the convolutional auto-encoders (CAE), send compressed data units to an edge server (ES) that performs a specific learning task, such as image classification. The training of both the CEs and the ES classification networks is performed in a off-line fashion, employing a cross-entropy loss, regularized by the mean squared error of the CAE expanded output. Then, exploiting such goal-oriented architecture, and employing a Lyapunov optimization framework, we considered the joint management of computation and transmission resources for the overall system. In partic-ular, we considered a Multi-User Minimum Energy Resource Allocation Strategy (mu-MERAS), which provides the optimal resource allocation for both the devices and the ES, in a energy-efficient perspective. Simulation results highlight a

classical EML trade-off between energy, latency, and accuracy, as well as the effectiveness of the proposed approach to adaptively manage resources according to wireless channels conditions, computing requests, and classification reliability.

6. F Pezone, S Barbarossa, P Di Lorenzo (SAP), "**Goal-Oriented Communication for Edge Learning Based On the Information Bottleneck**", ICASSP 2022

Abstract

Whenever communication takes place to fulfill a goal, an effective way to encode the source data to be transmitted is to use an encoding rule that allows the receiver to meet the requirements of the goal. A formal way to identify the relevant information with respect to a goal can be obtained exploiting the information bottleneck (IB) principle. In this paper, we propose a goal-oriented communication system, based on the combination of IB and stochastic optimization. The IB principle is used to design the encoder in order to find an optimal balance between representation complexity and relevance of the en-coded data with respect to the goal. Stochastic optimization is then used to adapt the parameters of the IB to find an efficient resource allocation of communication and computation resources. Our goal is to minimize the average energy consumption under constraints on average service delay and accuracy of the learning task applied to the received data in a dynamic scenario. Numerical results assess the performance of the proposed strategy in two cases: regression from Gaussian random variables, where we can exploit closed-form solutions, and image classification using deep neural networks, with adaptive network splitting between transmit and receive sides.

7. L. N. Dinh, M. Maman and E. Calvanese Strinati (CEA), "**Proactive Resource Scheduling for 5G and Beyond Ultra-Reliable Low Latency Communications**," IEEE 95th Vehicular Technology Conference: (VTC2022-Spring, 10.1109/VTC2022-Spring54318.2022.9860872.

Abstract

Effective resource use in Ultra-Reliable and Low-Latency Communications (URLLC) is one of the main challenges for 5G and beyond systems. In this paper, we propose a novel scheduling methodology (combining reactive and proactive resource allocation strategies) specifically devised for URLLC services. Our ultimate objective is to characterize the level of proactivity required to cope with various scenarios. Specifically, we propose to operate at the scheduling level, addressing the trade-off between reliability, latency and resource efficiency. We offer an evaluation of the proposed methodology in the case of the well-known Hybrid Automatic Repeat reQuest (HARQ) protocol in which the proactive strategy allows a number of parallel retransmissions instead of the ''send-wait-react'' mode. To this end, we propose some deviations from the HARQ procedure and benchmark the performance in terms of latency, reliability outage and resource efficiency as a function of the level of proactivity. Afterwards, we highlight the critical importance of proactive adaptation in dynamic scenarios (i.e. with changing traffic rates and channel conditions).

8. L. N. Dinh, I. Labrij, M. Maman, and E. Calvanese Strinati (CEA), "**Toward URLLC with Proactive HARQ Adaptation,**" in 2022 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), pp. 220–225. doi: 10.1109/EuCNC/6GSummit54941.2022.9815615.

Abstract

In this work, we propose a dynamic decision maker algorithm to improve the proactive HARQ protocol for beyond 5G networks. Based on Lyapunov stochastic optimization, our adaptation control framework dynamically selects the number of proactive retransmissions for intermittent URLLC traffic scenarios under time-varying channel conditions without requiring any prior knowledge associated with this stochastic process. It then better exploits the trade-off between Radio Access Network (RAN) latency, reliability and resource efficiency, which is still limited in its realization on current HARQ designs. We then evaluate the performance of several HARQ strategies and show that our proposal further improves latency over the reactive regime without affecting the resource efficiency such as fixed proactive retransmission while maintaining target reliability.

