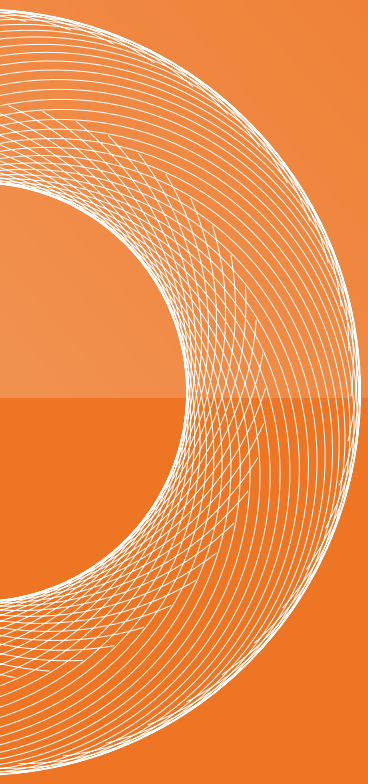
2021

ANNUAL REPORT

Advanced research for everyday life

INDEX

Providing 5G wireless and network technologies



Editorial

Taking care of the researcher to excel in research.

The year 2021 has been a transition year due to the change of Director and several new things have been put in place and begun with the aim at facilitating the CTTC growth.

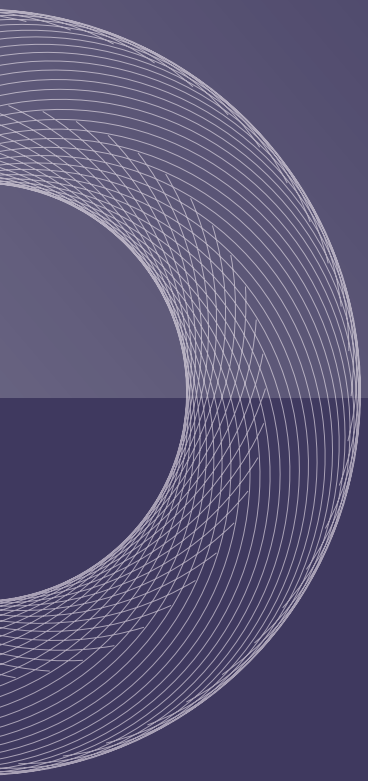
In terms of organization, from the four Research Divisions we have restructured into nine Research Units, which has helped, among other things, to initiate and or intensify new research topics, such as Artificial Intelligence or Quantum Communications. The transition has been smooth and followed the researchers interests, after a final supervision by the Direction. This change has been accompanied by a change in the Strategic and Functional plan and also in the Scientific and Advisory Board. Both of them initiated in 2021 and finalized in 2022. The Direction Unit has also changed in order to better address some compelling aspects, such as the development of an integral communication project or the industrial projects and IPR.

Concerning the working conditions, the implementation of the HRS4R has been finalized, which has helped very much also to improve the recruitment transparency and process. The Direction has also put several efforts in reviewing the salary policy in order to allow a longer promotion path. An internal promotion was put in place for the permanent structural people and will be followed by yearly promotions. Also, the goal is to increase the number of permanent structural positions for researchers.

The budget closed in 2021 with a healthy superhabit that has allowed to stabilize some initiatives to empower research: calls for internal projects and for transitional predoctoral grants. An outcome worth standing out is CTTC success in the UNICO5G national call, with 22 M€. New spaces in the building B6 have begun to be conditioned to accommodate new labs.

Ana Isabel Pérez-Neira
Director

Imagining network architectures for disruptive services



CTTC: mission, vision & values

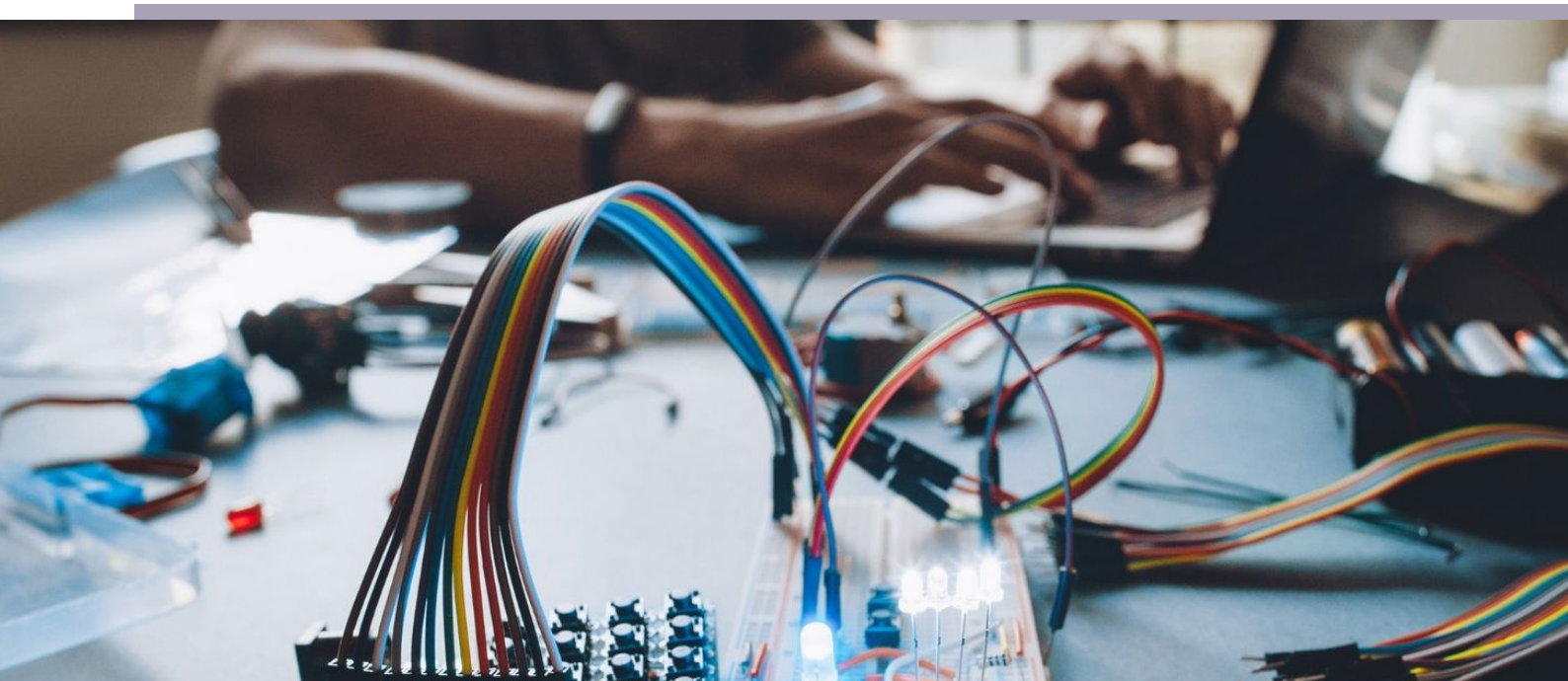
CTTC's core activity is the conception, design, implementation and experimentation of research and development projects in telecommunications and geomatics, which must **produce innovative results** in their different development phases, both in scientific and in engineering terms.

Of outmost importance is to establish durable links with the industrial and business sectors, reinforcing CTTC's position as a player of innovation process through its research with industry. CTTC's ultimate mission is to be an Excellence flagship Center that serves as a bridge between academia and industry. A center that influences the future paths of communication technologies, systems, networks, and geomatics. Started in 2001 with young graduates, with engineering or PhD degrees. Currently CTTC staff has achieved a level of maturity that favors developing research in future emerging fields and reinforcing areas of expertise.

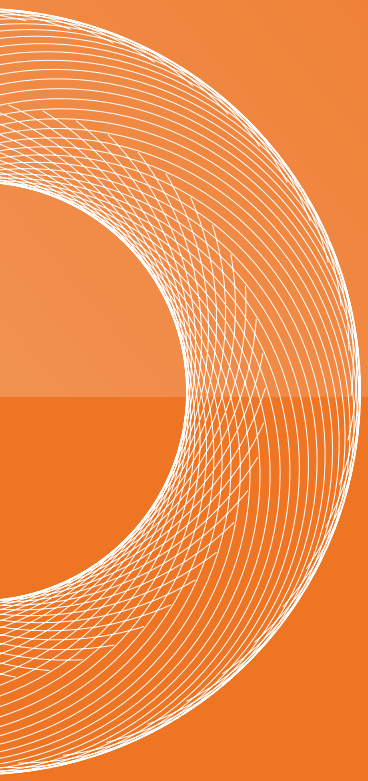
It is our vision that research and technology development in communications, although starting from a public initiative, can be integrated in the competitive R&D market to rely on the private initiative in the long term (20-30 years). This vision implies to **"interact with local but offer global"** both in terms of research and engineering and to select partners heading for international R&D markets.

Our model consists in starting new activities both in research and engineering from young graduates really committed with research and development in engineering. The institution provides an adaptive and flexible environment, where personal position, responsibilities and rewards are strongly related with research and engineering reputation. Resources are dynamically associated to new projects in a structured scheme, i.e. AENOR UNE 166002:2014 Quality on R&D. The institution checks yearly personnel's motivation for R&D with an anonymous poll.

Our main objective is **to create the maximum number of new permanent jobs** on R&D in communications engineering, with the best tradeoff between quantity and quality of our funding resources. We are convinced that, in this kind of initiatives, people are what configures the international reputation of the institution and not vice versa. A **highly motivated staff**, working at the cutting edge of research, are the key factor for CTTC success. CTTC is a CERCA center and, as such, it promotes research with scientific integrity and professional ethics. These dynamics must allow to lead the future CTTC course towards an institution that outstands in the green economy and open science, always meeting the needs of the end users, in **Catalunya, Spain** and **worldwide**.



Connecting people, connecting objects for a smarter and more secure society

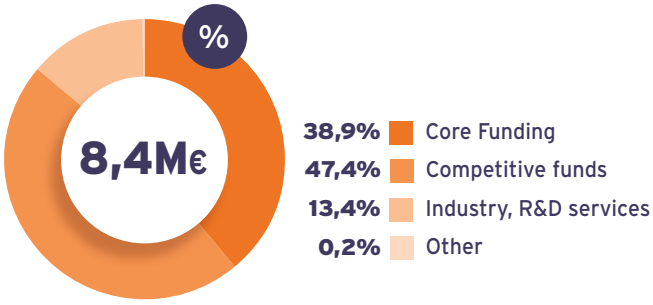


Facts & Figures

CTTC 2021 in numbers

PROJECTS

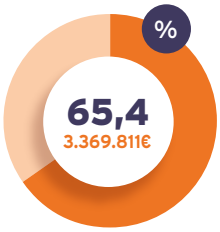
Income distribution



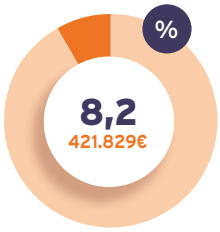
Total amount of competitive funding

~4M€

Income Projects



EUROPEAN ADMINISTRATION



SPANISH ADMINISTRATION

CATALAN ADMINISTRATION

R&D SERVICES (INDUSTRY)

OTHER

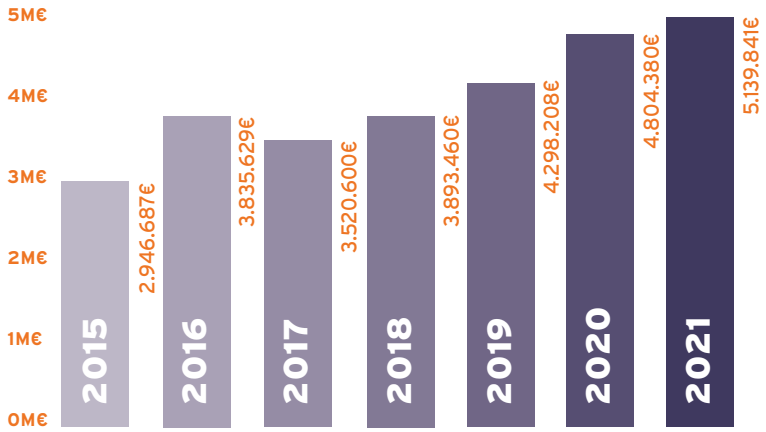
Project distribution

37 29 % European projects

50 39 % National projects

41 32% Industrial projects

Total Income (raised own funds) from 2015 to 2021



74%

GROWTH RATE FROM 2015 TO 2021

Project Rankings

In terms of EC funding

22nd in H2020 in Spain

25th in LEIT-ICT (4th in Spain)

2nd in 5G-PPP (1st in Spain)

In terms of project participation

27th in H2020 in Spain

26th in LEIT-ICT (6th in Spain)

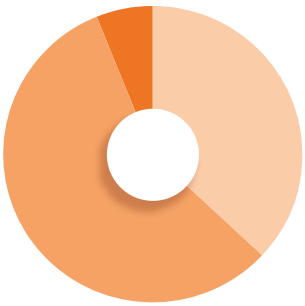
2nd in 5G-PPP (1st in Spain)

In terms of Spanish funding

1st In UNICO 5G I+D funding (NextGeneration)

SCIENTIFIC PUBLICATIONS

Number of Scientific Publications



91 Journals (Indexed)

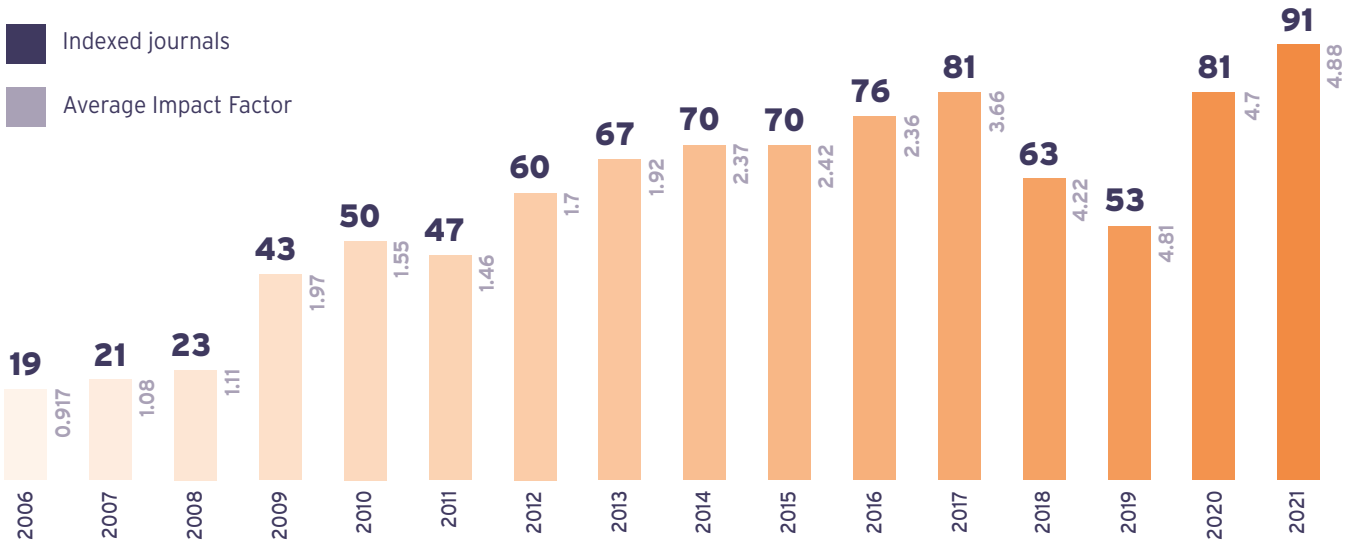
140 Conferences

15 Books and Chapters

62 % FIRST QUARTILE

4.88 % AVERAGE IMPACT FACTOR

Evolution of the average impact factor (Indexed journals)



