ANNUAL

2022

REPORT

Cttc

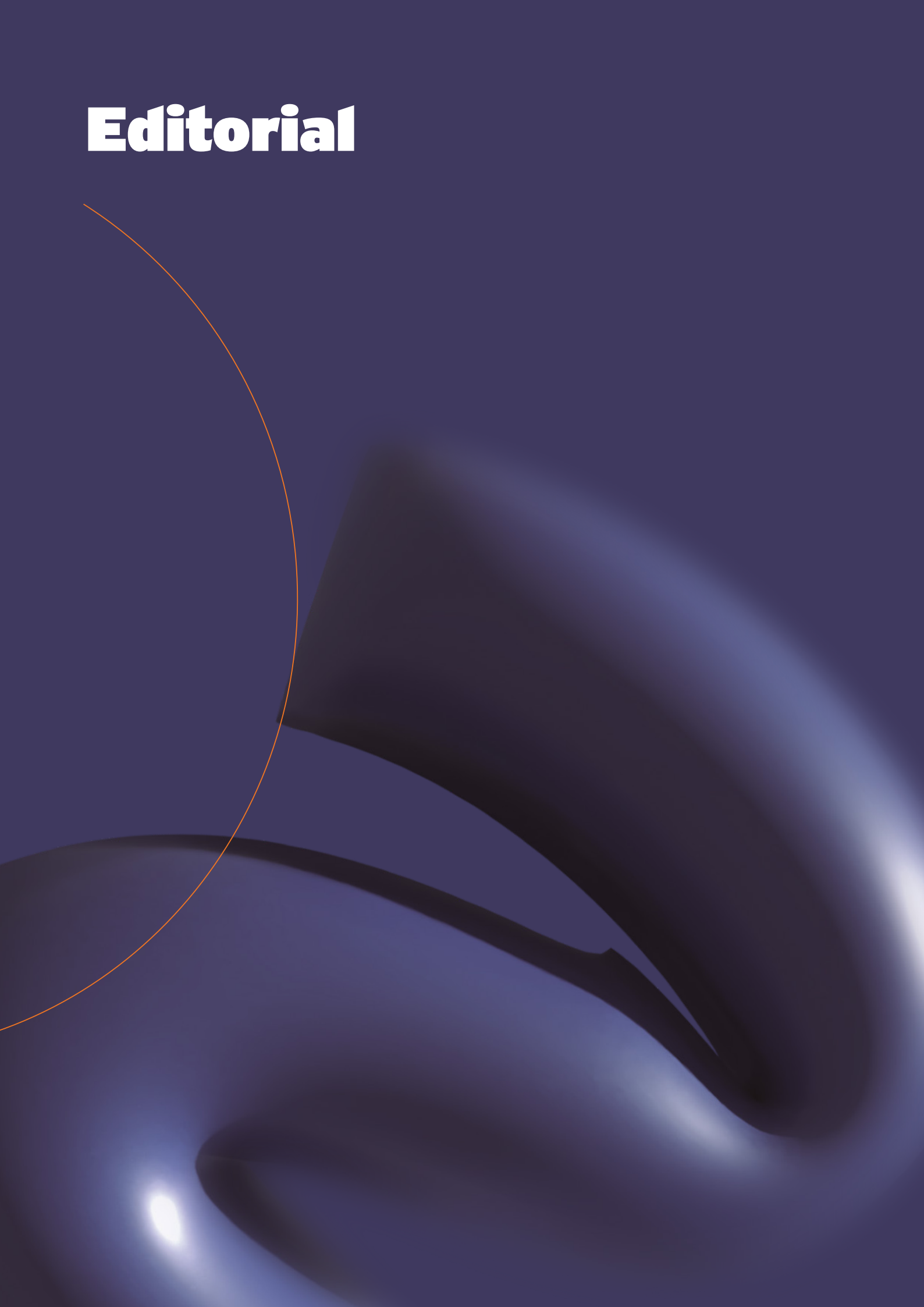
Advanced research for everyday life

2022

ANNUAL REPORT

Index

Editorial



Ana Isabel Pérez-Neira
Director

After more than one year of mandate, the overall trend in CTTC is very positive with evident signs that indicate stability and a reasonable growing capacity in capabilities and competitiveness. The total income growth of CTTC since 2020 is 118.5%. In this last year, the Board of Trustees' contribution and matching funds stay on a 36% basis.

Personnel is the major asset of CTTC. CTTC received the "HR Excellence in Research" award in 2015 from the European Commission and in 2022 it successfully passed into the Award Renewal phase in 2023. This is a recognition of the Institute's commitment to develop a Human Resources Strategy for Researchers (HRS4R), designed to bring the practices and procedures in line with the principles of the European Charter for Researchers and the Code of Conduct for the Recruitment of Researchers (Charter and Code). Our institution's comprehensive analysis and HRS4R action plan meet all the requirements of progress and quality of our HR policies.

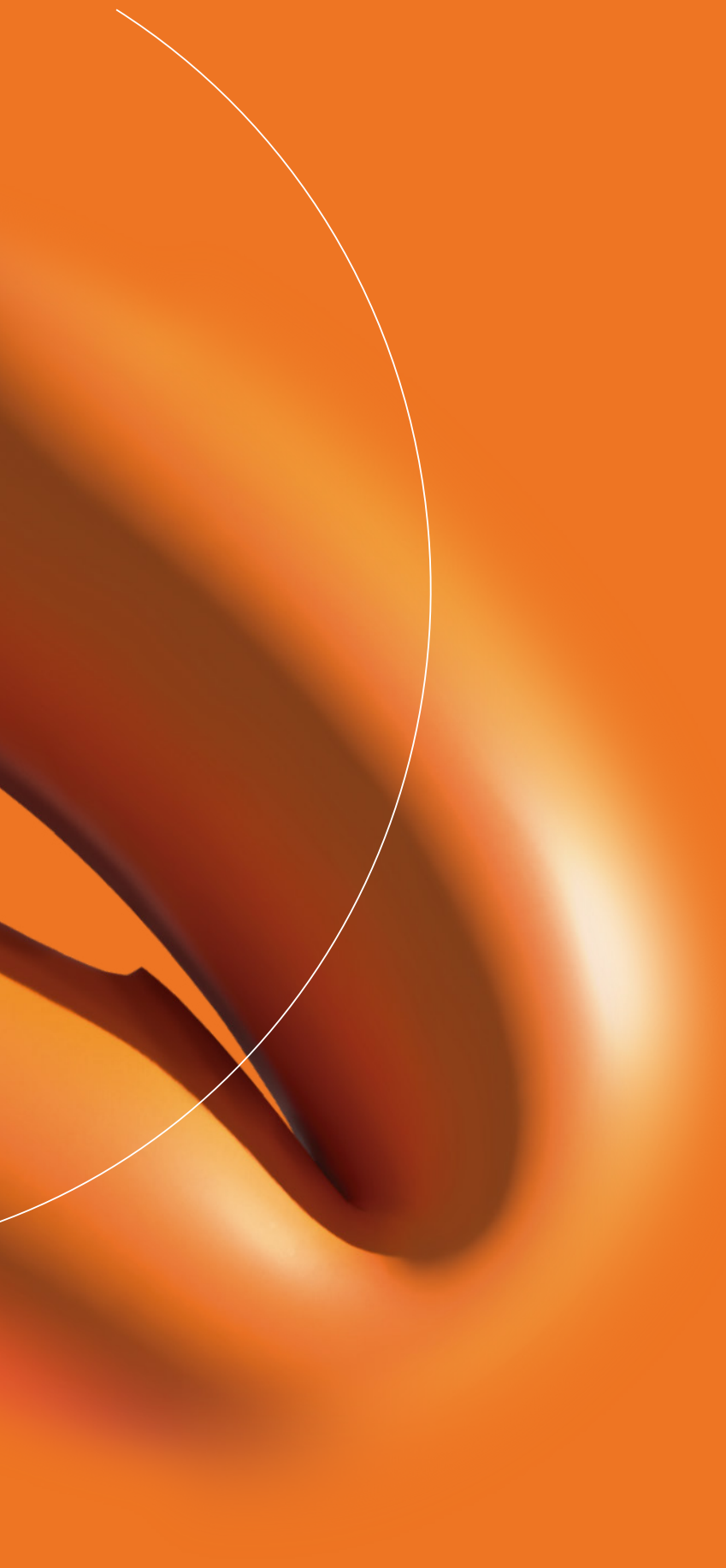
Thanks to the high percentage of the staff that enjoys permanent positions, CTTC can consolidate knowledge and experience and continuously build on it, which is an asset that provides strength to the institution. Proof of it is CTTC's actual experimental platform with 7 testbeds, most of which are the result of continuous engineering and scientific work along 20 years. During 2022, the labs have been growing considerably, based on the researchers' demand, which has involved over 130 m2 more of experimental space. The facilities are two buildings both located at the Parc Mediterrani de la Tecnologia: B4 building (3500 m2) and B6 building (3500 m2). Building B6 is focused on experimental facilities.