9. A. Schultze, M. Schmieder, S. Wittig, H. Klessig (BOSCH), M. Peter and W. Keusgen (HHI), **"Angle-Resolved THz Channel Measurements at 300 GHz in an Industrial Environment,"** 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), 2022, pp. 1-7, doi: 10.1109/VTC2022-Spring54318.2022.9860598.

Abstract

This paper presents first angle-resolved measurement results in the terahertz domain for an industrial environment. The measurement campaign carried out is to be understood as a feasibility study on terahertz communication in industrial environments. Impulse response data accumulated with a correlative time-domain channel sounder that operates at a carrier frequency of 300 GHz with a measurement bandwidth of 2 GHz is analyzed with regards to channel parameters such as path gain, path loss, delay spread and angular spread. Three distinguishing carried out industrial measurement scenarios each report a successful execution. Multipath component analysis is realised based on an exceptionally high dynamic range of about 60 dB. The analysis of the collected data shows that mentioned channel parameters can be obtained for industrial surroundings that are heavily dominated by machinery, metal cladding and concrete.

10. S. Wittig, M. Peter and W. Keusgen (HHI), **"A Reference Model for Channel Sounder Performance Evaluation, Validation and Comparison,"** 2022 16th European Conference on Antennas and Propagation (EuCAP), 2022, pp. 1-5, doi: 10.23919/EuCAP53622.2022.9769264.

Abstract

In this paper, we propose a detailed generic reference plane model for performance evaluation and system validation of radio channel sounders. It allows to abstractly describe a broad variety of channel sounder implementations and architectures in a common framework, thus facilitating systematic evaluations and comparisons. To illustrate the utility of the concept, we present the mapping of two practical channel sounder realizations—one time domain and one frequency domain—to the model, along with selected performance metrics defined on its reference planes. For the two presented channel sounders, we give measurement examples for these metrics.

11. L. N. Dinh, R. Bertolini, M. Maman (CEA), "**Dynamic Resource Scheduling Optimization for Ultra-Reliable Low Latency Communications: From Simulation to Experimentation**," in 2022 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Sep. 2022.

    Abstract

    In this paper, we propose a dynamic and efficient resource scheduling based on Lyapunov's optimization for Ultra-Reliable Low Latency Communications, taking into account the traffic arrival at the network layer, the queue behaviors at the data link layer and the risk that the applied decision might result in packet losses. The trade-off between the resource efficiency, latency and reliability is achieved by the timing and intensity of decisions and is adapted to dynamic scenarios (e.g., random bursty traffic, time-varying channel). Our queue-aware and channel-aware solution is evaluated in terms of latency, reliability outage and resource efficiency in a system-level simulator and validated by an experimental testbed using OpenAirInterface.

12. L. N. Dinh, M. Maman and E. Calvanese Strinati (CEA), "**Hybrid Radio Resource Management for Ultra-Reliable Low Latency Communications based on Multi-Agent Reinforcement Learning**," submitted to IEEE ICC conference 2023, Rome, Jun. 2023.

    Abstract

    In this paper, we propose a novel hybrid grant-based and grant-free radio access scheme for Ultra Reliable and Low Latency Communications (URLLC). We provide two multi-agent reinforcement learning algorithms to optimize a global network objective in terms of latency, reliability and network throughput: Multi-Agent Deep Q-Learning (MADQL) and Multi-Agent Deep Deterministic Policy Gradient (MADDPG). In MADQL, each user (agent) learns its optimal action-value function, which is based only on its local observation, and performs an optimal opportunistic action using the shared spectrum. MADDPG involves the attached gNB function as a global observer (critic), which criticizes the action of each associated agent (actor) in the network. By leveraging centralised training and decentralised execution, we achieve a shared goal better than the first algorithm. Then, through a system level simulation where the full protocol stack is considered, we show the gain of our approach to efficiently manage radio resources and guarantee URLLC.