100 % PUBLICATIONS IN OPEN ACCESS

KNOWLEDGE & TECHNOLOGY TRANSFER

1 spin-off

GEO KINESIA

LAND AND STRUCTURE DEFORMATION
Detection. Monitoring. Prediction

geokinesia.com

Granted patents in force

30

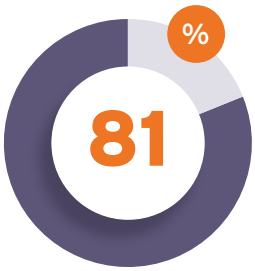
industry innovation

16

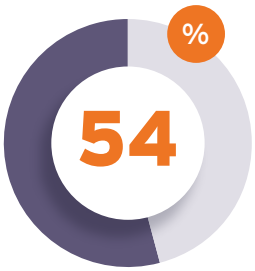
STAFF

130 TEAM MEMBERS

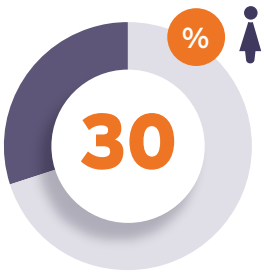
Details of team members



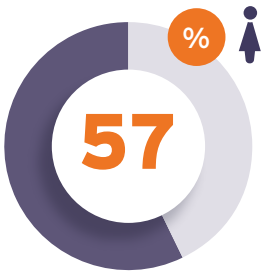
OF RESEARCHERS



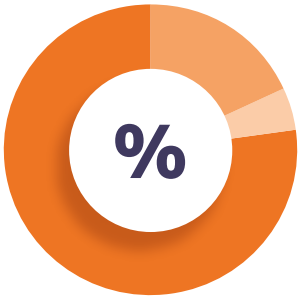
OF DOCTORS



OF WOMEN (IN RESEARCH)



OF WOMEN (IN MANAGEMENT)



5% Direction **19%** Support **81%** Research

R&D Personnel distribution

RESEARCH DIRECTOR **R4**

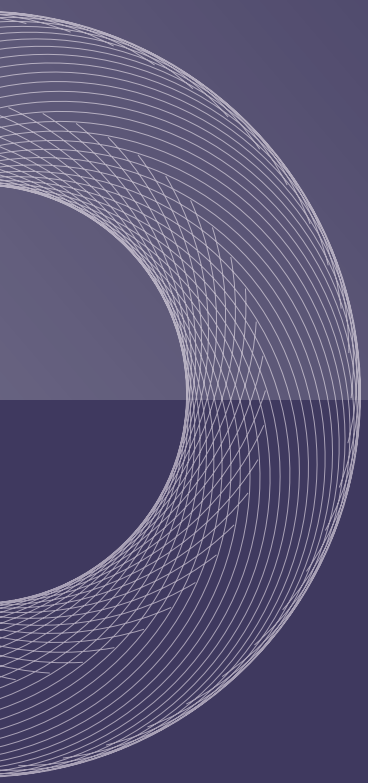
SENIOR RESEARCHER **R3**

RESEARCHER **R2**

RESEARCH TRAINEE **R1**

25 total number of different nationalities

Providing resilient global coverage and positioning



People

Management

is assisted by the Management team composed by the General Administrator and the Direction Unit:

The CTTC's Director
Prof. ANA ISABEL PÉREZ-NEIRA

MERCÈ CARRASCO
› **General Administrator**

DR. CARLES ANTÓN-HARO
› **Director of European Programs & Industry Contracts**

DR. MONICA NAVARRO
› **Director of Institutional Relations & Communication**

DR. MIQUEL PAYARÓ
› **Director of National Programs and their Industry Leads (Open Innovation & Science)**

DR. MICHELA SVALUTO MOREOLO
› **Director of Quality Programs**

DR. XAVIER MESTRE
› **Scientific Coordinator**

Board of Trustees

The Board of Trustees is the management organ and is currently constituted by members of the five promoting institutions.

- **Department of Economy and Knowledge (DECO) of Autonomous Government of Catalonia, General Direction of Research of Autonomous Government of Catalonia.**
- **Technical University of Catalonia (UPC).**
- **Ramon Llull University (URL).**
- **Department of Territory and Sustainability of Autonomous Government of Catalonia.**
- **Secretary of Telecommunications, Cybersecurity and Digital Society of Autonomous Government of Catalonia.**

Scientific Advisory Board

Given the transitional period of 2021 due to the retirement of the former Director, the Scientific Advisory Board was set inactive of its functions until the new Director was appointed and the Scientific Advisory Board could be reviewed under the new Direction.

As of the 31st of December 2021, the members' representatives were:

GEMMA GEIS I CARRERAS
Ministry of the Department of Research and Universities

DANIEL CRESPO I ARTIAGA
Chancellor of the Technical University of Catalonia (UPC)

JOSEP M. GARRELL
Chancellor of the University Ramon Llull (URL)

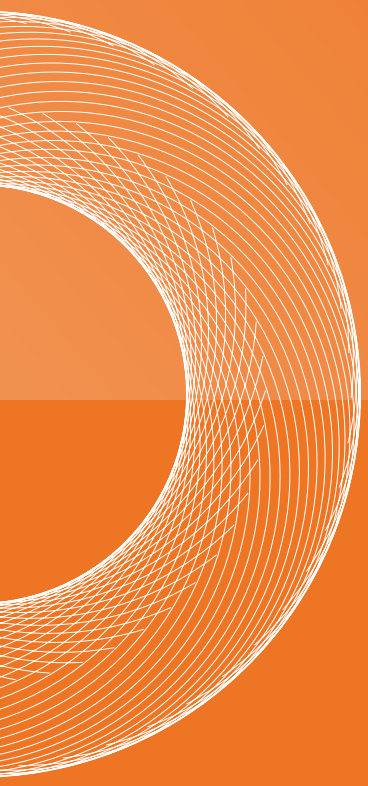
JOAN GÓMEZ I PALLARÈS
Director of Research of the Department of Research and Universities

XAVIER BAULIES I BOCHACA
Responsible of Research & Innovation of the Department of Vice-Presidency, Digital Policies and Territory

ORIOL PUIG I GODES
Sub-Director of Planification & Projects of the Department of Vice-Presidency, Digital Policies and Territory

DAVID FERRER I CANOSA
Secretary of Digital Policies

Preventing natural disasters and infrastructure failure



Research

Research units

Driven by the new Direction, research groups started a reorganization with the aim of improving CTTC's structuring to better cope with the research and development challenges posed by the evolution of wireless technologies, 5G networks and their applications.

As a result, 9 Research Units (RU) have emerged addressing

- **Terrestrial/satellite/space wireless communication systems and networks**
- **Network architectures, technologies, and tools**
- **Fundamental and applied research**
- **Testbeds and experimental platforms development**

This process has also given the opportunity for inhouse talent to take on new responsibilities and leadership roles.

Services as Networks

Dr. Josep Mangues
Head of SaS

The overall theme of the research unit is to design all the components related with what next generation networks need. These are divided in two main groups, one dealing with architectural components (Architectures for autonomous service networks) and its future evolution and the other related with all the required intelligence given the increasing complexity, dynamicity, and heterogeneity (Intelligence for service networks).

Furthermore, the underlying framework defined by these research lines will be used to serve the needs of multiple use cases, with particular interest in those putting more stringent requirements on the network, such as automotive, extended reality, and (industrial) IoT. Additionally, this research unit also envisions to extend its reach and scope as technologies evolve and new fields of application, potentially beyond networking, are identified. This is expected to be more likely in technologies like distributed ledgers or artificial intelligence, which have a huge potential in other fields (e.g., eHealth or smart city use cases).

Research activities focuses on the following topics of interest:

- **Architectures for autonomous service networks**
- **Intelligence for service networks**

Packet Optical Networks and Services

Dr. Raul Muñoz
Head of PONS

Packet Optical Networks and Services addresses packet optical communications and networking technologies, edge and cloud computing infrastructure for virtual functions and applications, and network and service management to provide high-speed, cost-effective, energy-efficient, secured, and reliable connectivity, network and slice services for multi-tenancy. It spans from the access to the metro and long-haul network segments, as well as inter and intra data center communication. To address sustainable high-capacity scaling and support network dynamicity, the adoption of spectrally and spatially multiplexed transmission systems with suitable photonic technologies and adaptive transceivers becomes crucial. Moreover, the emergence of quantum technologies and the prospect of quantum computing (which represents a threat for future network security) require to consider reliable security mechanisms and appropriate solutions to be adopted in the network infrastructure.

The main research activity falls into the following topics of interest:

- **Photonic and quantum communication technologies**
- **Control and Telemetry of Autonomous Packet/Optical Networks**
- **Zero-touch management and secured network service orchestration**

Developed optical communications and networking technologies will be essential to provide high-speed, cost-effective, energy-efficiency, secured and reliable connectivity services for 6G, spanning from the fixed access to the transport network, as well as for inter and intra data center communication.

Sustainable Artificial Intelligence

Dr. Paolo Dini
Head of SAI

Sustainable Artificial Intelligence aims to address the sustainability of developing and using Artificial Intelligence (AI) systems and to promote the use of AI towards the sustainable development goals. The priority is therefore on the design of AI systems for sustainable development while targeting the sustainability of AI training and usage. This RU is multi-disciplinary in nature and spans several research areas including data science, computer science, network science, information engineering, wireless communications, energy engineering, environmental engineering and remote sensing. In particular, the RU contributes to the design distributed/decentralized, energy-aware, low-complex, highly accurate and efficient, and interpretable ML methods enabling edge intelligence. In contrast with the centralized paradigm, it adopts a distributed and decentralized paradigm by exploiting edge intelligence, which leverages the intrinsically distributed nature of data sources to share computations among the edge devices that shall overcome current limitations.

Research activities focus on the following topics of interest:

- **Distributed and collaborative learning**
- **Sustainable computing for networked cyber-physical systems**
- **Machine learning operations for sustainable**

Open Simulations

Dr. Sandra Lagen
Head of OpenSIM

Open Simulations focuses on the design of the radio access network towards an open disaggregated Radio Access Network (RAN) in 6G. This includes developing advances in architectural aspects and controllers, spectrum sharing, Self-Organized Networks (SON), and Radio Resource Management (RRM), by using an analytical problem formulation and solving, through convex/non-convex optimization and/or ML-based techniques. This Research Unit also considers the design and the integration of the developed architectures, procedures and algorithms in a system level simulation framework. More specifically, in the open-source ns-3 network simulator, where CTTC develops and maintains the LTE, LTE-A and 5G NR modules. Leveraging on ns-3 5G-LENA design, development, validation, calibration, and evaluations, we will path the way towards the ns-3 6G-LENA implementation.

Research activities focus on the following topics of interest:

- **Spectrum sharing and 3GPP/IEEE**
- **Radio Resource Management and Self-organizing Network in disaggregated RANs**
- **RAN: models, algorithms, and architectures**

Information and Signal Processing for Intelligent Communications

Dr. Jesús Gómez
Head of ISPIC

Information and Signal Processing for Intelligent Communications, leveraging on a strong signal processing, communication, and information theory background, drives its activity towards the development of

- **Artificial Intelligence for PHY/MAC**
- **Large/distributed antenna systems**
- **Signal processing and coding for advanced communication systems**
- **Coding for fast, reliable, and secure computing and learning**

The conventional thinking of a communication system as a means of transmitting data from one point to another as efficiently as possible is radically changing nowadays. The prevalence of communication systems for communications between humans is being rapidly replaced by a dominance of communications between highly autonomous and intelligent devices such as IoT, M2M devices, which are mainly characterized by being massive in number and having very definite tasks to accomplish. The communication needs are not only changing in traditional notions such as connectivity, throughput, or latency, but are also being merged with those of the inherent task involved. This, together with the increasing importance of data driven applications, is deeply transforming today's communication systems. With these scenarios in mind, this research group relies on its deep background in signal processing, information theory and coding for communication systems to explore and incorporate into its expertise some of the technologies and paradigms that we believe are key for the success of this transformation. Specifically, our research efforts are focused on incorporating the rapid advances in machine learning technologies into the design of intelligent radio communication systems; on addressing the massive connectivity challenge through multi-user coding theory and advanced signal processing tools such as random matrix theory; on tackling the design of new large/distributed antenna system such as Extremely Large Antenna Arrays (ELAA) and cell free Massive Multiple Input Multiple Output (MIMO) systems; and on applying our expertise in error-correcting codes for communications to a variety of computing and learning tasks, including over-the-air computing, physical-layer network coding and Quantum Key Distribution.