The existing capacities of CTTC R&D staff are significantly much better than 10 years ago. Currently these capacities properly match the existing R&D demand. There are around 120 R&D active projects in 2022 with an overall income of 6.1 M€ in 2022. During the years from 2013 to 2022 CTTC has closed with surplus, allowing productivity incentives, a novel plan for internal promotion, new research positions, and some reserve funds. These latter are distributed in programs mainly focused on infrastructure investment, improvement of labor conditions and programs that promote leading research and student fellowships. For instance, in 2022 a third internal project has been launched on Quantum Networks.

In 2022, the new 9 RUs have been put in place very smoothly and allowing to renew the certification UNE 166002:2021 for Research and Scientific Management. The RUs are the cornerstone of the strategic and functional plan. Budget control and decision making is decentralized towards the RUs, thus softening the traditional barrier between institutional and division objectives. By the end of 2022, the new Scientific Advisory Board (SAB) was created, and it oversaw revisiting the scientific RU structure.

Finally, under the spirit of continuously improving our dissemination and outreach, the new communication plan initiated in 2021 continues with its full deployment. CTTC's new corporate web was launched in February 2022, synchronized with the yearly edition of the Mobile World Congress.

Mission & Vision



CTTC is a non-profit research center, from a public initiative and with a high degree of self-financing, open to the participation of other public and private bodies, as well as to partnership with the industrial and business sectors.

It is our vision that research and technology development in communications and geomatics, 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 establish durable links with partners heading for international R&D markets.

With a professional scientific management, the institution's vision is to have enough critical mass of projects and researchers (fostering PhD among them) in order to be a worldwide lighthouse in terms of scientific Excellence and leadership of technological projects in the telecom and geomatics market, both at national and international levels.

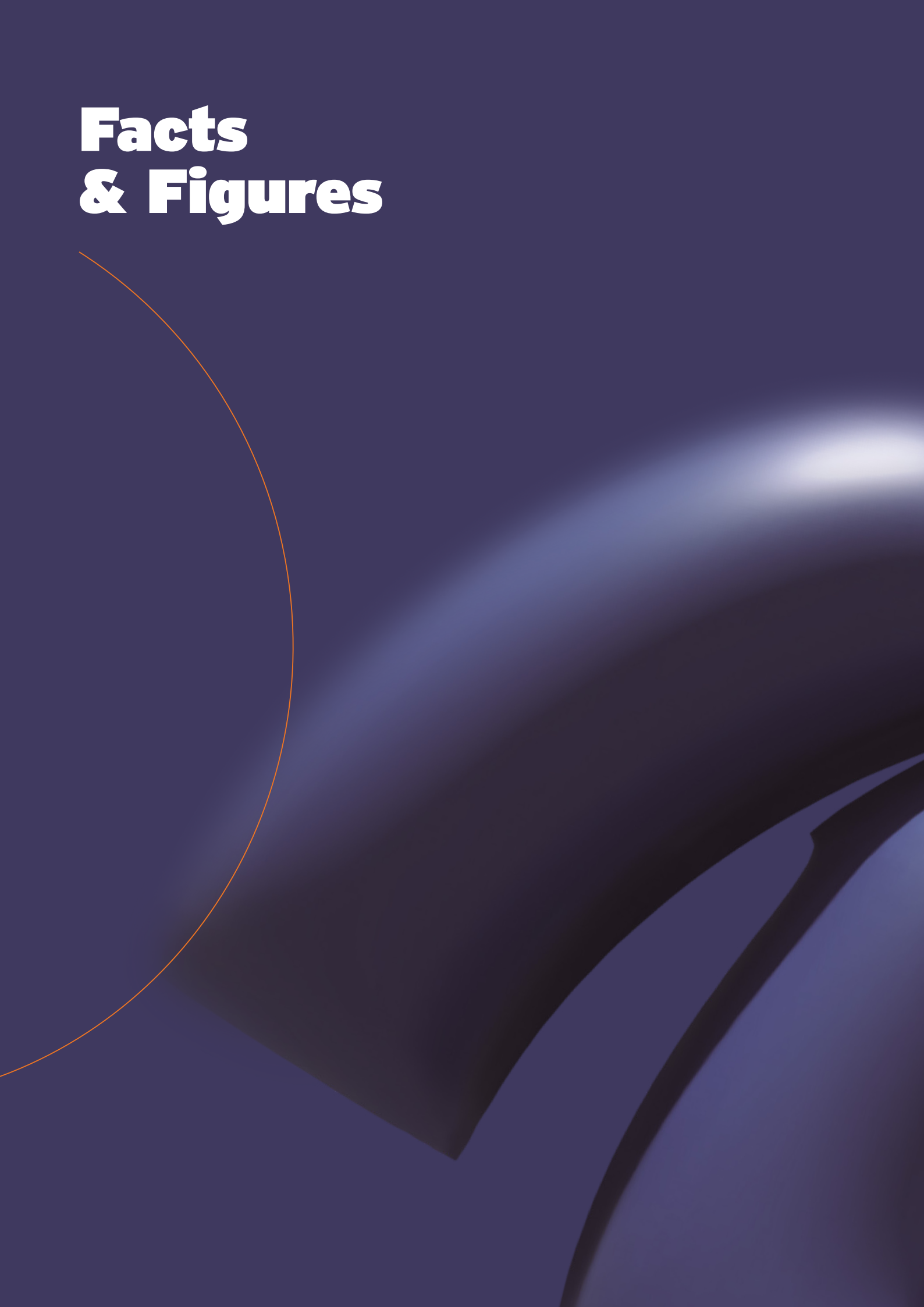
CTTC's core activity is the conception, design, implementation and experimentation of research and development projects in telecommunications and geomatics, which must produce innovative results in all their development phases, in both scientific and engineering terms. Our ultimate mission is to be an 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.

First, it is of utmost importance 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 aims at fostering innovation potential by making new scientific knowledge accessible and supporting its implementation. The second objective is to consolidate an international reputation in its scientific and technological activity, which means **enhancing its scientific production**. This will significantly support CTTC's mission of becoming an Excellence Flagship Center, **developing research in future emerging fields** and reinforcing the areas of expertise.

People are what configure the international reputation of the institution and **a good balance between permanent and temporal positions** will help to achieve a dynamic, successful and motivated environment. 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. Our excellence in managing Human Resources in Research is supported by HRS4R certification, which ensures a guarantee of ethical and professional standards at all levels of recruitment, working conditions and training.

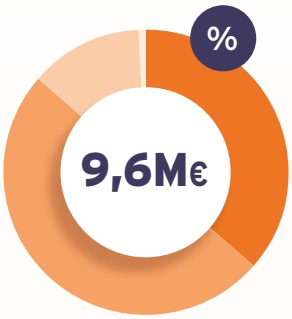
These dynamics must allow to lead the future CTTC course towards an institution that stands out in green economy and open science, always meeting the needs of the end users, in Catalonia, Spain and worldwide.