2.3.2 Scientific Journals

In addition, contributions to scientific journals are a suitable means to disseminate mature and substantial results of the 5G CONNI consortium with great visibility in the scientific community. A list of the seven published targeted journal papers is given in the following:

1. M. Maman et al., "**Beyond private 5G networks: applications, architectures, operator models and technological enablers**," Journal on Wireless Communications and Networks 2021, 195 (2021). https://doi.org/10.1186/s13638-021-02067-2

    Abstract

    Private networks will play a key role in 5G and beyond to enable smart factories with the required better deployment, operation and flexible usage of available resource and

infrastructure. 5G private networks will offer a lean and agile solution to effectively deploy and operate services with stringent and heterogeneous constraints in terms of reliability, latency, re-configurability and re-deployment of resources as well as issues related to governance and ownership of 5G components, and elements. In this paper, we present a novel approach to operator models, specifically targeting 5G and beyond private networks. We apply the proposed operator models to different network architecture options and to a selection of relevant use cases offering mixed private–public network operator governance and ownership. Moreover, several key enabling technologies have been identified for 5G private networks. Before the deployment, stakeholders should consider spectrum allocation and on-site channel measurements in order to fully understand the propagation characteristic of a given environment and to set up end-to-end system parameters. During the deployment, a monitoring tools will support to validate the deployment and to make sure that the end-to-end system meet the target KPI. Finally, some optimization can be made individually for service placement, network slicing and orchestration or jointly at radio access, multi-access edge computing or core network level.

2. M. Merluzzi, N. d. Pietro, P. Di Lorenzo, E. C. Strinati (CEA) and S. Barbarossa (SAP), "**Discontinuous computation offloading for energy-efficient mobile edge computing**," in IEEE Transactions on Green Communications and Networking, vol. 6, no. 2, pp. 1242-1257, June 2022, doi: 10.1109/TGCN.2021.3125543.

   Abstract

   We propose a novel strategy for energy-efficient dynamic computation offloading, in the context of edge-computing-aided beyond 5G networks. The goal is to minimize the energy consumption of the overall system, comprising multiple User Equipment (UE), an access point (AP), and an edge server (ES), under constraints on the end-to-end service delay and the packet error rate performance over the wireless interface. To reduce the energy consumption, we exploit low-power sleep operation modes for the users, the AP and the ES, shifting the edge computing paradigm from an always on to an always available architecture, capable of guaranteeing an on-demand target service quality with the minimum energy consumption. To this aim, we propose an online algorithm for dynamic and optimal orchestration of radio and computational resources called Discontinuous Computation Offloading (DisCO) . In such a framework, end-to-end delay constraints translate into constraints on overall queueing delays, including both the communication and the computation phases of the offloading service. DisCO hinges on Lyapunov stochastic optimization, does not require any prior knowledge on the statistics of the offloading traffic or the radio channels, and satisfies the long-term performance constraints imposed by the users. Several numerical results illustrate the advantages of the proposed method.

3. C Battiloro, P Di Lorenzo, M Merluzzi, S Barbarossa (SAP), "**Lyapunov-based optimization of edge resources for energy-efficient adaptive federated learning**", IEEE Transactions on Green Communications and Networking, 2022

   Abstract

   The aim of this paper is to propose a novel dynamic resource allocation strategy for energy-efficient adaptive federated learning at the wireless network edge, with latency and learning performance guarantees. We consider a set of devices collecting local

data and uploading processed information to an edge server, which runs stochastic gradient-based algorithms to perform continuous learning and adaptation. Hinging on Lyapunov stochastic optimization tools, we dynamically optimize radio parameters (e.g., set of transmitting devices, transmit powers, bits, and rates) and computation resources (e.g., CPU cycles at devices and at server) in order to strike the best trade-off between power, latency, and performance of the federated learning task. The framework admits both a model-based implementation, where the learning performance metrics are available in closed-form, and a data-driven approach, which works with online estimates of the learning performance of interest. The method is then customized to the case of federated least mean squares (LMS) estimation, and federated training of deep convolutional neural networks. Numerical results illustrate the effectiveness of our strategy to perform energy-efficient, low-latency, adaptive federated learning at the wireless network edge

4. F Binucci, P Banelli, P Di Lorenzo, S Barbarossa (SAP), "**Adaptive Resource Optimization for Edge Inference with Goal-Oriented Communications**", accepetd for publication on the EURASIP Journal on Advances in Signal Processing, 2022.