Adaptive Processing Technologies

Dr. Nikolaos Bartzoudis
Head of ADAPT

Adaptive Processing Technologies is very much focused on technology development for

- **Agile signal and data processing for smart 6G communication technologies**
- **AI-assisted processing for energy efficient B5G and 6G transmitters**

This unit concentrates its efforts on a seamless and intelligent Radio Access Network (RAN) reconfigurability at all-levels. Including the underlying hardware-accelerated functions (FPGA-based), the digital signal processing elements, the Radio Frequency (RF) subsystems, the digitally controlled Power Amplifiers (PAs) and the air interface. A holistic RAN reconfigurability and resource's orchestration will be a key to reach a whole new level of network automation and virtualization featuring fully adaptive and flexible building blocks. In addition, AI-assisted fast-adaptive processing techniques are also required to boost the energy efficiency and sustainability of the upcoming 6G base station and user equipment radios, while improving coverage and minimizing the radio interference. The currently proposed Beyond 5G (B5G) RAN architectures based on open, softwarized and disaggregated building blocks (e.g., O-RAN, together with edge computing solutions will be the blueprint allowing to capitalize the benefits of the fully reconfigurable RAN solutions proposed by the RU. In particular, this Research Unit aims to add intelligent adaptive processing and a virtualization-ready computing substrate to serve close-loop management of the RAN and the edge computing resources at intra-node level (i.e., micro-orchestration of resources); at the management plane, this will also help to provide services to hierarchic orchestration decisions (e.g., RAN slice managers, RAN intelligent controllers for virtual RAN) and ultimately be a piece in the puzzle of forthcoming 6G inter-node multi-site orchestration. Additionally, we will explore new distributed AI-DPD processing paradigms for terrestrial and satellite Cloud Radio Access Network (CRAN)-MEC architectures, MIMO cell-free O-RAN topologies, and MIMO/Hybrid Beam Forming digital linearization schemes. The mentioned topics could be extended in digital linearization for optical, photonic and quantum communications.

Space and Resilient Communications and Systems

Dr. Miquel Ángel Vázquez
Head of SRCOM

Space and Resilient Communications and Systems develops solutions for space communications and their integration with terrestrial networks. The main goal is to contribute to defining the evolution of future new space communication systems, spanning from inter-satellite links to fixed and mobile space-to-Earth communication towards intelligent space systems with autonomous operation integrated with the terrestrial telecom infrastructure and cloud and storage services. The aim is not only to impact space systems but also terrestrial ones. In particular, the resilient communication services. Space and Resilient Communications and Systems technology outcomes can spin into terrestrial systems and scout novel terrestrial activities to be included in the roadmap of the space domain. For instance, the inclusion of security aspects in the context of the satellite European industry development. A crucial feature to attend governmental requirements and the geostrategic value of space systems. Demonstration and validation of proof-of-concepts plays an important role, which are supported by CTTC's CASTLE Platform® Testbed.

The main topics of interest are:

- **Space Air Interface Communications and Subsystems**
- **Space Networks Resource Control and Management**
- **Space technologies spin-in terrestrial systems applications**

Navigation and Positioning

Dr. Carles Fernández
Head of N&P

Navigation and Positioning is one of the Research Units working towards the development of navigation technologies, with strong focus on Global Navigation Satellite Systems (GNSS) such as GPS or Galileo. The Research Unit aims to become a world-leading reference in bringing GNSS and Microwave Device Technology to the people, either for scientific, business, or social endeavors. In order to tackle the challenges arisen by modern Navigation and Positioning systems and services, our research approach is based on the systematic application of Statistical Inference principles to the design of navigation devices [74], including digital Phase and Delay Lock Loops, antenna array synchronization, open loop synchronization schemes, vector tracking loops, Kalman filters, nonlinear Gaussian filters, and particle filters, but also detection theory (high-sensitivity receivers), communication theory (waveform design), and coding theory (such as the turbo concept and belief propagation algorithms), delivering innovative solutions in industry-grade form factors. Complementarily, we develop microwave and optical sensors for gas, liquid, and solid detection, including microwave components for advanced communication systems, such as 6G. Sensors and microwave devices are designed and made using micro/nano fabrication, 3D printing, inkjet printing, laser machining, Microelectromechanical Systems (MEMS), superconductivity and Low Temperature Co-Fired Ceramic (LTCC).

Research activities focus on the following topics of interest:

- **Signal Processing for Navigation**
- **Software-Defined Radio**
- **Interdisciplinary Driven Sensors and Microwave Devices**
- **Deployment of Research products**

Geomatics

Dr. Michele Crosetto
Head of Geomatics

The Geomatics Research Unit works with a variety of data capture sensors and methods for the treatment, analysis, interpretation, and diffusion of geographic information. The key characteristic of geographic information is the geo-location, that is, the attribution of spatial coordinates. Geomatics connects various traditional disciplines, like geodesy, photogrammetry or cartography, with more recently developed fields like remote sensing, satellite navigation and geographic information systems. More specifically the research activities encompass a group of methods for the analysis, interpretation, and dissemination of geographic information that are based on satellite, airborne or terrestrial close-range sensors.
Research activities focus on the following topics of interest:

- **Active remote sensing (mainly radar and lidar)**
- **Passive remote sensing (optical and multi-spectral) and photogrammetry**
- **Seamless indoor/outdoor navigation**
- **Advanced techniques for geomatics**

Highlight Projects 2021

2021 has been a fruitful year on R&D projects. CTTC has continued to lead and contribute to the design and development of 5G networks. We provide a few examples such as 5GROWTH where the potential and feasibility of 5G as underlying technology to vertical industries is demonstrated, or PASSION where a novel optical transmission system architecture, based on photonic technologies and integrated devices was demonstrated to achieve several Terabit transmissions. The projects DARLENE and 5G-Croco are examples of feasible 5G deployment and application to two strategic sectors: the automotive and intelligent transport systems, exploring cross-border control, and secure services and applications, where augmented reality services are evaluated in the framework of law enforcement. Continuing under the scope of 5G CTTC leverages on its expertise on system level simulators development, such as the open-source ns3 LTE/NR modules, to analyze mutual interference between LTE/5G New Radio (NR) cell phone systems and critical assets and recommend spectrum management approaches. In the area of further developing the implementation of 5G solutions and designing future 6G networks, 2021 initiated an important set of research and innovation projects funded by Spanish UNICO program.

Our contribution to continue improving communication systems and devices, extends also to the sector of satellite and space Communications, where we highlight the application of Artificial Intelligence to the design of flexible payloads for new generation of communication satellites and ground control stations, as well as the development of new modems for Deep Space missions or the implementation of hybrid hardware/software advanced GNSS receivers for low orbit satellites.

Another area of research is on Geomatics, Navigation and Positioning which was represented in projects such as GNSS-in-Space, where new hardware prototypes for on-board GNSS receivers were developed or GMAB and CUPRUM where services based on the active remote sensing technique of SAR interferometry were applied to land deformation monitoring and detection. CTTC supported the definition, implementation, and dissemination of Copernicus European Ground Motion Service. An example of navigation solutions is CATERPILLAR, an SME R&D project for the detection and tracking of caterpillar nests for the application of phytosanitary product injection assisted by autonomous drone navigation system.

5G-enabled growth in vertical industries

The vision of the 5Growth project was to empower verticals industries such as Industry 4.0, Transportation, and Energy with an AI-driven Automated and Sharable 5G End-to-End Solution that allowed these industries to achieve simultaneously their respective key performance targets. Towards this vision, 5Growth automated the process for supporting diverse industry verticals through (i) a vertical portal in charge of interfacing verticals with the 5G End-to-End platforms, receiving their service requests and building the respective network slices on top, (ii) closed-loop automation and SLA control for vertical services lifecycle management and (iii) AI-driven end-to-end network solutions to jointly optimize Access, Transport, Core and Cloud, Edge and Fog resources, across multiple technologies and domains.

The main objective of 5Growth was the technical and business validation of 5G technologies from the verticals' points of view, following a field-trial-based approach on vertical sites (TRL 6-7). Multiple use cases of vertical industries (Comau, Efacec_S, Efacec_E, Innovalia) were field-trialed on four vertical-owned sites in close collaboration with the vendors (Ericsson, Interdigital, NEC, Nokia) and the operators (Altice, Telecom Italia, Telefonica) in the project.

5Growth leveraged on the results of 5G-PPP Phase 2 projects where slicing, virtualization and multi-domain solutions for the creation and provisioning of vertical services were developed and validated, e.g. 5G-TRANSFORMER and 5G-MONARCH. Two ICT-17-2018 5G End-to-End platforms, 5G EVE and 5G-VINNI, were selected for the Trials to demonstrate the 5Growth specific vertical use cases. In addition to the impact on vertical-oriented standards (e.g., EN50126 (IEC62278) for railway signaling), the verticals in the consortium were offered an opportunity to influence ongoing 5G standardization by leveraging the involvement of leading experts in the various relevant SDOs.

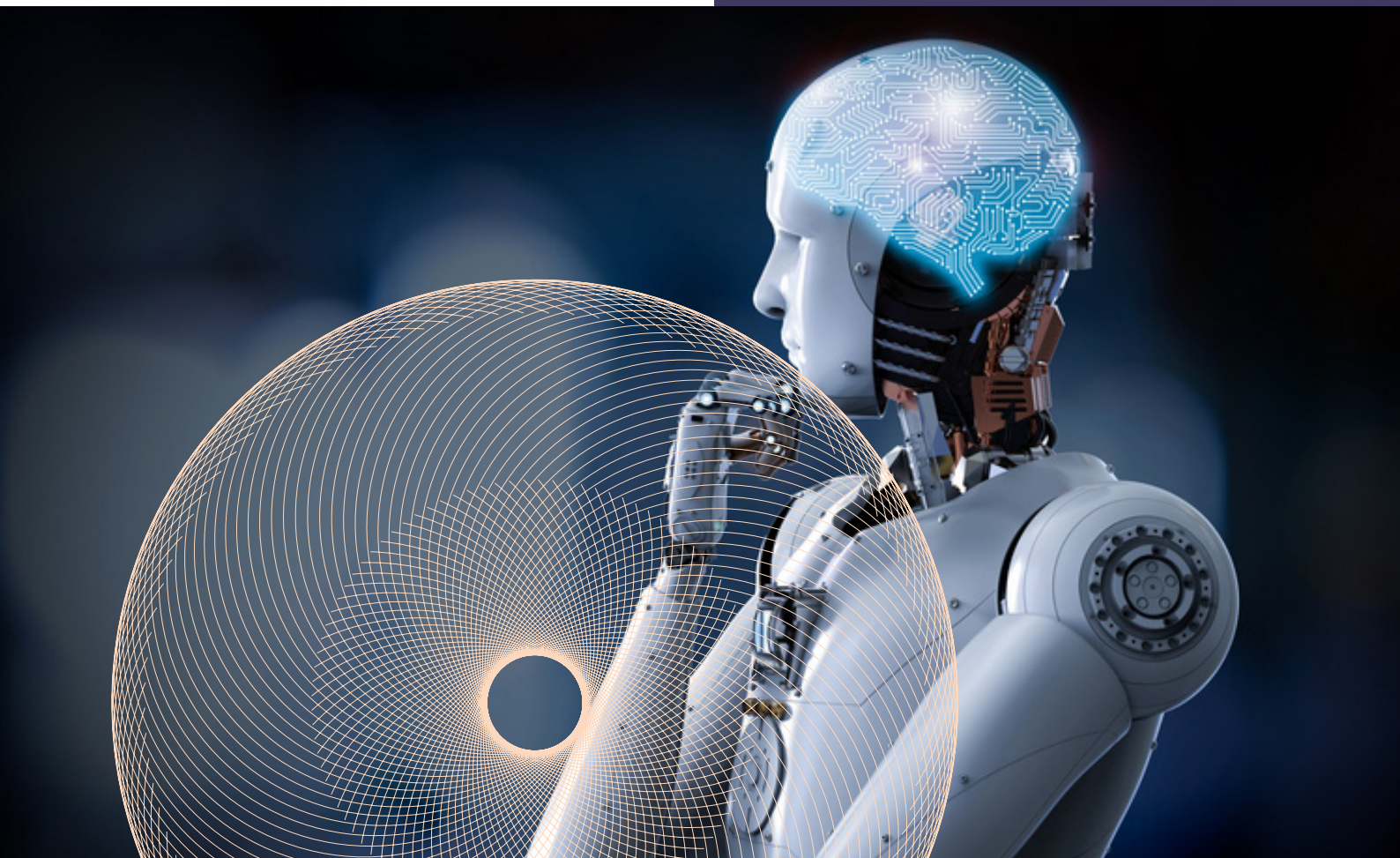
For more information, please visit: *http://5growth.eu/*

5GROWTH

Photonic technologies for programable transmission and switching modular systems based on scalable spectrum/space aggregation for future agile high capacity metro networks

is a H2020 project of the Photonics Key Enabling Technologies (Photonics KET) call (ICT-30-2017), focusing on sustainable dynamic multi-Tb/s connectivity over large (beyond) 5G-supportive Metropolitan Area Networks. A novel optical transmission system architecture, based on photonic technologies and integrated devices, efficient in terms of cost, power consumption and footprint, programmable via software-defined networking, was proposed and demonstrated for supporting multi-Terabit capacities and dynamic traffic, in very large and dense metropolitan area networks. CTTC contributed to the design, assessment, implementation and integration of the PASSION network architecture and photonic systems, hosting the first joint demo and the final experimental demonstration. The results, showing programmable spectral/spatial connectivity over more than 100km multi-hop paths (including 25 km of 19-cores multicore fiber) and up to 1.6 Tb/s, were presented at the most relevant conference on optical communications at international level (as demo OFC 2021 and top-scored paper at OFC 2022, respectively). The demos have been developed and implemented at CTTC labs, during the pandemic period, integrating multiple photonic integrated devices fabricated/developed at the different partners premises (VCSEL lasers of VERTILAS, Germany, photonic integrated coherent receiver of EFFECT Photonics, Netherlands, and a spatial photonic switch from ETRI, Korea), and in collaboration with Telefonica, UC3M (Spain), University of Eindhoven (Netherlands) and Politecnico of Milan (Italy).

PASSION



Spectrum Sharing Simulator

In March 2014, the Federal Communications Commission (FCC), in collaboration with National Telecommunications and Information Administration (NTIA), developed rules for Advanced Wireless Service (AWS-3) auction and reallocation of the 1695-1710 MHz and 1755-1780 MHz radio frequency bands, which at that time were allocated exclusively for Federal use. Most Federal systems using the 1755-1780 MHz band, including those of the Department of Defense (DoD), will relocate out of the band; however, the FCC's rules provide for indefinite sharing with selected Federal systems. The NTIA's Commerce Spectrum Management Advisory Committee (CSMAC) Working Groups 3, 4, and 5 established protection distances around Federal systems operating in the AWS-3 bands to ensure interference-free operation between DoD and commercial AWS systems as the AWS systems enter the bands. The military Services and the Defense Information Systems Agency (DISA) Defense Spectrum Organization (DSO) developed transition plans to facilitate increasingly less restrictive sharing arrangements for early entry of commercial AWS systems and permanent sharing between commercial systems and DoD systems that will continue operating in the 1755-1780 MHz band. These transition plans include different tasks, among which to 1) facilitate expedited and expanded entry of commercial deployments into the 1755-1850 MHz band, 2) to identify, assess, test/demonstrate, and operationalize coexistence techniques, interference mitigation, and other spectrum sharing enablers that support increased sharing between 4G/5G and incumbent DoD systems.