Facts & Figures



Projects

Total income



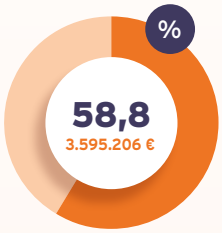
Income distribution

36,5% Core Funding
50,1% Competitive Funds
12,8% R&D Services
0,6% Other

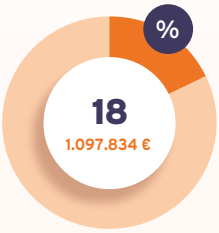
Total own-raised funds

~6M€

R&D projects



EUROPEAN ADMINISTRATION



SPANISH ADMINISTRATION

CATALAN ADMINISTRATION

DIRECT R&D CONTRACTS

OTHER

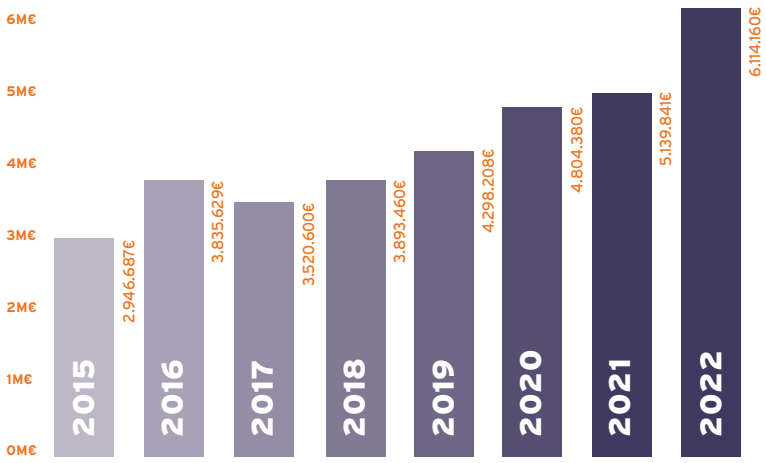
Project distribution

European projects

National projects (Spanish + Catalan)

Industrial projects

Income evolution (raised own funds)



107%

INCREMENT SINCE 2015

(AVERAGE GROWTH RATE/YEAR ~15%)

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)

2nd in SNS JU (1st in Spain)

Among research centers

In terms of project participation

27th in H2020 in Spain

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

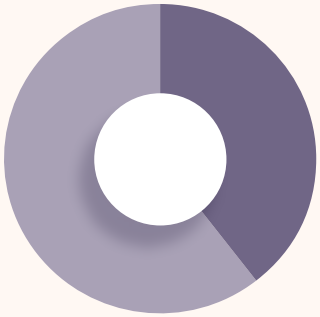
2nd in 5G-PPP (1st in Spain)

In terms of Spanish funding

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

Scientific publications

Number of Scientific Publications



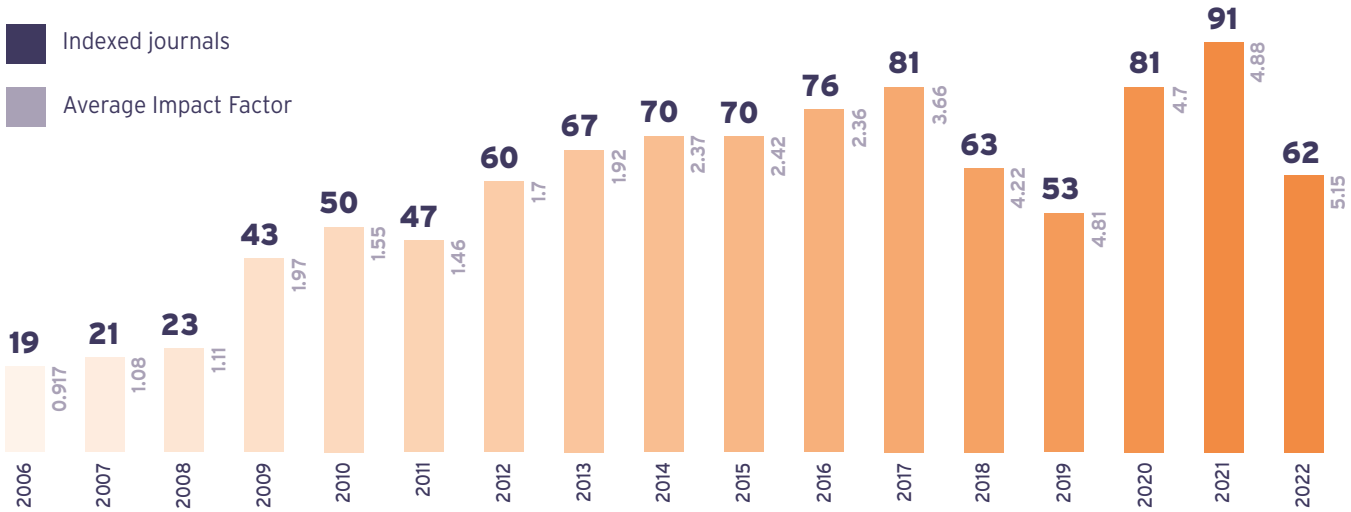
62 Journals (indexed)

95 Conferences

58,7 % FIRST QUARTILE

5,15 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

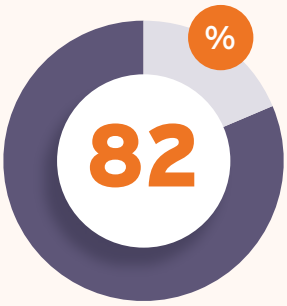
28

industry innovation

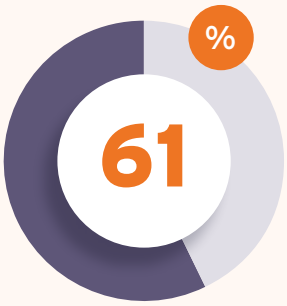
18

Staff

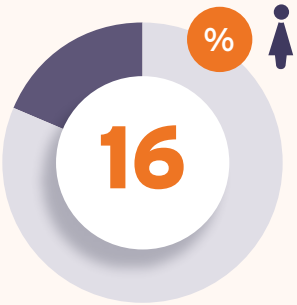
Details of team members



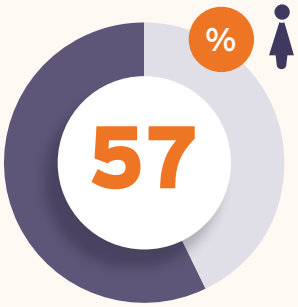
OF RESEARCHERS



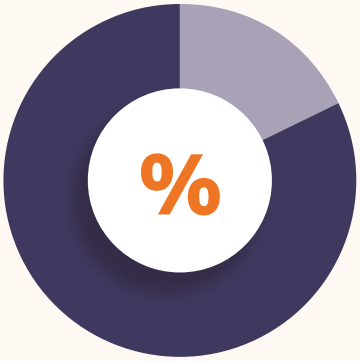
OF DOCTORS



OF WOMEN
(IN RESEARCH)



OF WOMEN
(IN MANAGEMENT)



18% Admin & Support

82% Research

5% MANAGEMENT

R&D Personnel distribution

RESEARCH DIRECTOR **R4**

SENIOR RESEARCHER **R3**

RESEARCHER **R2**

RESEARCH TRAINEE **R1**

25 total number of different nationalities

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 maximum representation and management organ of the CTTC** and it is currently constituted by the representative members of the promoting institutions: the **Generalitat de Catalunya**, the **Universitat Politècnica de Catalunya - Barcelona TECH (UPC)** and the **Ramon Llull University** (URL).