Abstract

Goal-oriented communications represent an emerging paradigm for efficient and reliable learning at the wireless edge, where only the information relevant for the specific learning task is transmitted to perform inference and/or training. The aim of this paper is to introduce a novel system design and algorithmic framework to enable goal-oriented communications. Specifically, inspired by the information bottleneck principle and targeting an image classification task, we dynamically change the size of the data to be transmitted by exploiting banks of convolutional encoders at the device in order to extract meaningful and parsimonious data features in a totally adaptive and goal-oriented fashion. Exploiting knowledge of the system conditions, such as the channel state and the computation load, such features are dynamically transmitted to an edge server that takes the final decision, based on a proper convolutional classifier. Hinging on Lyapunov stochastic optimization, we devise a novel algorithmic framework that dynamically and jointly optimizes communication, computation, and the convolutional encoder-classifier, in order to strike a desired trade-off between energy, latency, and accuracy of the edge learning task. Several simulation results illustrate the effectiveness of the proposed strategy for edge learning with goal-oriented communications.

5. S. Barbarossa et al. (SAP), **Semantic Communications Based on Adaptive Generative Models and Information Bottleneck**"", submitted to IEEE Communication Magazine, 2022

Abstract

Semantic communications represent a significant breakthrough with respect to the current communication paradigm, as they focus on recovering the meaning behind the transmitted sequence of symbols, rather than the symbols themselves. From the semantic perspective, given a set of symbols encoding the semantic message to be communicated, the scope of the destination is not to recover a list of symbols symbolically identical to the transmitted one, but rather to recover a message that is semantically equivalent to the semantic message emitted by the source. This paradigm shift adds many degrees of freedom to the encoding and decoding rules that can be exploited to

make the design of communication system much more efficient. In this paper, we present an approach to semantic communication that exploits probabilistic generative models and the information bottleneck principle to capture the semantic of the data and adapt the amount of information to be transmitted to the channel state and to the online check of performance. The method is suitable for transmissions over a wireless channel because it adapts the information bottleneck in order to strike an optimal trade-off between transmit power, reconstruction accuracy and delay

6. F. Costanzo, P. Di Lorenzo, S. Sardellitti. S. Barbarossa (SAP), "**Energy-Efficient Edge Computing with Dynamic Virtual Network Service Placement and Routing**", ready for submission to the IEEE Wireless Communication Letters.

   Abstract

   In this paper, we propose a dynamic algorithm to enable energy-efficient mobile edge computing with end-to-end delay guarantees, jointly optimizing placement and routing of network services with radio and computation resources. We consider a dynamic network scenario that is modeled and controlled using proper communication and computation queues. Merging Lyapunov stochastic optimization and approximating algorithm for binary problems, we jointly optimize communication parameters (i.e., transmit power) and computing resources (i.e., server CPU frequencies), while solving the virtual service placement and request routing problem. Numerical simulations assess the effectiveness of our dynamic optimization, assessing its performance with respect to the state of the art.

7. F. Costanzo, P. Di Lorenzo, S. Sardellitti. S. Barbarossa (SAP), " **Virtual Service Placement and Routing with Resource Scheduling in Edge Cloud Networks**", to be submitted to IEEE Transactions (to be decided)

   Abstract

   The role of efficient network resource management has become more and more important with the increase of network service requirements. User device demands for such applications have grown beyond all expectations and with them the knowledge of the need for accurate network control. In this work, we propose a novel method to optimize the placement of network services and jointly routing device requests, in the context of Edge Clouds architecture. At the same time, we further improve the optimization of communication and computation resources, leveraging the Franke-Wolfe method, aiming at minimize the overall delay experienced by any device to obtain requested services

2.3.3 Workshops and (invited) speeches

The 5G CONNI consortium achieved publicity not only through dissemination of scientific publications, but also through the organization of workshops, industrial seminars and panels at international top ranked conferences and events. The main intention was to disseminate the project vision and results at large, targeting different audiences from academia and research, to industry and vertical markets operators, to institutional policy makers and standardization bodies. Besides the organization of workshops, this was also achieved through several invited talks, where the key results of the project were shared.

5G CONNI partner Fraunhofer HHI organized the Workshop on Terahertz Channels and Systems in collaboration with 5G mmW Channel Model Alliance, IEEE VT-S Propagation Committee and IEEE SA P2982. In line with one of the project's focus areas, the workshop focused on latest results in the field of radio propagation research at Terahertz frequencies. In a talk ntitled “A High Performance Channel Sounder at 300 GHz: Design, Verification and Measurements”, the channel sounder that was used for the 300 GHz measurements in the project was presented.