Different working groups have been created to target these tasks. One of them (WG4), is responsible for characterizing LTE/NR system performance in two major ways. In one case, the LTE system may be viewed as a system emitting transmissions that may potentially cause harmful interference to government receivers. In the other case, the LTE systems may have receivers that could be the recipients of harmful interference from government transmitters. For the case where the LTE system is viewed as the emitter, WG4 is attempting to determine how the LTE emissions behave over a wide, metropolitan area and over extended periods of time.

In the above defined context, the objective of this Project was to develop a scalable (parallel, optimistic, dynamic load balancing) discrete event simulator capable of analyzing mutual interference between current and near future LTE/New Radio (NR) cell phone systems and Department of Defense (DoD) assets. The goal was to build up a substantial body of knowledge on LTE/NR system behavior over a wide range of realistic conditions. The open source network and LTE/NR simulator ns-3 was the starting capability for this program. In order to provide the best execution performance, the parallel execution of the simulator was explored using "optimistic" synchronization, and dynamic load balancing across the computing cluster, in order to scale the simulation to the order of thousands of eNBs and millions of users (UEs).

The coordination of the whole project was carried out by the Lawrence Livermore National Lab (LLNL) in US, and CTTC and Pathfinder Wireless were partners of the project.

Deep AR law enforcement ecosystem

DARLENE is investigating means by which Augmented Reality (AR) can be deployed in real time to aid in Law Enforcement Agency (LEA) decision-making by employing AR capabilities and combining them with powerful Machine Learning (ML) algorithms, sensor information fusion techniques, 3D reconstruction, wearable technology and personalized context-aware recommendations. Hence DARLENE offers European LEAs a proactive security solution which provides an Internet-of-Things (IoT) level of situational awareness, detection and recognition, combining cutting edge technology and public security in all security verticals. It enables LEAs to reduce and prevent crime, and to more quickly respond to crimes already in progress, by enabling them to sort through massive volumes of data to predict, anticipate and prevent criminal activities, make better informed tactical decisions and provide enhanced protection services for European citizens. DARLENE is developing practical and beneficial policing applications through the use of affordable, light-weight and inconspicuous AR glasses. Such applications capitalize on cutting edge research that combines with AR Technology to create innovative methods for combating crime and even terrorist acts. To align technology development with actual security needs and requirements, DARLENE is building a community of LEAs organization and security stakeholders that is guiding the development process and evaluating the entire DARLENE ecosystem. In this regard, DARLENE foresees extensive demonstration and training activities for LEAs while the entire solution will be demonstrated and validated in realistic scenarios during the pilot phase of the project, thus paving the way to its field deployment and commercial uptake.

DARLENE

5G cross-border control

5G connectivity has the potential to tremendously simplify today's purely sensor-based approach to automated driving where it is a difficult task to anticipate what other vehicles intend to do by just using local sensor-based information. However, services for Connected and Automated Mobility (CAM) applications demand uninterrupted network connectivity. In Europe, where Mobile Network Operators (MNOs) usually only serve a single country, this is especially challenging when driving through national borders. Currently, vehicles search and register with an MNO in the country they enter only after the MNO connection in the country of origin is lost, which can interrupt the service for several minutes. Clearly, this situation is not acceptable for CAM services where service continuity is key. In this context, 5GCroCo research focuses on 5G-related technologies that can (i) enhance CAM functionalities and (ii) enable seamless service continuity at country borders.

5GCroCo

Using 5G as a reliable communication technology in CAM applications, including when traversing country borders, improves assisted and automated driving systems that without doubt have a tremendous impact on safety.

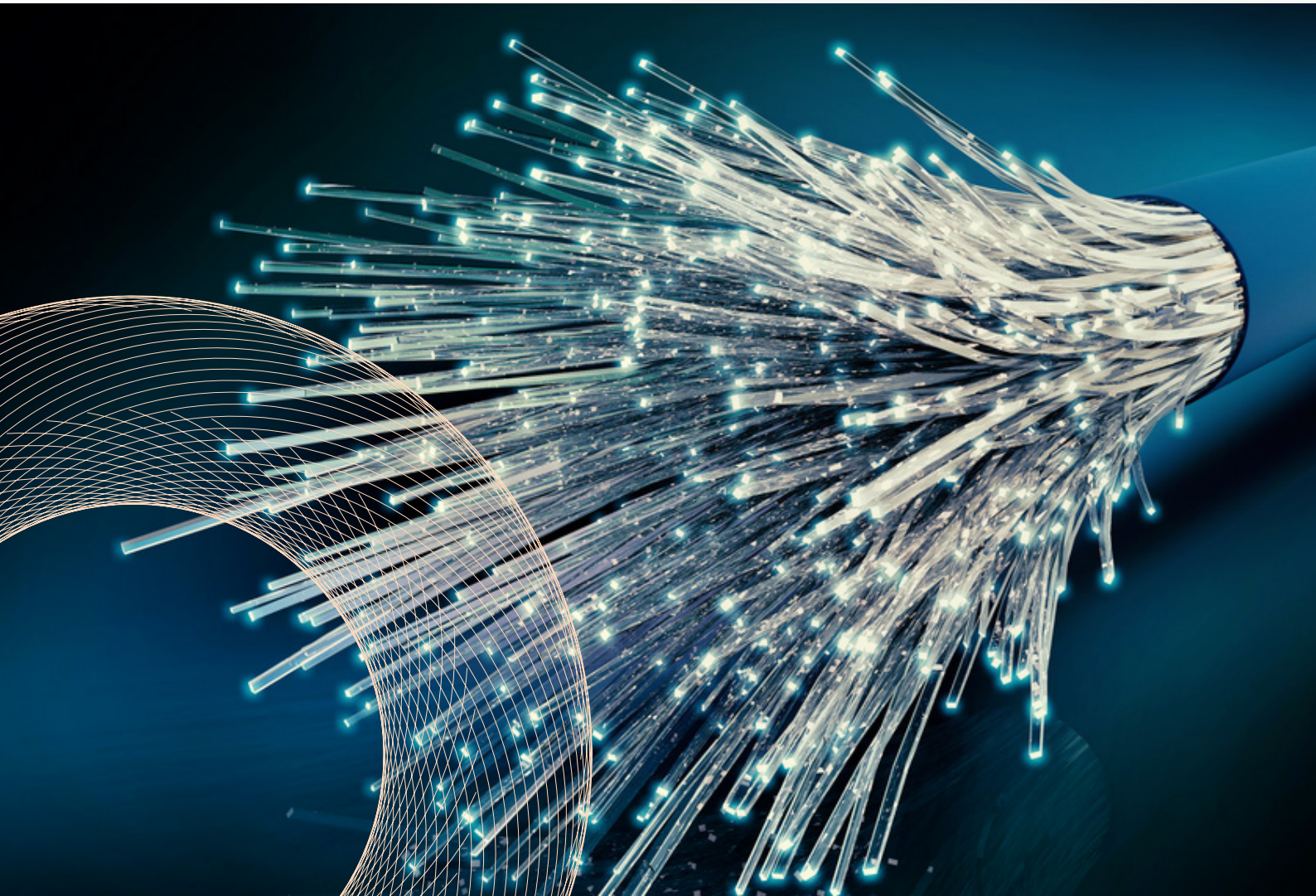
In this context, the overall objective of the project was to trial and validate different 5G technical solutions (i) that enhance CAM services, like MEC and QoS prediction, and (ii) that minimize the service interruption time when traversing a country border, like cross-MNO handover. For the latter, the project concluded that it is technically feasible to have service interruption times when crossing a border as short as 120 ms, allowing the continuity of CAM services.

AI-powered ground segment control for flexible payloads

is a European project funded by Horizon 2020 under the Space leadership program in enabling and industrial technologies. Artificial Intelligence is applied to the reconfiguration of wireless communication systems from satellites. The project addresses the space market trend on the design on a new generation of satellite with flexible payload and configuration. The goal is to design and develop an AI-based tool, denoted AI-PCS which can be applied to a vast number of payload design requirements. In particular, AI-PCS will enable autonomous optimal configuration of satellite resources based on services requests. The core functionality consists of a digital processor (digital transparent payload), which will enable new capabilities within 5G evolution paradigm and realize the future integration of non-terrestrial with terrestrial communication networks. As in terrestrial networks, this flexibility comes hand by hand with the softwarization of satellite systems, with the consequent development of new space compliant technology evolving from custom hardware solutions fixed during its life cycle, to customizable software alternatives, configured in orbit from ground stations. ATRIA pays special attention to ground segment technologies. From a technical perspective flexibility will be managed with AI to implement variable and adaptative signal bandwidth, flexible connectivity and coverage and energy management. The applicability of such AI tools to generic payloads, aims at achieving a cost-effective solution for satellite manufacturers, which is expected to increase the attractiveness of its standardization.

Multiple Frequency-Shift Keying modem for very low data rates

is a research project funded by the European Space Agency which deals with the receiver design for non-coherent detection of MFSK signals used in telemetry and telecommand in Deep-Space missions. This project continues the line of the work initiated between CTTC and the ESA on modem design and implementation for Deep Space communications, which started with the development of coupled turbo codes demodulation and decoding schemes for the telemetry of Deep-Space missions (such as BepiColombo and EXOMARS) with more and more demanding requirements in terms of received low signal power and high data rate; it then followed with the study on acquisition and synchronization schemes for Next Generation Uplink Coding Techniques for telecommand which allowed to lower the operative SNR of the synchronization stage. In this case, the transmission format considers new waveforms based on two variants of MFSK modulation which have proven to best satisfy the requirements of future Deep-Space missions for direct transmissions to Earth over very large astronomic distances. We analyse the non-coherent receiver performance for several scenarios that exhibit extreme channel conditions such as high and variant Doppler dynamics (represented by the Entry-Descent and Landing scenario), extremely low SNR (featured in Safe and Survival mode) or channel scintillation (experienced under solar conjunction, i.e. closest approach to the Sun). In this study, we will design and implement a baseband receiver to measure performance of MFSK signals critically affected by the challenging communication channel, which will need advanced receiver demodulation and frame decoding for very low data rate that optimizes non-coherent performance. Standard performance of well-known powerful coding schemes such as LDPC does not directly translate to non-coherent demodulation and demapping. Hence, the study needs to consider frame structure and the coding scheme for the end-to-end performance evaluation.



GNSS-in-Space

This project, funded by the European Space Agency, deals with the implementation of a real-time GNSS signal rebroadcaster in an all-programmable system-on-chip platform. Among its objectives we found the design and implementation of a new equipment to support research activities involving:

- **The design, testing and validation of new GNSS signal features in real time**
- **The protection of GNSS receivers against the broadcast of counterfeit GNSS signals**
- **And the overcoming the limited flexibility of existing commercial signal generators and receivers.**

The project also explores the possibility to implement non-standard features in GNSS transmitter and receiver, such as a GNSS-synchronized GNSS signal generator for low-cost implementation of LEO-based GNSS augmentation systems and a GNSS receiver advanced security auditory.

The outcome of the project allows to extend GNSS receiver features to regenerate the received satellite signals in real-time while simultaneously rebroadcasting a PVT solution that differs from the PVT fixes obtained by the SDR receiver. The flexible Software-Defined GNSS rebroadcaster architecture can generate, or receive and regenerate, GNSS signals with very low latency. More specifically the Telemetry Symbol Link module allows low latency GNSS signal regeneration (below 30 ms for the regenerated data symbols, 1 s for the regenerated PVT) which enables maintaining the consistency with other sensors (e.g. IMU, where available). The Telemetry Symbol Link module can only be enabled when using Galileo E1 B/C signals.

The proof-of-concept implementation includes a GNSS signal rebroadcaster that can generate and regenerate up to 8 GNSS satellite signals: either GPS L1 C/A, Galileo E1B+C or a combination of both systems.

Ground Motion Advisory Board

In this project, CTTC provided an important support to the definition, implementation, and dissemination of the Copernicus European Ground Motion Service (https://egms.land.copernicus.eu/). The service is based on the active remote sensing technique of SAR interferometry and uses the SAR images coming from the Sentinel-1 sensors. Additionally, the service makes use of GNSS data coming from thousands permanent stations spread across Europe. The Sentinel-1 sensors belong to the European Union's Copernicus Programme. The establishment of this Service represented a milestone for the interferometric SAR community. In fact, the Service represents the largest and more important interferometric SAR project for deformation monitoring ever realized, where deformation measurement over 39 European States is made. The support provided by CTTC involved two key levels. The first one was the coordination of the Advisory Board of the Service. This Board supervised all aspects related to Service specification, production, validation, and dissemination. The second level was providing an expert in SAR interferometry to directly support the European Environment Agency in the implementation and management of the Service.

Mining deformation monitoring

This project was carried out in collaboration with three Polish institutions. In this work we adopted a multitemporal Distributed Scatterer InSAR methodology to study the terrain deformation phenomena in the Legnica-Glogow copper district (Poland), aimed at enabling a robust monitoring routine on both the slow and fast (i.e. tremors) phenomena that affect the area. The employed datasets were Sentinel-1 A/B Single Look Complex SAR images collected from September 2019 to September 2020 at both ascending and descending passes. We adopted a SBAS approach based on a simplified procedure to form a sub-optimal interferogram network, aiming at eliminating interferograms with a low coherence, while preserving the temporal resolution. The processing software employed for image co-registration, interferogram generation, phase unwrapping and time series extraction is part of the PSI processing chain of the Geomatics Research Unit of CTTC. The final product obtained via the proposed processing was compared with in-situ data collected by four GNSS stations in the proximity of points affected by severe deformation phenomena. Additionally, an analysis of co-seismic differential interferograms was performed to analyse the seismic events recorded by few seismometers located in the area of interest.