As of 31st of December 2022, the members' representatives are:

HBLE. SR. JOAQUIM NADAL I FARRERAS
Minister for Research and Universities

EXCM. MGFC. SR. JOSEP ANTONI ROM RODRÍGUEZ
Chancellor of the Ramon Llull University (URL)

SR. XAVIER BAULIES I BOCHACA
Responsible of Research & Innovation

SR. SERGI MARCÉN I LÓPEZ
Secretary of Telecommunications and Digital Transformation

EXCM. MGFC. SR. DANIEL CRESPO I ARTIAGA
Chancellor of the Universitat Politècnica de Catalunya - Barcelona Tech (UPC)

SR. JOAN GÓMEZ I PALLARÈS
Director General for Research

SR. ORIOL PUIG I GODES
Secretary of Infrastructures and Mobility Adviser

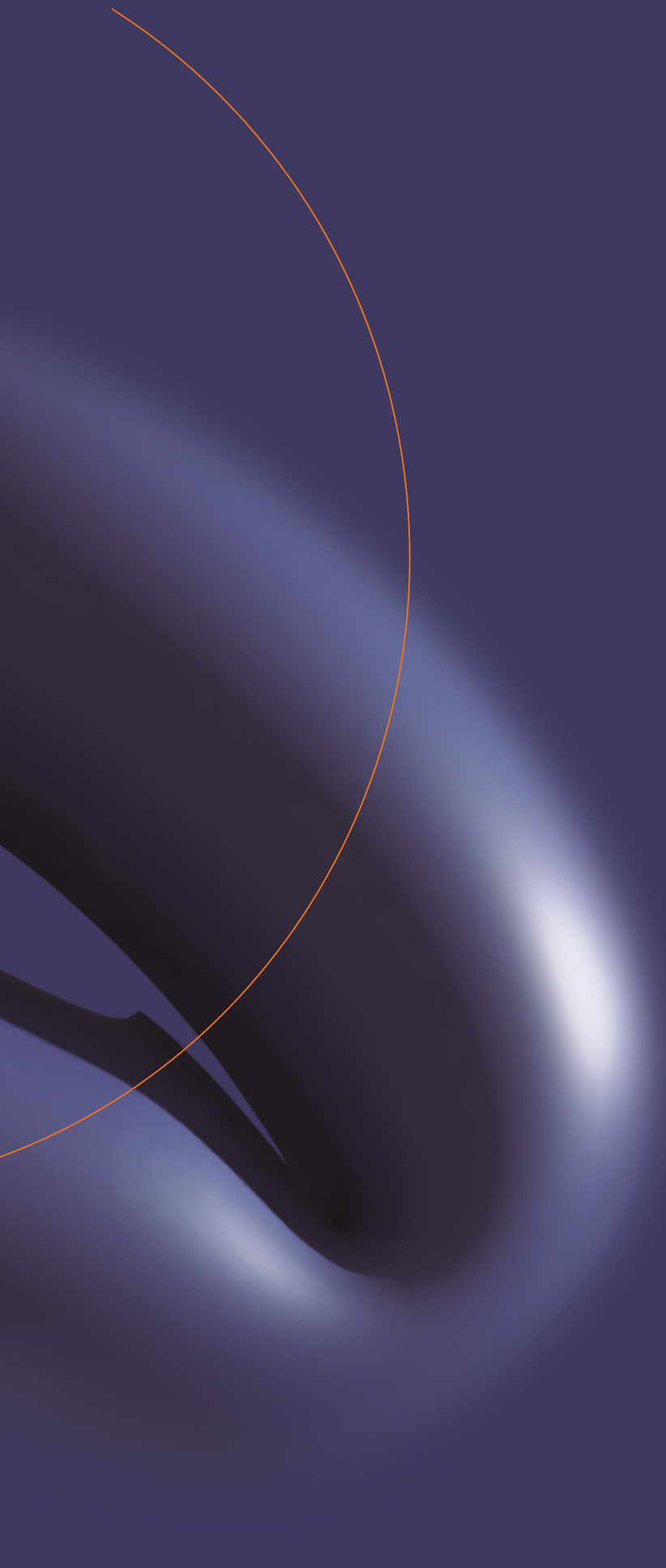
Scientific Advisory Board

The **Scientific Advisory Board** is responsible for the orientation and scientific evaluation for the CTTC and ensures external advice concerning the adequateness of CTTC's research strategy and of the scientific quality of the R&D work performed. The Scientific Advisory Board is composed of internationally distinguished scientists and advises CTTC's Director and Board of Trustees.

During 2022 the SAB was renewed resulting in the following composition (in alphabetical order):

Prof. José Campmany Univeritat Politècnica de València
Prof. Carla Fabiana Chiasserini Politecnico di Torino
Dr. Markus Dillinger Huawei Technologies
Prof. Octavia Dobre Memorial University
Prof. Elza Erkip New York University
Dr. Riccardo De Gaudenzi European Space Agency
Dr. Rosa María Mateos Ruiz Instituto Geológico y Minero de España
Dr. Carolina Pinart Nestlé
Dr. Colin Willcock Nokia Networks

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

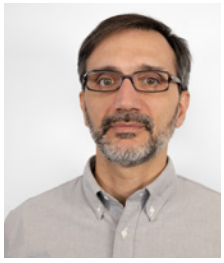
Dr. Jesús Gómez
Head of ISPIC

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**

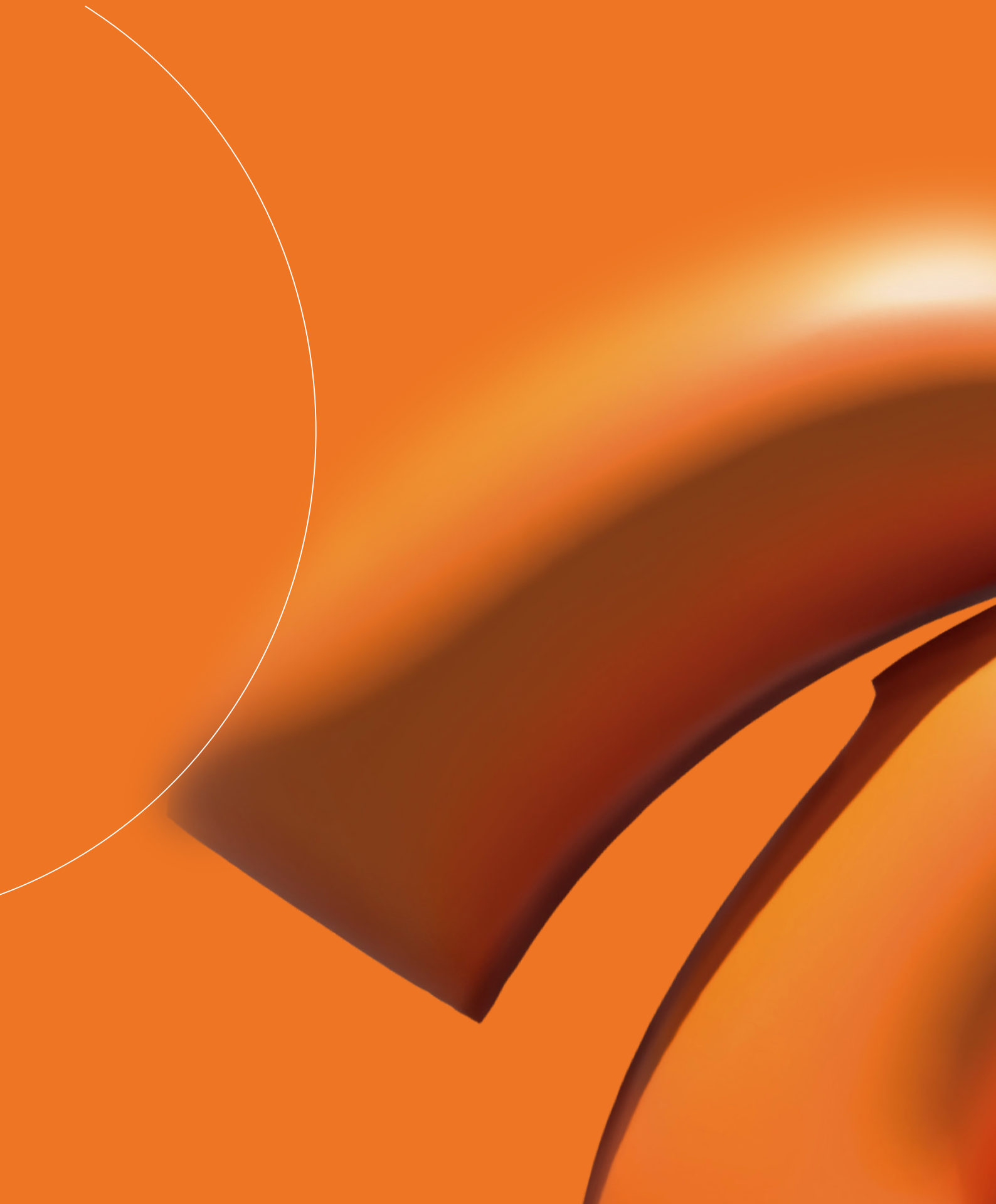
Geomatics

Dr. Michele Crosetto
Head of GM

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**

R&D Projects



2022 catalyzes the development of 6G. In this context, the following are a representative sample of such works, which are complemented by other substantial contributions nourished through CTTC's R&D framework.