Several 5G CONNI consortium members were invited to talk at international conferences and events where they were able to share the project results and ideas with a broad audience. Prof. Sergio Barbarossa (SAP) has been an invited speaker at the following international conferences

- S. Barbarossa, "New tools for next generation networks: From topological signal processing to goal-oriented communications", Como PhD Summer School, July 2021
- S. Barbarossa, "Wireless Edge Machine Learning", Futurewei University Days Workshop, August 2021
- S. Barbarossa, "Goal-oriented communications: How to be more efficient by transmitting less", 17th International Symposium on Wireless Communication Systems, Berlin, Sep. 6, 2021
- S. Barbarossa, "Semantic and goal-oriented communications via information bottleneck and topology", EuCNC Workshop on Semantic and Goal-Oriented Communications", June 2022.
- S. Barbarossa, "Network Intelligence", 61st FITCE International Congress, Sep. 2022.
- S. Barbarossa, "Semantic and goal-oriented communications", IFIP/IEEE PEMWN 2022: The 11th IFIP/IEEE international conference on performance evaluation and modeling in wired and wireless networks, Nov. 2022.
- S. Barbarossa, "Intelligent and autonomous systems and services", 5G-Italy, Nov. 2022

Emilio Calvanese Strinati (CEA) has been an invited speaker at the following international conferences:

- E. Calvanese Strinati, „6G Fundamentals – Panel Discussion 6G Symposium – Shaping Industry & Society Beyond 5G, May 2021, Virtual Conference.
- E. Calvanese Strinati, „ Beyond 5G Networks with Semantic Communications, Digiscom Seminars, Paris, 1 of June 2021.
- E. Calvanese Strinati, "Toward 6G with Semantic and Goal-Oriented Communications", Como PhD Summer School, July 2021.
- E. Calvanese Strinati, „Revolution is in the Air – Part 1: The Air Interface“, Plenary Panel at 6G Symposium, Fall 2021, 21 of September 2021.
- E. Calvanese Strinati, "Semantic and goal-oriented communications in 6G Networks", EuCNC Workshop on Semantic and Goal-Oriented Communications", June 2022.
- E.Calvanese Strinati, “6G and the role of expressive languages’, 6G Summit Abu Dhabi, Nov. 2022

2.4 Standardization activities

Besides sharing project results with the academic community, the 5G CONNI consortium was actively monitoring the progress and outcome of relevant standardization bodies working on topics related to the project. While the consortium initially focused activities within 3GPP, active, continuous, and effective participation in 3GPP standardization is a resource-intensive effort that cannot be maintained in the scope of individual funded projects alone. At the start of 5G CONNI, project partner HHI was maintaining relevant supporting activities to disseminate

project results to 3GPP. It was this activity that was intended to provide the main access to 3GPP for the 5G CONNI consortium. These activities, however, were scaled back during the COVID-19 pandemic by management decision, effectively eliminating the capability to contribute to 3GPP working groups.

Standardization efforts have since focused on those bodies to which partners had most effective access, such as ETSI MEC. Where possible, the consortium tried to push the main results coming out of the project into standards. In the following sub-sections, the specific activities in each forum will be described.

2.4.1 ETSI MEC

In line with the activities carried out in the previous reporting period, 5G CONNI partner Athonet kept contributing to the work item DGS/MEC-0033 IoT API of the ETSI MEC Industry Standardization Group. As previously reported, the ETSI MEC aims at creating a standardized, open IT service environment which allows the efficient and seamless integration of applications from vendors, service providers, and third parties at the edge of the radio access network. The potential of MEC platforms for an Industry 4.0 scenario entailing Internet of Things (IoT) traffic exchange, which is the core of the 5G CONNI project, is tremendous, as these edge servers and their capabilities are crucial enablers of low-latency applications and a guarantee of user-plane traffic confidentiality.