CATERPILLAR2

This is a one-year research project requested by FitoStinger, a Catalan SME, and it was about the automatic detection of caterpillar nests from drone imagery. The processionary caterpillar pest is an environmental problem affecting pine forests as they make their nests in trees and feed on their needles and shoots. This pest is capable of completely exfoliating a pine tree and spreads rapidly through forests. The aim of the FitoStinger product is to control these pests by eliminating the caterpillars by targeting the problem and attacking only their nests, while respecting the affected trees. Currently, the procedure is based on mass spraying, which causes great ecological impact. In this way, the aim is to cut the evolutionary and reproductive cycle and thus reduce the proliferation of the processionary pest, using a more environmentally friendly procedure. This project was a continuation of the predecessor CATERPILLAR project. Based on that, the CATERPILLAR2 project aimed to develop and implement algorithms for the detection and tracking of caterpillar nests within the framework of the development of a pre-commercial prototype of an autonomous drone navigation aid system for the application of phytosanitary product injection in caterpillar nests.

Highlight Publications 2021

Contributions to mathematical and information theoretical tools applied to telecommunications, such us the characterization of the asymptotic behaviour of a particular class of random matrices widely applied to the design of large multiple antenna systems or the fundamental limits of a coding technique applied to caching systems to increase multimedia distribution and access efficiency through the communication network.

P. Loubaton and X. Mestre, "On the asymptotic behavior of the eigenvalue distribution of block correlation matrices of high-dimensional time series", in Random Matrices: Theory and Applications, Vol. 11, No. 03, 2250024 (2022)

We consider linear spectral statistics built from the block-normalized correlation matrix of a set of M mutually independent scalar time series. This matrix is composed of M2 blocks. Each block has size LxL and contains the sample cross-correlation measured at L consecutive time lags between each pair of time series. Let N denote the total number of consecutively observed windows that are used to estimate these correlation matrices. We analyze the asymptotic regime where $M,L,N \to +\infty$ while $ML/N \to c_*$, $0 < c_* < \infty$. We study the behavior of linear statistics of the eigenvalues of this block correlation matrix under these asymptotic conditions and show that the empirical eigenvalue distribution converges to a Marcenko–Pastur distribution. Our results are potentially useful in order to address the problem of testing whether a large number of time series are uncorrelated or not.

S. Shao, J. Gómez-Vilardebó, K. Zhang and C. Tian, "On the Fundamental Limits of Coded Caching Systems With Restricted Demand Types," in IEEE Transactions on Communications, vol. 69, no. 2, pp. 863-873, Feb. 2021, DOI:10.1109/TCOMM.2020.3038392.

Caching is a technique to reduce the communication load in peak hours by prefetching contents during off-peak hours. An information theoretic framework for coded caching was introduced by Maddah-Ali and Niesen in a recent work, where it was shown that significant improvement can be obtained compared to uncoded caching. Considerable efforts have been devoted to identify the precise information theoretic fundamental limits of the coded caching systems, however the difficulty of this task has also become clear. One of the reasons for this difficulty is that the original coded caching setting allows all possible multiple demand types during delivery, which in fact introduces tension in the coding strategy. In this paper, we seek to develop a better understanding of the fundamental limits of coded caching by investigating systems with certain demand type restrictions. We first consider the canonical three-user three-file system, and show that, contrary to popular beliefs, the worst demand type is not the one in which all three files are requested. Motivated by these findings, we focus on coded caching systems where every file must be requested by at least one user. A novel coding scheme is proposed, which can provide new operating points that are not covered by any previously known schemes.

Contributions to architectural network design, communication, orchestration and management protocols applied to 5G/B5G networks.

X. Li, et al., "5Growth: An End-to-End Service Platform for Automated Deployment and Management of Vertical Services over 5G Networks", IEEE Communications Magazine, March 2021. DOI: 10.1109/MCOM.001.2000730.

This article introduces the key innovations of the5Growth service platform to empower verticals industries with an AI-driven automated 5G End-to-End (E2E) slicing solution which allows industries to achieve their service requirements. Specifically, we present multiple vertical pilots (Industry 4.0, Transportation and Energy), identify the key 5G requirements to enable them and analyze existing technical and funcional gaps as compared to current solutions. Based on the identified gaps, we propose a set of innovations to address them with: (i) support of 3GPP-based RAN slices by introducing a RAN slicing model and providing automated RAN orchestration and control, (ii) an AI-driven closed-loop for automated service management with Service Level Agreement (SLA) assurance, and, (iii) Multi-domain solutions to expand service offerings by aggregating services and resources from different provider domains and also enable the integration of private 5G networks with public networks.

P. Alemany et al., "A KPI-enabled NFV MANO architecture for network slicing with QoS", IEEE Communications Magazine, vol. 59, no 7, p. 44-50, July 2021. DOI: 10.1109/MCOM.001.2001077.

This article presents and experimentally validates a KPI-enabled Network Function Virtualisation (NFV) Management and Orchestration (MANO) architecture able to manage network slices, to monitor the vertical KPI requirements and react in case they are not met.

J. M. Fabrega, et al., "Experimental Demonstration of Extended 5G Digital Fronthaul Over a Partially-Disaggregated WDM/SDM Network", IEEE Journal on Selected Areas in Communications, vol. 39, no 9, p. 2804-2815, March 2021. DOI: 10.1109/MCOM.001.2001077.

We experimentally demonstrate a 5G digital fronthaul network that relies on multi-adaptive bandwidth/bitrate variable transceivers (BVTs) and an autonomic SDN control system for partially-disaggregated wavelength division multiplexing (WDM)/space division multiplexing (SDM).

L. Sanabria-Russo, J. Serra, D. Pubill and C. Verikoukis, "CURATE: On-Demand Orchestration of Services for Health Emergencies Prediction and Mitigation", IEEE Journal on Selected Areas in Communications, vol. 39, no. 2, pp. 438-445, February 2021, DOI: 10.1109/JSAC.2020.3021570.

The proposed platform, CURATE, leverages Network Functions Virtualisation Management and Orchestration (NFV MANO) for the on-demand instantiation of the required virtual resources on the operator's infrastructure to guarantee efficient resource allocation and tenant isolation. Results show the proposed platform is able to efficiently make use of the available hardware resources via Network Slices, as well as provide cost-effective service guarantees employing dynamic scaling operations.

R. Sedar et al., "Standards-Compliant Multi-Protocol On-Board Unit for the Evaluation of Connected and Automated Mobility Services in Multi-Vendor Environments", Sensors, March 2021, DOI: 10.3390/s21062090

This paper presents the development of a standards-compliant experimental vehicular on-board unit (OBU) that supports the integration of multiple V2X protocols from different vendors to communicate with heterogeneous cloud-based services that are offered by several original equipment manufacturers (OEMs). We experimentally demonstrate the functionalities of the OBU in a real-world deployment of a cooperative collision avoidance service infrastructure that is based on edge and cloud servers.

Artificial Intelligence and Machine Learning solutions to improve communications

H. Chergui, et al, "Zero-Touch AI-Driven Distributed Management for Energy-Efficient 6G Massive Network Slicing", IEEE Network, vol. 35, no. 6, pp. 43-49, December 2021, DOI: 10.1109/MNET.111.2100322.

This article introduces a novel statistical federated learning-based analytic engine for zero-touch 6G massive network slicing, which performs slice-level resource prediction by learning in an offline fashion while respecting some preset long-term service level agreement constraints defined in terms of the empirical cumulative distribution function and the percentile statistics, and hence uses a new proxy-Lagrangian two-player strategy to solve the local non-convex federated learning task without settling for surrogates only.

M. Á. Vázquez et al., "Machine Learning for Satellite Communications Operations," in IEEE Communications Magazine, vol. 59, no. 2, pp. 22-27, February 2021, DOI: 10.1109/MCOM.001.2000367.

This article introduces the application of machine learning (ML)-based procedures in real-world satellite communication operations. While the application of ML in image processing has led to unprecedented advantages in new services and products, the application of ML in wireless systems is still in its infancy. In particular, this article focuses on the introduction of ML-based mechanisms in satellite network operation centers such as interference detection, flexible payload configuration, and congestion prediction. Three different use cases are described, and the proposed ML models are introduced. All the models have been constructed using real data and considering current operations. As reported in the numerical results, the proposed ML-based techniques show good numerical performance: the interference detector presents a false detection probability decrease of 44 percent, the flexible payload optimizer reduces the unmet capacity by 32 percent, and the traffic predictor reduces the prediction error by 10 percent compared to other approaches. In light of these results, the proposed techniques are useful in the process of automating satellite communication systems.

Radio Access solutions

C. Mosquera, N. Noels, T. Ramírez, M. Caus and A. Pastore, "Space-Time Rate Splitting for the MISO BC With Magnitude CSIT," in IEEE Transactions on Communications, vol. 69, no. 7, pp. 4417-4432, July 2021, DOI: 10.1109/TCOMM.2021.3074519.

A novel coding strategy is proposed for a broadcast setting with two transmitter (TX) antennas and two single-antenna receivers (RX). The strategy consists of using space-time block coding to send a common message (to be decoded by both RXs) across the two TX antennas, while each TX antenna also sends a private message to one of the RXs. The relative weight of the private and common messages from each TX antenna is tuned to maximize the instantaneous achievable sum-rate of the channel. Closed-form expressions for the optimal weight factors are derived. In terms of the generalized degrees of freedom (GDoF) metric, the new scheme is able to achieve the sum-GDoF with finite precision channel state information at the transmitter (CSIT) of the two user broadcast channel. Moreover, as opposed to the existing rate-splitting schemes, the proposed scheme yields instantaneous achievable rates that are independent of the channel phases. This property is instrumental for link adaptation when only magnitude CSIT is available. Our numerical results indeed demonstrate the superiority of the scheme for the 2-user setting in case of magnitude CSIT. Extension to a more general K-user scenario is briefly discussed.

S. Lagen, X. Gelabert, L. Giupponi, A. Hansson, "Fronthaul-aware Scheduling Strategies for Dynamic Modulation Compression in Next Generation RANs", IEEE Transactions on Mobile Computing, November 2021, DOI: 10.1109/TMC.2021.3128700.

In this paper, a multi-cell multi-user scenario with a shared fronthaul link across multiple cells is considered. We focus on optimizing the resource allocation and modulation compression of each user, in a centralized and dynamic manner, aiming to maximize the air interface performance subject to a shared fronthaul capacity constraint. The problem is formulated as a convex optimization problem, which allows deriving the optimal resource allocation and modulation compression per user. Then, we evaluate the proposed fronthaul-aware scheduling methods against baseline holistic strategies over an end-to-end dynamic 5G NR system-level simulator based on ns-3.

Novel device technologies

Y. Lee, J. Kim, S. Sim, I. Llamas-Garro and J. Kim, "Air-Gap Interrogation of Surface Plasmon Resonance in Otto Configuration", Micromachines , August 2021. DOI: 10.3390/mi12080998.

In this study, a micromachined chip in Otto configuration with multiple air-gaps was fabricated, and the resonance characteristics for each air-gap was measured with a 980 nm laser source. We experimentally verified that the Surface Plasmon Resonance characteristics of the Otto chip configuration have a dependence on the air-gap distance and wavelength of the incident light (e.g., the minimum reflectance becomes 0.22 when the displacement of the piezoactuator is about 9.3 μm).

Remote sensing, radar and geomatic solutions

P. F. Espín-López, et al., "Proof-of-Concept for a Ground-Based Dual-Receiver Radar Architecture to Estimate Snowpack Parameters for Wet Snow", IEEE Transactions on Geoscience and Remote Sensing, DOI: 10.1109/TGRS.2021.3103834.

This article presents an innovative radar architecture to study wet snow. The approach determines the snowpack depth and bulk density, but also the liquid water content. The method is discussed in detail, along with the experimental validation of the operating principle for two cases.

V. Krishnakumar et al., "Sentinel-1 A-DInSAR Approaches to Map and Monitor Ground Displacements", Remote Sensing, Vol. 13, March 2021, DOI: 10.3390/rs13061120.

This paper proposes two different and complementary data-driven procedures to obtain terrain deformation maps. These approaches aim to exploit Sentinel-1 highly coherent interferograms and their short revisit time. The first approach, called direct integration, aims at providing a very fast and straightforward approach to screen-wide areas and easily detects active areas. The second method provides a constrained application of the PSIG chain.

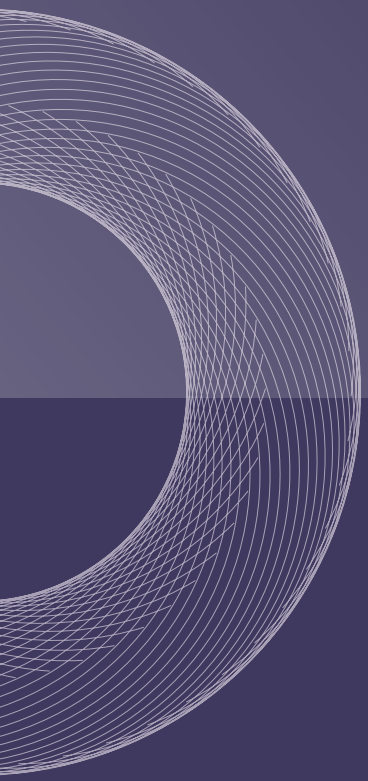
Luzi, G.; Espín-López, P.F.; Mira Pérez, F.; Monserrat, O.; Crosetto, "A Low-Cost Active Reflector for Interferometric Monitoring Based on Sentinel-1 SAR Images", Sensors, Vol. 21, March 2021, DOI: 10.3390/s21062008.

This paper describes the design, implementation, and test of an active reflector prototype, designed to operate with the Sentinel-1 synthetic aperture radar (SAR), aimed at providing a fair performance/cost benefit. These characteristics, obtained through a trade-off between the use of off-the-shelf components and a simple architecture, can make the setup of a dense network in the monitored areas feasible.

Z. Qiu, O. Monserrat, M. Crosetto, V. Krishnakumar and L. Zhou, "An innovative extraction methodology of active deformation areas based on sentinel-1 SAR dataset: the Catalonia case study", International Journal of Remote Sensing, Vol. 42, June 2021, DOI: 10.1080/01431161.2021.1937749.

This paper describes an innovative methodology to process S1 SAR data. It includes two key processing stages: high and low frequency splitting from wrapped phases, prior to atmospheric filtering, and final direct integration to generate the complete deformation with time series containing linear and nonlinear components.

Raising pollution and climate-change awareness



NEWS 2021

Knowledge and Technology Transfer (Open Innovation)

Spin-offs

After the constitution of CTTC's spin-off Geokinesia, S.L in July 2020, CTTC has continued with the research collaboration addressing specific research needs from the company. Geokinesia exploits a remote sensing technique developed by CTTC after the accumulated know-how from more than a decade of research work. The technique, based on satellite radar images allows to measure and monitor deformations in a vast range of scenarios and applications including urban terrain deformations detection, risk management associated to landslides or subsidence, or maintenance of general infrastructures (roads, train tracks, etc.). The satellite based remote sensing solution allows the company to provide services with an international coverage.