5G solutions for european citizens

5G-SOLUTIONS aimed to prove in the field that the 5G capabilities provide ubiquitous access to a wide range of forward-looking applications and services with substantial improvements over the current technology and infrastructure on resilience, coverage and continuity, higher resource efficiency with concurrent usage by multiple verticals, boosted capacity and greater reliability, thus bringing the 5G vision closer to fulfillment. This was achieved through conducting advanced field trials of innovative use cases, directly involving end-users across four most plausible industry vertical domains: Factories of the Future, Energy, Smart City & Port, and Media & Entertainment. In this respect, 5G-SOLUTIONS contributes to the creation of new connected digital markets and to the EC's broader industry digitization and policy objectives in support of the Digital Single Market and maintaining Europe's leadership position in mobile telecommunications.

The SaS and GM RUs of the CTTC participated in the Media & Entertainment living lab by providing an advanced 5G experimental framework featuring an end-to-end 5G mobile network and a cloud and edge computing infrastructure as part of the distributed services and mobile computing lab. In this way, all use cases deployed could exploit the higher performance and automated management that 5G brings. More specifically, the CTTC participated in the following use cases:

- **On-demanding Streaming**
- **Multi-CDN (Content Delivery Network) Selection and Adaptation**
- **Auto-scaling Game Servers**
- **Multi-living Lab (On-demanding streaming UC with Multi-CDN selection UC)**

Additionally, SaS researchers also conceived and experimentally evaluated an AIML-based video-on-demand caching scheme that exploited reinforcement learning to adapt to time-location-dependent popularity patterns for video content, MCDN selection with proper AIML-based algorithms, and autoscaling game servers according to the game service metrics in K8S.

5th Generation connected and automated mobility cross-border EU trials conducted advanced field trials of some representative and innovative Connected and Automated Mobility (CAM) applications, seamlessly functioning across a designated 5G cross-border corridor ('Via Baltica-North') traversing Finland, Estonia & Latvia, in order to validate features and 3GPP specifications under realistic conditions, so as to accelerate the widespread deployment of 5G end-to-end (E2E) interoperable CAM ecosystems and virtualized services in digitized motorways and shipways throughout Europe. Indeed, one of the distinctive features of 5G-ROUTES includes aspects related to the deployment, testing and trialing of actual mobile networks endowed with a satellite component and multi-hop technology in maritime environments to guarantee seamless 5G connectivity in the Baltic Sea. CTTC has contributed to the project with its expertise on the management and orchestration of virtualized services in next generation mobile networks gained through its participation in different 5G-PPP projects and working groups. Such expertise is useful for understanding the needs of CAM service designers and to lead the design and validation of different technological enablers providing enhanced capabilities (e.g., cross- administrative domain integration fabric, proactive resource allocation of network services in cross-border environment) to the CAM services considered in the different use cases. CTTC provided its 5G testbed to carry out the mentioned activities as well as to perform lab-trials validating and assisting the development of different use cases related with infotainment and automated cooperative driving applications. Based on the gained knowledge, CTTC will collaborate in the final large-scale field trials validating the technological and business performance of the considered used cases over 5G network deployments.

Bringing higher quality of service to applications

Facebook-XR: XR-awareness in RAN and RAN-awareness in XR application Is an industrial collaboration with Meta aimed to investigate quality-of-service (QoS) control mechanisms/policies in 5G networks for eXtended Reality (XR) use cases and mixed traffic scenarios. The focus was on system-level simulations for AR/VR (augmented and virtual reality) use cases through the ns-3 5G-LENA simulator. CTTC researchers (in collaboration with Meta staff) have implemented mixed NGMN traffic models and 3GPP AR/VR traffic models, designed and developed new XR loopback mechanisms with XR application taking reaction to Radio Access Network (RAN) feedbacks based on 5G network key performance indicators, and derived new QoS MAC schedulers and timing adjustments for XR. The preliminary simulations show the importance of cross-layer optimization between the XR application and the RAN for XR traffic and QoS management.

Evolving radio Access protocols

EmMAC the medium access control (MAC) protocols of all modern communication networks (including 5G NR), have been designed and refined by numerous engineers and carved in stone by a standardization process. However, recent progress in the application of machine learning has opened up new possibilities to automate these design steps and potentially learn new protocols that outperform their conventionally designed counterparts. In fact, some reserved fields in the 5G NR protocol specification that are free to use for implementations, can be exploited to develop a new "language" to be used for exchanging control information between base stations and terminals, without enforcing any particular semantics on the vocabulary.

The longterm vision is to enable the emergence of an entirely new MAC control plane. This ambitious goal, however, can only be reached in smaller steps, since current algorithmic approaches do not scale sufficiently well to allow for a fully clean-slate approach to protocol design. Instead, and as a starting point, this project has focused on certain functions of the MAC protocol stack that leverage phases of low traffic demand to temporarily drive down energy consumption via coordinated, intermittent sleeping periods.

Moving forward towards 6G – Distributed solutions

Distributed management of Network Slices in beyond 5G
The MonB5G project (https://www.monb5g.eu/) has been co-funded by the EU through the Horizon 2020 framework. Twelve organizations from eight European countries (Greece, Spain, France, Ireland, Poland, Germany, Cyprus and Finland) have participated, and the total duration of the project was 42 months. MonB5G project, capitalised on artificial intelligence (AI) for smart, flexible and automated management of 5G and 6G network resources. The project used AI-based mechanisms for zero-touch management and orchestration of massive-scale network slices. With the application of AI algorithms, networks acquired self-configuration, self-monitoring, self-healing and self-optimization capabilities, without the need for human intervention. MonB5G project presented hierarchical, fault-tolerant, AI-based, automated network management framework that includes security and energy efficiency techniques for orchestrating many parallel network slices. AI-driven zero-touch closed-loop management was based on the three administrative elements of monitoring system (MS), analytic engine (AE), and decision engine (DE), with feedback interfaces used to reconfigure MS, AE, and DE to meet energy efficiency, security and scalability objectives along with network automation and service management goals.

CTTC has been the project coordinator of the MonB5G project and provides a beyond 5G lab environment to project partners where final proof of concept (PoC) is demonstrated. CTTC has also developed its own AI-based network management algorithms and worked closely with project partners to contribute to standards, generate patents and scientific publications that envision the next generation of mobile networks.

The blurring RAN is one of the Spanish Government funded projects from the UNICO-5G I+D program (UNICO-5G TSI-063000-2021-56/57). This project aims to develop an end-to-end blurring open RAN vision, through 6GBLUR-smart (smart decision-making algorithms for efficient end-to-end resource management) and 6GBLUR-joint (joint RAN and transport network control/orchestration mechanisms). The main objectives are to derive efficient end-to-end resource management procedures and smart decision-making control mechanisms for virtualized, adaptive, and blurring mobile network architectures. The resources to manage can be distributed and disaggregated through the mobile network, and include spectrum, network capacity, transport and fronthaul resources, baseband processing functions, energy, computing, or storage. To manage the resources from an end-to-end perspective and control the network smartly, in real-time and non-real time, we exploit AI/ML processes, targeting specific use cases.

Moving forward towards 6G – Integrating the space segment

Reliable B5G/6G Communications in 3D networks

Aims to perform a significant step forward by paving the path for the 5G NTN evolution towards 6G. 5G mobile networks has stimulated a complex and dynamic network ecosystem, where optimized end-to-end satellite support is key to manage requirements imposed by multiple vertical industries requiring full global connectivity. In this context, TRANTOR targets the in-orbit validation of a complete satellite value chain involving an automated management of satellite resources across multiple bands, satellites, and orbits, and a converged radio access network. The project addresses both the ground and user segments. At the ground segment, it targets the development of novel satellite network management solutions, fully integrated in the 3GPP management framework, which will allow the significant scaling up of heterogeneous satellite traffic demands and capacities in a cost-effective, highly dynamic, band and orbit agnostic manner. AI governance is the main pillar for enabling real time radio resource management across multiple satellite systems to efficiently and trustworthy addressing satellite client needs. At the user segment, the project aims to radically increase the flexibility of access architecture by enabling pre-6G non-terrestrial multiconnectivity. It will be supported by the design of a multi-orbit and multi-band antenna for satellite UEs as well as by the development of gNB and UE 5G NTN equipment able to attend the multiconnectivity needs. Security mechanisms to provide resilience against cyber-threads are also addressed.