In particular, ATH continued its work on the IoT API specifications with a series of submitted items accepted by the standardization group. Here follows a list of the main contributions:

- MEC(22)000396
- MEC(22)000395
- MEC(22)000394
- MEC(22)000393
- MEC(22)000392
- MEC(22)000386
- MEC(22)000309
- MEC(22)000290
- MEC(22)000092
- MEC(22)000091

They concern the means to integrate non-standard IoT platforms in a system that is instead compliant with the ETSI MEC framework. This happens via the exposition of IoT APIs, that allow to parametrize the components of the overall IoT system. Namely, the specified IoT APIs enable IoT platform discovery, IoT device provisioning, and user transport configuration.

Moreover, ATH gave a presentation and demonstrated a proof-of-concept MEC IoT Service at the ETSI IoT Week, held in Sophia Antipolis (France) between Oct. 10th to 14th, 2022. The presentation focused on illustrating the IoT platforms of major cloud providers such as AWS and Microsoft Azure and their architecture, emphasizing the common procedures of deployment and configuration of message buses, IoT applications, and IoT devices. ETSI IoT APIs would then play a role in discovering IoT platforms, provisioning IoT devices, and connecting the two in a standardized way. In this way, it would no longer be the IoT devices that would have to communicate directly to an IoT platform, having to use each one's proprietary software development kits, but it would be the MEC IoT Service that would act as a conduit. This service offered by the MEC host would give the ability to communicate toward IoT platforms even to IoT devices that do not have a full TCP/IP stack.

The proof of concept, instead, was about demonstrating a prototype MEC IoT Service configurable via IoT APIs that allow provisioning of IoT devices (the users) and provisioning of transports (sockets to an IoT application). The demonstration was focused on showing how, with only the information passed to the MEC IoT Service via API, one could connect a mobile device to an IoT application. In this specific case, we used simulated UE and RAN devices attached to ATH's core network, and the open-source tools 'EMQX' and 'MQTT Explorer' were used to implement the MQTT message broker and IoT application. It was then shown how through the MEC IoT Service the UE was able to communicate with the IoT application by posting messages on the uplink topic.

2.4.2 IEEE

HHI has been maintaining its activities within working group IEEE P2982 "Recommended Practice for millimeter-wave channel sounder verification", which it helped to establish in early 2021 and is currently vice-chairing. The project results published in conference papers 1 and 10 as reported in Sec. 2.3.1 are directly related to this activity and have also been contributed to the P2982 working group

HHI is continuing to contribute to the newly developed standard in the areas of performance metric definition, conducted verification and OTA verification of its millimeter-wave and sub-THz channel sounders.

2.4.3 ITU

Results of work package 3 were used in a contribution to the ITU Study Group 3 that is refining ITU recommendation P.1238: Propagation data and prediction methos for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 450 GHz. Path loss data extracted from the measurements that were conducted during the 5G CONNI project was submitted to ITU and are now included in the Study Group 3 databanks containing radiowave propagation measurement data.

2.4.4 Regulatory bodies impact

One of the objectives of the 5G CONNI project was to provide input to regulatory bodies to facilitate realization of the developed operator models. Throughout the year 2022, Fraunhofer HHI held regular phone conferences with the German telecommunications regulation agency BNetzA. In December 2022, an in-person workshop was held at HHI Berlin with representatives from BNetzA's national frequency allocation group, campus network group, ITU-R mission, and millimeter-wave team. HHI gave an in-depth presentation of the project's results and findings with respect to 5G campus networks practice, radio propagation in the industrial domain and sub-THz frequency range. BNetzA agreed on an ongoing cooperation with further meetings to be held in 2023.

3 Updated Exploitation plans

Over the course of the project, the consortium was continuously disseminating project results. As the work packages progressed in the second half of the project, more and more results were generated that could be disseminated to both scientific and non-scientific audiences. Even though the status quo for dissemination was heavily impacted by the ongoing COVID-19 situation and in-person meetings were cancelled on a large scale, alternative means for dissemination were leveraged and no magor updates on the project's general dissemination and exploitation plan as laid out in the grant agreement and the dissemination plan are required.

Several partners are planning to further exploit the project results even beyond the lifetime of the 5G CONNI project. Furthermore, several aspects developed within the project form the basis for invention disclosures that will lead to patents held by consortium members.

3.1 Partner Update

In this subsection, each partner of the 5G CONNI consortium elaborates on its own specific exploitation plan for the project results.