IPR protection

As one of the tools to foster technology transfer CTTC relies on IPR protection through the national and international patent system. Being a CERCA research centre, CTTC regularly participates in the GINJOL Patents Fund by presenting innovative solutions candidatures. In 2021, CTTC present the "microSDNcontrol" solution to the 8th program edition of GINJOL, resulting awarded with the financial support. This solution is protected by the European Patent "Method and System for Cloud-Native Applications-Based Network Operations System for Cloud-Native Applications-Based Network Operations", Patent ID: EP3809631. The **microSDNcontrol** comprise a cloud-native architecture for Software Defined Network (SDN) Controllers based on ABNO architecture and gRPC interfaces with autoscaling mechanisms for high request loads and auto-healing support. The cloud-native micro-ABNO architecture has several key benefits that benefits network automation. The micro-ABNO of the invention provides a higher degree of flexibility, stability, and scalability than current monolithic SDN controllers. The application of cloud-native network control and management will provide network operators with a higher degree of network automation.

Industrial Collaboration

One of the most significant milestones from 2021 was the consolidation of CTTC as a 5G expert with the award of more than 26 R&D projects within Spanish program "Universalización de Infraestructuras Digitales para la Cohesión - 5G I+D" (UNICO-5G I+D), as part of the "Plan de Recuperación, Transformación y Resiliencia. CTTC leads the individual and coordinated projects, accounting for a total of over 22M€ budget. This program is an excellent opportunity to strengthen the collaboration with the national industry and private sector, boost the development of own 5G technology and help Spain to be one of the leaders on the development of 6G in Europe. CTTC's leadership and valuable contributions to former European Horizon 2020 program, specially within the 5G PPP for the design and development of 5G networks and technologies, has positively contributed to being the R&D institution leading the larger number of projects within this program.

Software

Besides CTTC testbeds, software development is another of our significant assets. Not only to aid research progress but to facilitate knowledge and technology transfer. These software solutions are in continuous evolution. We highlight two open-source solutions and two other developments very well received within the international community and stakeholders.

Open-source software

GNSS-SDR®

Is an open-source Global Navigation Satellite Systems software-defined receiver. Inspire by Software Defined Radio implementations, CTTC leads the development and maintenance of this open-source GNSS SDR receiver, supporting different constellations and frequency bands. It can be downloaded from **https://gnss-sdr.org/**

LENA/LENA-5G

ns-3 modules for LTE/LTE-A and 5G network simulation according to standards defined by 3GPP, **https://5g-lena.cttc.es/**

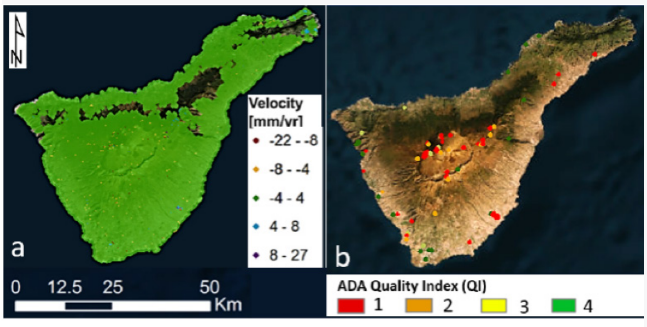
These two open-source software have proven to be a successful strategy for being recognized as experts in the respective fields and contributed to knowledge transfer among the research community, having also rise interest among their respective industrial stakeholders. Both solutions have received a strong international attention, being widely use, including students and trainees. The continuous timely effort to upgrade the software modules has position CTTC as a reference research center in solutions for advanced GNSS receivers and system level analyst for LTE/LTE-A/5G. Especially on mobility and spectrum sharing/coexistence solutions.

Other software

The following software packages are not open source but can be use free of charge according to the respective licenses. They belong to the category of Earth Observation research activities, providing tools for interferometry and the detection and classification of terrain deformations.

GEOKINESIA PSIG® Persistent Scatterer Interferometry: is a remote sensing SAR tool that allows to monitor with high sensitivity small terrain deformations. Either on individual infrastructures or wide geographical areas spanning from regional to transnational regions. This software tool includes the entire interferometric processing chain, being able to produce a velocity map with the observed deformations in each point of the map.

ADA (Active Deformation Area) Tools (ADA Finder, ADA Classifier, ADA Thex-finder, ADA LOS2HV): this is a software package including several tools for the detection and classification of areas with active deformations and terrain movements. These tools facilitate the postprocessing of GEOKINESIA PSIG® output or any other software that returns interferometric measurements, for an improved management and classification of such detected deformations. Typically, measurements directly obtained from Earth Observation satellites contain millions of measurement points, which are required to be pre-processed, before the actual identification of the areas experiencing movements of the terrain and the associated indication of the quality of the certainty of such movement.



Application example of ADA Finder software: velocity of movement (left), quality indicator of movement certainty (right). Measurements taken over the island of Tenerife.

New infrastructure

GENERAL

Besides new works on experimental and technical infrastructures and laboratories, we have put an effort to improve the common and generic facilities.

HUB

Prior to the pandemic we detected the need for additional common spaces that could hold a variety of events, from work meetings to informal gatherings. This need came to reality in 2021 by creating a multipurpose meeting room aimed at holding more inspiring and productive meetings and trainings. The hub environment aims to remove the traditional rigidity of the spaces to give it a new vision and a new approach.

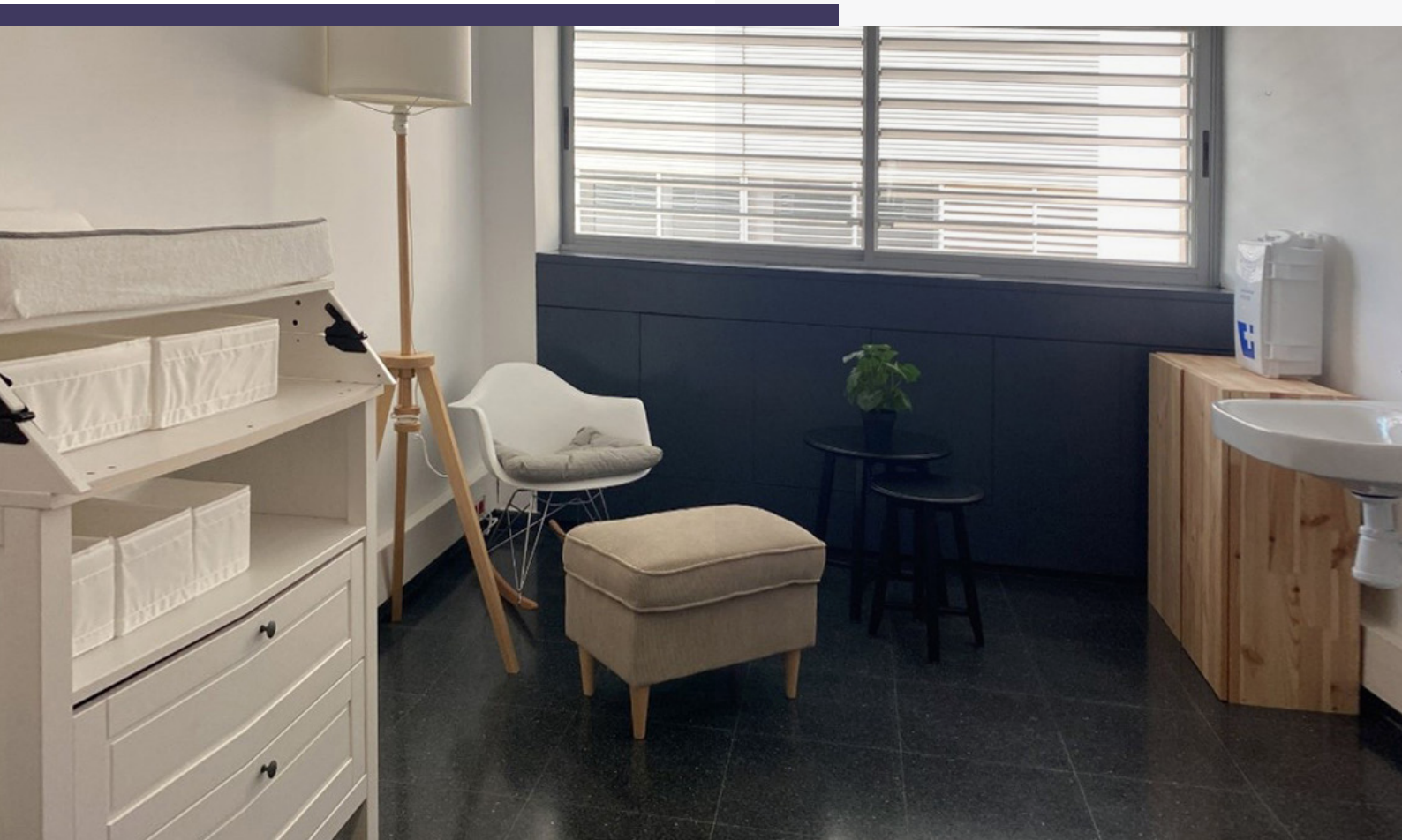
In particular, the Hub combines a ludic space next to a new kitchen facility, an open space to hold trainings and meetings of average size 15-20 people and a library complemented with round tables to enable more individualized gatherings or consulting.

Lactation room/nursery

The challenge of combining professional work and breast-feeding is one of the key factors why women choose not to breastfeed or the stop breastfeeding earlier. We posited that having access to a high-quality lactation room at the work-place could influence working mother's satisfaction.

- **It allows a more balanced combination between breastfeeding and work.**
- **Improves the emotional state of the breastfeeding woman during the working day and in her life in general.**
- **Increases the sense of commitment of the breastfeeding woman in the company.**

The opening of the lactation room on the ground floor of the B6 building, was highly welcome, providing space for breast-pumping and nursing. The room with natural lighting, is equipped with an armchair, baby changing table, a bath-room sink. It also serves as a quiet room if someone feels unwell or indisposed.



Lobby

As part of the new communication project and corporate image, CTTC's lobbies have been remodeled. Specially the reception at CTTC building B6. This building required numerous remodeling actions to adapt the building to new uses and improve its illumination and to provide a warmer environment by painting the walls in lighter color and increasing the number of plants among other actions. New corporate image and stands out in the lobby.

New infrastructure

NEW LABS

One of the most valuable assets of CTTC are its testbeds, demonstrators, and experimental infrastructure. It allows to thrust research into pre-competitive solutions and back-up theory and analytical results. Endowing CTTC researchers with cutting edge experimental equipment and facilities has been one of our priorities. A significant milestone was achieved in 2021, as a result of the reorientation of space-usage in CTTC buildings and the allocation of additional resources for the realization of additional spaces dedicated to experimental activities, testbed enhancements and laboratories upgrades.

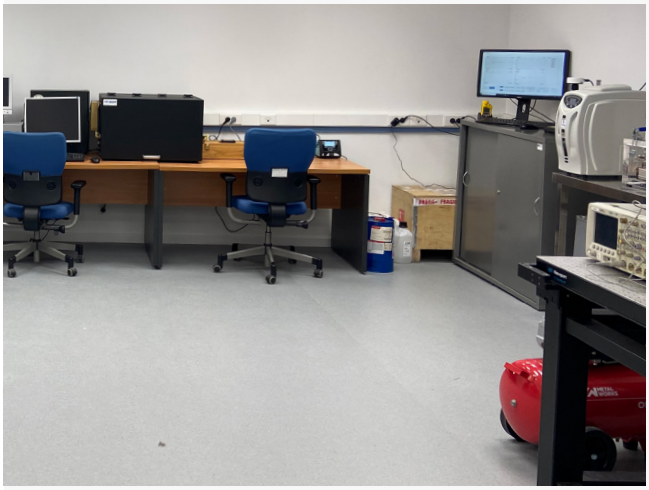
We highlight the completion of the Indoor Navigation Lab., co-funded by structural FEDER funds and the new creation of the "Interdisciplinary driven sensors and microwave devices" laboratory. The latter is funded with own resources as part of the internal program to support and encourage excellence research through innovative projects with a large potential to push current knowledge and technology far beyond the state of the art.

New Laboratory: Interdisciplinary driven sensors and microwave devices

The Lab supports the research led by Dr. Ignacio Llamas, on the development of sensors based on a new interdisciplinary sensor technology that combines microwave and optical sensor technologies. Among the activities carried out during 2021 we remark the design of a low-cost sensor for the detection of hydrogen or the development of a wireless sensor network for the detection of toxic chemical components.

The equipment includes the design, fabrication, and testing facility, devoted to microwave and optical sensor development, including microwave device implementation for wireless communications and sensing. The operating frequencies extend from a few MHz to visible light wavelengths, including direct current. The laboratory counts with computer aided design software COMSOL, HFSS or ADS, and contains fabrication and testing facilities such as 3D and 2D printing, electroplating, optical bench, probing station, diverse spectrometers, power meter, optical fibre splicing machine, automated reflectometer, network analyser, complete hydrogen detection sensor development setup, hotplate, stirrer, wire bonding machine, weigh-in machine, optical microscopes.

The facility enables faster development wireless sensor node prototypes in higher controlled and clean environment, sensor node integration and packaging.



New Laboratory: Indoor Navigation

CTTC's Indoor Navigation Lab is a dedicated space for development, test and measurement of positioning and navigation solutions. Developed as a joint effort from the Navigation & Positioning (N&P) and the Geomatics Research Units, partially funded by FEDER under the 5GLab project.

The lab is composed of a control room that offers control software equipment, including several workstation and monitors, as well as a dedicated basic laboratory working station and a clean dedicated space for test and measurements with marked vinyl floor that facilitates visual location and position of equipment, targets, etc. It also includes reference points that have been referenced with high accuracy using a total station during the calibration and set-up phase. The lab is equipped with several sets of UWB anchors, target nodes and development kit, lidar and ultrasound sensors, as well as an optical lighthouse system. Radar equipment is also available, including a FMCW radar at 24 GHz (K-Band) development kit and a SDR (Software Defined Radio) development platform aimed for developing new radar systems up to 6 GHz (C-Band). Additional equipment includes a set of IEEE 802.11p OBUs compatible with ITS-G5.

European Union
European Regional Development Fund

Upgrade of existing Laboratories and Testbeds

CTTC's testbeds, hosted in the different experimental facilities and laboratories, have enjoyed significant improvements and upgrades in 2021.