Moving forward towards 6G: empowering equipment manufacturers and operators with new software technologies

Secured Autonomic Traffic Management for a Tera of SDN flows is delivering a new generation open-source cloud-native SDN controller to provide secured and smart connectivity services to B5G/6G networks. This new SDN controller has been established as an open-source group (OSG) at ETSI as TeraFlowSDN (TFS). TeraFlowSDN controller is able to integrate with current NFV and MEC frameworks as well as to provide revolutionary features for flow aggregation, management (service layer), network equipment integration (infrastructure layer), and AI/ML-based security and forensic evidence for multi-tenancy. The project proposes an integrated solution for tackling various challenges of B5G networks to support service providers and telecommunication operators in their journey towards future networks.

TeraFlowSDN is a cloud-native SDN controller composed of multiple container-based services using novel virtualization techniques, which are deployed as micro-services and managed on elastic infrastructure through agile DevOps processes and continuous delivery workflows. These micro-services are structure an application as a collection of interconnected and related services using a common integration fabric. In a micro-services architecture, services are simple and detailed, and the protocols are lightweight. Release 2 provides extended support for OpenConfig-based routers and a new type of interaction with optical SDN controllers through the ONF Transport API. Moreover, release 2 includes complete integration for microwave network elements (through the IETF network topology YANG model), and Point-to-Multipoint integration of XR optical transceivers and P4 routers. New capabilities for P4 routers include the ability to load a P4 pipeline on a given P4 switch; to obtain runtime information (i.e., flow tables) from the switch; and to push runtime entries into the switch pipeline. SLA validation has been re-engineered through all the workflows, from device monitoring, up to service and slice life cycle management. Thus, the Slice, Service, Policy, Device and Monitoring Components have been updated to support the necessary network automation workflows. Moreover, Release 2 brings a new component called Path Computation, enabling new use cases, such as energy-aware service placement. Cyber-security mechanisms have been improved, including new components for distributed or centralized attack detection, inference, and mitigation, enabling also novel use cases. DLT has been extended to interact with the Inter-domain Component and make use of a deployed Hyperledger Fabric.

Intelligent Security and Pervasive Trust for 5G and Beyond aims to advance 5G security and devise a smart, trustworthy and liability-aware 5G security platform for future connected systems. This vision is facilitated with the exploitation of Zero-Touch Service and Network Management (ZSM), Software-Defined Security (SD-SEC), Artificial Intelligence/Machine Learning (AI/ML) techniques, Moving Target Defense (MTD), PoT (Proof of Transit), blockchains and Trusted Execution Environment (TEE). A comprehensive set of novel security assets were developed to address some known challenges, e.g., adaptive slice security, and new ones like proactive security integrated into a high-level security architecture (HLA) developed by the project. Security-wise contributions were accompanied by the second research pillar of the project, namely trust and liability, through integration of novel mechanisms supporting confidence between parties and compliance with regulation.

INSPIRE-5Gplus achieved the following main outcomes and innovations during its execution:

- **Designed and implemented a closed-loop and automated end-to-end smart network and service security management framework that empowers not only protection but also trustworthiness and liability in management of 5G network infrastructures across multiple domains. This goal was achieved while ensuring that the provided security is compliant with the expected Security Service Level Agreement (SSLA) and the regulation requirements.**
- **Intelligent and autonomic end-to-end cybersecurity services that can detect and mitigate existing and new threats targeting 5G networks were developed. These assets operate following a Zero-touch network and Service Management (ZSM) paradigm to provide a software-defined security orchestration and management that enforces and controls security policies of network resources and services.**
- **Evolved and new security assets using novel tools and techniques with a focus on trust and liability across 5G infrastructure and services: liability-related metrics and KPIs which can be used to create a closed loop for liability-management have been defined. We investigated how Root Cause Analysis (RCA), Deep Attestation and these liability metrics can be used to enhance each other.**
- **A comprehensive analysis of the current security landscape of 5G networks, and the foreseen evolution trends of this landscape regarding security threats and security requirements was generated.**
- **An integration and experimentation framework and three demonstrators aiming to validate specific 5G security use cases were created. To maximize the synergy between the partners and their assets, it was essential to deploy this joint testing infrastructure.**

Beyond 5G – Optical Network Continuum targets the design, prototyping and demonstration of a novel end-to-end integrated packet-optical transport architecture based on MultiBand(MB) optical transmission and switching networks. MB expands the available capacity of optical fibres, by enabling transmission within S, E, and O bands, in addition to commercial C and/or C+L bands, which translates into a potential 10x capacity increase and low-latency for services beyond 5G.

To realize multiband networks, technology advances are required, both in data, control and management planes. Concerning devices, these include new amplifiers, filterless subsystems, add/drop multiplexers, etc. Such technology advances complement novel packet-optical white boxes using flexible sliceable Bandwidth Variable Transceivers and novel pluggable optics. The availability of MB transmission will also lead to a complete redesign of the end-to-end architecture, removing boundaries between network domains and reducing electronic intermediate terminations. The control plane is being extended to support multiband elements and a 'domain-less' network architecture. It will rely on physical layer abstraction, new impairment modelling, and pervasive telemetry data collection to feed AI/ML algorithms that will lead to a Zero-Touch networking paradigm including a full featured node operating system for packet-optical whiteboxes.

The results will be shown in two final demonstrations exposing the project benefits from operator and user perspectives. B5G-OPEN will have a clear impact on the society showing the evolution towards a world with increased needs of connectivity and higher capacity in support of new B5G services and new traffic patterns. CTTC participates across WP, including notably the design and implementation of a multiband transceiver and as WP leader in control and orchestration, focusing on TAPI enabled network orchestration.

AI-Powered Evolution Towards Open and Secure Edge Architectures drives the evolution of edge computing towards an integrated, next-generation edge-cloud compute continuum, as a key enabling technology to deliver the most demanding applications and use cases in the road towards 6G.

By adopting an interdisciplinary approach to converge techniques from multiple areas, including telecommunications, edge and cloud technologies, embedded and distributed computing, cybersecurity and AI, VERGE will achieve its vision based on three technical pillars, which can be briefly summarised as: i) building an "edge for AI" framework (Edge4AI), to support the flexible and efficient deployment and execution of the emerging 6G AI-enabled applications across a jointly orchestrated compute and communication continuum, while meeting the ultra-high computational and communication requirements, ii) leveraging "AI for edge" (AI4Edge), by employing cutting-edge AI methods to learn and optimise the network performance in the highly heterogeneous and rapidly changing B5G and eventually 6G environments, and iii) providing the necessary Security, Privacy and Trustworthiness "SPT for AI" methods (SPT4AI), to address the relevant challenges that specifically emerge due to the decentralized edge computing environment and the extensive use of distributed AI methodologies in a dynamic and heterogeneous network structure.