3.1.1 Alpha Networks

During the 5G CONNI project, ANI contributed the 5G RAN system including the CPE, indoor 250mW RU and CDU (CU+DU) which can work with the 5GC provided by III and ATHONET. The end-to-end system provides the 5G service for selected use cases in WP5.

Based on this outcome, ANI continues to deploy this system to enable several up-coming field trials for PoS and PoB. The uses cases in the PoS and PoB are different from those in 5G CONNI project. So the current indoor RU will integrated with DAS and a new 5W outdoor RU will be developed to be deployed in the field of factory and outdoor harbor.

ANI will continue to explore the 5G & B5G opportunities and provide the robust & cost-effective mobile communication system for the enterprise market.

3.1.2 Athonet

Athonet will benefit from the results of the 5G CONNI project in several ways. The integration/interoperability with other consortium partners will foster the development of a top-level virtualized solutions for 5G connectivity. Moreover, the project pilots will promote the adoption of private deployments of 5G mobile networks, thus increasing the awareness and business opportunities created by this technology for industrial applications. This trend will eventually accelerate the corporate market growth. In addition, Athonet would like to highlight that its obtained results within the activities of WP4 are particularly suitable for further exploitation. Athonet is counting to build upon those results for its research and innovation activities and utilize the developed in-lab testbed for further activities in other subsidized European or national projects.

3.1.3 BOSCH

BOSCH has been following the initially planned exploitation plan until the end of the project in December 2022. Of particular importance were the understanding of the operation and maintenance of private 5G networks, their different architectures, the concerns and requirements of operator models and IT security requirements in the 5G CONNI activities in the previous two project years. In the third year, BOSCH was concentrating on the implemenation of and experimentation with the 5G CONNI use cases. These evaluations provided an excellent understanding of private 5G particularities on robotic use cases with an impact on corresponding product concepts, and with this on new business opportunities in the context of 5G-enabled factories. The insights gained from the 5G CONNI project will help BOSCH advance further in research and innovation towards 6G. In this context, the concepts of network-of-networks and

subnetworks are certainly of particular interest. Here, the work with private 5G networks laid a considerable part of the foundation to start future work in the direction of these two new concepts.

3.1.4 CEA

CEA has followed the initial exploitation plans until now. On the one hand, the outcomes of CEA's investigations on how to manage a private 5G network (orchestration and mobile edge computing), having the specific targets of improving QoS (reliability, latency, availability...) in future 5G networks, have been protected through patents (e.g. 1 filled and 1 under progress patent), and they have been disseminated through publications in high-rank international conferences, journals, and workshops. With 5GCONNI project, CEA has gained expertise in 5G private networks and will go on investigations on 5G network orchestration using deep reinforcement learning and on semantic and goal-oriented communications CEA will continue to promote the researches initiated in the project in several tutorials and workshops. On the other hand, CEA aims at the integration of some of the most promising concepts of multiple access in future communication devices with the objective to address a wide range of services. The results of 5G CONNI will contribute to enhance the offers of CEA to industrial partners in search of wireless URLLC solutions for future applications.

3.1.5 Chunghwa Telecom

CHT has followed the initial exploitation plans until now. CHT contributes bump-in-the-wire 5G SA MEC for the Taiwanese testbed of the 5G CONNI project. CHT has developed a 5G SA MEC prototype and the monitoring mechanism of VNF on the ECoreCloud (ECC) platform and integrated Process Diagnostics using an Augmented Reality application. With the MEC offered by CHT, the system is able to achieve the point of view of a higher bandwidth, lower latency, increased security, and reduced network congestion by performing applications and processing tasks closer to the enterprise site. Moreover, industrial applications will also be managed by the ECoreCloud (ECC) platform for onboarding and monitoring, as well as optimizing transmission performance. These results are implemented on ITRI's IMTC demo site, exhibited at IEEE Globecom 2020 event and APNOMS 2022 technical session and EU-TW 6G SNS Workshop. CHT will continue to observe edge computing development and propose suitable 5G solutions for industrial applications.

3.1.6 HHI

HHI continues to follow its initial plan for exploitation and dissemination of project results. No updates to the plan itself are reported. Within the 5G CONNI project, HHI has followed two primary lines of work: characterization of radio channels in the industrial environment and design and deployment of private 5G networks.