The ADRENALINE® testbed for optical technologies, protocols, management, control & services, included new generation and detection modules for fronthaul signals based on CPRI for 5G-NR, sliceable bandwidth variable transceivers (S-BVTs), multiband transmission systems and a multi-Tb/s photonic system for programmable connectivity (both spatially and spectrally) with application to metropolitan networks. The EXTREME Testbed® featuring multi-purpose fully reconfigurable networking solutions with mobility enhancements, was expanded to include a new server bringing larger capacity for network virtualization and data processing. Data storage was also substantially increased, allowing for the implementation of different machine learning techniques applied to the management and control of the end-to-end network resources. Both enhancements contribute to the realization of 5G networks vision.

Related to the upgrade of 5G features, the CASTLE PLATFORM® also extended its potential with the acquisition of a standard compliant 5G base station, equipped with multiple antennas. The current equipment deploys an autonomous 5G network, which can be connected to external networks via satellite. Experimental upgrade includes a wideband channel emulator by which one can emulate multiple coverages for both geostationary and low altitude orbits. The other line of enhancement was on the integration of terrestrial and on-terrestrial communication systems. In particular, the CASTLE PLATFORM® incorporates millimetre wave wideband radio heads, which provides the testbed with hardware capabilities to develop multiantenna solutions in the millimetre wave frequency band (64 antenna elements enabling hybrid beamforming). The Visible Light Communication (VLC) testbed module benefited from the acquisition of new devices for transmission and reception, as well as the development of a new hardware driver to support multiple LEDs.

These upgrades open the infrastructure for new use cases. Developments were also carried out on the control software to improve experimental work, including new computational features for statistical characterization.

The experimental platform for IoT solutions, IoTWORLD® testbed, increased the number and variety of sensors, as well as its processing and computing power.

On the experimental provisions for radio access, the modular testbed for prototyping agile SDR systems, GEDOMIS® testbed, updated its hardware components to expand and update the testbed functionalities. For instance, the continue edge computing and open-RAN architectures in line with the standardization bodies (e.g. 3GPP). Prototyping work towards functional slicing and orchestration via Kubernets were possible because of the new hardware equipment for the use of containers and FPGAs implementations. Another very powerful hardware is the development kit AMD Zynq UltraScale+ RF System on Chip (RFSoC), unleashing very powerful signal processing and computational power. The platform includes a small cell RF front-end for communication with Matlab 5G NR toolbox (software simulator of 5G New Radio) allowing to validate Over the Air Transmissions. The equipment is envisioned to validate use cases focused on heterogenous small-cell scenarios, satellite communications or hardware acceleration of software defined radio solutions for Digital Pre-Distortion power amplifiers.

Testbeds also enjoyed improvements on methodology, aiming either for more efficiency on code development or increase in experimental reproducibility. An example is the software Continuous Integration System developed for GESTALT® testbed for Global Navigation Satellite Systems. The testbed was endowed with a powerful Continuous Integration System and Gitlab servers (for both execution and data storage) that allows the automation of the compiling process, source code testing or validation procedures, independently of the programming language or who implements the code.

New Corporate Image

A new communication plan and digital strategy was initiated in 2021, accompanying the 20-year anniversary of CTTC. The corporate graphical image was renewed, resulting in a new logo and institutional moto.

The web has also been fully renewed, with its launch postponed to early 2022.

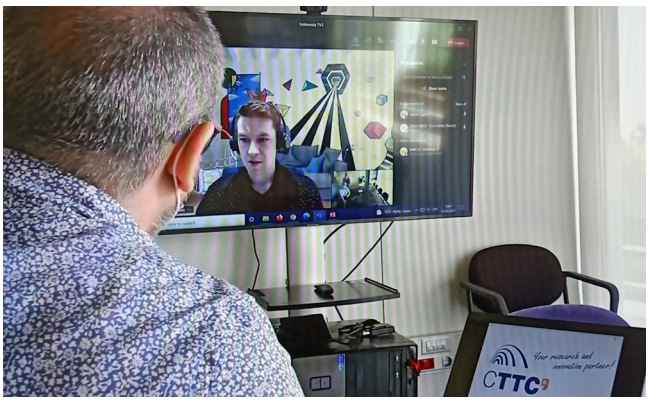
Although the web has always displayed a very comprehensive content of the scientific production and research activity, additional efforts were committed to further facilitate the access to our results and publications. In particular, the implementation of a new scientific production management system has allowed the integration with the "Portal de la Recerca de Catalunya" managed by the "Consorci de Serveis Universitaris de Catalunya" and the "Recolector de Ciencia Abierta" from the "Fundación Española para la Ciencia y Tecnología".

Events

Although still under the restrictions from the Covid-19 Pandemic, and that significant events suffered cancellations or substantial changes during 2021 we managed to actively participate in several events.

The regular participation of CTTC in the Mobile World Congress was altered due to the external circumstances coming from the organizers as a result of the pandemic. Besides the MWC was postponed to July 2021, the event suffered from a reduced number of attendees and ambition. Nevertheless, the effort from all stakeholders to have a physical event resulted in a successful outcome. During the 2021 Mobile World Congress, CTTC showcased several developments and results from the ongoing research projects. It presented a demonstration on the Connected and Automated Mobility (CAM) "Zero Vision" solution within the European project 5G-CROCO, which aimed for achieving zero road accidents by 2050. Other relevant achievements within the 5G Private-Public-Partnership program focused on the optimization of 6G networks and communication systems by deploying Artificial Intelligence techniques. These were the case of 5Growth and its application to health emergency responders, MARSAL and TeraFlow which propose management and orchestration of network resources in 5G and Software Defined Network controllers, or ATRIA which is developing flexible ground systems for next generation satellite communication systems, that allows to increase efficiency, as well as to provide higher resilience to interference or intended attacks. Additional contributions to the open-source system level simulation tool 5G-LENA were presented. The smart antenna array for positioning and navigation systems was another example of prototype development at CTTC shown at the institutional stand.

Additionally, this edition allowed for rich and agile online peer-to-peer meetings with potential industrial partners.



Other international events held in Barcelona where we regularly present our solutions (focus on the Internet of Things and Cities transformation) were postponed beyond 2021. This was the case of the Smart City Expo World Congress and the IoT Solutions World Congress.

Other activities on specialized technical conferences have been an active part of dissemination and contribution to the ecosystem. After the great success of the first large conference held fully virtual during the pandemic with over 15,000 attendees (the flagship conference from the IEEE Signal Processing Society), CTTC was awarded once more with the organization of the next 2026 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). This time expected to be held physically in Barcelona. CTTC's Director and Scientific Coordinator are the General Chairs.

Dissemination and participation in expert panels also took place, such as the participation as panellist in the 5G National Observatory event on Smart Mobility **"Conectados 5G. Europa y España ante el reto de la movilidad inteligente".**

Others

Awards, Acknowledgements and Associations

CTTC acknowledges the peer recognition and trust laid up in our colleagues from the different associations, bodies, and panels.

In 2021 Prof. Ana I. Pérez-Neira was awarded with EURASIP Fellow for her contributions to Signal Processing for Satellite and Wireless Communication Systems. Each year the European Association for Signal Processing (EURASIP) recognizes the outstanding achievements of its members granting a selected group of researchers in signal processing the 'EURASIP Fellow', the Association's most prestigious honor.

The scientific publication "Offline SLA-Constrained Deep Learning for 5G Networks Reliable and Dynamic End-to-End Slicing," authored by Hatim Chergui and Christos Verikoukis, received the **Best Journal Paper Award** from the IEEE Communication Society. The paper was published in the IEEE Journal on Selected Areas in Communications. Other awards like the **Best Demo Award** at the IEEE SECON 2021 for the contribution on "Deploying Hybrid Network Services: Mixing VNFs and CNFs in Multi-site Infrastructures" and the **Best EUCNC'21 booth** at the European Conference on Networks and Communications for the Organization of the stand and presentation of the activities dedicated to the 5Growth project during the event supported by the European Commission, recognized the high quality experimental and demonstration work.

Two CTTC researchers received the accreditation of "recerca avançada AQU-Catedratic (accreditation of Advanced Research in the field of Engineering and architecture of the agency for the quality of the University System of Catalonia). Besides being a re-elected member of the Governing Board of the **6G Smart Networks and Services Industry Association** (before "5G Infrastructure Association"), CTTC researchers were appointed to serve in several boards and steering committees such as the Board of stakeholders of **Photonics21**; the Technical Steering Team (TST) member del Open Networking Foundation (ONF), Optical Transport Configuration and Control (OTCC) or the Huawei European Optical Communication Advisory Board.

Moreover, CTTC contributes to the identification and definition of technological and research challenges in different fora, supporting European Commission and National Representatives to devise future work programs. During 2021, CTTC was one of the leading contributors to the Smart Networks and Services Joint Undertaking in quality of board member of the 6G-IA where equipment vendors, mobile network operators, research centres and other relevant European institutions developing mobile wireless networks and services are represented. One of the relevant items towards the workprogram preparation if the Strategic Research and Innovation Agenda. This agenda is elaborated by the technology platform **NetWorld Europe**, where CTTC is is a member of the Steering Board and part of the editorial committee. The document provides a summary of the key research areas for future telecommunications technologies. The workprogram has allocated 240 million euros to support R&D activities ranging from 5G evolution and large-scale pilots with vertical industries to frontier knowledge towards 6G systems.

In the context of space and non-terrestrial systems, CTTC has consolidated its activity in the scope of wireless communications and remote-sensing and Earth Observation. In the former, CTTC continued to lead the Satellite Network of Experts supported by the European Space Agency and started new projects with the Agency in the field of deep space communications for telecommand, telemetry and control; and satellite navigation. Also, the participation in the 3GPP standardization work for terrestrial/non-terrestrial systems integration was strengthened, leading to new collaborations with industrial partners in the sector. With respect to the later, CTTC coordinated in 2021 the Advisory Board of the new European Ground Motion Service (EGMS) from the Copernicus Program. This Advisory Board consists of experts in the analysis and interpretation of inSAR data, area of expertise of the Geomatics group at CTTC.

Transitional Predoc Contracts

CTTC has supported the development and training of early-stage researchers by hosting doctoral students, postdoctoral researchers and visitors, as well as master and undergraduate students. It is part of our mission to provide high quality training and career development opportunities in the sector of telecommunications research and development. To support this goal, a new program was launched this year in order to aid excellent students to start their research career path in telecommunications and geomatics. Financial support and a mentoring program of one year duration is in place to facilitate the preparation of an official scholarship or award application that financially supports their doctoral studies. Be aware of new posts in our web. There will be new openings every year!

PhD Theses

We are proud of our new PhD graduates, which defended their doctoral work in 2021.

Dr. Jorge Baranda

"End-to-End Network Service Orchestration in Heterogeneous Domains for Next-generation Mobile Networks"

5G marks the beginning of a deep revolution in the mobile network ecosystem, transitioning to a network of services to satisfy the demands of new players, the vertical industries.

Software Defined Networking (SDN), Network Function Virtualization (NFV) and Network slicing are key enabling techniques to such revolution. They are complementary, but they are still in its infancy and the synergies between them must be exploited to realise the mentioned vision. The aim of this thesis is to further contribute to its development and integration in next generation mobile networks by designing an end-to-end (E2E) network service orchestration (NSO) architecture, which aligned with some guidelines and specifications provided by main standardization bodies, goes beyond current management and orchestration (MANO) platforms to fulfill network service life-time requirements in heterogeneous multi-technology/administrative network infrastructures shared by concurrent instances of diverse network services.

Jorge Baranda received his MSc. degree in Telecommunications Engineering and his MSc. in Science of Information and Communication Technologies (MINT) from the ETSETB-Technical University of Catalonia (UPC) in July 2008. His Master Thesis consisted of the development of a system to detect and locate people in images and videos using Histogram of Oriented Gradients and Machine Learning techniques. This work was developed within the Video Processing and Analysis group (VPA) of Philips Research at the High Tech Campus in Eindhoven (The Netherlands). In November 2009 he joined the CTTC as a Research Engineer at the former Engineering Unit. In 2013, he became a Researcher in the Mobile Network Department of the Communication Networks Division. During his time in CTTC, he has participated in several European-funded projects (H2020, FP7), national funded projects (Retos Investigación I+D+I, COINCIDENTE) and industrial-funded projects. The development of such projects has allowed him to gain experience in the research and development of standardized wireless communication systems (WiMAX, LTE, Li-Fi), mobile and transport networks and its orchestration and management using SDN and NFV techniques. He is also involved in the preparation of research proposals for competitive programs (European and National), as well as in the design, development, and maintenance of the wireless segment of the EXTREME experimental facility. His main research interests are focused mainly on SDN, NFV and Network Slicing, and how these trends can complement or be integrated with former distributed networking concepts like efficient routing to develop next-generation mobile networks while integrating vertical industries to the telco ecosystem.

Abstract

5G marks the beginning of a deep revolution in the mobile network ecosystem, transitioning to a network of services to satisfy the demands of new players, the vertical industries. This revolution implies a redesign of the overall mobile network architecture where complexity, heterogeneity, dynamicity, and flexibility will be the rule. Under such context, automation and programmability are essential to support this vision and overcome current rigid network operation processes. Software Defined Networking (SDN), Network Function Virtualization (NFV) and Network slicing are key enabling techniques to provide such capabilities. Following a bottom-up approach, this thesis starts studying SDN aspects related to the management of wireless network elements and its integration into hierarchical control architectures orchestrating networking resources in a multi-technology (wireless, optical, packet) infrastructure. Then, this work is integrated in an infrastructure manager module executing the joint resource abstraction and allocation of network and compute resources in distributed points of presence (PoPs) connected by a transport network. Above them, a Service Orchestrator module automates the E2E lifecycle management of network services implementing network slices (NS) based on the vertical requirements, the available infrastructure resources, and, while fulfilling service level agreement (SLA) also during run-time operation. This architecture, focused on single administrative domain (AD) scenarios, constitutes the first group of contributions of this thesis. The second group of contributions evolves this initial architecture to deal with the orchestration and sharing of NS and its network slice subnet instances (NSSIs) involving multiple ADs. Additionally, this work also considers SLA management aspects by means of scaling actions during run-time operation in such complex scenarios. The third group of contributions demonstrate the validity and applicability of the resulting architecture by implementing and evaluating it in real experimental infrastructures featuring multiple ADs and transport technologies interconnecting distributed computing PoPs. The performed experimentation considers network service definitions close to real vertical use cases, namely automotive and eHealth, which help bridging the gap between network providers and vertical industries stakeholders.