Machine Learning-based Cell-free Networks for 6G provides an evolved radio access network (RAN) architecture towards 6G. It is structured in three areas:

- **Radio Edge, which focuses on innovations at the RAN and fronthaul domains to exploit the potential of cell-free networking in future 6G networks. It combines mmwave hybrid beamforming radios, distributed processing, algorithms for adaptive access point (AP) clustering and open disaggregated RAN initiatives for cost-effective deployment. At the midhaul interfaces, optical ethernet technologies will be leveraged and the network will allow flexible sharing of the optical fibres with fixed services.**

- **Regional Edge, which provides elastic edge Cloud with machine learning (ML) driven dynamic slicing support and zero-perceived latency for the mobile edge computing (MEC) applications. This implies supporting advanced intra and inter data center load balancing to reduce the latency. Dynamic slicing approaches will be explored to trigger predictive slice reconfiguration.**

- **And Security, which targets the security and privacy of multi-tenant RAN infrastructures. It focuses on blockchain-based solutions to foster collaboration between tenants via smart contracts, and to support the flexible negotiation of network slice contracts; as well as on federated learning solutions with blockchain technologies to provide system-level security in 6G server-less architectures.**

Developing tools for climate change risk mitigation

RISKCOAST is concerned with the vulnerability of the coast. This is a territory that is highly vulnerable to the effects of climate change. The increase in the frequency of extreme weather events induces geological hazards that significantly affect the economy of coastal regions and represents a threat to its inhabitants. The RISKCOAST project promoted innovation to address a range of threats: landslides, land subsidence, erosion, and loss of soil due to torrential events, erosion of sandy coasts and regression of deltas. Coastal processes are often complex and have cascading effects that are difficult to predict. RISKCOAST offered a comprehensive vision of the risks that threaten the coast, considering the whole hydrological basin; and proposed a wide range of natural rehabilitation measures, adapted to each risk and territory. Strategies were developed for more coordinated and effective risk management. RISKCOAST provided innovative tools, methodologies, and solutions to face common coastal risks. The generated products support the three phases of emergency management: prevention, response, and rehabilitation.

Navigation and space applications

GNSS Antenna Array
It is well known that the presence of unintentional or intentional Radio Frequency Interference (RFI) signals in the Global Navigation Satellite Systems (GNSS) frequency bands can cause severe positioning performance degradation and even a complete service unavailability. Moreover, with the development of Software Defined Radio (SDR) GNSS signal generators and the popularization of low-cost SDR front-ends, the spoofing of the GNSS civil service turns out to be a real threat for GNSS receivers. Complementary to time and frequency-domain mitigation techniques, antenna-array based receivers can benefit from spatial domain processing. An antenna array receiver can also discriminate between legitimate GNSS signals from these being broadcasted by the spoofer. In this Project, we developed a receiver-independent GNSS smart antenna architecture for a real-time, automatic and autonomous, simultaneous anti-jamming and anti-spoofing spatial filtering for GNSS bands.

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. The signal format considers 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. In the project we have analyzed sub-optimal non-coherent receivers for 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); and characterized the output statistics for the optimal detector for the different scenarios, that allows for an approximate analytical calculation of the detection error probability. Of special interest are the results for solar scintillation and the obtained analytical expressions (channel model characterization and output statistics). The impact of Doppler frequency uncertainty on the capacity of non-coherent channels have also been studied showing that the coding gains typically obtained in additive Gaussian channels do not directly translate to non-coherent demodulation and demapping in the presence of Doppler frequency uncertainty. Further insights are expected to be obtained with the implementation of the real-time receiver.

IOPESA is a collaboration between CTTC and the European Space Agency (ESA) for the generation of reference trajectories in adverse environments for UAV applications based on combining RTK+INS/stereo camera data. GNSS technology can be combined with Inertial Navigation Systems (INS) and the data provided by a stereo camera by implementing a sensor fusion algorithm. The data offered by the INS and the stereo camera offer decisive information to improve the performance of GNSS in degraded scenarios.

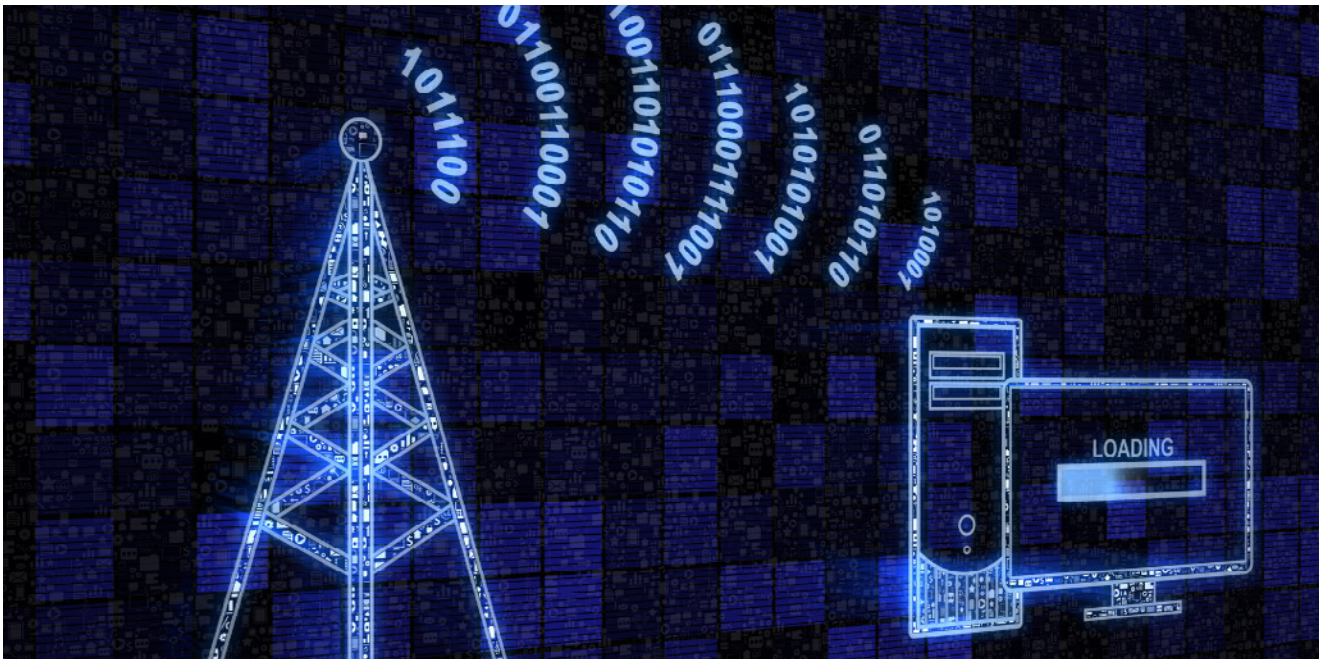
The IOPESA project implements an algorithm based on combining GNSS data obtained from a RTK solution with the data provided by the stereo camera to obtain a reliable reference trajectory in harsh scenarios. The project seeks to improve the sensor fusion algorithm developed in the frame of the EU project IOPES and to demonstrate that the implemented algorithm provides an appropriate reference trajectory in harsh environments for GNSS data such as forest, indoor or urban canyon. The tool developed in the frame of this project is planned to be used in ESA ESTEC to compute reference trajectories in post-processing for unmanned aerial vehicle (UAV) applications.