With respect to radio channel characterization, the work conducted in 5G CONNI led to major new developments and a modernization of HHI's channel sounding equipment and software toolchain. Internally, this has been used for introduction of new PhD and Master students into the topic and serves as the basis for their future work. Externally, software and measurement methodology is shared with partners and customers as part of HHI's channel sounding solution. The extensive body of measurement data obtained from factory premises in the first half of the project continue to be analyzed and evaluated by PhD students. Selected results have been contributed to ITU-R standardization.

Furthermore, 5G CONNI enabled HHI to acquire expertise in the area of private 5G campus networks, both conceptually and operationally. Within the project, a major part of HHI's own multi-site 5G campus network and testbed infrastructure was planned and built. This continues to serve as the basis for a larger number of ongoing and new funded research projects, as well as cooperation with industry partners and small to medium sized enterprises, for example in

the context of 5G Berlin innovation cluster. Through the expertise gained within the project, HHI was able to build a continuing exchange with the German national telecommunications regulator BNetzA, providing independent insights on matters related to private mobile radio networks and radio propagation. This exchange is already planned to extend well beyond the project's end date.

3.1.7 III

III is the main maintainer and key contributor of the 5G SA core network for use cases in Taiwanese demo site. For the additional exploitation plan from III, including deploying the III Core for system integration and new functions development. The 5G Core Network Manager (CNM), the network monitoring functions, has been implemented, which provides FCAPS (fault management, configuration management, accounting management, performance management and security management) functions. Also, a unified centralized provisioning system has been implemented.

3.1.8 ITRI

ITRI has been disseminating the project results through publications and demonstration in public events. More specifically, the inter-site use case "Remote Expert Support for Process Diagnosis" has been showcased at EU-Taiwan Joint 6G SNS Workshop. In addition, ITRI has contributed to the joint paper organized by CHT and accepted by APNOMS 2022. ITRI will continue this effort for the innovations and developments of the 5G CONNI project to maximize the exploitation for the common good of the mobile wireless industry as a whole.

3.1.9 SAP

SAP is planning to build on the expertise gained with 5G CONNI and in particular by continuing the research on semantic and goal-oriented communications initiated in 5G CONNI. The initial results obtained in this research field in 5G CONNI have quite a broad impact, as testified by the number of invited talks. These results are going to represent the starting point of an important Italian national project, RESTART, that is starting on Jan. 2023. SAP plans also to continue the dissemination activities of the main research areas initiated in 5G-CONNI through master students and it is also planning to open a number of PhD positions on this area.

3.2 Patents

In the second half of the project, 4 invention disclosures were prepared. CEA filed a patent on early decision maker for URLLC (M. Maman, L. N. Dinh, E. Calvanese Strinati, "Method to exploit latency distribution for early decision making,", FR2103542.) and one is under preparation (L. N. Dinh, M. Maman, E. Calvanese Strinati, "Methods and apparatus for jitter-aware scheduling in wireless Time Sensitive Network communications,"). Two further patents were filed; however, no detailed information may be given prior to their publication by the patent office due to confidentiality.

4 Conclusion

In this deliverable, the dissemination and standardization activities of the second half of the 5G CONNI project were summarized. During this period, the consortium used all means available, both online and in-person, to share the project vision and results with a broad audience. A conference paper co-authored by the whole consortium in the first period was extended to a publication in the Journal on Wireless Communication and Networks. Furthermore, six other journal and twelve conference publications were published in the second half of the project.

Several project partners held (invited) keynote talks and (co-)organized workshops and special sessions, where the 5G CONNI vision and perspective was disseminated to a broad audience, both academic and non-academic.

Another goal of work page 6 was pushing the results of the 5G CONNI project into standardization. In the second half of the project, the consortium focused on activities within ETSI MEC, IEEE, and ITU. Several contributions were prepared, and it is foreseeable that project results will still be of relevance beyond the lifetime of the project. For example, the German telecommunications regulation agency already agreed to an ongoing cooperation with further meetings to be held in 2023.

Finally, a report on the patents filed in conjunction with the project and an update to the exploitation plan beyond the time of the project is provided by each partner.