CTTC

Parc Mediterrani de la Tecnologia (PMT)
Av. Carl Friedrich Gauss, 7 - 08860 - Castelldefels (Barcelona)
Voice: +34 93 645 29 00 - Fax: +34 93 645 29 01
info@cttc.es / www.cttc.es

CTTC

End-to-End Network Service Orchestration in Heterogeneous Domains for Next-generation MobileNetworks

Jorge Baranda Hortigüela

2021

CTTC

PH.D. THESIS

End-to-End Network Service Orchestration in Heterogeneous Domains for Next-generation Mobile Networks

Jorge Baranda Hortigüela

Advisor: Dr. Josep Mangues-Bafalluy

Tutor: Dr. Albert Cabellos-Aparicio

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Departament d'Arquitectura de Computadors

Dr. Fabiano Locatelli

"Study and Application of Spectral Monitoring Techniques for Optical Network Optimization"

One of the possible ways to address the constantly increasing amount of heterogeneous and variable internet traffic is the evolution of the current optical networks towards a more flexible, open, and disaggregated paradigm. In such scenarios, the role played by Optical Performance Monitoring (OPM) is fundamental. In fact, OPM allows to balance performance and specification mismatches resulting from the disaggregation adoption and provides the control plane with the necessary feedback to grant the optical networks an adequate automation level. Therefore, new flexible and cost-effective OPM solutions are needed, as well as novel techniques to extract the desired information from the monitored data and process and apply them. In this dissertation, we focus on three aspects related to OPM. We first study a monitoring data plane scheme to acquire the highresolution signal optical spectra in a nonintrusive way. Then, we identify two main placement strategies for such monitoring solutions, enhancing them using two spectral processing techniques to estimate signal- and optical filter-related parameters. Specifically, we propose a way to estimate the Amplified Spontaneous Emission (ASE) noise using optical spectra acquired at the egress ports of the network nodes and the filter features, using spectra captured at the ingress ports of the network nodes. To do so, we leverage Machine Learning (ML) algorithms and the function fitting principle, according to the considered scenario. Finally, we identify a potential application for the monitored information. Specifically, we propose a solution for the optimization of the subchannel spectral spacing in a superchannel. Leveraging convex optimization methods, we implement a closed control loop process for the dynamical reconfiguration of the subchannel central frequencies to optimize specific Quality of Transmission (QoT)-related metrics.

Dr. Ankush Mahajan

"Machine Learning Assisted QoT Estimation for Optical networks Optimization"

The tremendous increase in data traffic has spurred a rapid evolution of the optical networks for a reliable, affordable, cost effective and scalable network infrastructure. For effective optical network planning, operation and optimization, it is necessary to estimate the Quality of Transmission (QoT) of the connections. Typically, QoT estimation is performed using a Physical Layer Model (PLM) which is included in the QoT estimation tool or Qtool. A design margin is generally included in a Qtool to account for the modeling and parameter inaccuracies, to re-assure an acceptable performance. PLM accuracy is highly important as modeling errors translate into a higher design margin which in turn translate into wasted capacity or unwanted regeneration. The first part of the thesis focuses on the machine learning (ML) assisted accurate QoT estimation techniques with reduced design margin. In this regard, we developed models that uses monitoring information from an operating network combined with supervised ML regression techniques to understand the network conditions. In particular, we model the generated penalties due to i). EDFA gain ripple effect, and ii). filter spectral shape uncertainties at ROADM nodes. Furthermore, with the aim of improving the Qtool estimation accuracy in multi-vendor networks, we propose PLM extensions. In particular, we introduce four TP vendor dependent performance factors that capture the performance variations of multi-vendor TPs. In consequence, the last part of this thesis aims at investigating and solving the issue of accuracy limitation of Qtool in dynamic optimization tasks. To keep the models aligned to the real conditions, the digital twin (DT) concept is gaining significant attention in the research community. Based on the DT fundamentals, we devised and implemented an iterative closed control loop process that, after several intermediate iterations of the optimization algorithm, configures the network, monitors, and retrains the Qtool. The key advantage of this novel scheme is that whilst the network operates, the Qtool parameters are retrained according to the monitored information with the adopted ML model.

Ankush Mahajan received Bachelor's and Master's degree in Electronic and Communication Engineering from SVITS Indore and Indian Institute of Technology (IIT-ISM), Dhanbad, India respectively. After completion of his Master's degree, he joined Centre of Excellence, R&D department at Sterlite Tech Limited, Aurangabad, India. In Sterlite Tech, he was associated with long haul transmission system and access network research groups. In September 2018, he joined CTTC as an Early Stage Researcher (ESR-2) for ONFIRE (Future Optical Networks for Innovation, Research and Experimentation) project under the framework of the Horizon 2020 Marie Sklodowska-Curie Actions. He also worked as a research intern in Nokia Bell Labs, Stuttgart, Germany from May'19 to Nov'20. In ONFIRE, he is particularly working on advance Machine Learning (ML) algorithms to estimate end to-end Quality of Transmission (QoT) for efficient planning, operation and optimization of next generation disaggregated optical network. His project is focused on how available monitored physical layer information can be collected and used by the corresponding ML based optimization strategies in disaggregated optical networks for QoT estimation. As a part of ONFIRE project, he is also pursuing his PhD degree at Signal Theory and Communication Engineering Department of Universitat Politècnica de Catalunya (UPC), Barcelona.

Abstract

The tremendous increase in data traffic has spurred a rapid evolution of the optical networks for a reliable, affordable, cost effective and scalable network infrastructure. For effective optical network planning, operation and optimization, it is necessary to estimate the Quality of Transmission (QoT) of the connections. Typically, QoT estimation is performed using a Physical Layer Model (PLM) which is included in the QoT estimation tool or Qtool. A design margin is generally included in a Qtool to account for the modeling and parameter inaccuracies, to re-assure an acceptable performance. PLM accuracy is highly important as modeling errors translate into a higher design margin which in turn translate into wasted capacity or unwanted regeneration. The first part of the thesis focuses on the machine learning (ML) assisted accurate QoT estimation techniques with reduced design margin. In this regard, we developed models that uses monitoring information from an operating network combined with supervised ML regression techniques to understand the network conditions. In particular, we model the generated penalties due to i). EDFA gain ripple effect, and ii). filter spectral shape uncertainties at ROADM nodes. Furthermore, with the aim of improving the Qtool estimation accuracy in multi-vendor networks, we propose PLM extensions. In particular, we introduce four TP vendor dependent performance factors that capture the performance variations of multi-vendor TPs. In consequence, the last part of this thesis aims at investigating and solving the issue of accuracy limitation of Qtool in dynamic optimization tasks. To keep the models aligned to the real conditions, the digital twin (DT) concept is gaining significant attention in the research community. Based on the DT fundamentals, we devised and implemented an iterative closed control loop process that, after several intermediate iterations of the optimization algorithm, configures the network, monitors, and retrains the Qtool. The key advantage of this novel scheme is that whilst the network operates, the Qtool parameters are retrained according to the monitored information with the adopted ML model.

CTTC

Parc Mediterrani de la Tecnologia (PMT)
Av. Carl Friedrich Gauss, 7 - 08860 - Castelldefels (Barcelona)
Voice: +34 93 645 29 00 - Fax: +34 93 645 29 01
info@cttc.es / www.cttc.es

Machine Learning Assisted QoT Estimation for Optical Networks Optimization

Ankush Mahajan

2021

CTTC

PH.D. THESIS

Machine Learning Assisted QoT Estimation for Optical Networks Optimization

Ankush Mahajan

Supervisor: Dr. Ricardo Martínez
Co-supervisor: Dr. Raul Muñoz

Industrial Supervisor: Dr. Konstantinos Christodoulopoulos
Tutor: Prof. Salvatore Spadaro

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Departament de Teoria del Senyal i Comunicacions

NOKIA Bell Labs

MARIE CURIE ACTIONS

TESIS_Dagnachew_CUB.indd 1 3/7/20 11:56

Dr. Eulàlia Parés

"A Geodetic Approach to Precise, Accurate, Available and Reliable Navigation"

The determination of a body position, velocity and attitude is the purpose of the navigation techniques.

The main objective of the research presented on this thesis is to contribute to the adoption of the geodetic method for navigation. The geodetic method is based on a proper problem abstraction, on optimal estimation criteria, on rigorous mathematical modelling, on the use of sufficiently redundant data and on the use of sufficiently heterogeneous data. This thesis focus mainly on a proper problem abstraction as well as on an optimal estimation criteria.

The first step to prove the geodetic approach suitability has been to design, implement and validate the GEMMA system. The GEMMA system is a set of SW modules allowing the validation of new trajectory determination algorithms. The system is made up of measurement generators, filters and analyzers, as well as trajectory generators and analyzers and, as its main component, a generic platform for the optimal determination of trajectories (NAVEGA). The main purpose of the signal and trajectory generators and filters is to provide data to test and validate new navigation algorithms. Signal and trajectory analysis are used to characterize the error of data sets. NAVEGA is a software platform for the optimal determination of trajectories or paths of stochastic dynamical systems driven by observations and their associated dynamic or static models. The second step has been the design of a new optimal estimation algorithm that maximize the benefits of redundant systems. The availability of several sensors allows reducing the noise and detecting possible outliers. In this thesis, a new bayesian filter implementation, named Simultaneous Prediction and Filtering (SiPF), providing access to the residuals of redundant measurements is presented. This approach allows to apply all the quality determination geodetic techniques to the navigation solution determination.

The thesis concludes that the geodetic approach is a suitable way to face the navigation problem and to improve its performance, its availability and its reliability.

-Bio

M. Eulàlia Parés (Barcelona, 1980) holds a M.Sc. degree in Mathematics from the University of Barcelona (UB) in 2004 and a MSc in Meteorology and Climatology from the University of Barcelona (UB) in 2005. In 2008, she received a Master Degree in Airborne Photogrammetry and Remote Sensing (IG). Ms. Parés research aims at contributing to the adoption of the geodetic method for navigation and to its application/validation to INS/GNSS navigation. More specifically, she is currently working in the development of new positioning algorithms -from GNSS to INS based multi-sensor systems, focused on urban and indor mapping applications. She is the main responsible of the GEMMA testbed development, and the Crowd-sourced Air Quality Monitoring invention. She is also co-inventor of the iPOLE granted patent. She is co-author of 4 journal papers and more than 25 conference papers. She is highly motivated for training and disseminating her knowledge: She has supervised and co-supervised 2 TFG thesis and 2 TFM thesis related to those applications, organized and imparted 4 specialized courses on INS, she collaborated with the EETAC drone's master, imparting lessons and supervising student. She is invited to several divulgation talks at Generalitat de Catalunya, Ajuntament de Castelldefels and Aula Senior. Regarding participation in research projects, she is one of the promoters of the European project IOPES and she is already its main coordinator. She has been WP leader of 3 other europcan projects, and has participated in more than 7 of those. She has been also involved in industrial, regional and national projects, being those more than 20 in total.

-Abstract

The determination of a body position, velocity and attitude is the purpose of the navigation techniques. The most extended navigation systems (INS/GNSS), as any other HW and SW system, provide precise and accurate enough trajectory determinations under the appropriate conditions. However, when those systems acquire data on non-friendly environments the computed navigation solution su ers from unacceptable errors. Since the foundation of the Geodesy and Navigation group of the former Institute of Geomatics, now at CTTC, its researchers have to deal with three fundamental issues: solution performance (precision-accuracy), specially for low-cost systems, reliability and environmentally independent availability.The main objective of the research presented on this dissertation is to contribute to the adoption of the geodetic method for navigation.The geodetic method is based on a proper problem abstraction, on optimal estimation criteria, on rigorous mathematical modelling,onthe use of su ciently redundant data and on the use of sufficiently heterogeneous data. Since rigorous modelling, redundancy and heterogeneous data have been widely used by the navigation community, this thesis focus on a proper problem abstraction as well as on an optimal estimation criteria.The first step to prove the geodetic approach suitability has been to design, implement and validate the GEMMA system. The GEMMA system is a set of SW modules allowing the validation of new trajectory determination algorithms. The system is made up of measurement generators, filters and analysers, as well as trajectory generators and analysers and, as its main component, a generic platform for the optimal determination of trajectories (NAVEGA). The main purpose of the signal and trajectory generators and hers is to provide data to test and validate new navigation algorithms. Signal and trajectory analysers are used to characterize the error of data sets. NAVEGA is a software platform for the optimal determination of trajectories or paths of stochastic dynamical systems driven by observations and their associated dynamic or static models. The second step has been the design of a new optimal estimation algorithm that maximise the benefits of redundant systems. Redundancy in the number of available satellites but also redundancy in the number of sensors. The availability of several sensors allows reducing the noise and detecting possible outliers. In this thesis, a new bayesian filter implementation, named Simultaneous Prediction and Filtering (SiPF), providing access to the residuals of redundant measurements is presented. This approach allows to apply all the quality determination geodetic techniques to the navigation solution determination.The benefits of the previous tools, together with the extended acceptance of the benefit of redundancy, rigorous modelling and heterogeneity lead us to conclude that the geodetic approach is a suitable way to face the navigation problem and to improve its performance, its availability and its reliability.

CTTC

Parc Mediterrani de la Tecnologia (PMT)
Av.Carl Friedrich Gauss, 7- 08860 - Castelldefels (Barcelona)
Voice: +34 93 645 29 00 - Fax +34 93 645 29 01
info@cttc.es / www.cttc.es

A Geodetic approach to precise, accurate, available and reliable navigation

M. Eulàlia Parés

CTTC

PhD Dissertation

A Geodetic approach to precise, accurate, available and reliable navigation

M. Eulàlia Parés

Advisor:
Dr. Ismael Colomina Fosch
Tutor:
Prof. Josep Gili Ripoll

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Department of Geotechnical Engineering and Geo-Sciences
PhD in Aerospace Science and Technology

2020

2021

ANNUAL REPORT

cttc

Advanced research for everyday life

Parc Mediterrani de la Tecnologia (PMT)
Av. Carl Friedrich Gauss, 7 | Building B4 · 08860 | Castelldefels | Barcelona | Spain
+34 93 645 29 00 | Fax: +34 93 645 29 29
www.cttc.es

MEMBERS OF: Institució CERCA Centres de Recerca de Catalunya

ACREDITED BY: tecnio catalonia ACCIÓ Generalitat de Catalunya — Fins a 31/12/2023

CERTIFIED BY: AENOR ER Gestión I+D+i UNE 166002 IDI-0024/2011