Training young researchers

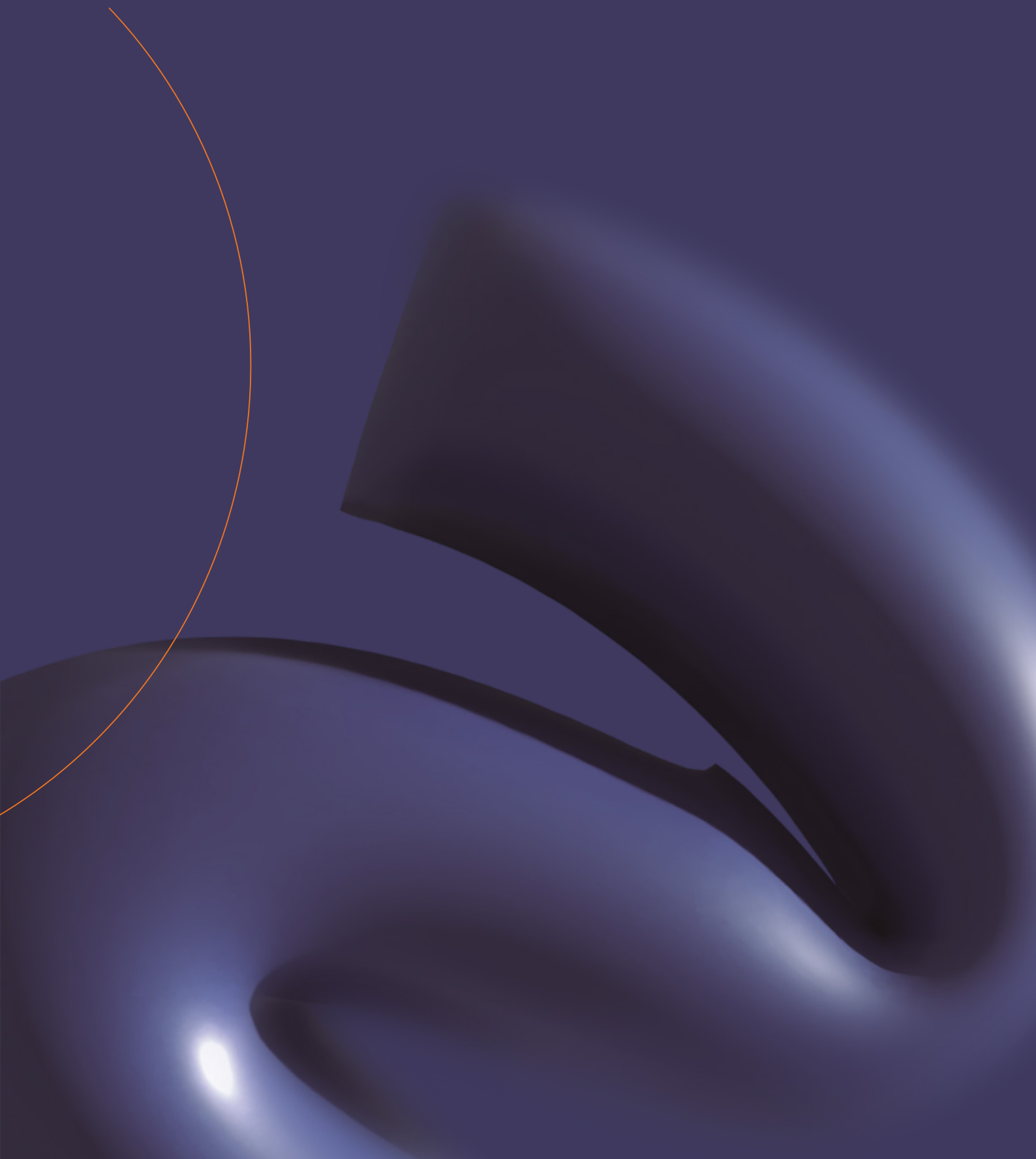
Integrating Wireless Communication Engineering and Machine Learning Innovative Training Network on the development of new machine learning (ML) methodologies for the design of wireless systems and the advancement of applied ML science aimed to, besides training early-stage researchers (ESR) on new frontiers for telecommunication systems, address several technical challenges by exploiting ML approaches. The project developed ML methods for the physical (PHY)-layer of wireless systems by learning and anticipating spatio-temporal features related to the wireless channel in multiuser multi-antenna networks; advanced the state of the art in the field of ML in order to address wireless communications constraints, such as is the highly dynamic environment, distributed wireless systems or stringent end-to-end delay constraints; provided new radio access policies in networks with massive connectivity and different QoS requirements and developed distributed and hierarchical ML architectures that enable cognitive network slicing and achieve system-wide optimization. With 10 beneficiary institutions from public and private sectors and over 10 partner organizations, 15 ESRs enjoyed multidisciplinary and specialized training on ML techniques for improved telecommunication networks and solutions.

Training for Sustainable Edge Computing Technology mission is to tame the growing carbon footprint of ML/AI based edge computing services adopting a twofold approach. Considering renewable energy resources to sustain the communication and computing tasks that run at the mobile network edge.

And developing fundamentally new and green-by-design computing and communication paradigms, to wisely exploit the available communication, computing and energy resources across the mobile edge network. This entails the design of novel ML/AI in-network processing techniques that have a small memory footprint, and that are at the same time trainable in an energy efficient manner. Particular attention will be paid to distributed computing approaches (federated learning). Besides coordinating the action the two Early-Stage Researchers are contributing to specific objectives such as the development advanced decentralised training of ML models for MEC in the presence of energy, memory and link reliability constraints or the profile energy consumption and memory footprint of ML algorithms on selected hardware architectures.



Scientific Publications



Contributions to mathematical and information theoretical tools applied to telecommunications, such us the characterization of the asymptotic behavior of a particular class of random matrices widely applied to the design of large multiple antenna systems or the application of coding theory to improve security and computational efficiency of distributed computation over wireless networks.

B. Hasırcıoglu, J. Gómez-Vilardebó and D. Gündüz, "Bivariate Polynomial Codes for Secure Distributed Matrix Multiplication," in IEEE Journal on Selected Areas in Communications, vol. 40, no. 3, pp. 955-967, March 2022, doi: 10.1109/JSAC.2022.3142355.
This paper considers the problem of secure distributed matrix multiplication (SDMM) using Bivariate polynomial codes. It is shown that, especially for upload communication or storage constrained settings, the proposed approach reduces the average computation time of SDMM compared to its competitors in the literature.

Philippe Loubaton, Xavier Mestre. On the asymptotic behaviour of the eigenvalue distribution of block correlation matrices of high-dimensional time series. Random Matrices: Theory Appl., 2022, 11 (31). (hal-02543994v2).
This paper studies the asymptotic behavior of linear spectral statistics built from block-normalized correlation matrices in multi-variate time series. Our results are based on the use of random matrix theory and are potentially useful in order to address the problem of testing correlation of a large number of time series.

D. Schenck, X. Mestre and M. Pesavento, "Probability of Resolution of MUSIC and g-MUSIC: An Asymptotic Approach," in IEEE Transactions on Signal Processing, vol. 70, pp. 3566-3581, 2022, doi: 10.1109/TSP.2022.3178820.
This work analyzes the asymptotic resolution probability of two subspace-based direction-of-arrival algorithms (MUSIC and g-MUSIC). Results are derived using random matrix theory and prove to be very useful in order to characterize situations where the sample volume is not much larger than the number of available antennas.

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

Ramon Casellas, Ricardo Martínez, Ricard Vilalta, Raul Muñoz, Alfredo González-Muñiz, Oscar González de Dios, and Juan-Pedro Fernández-Palacios, "Advances in SDN control and telemetry for beyond 100G disaggregated optical networks [Invited]," J. Opt. Commun. Netw. 14, C23-C37 (2022).
Evolution of software-defined networking (SDN) control for optical transport networks (OTNs) in disaggregated scenarios, focusing on its requirements and challenges when applied to "beyond 100G" networks, new challenges and requirements, such as the need to account for physical impairments, multiband/space-division multiplexing control, improved fault/alarm management, and optical telemetry and streaming.

C. Manso et al., "Scalability analysis of machine learning QoT estimators for a cloud-native SDN controller on a WDM over SDM network," in Journal of Optical Communications and Networking, vol. 14, no. 4, pp. 257-266, April 2022, doi: 10.1364/JOCN.449009.

In this paper, a solution to Machine Learning scalability for Quality of Transmission predictors is presented using a cloud-native SDN architecture. The proposed solution scalability is evaluated using three different ML QoT predictors and experimentally validated in a real wavelength-division multiplexing (WDM) over spatial-division multiplexing (SDM) testbed.

L. Nadal, M. S. Moreolo, J. M. Fàbrega and F. J. Vílchez, "SDN-Enabled Multi-Band S-BVT Within Disaggregated Optical Networks," in Journal of Lightwave Technology, vol. 40, no. 11, pp. 3479-3485, 1 June1, 2022, doi: 10.1109/JLT.2022.3158388.

In this paper, an SDN-enabled multi band (MB) sliceable bandwidth/bit rate variable transceiver (S-BVT) is proposed as a solution to provide future network capacity scaling. A proof of concept of the proposed MB transceiver is numerically and experimentally assessed targeting different scenarios up to 50 km of fiber.

P. Alemany, R. Vilalta, R. Munoz, R. Casellas and R. Martinez, "Evaluation of the abstraction of optical topology models in blockchain-based data center interconnection," in Journal of Optical Communications and Networking, vol. 14, no. 4, pp. 211-221, April 2022, doi: 10.1364/JOCN.447833.

In this paper, Blockchain is used as the key element for an cooperative optical multi-domain transport management solution to compose end-to-end Connectivity Services. The article compares abstraction models and evaluates which one is the most suitable option according to the Blokchain advantages and weaknesses.

E. Zeydan, J. Baranda, J. Mangues-Bafalluy, Y. Turk and S. B. Ozturk, "Blockchain-Based Service Orchestration for 5G Vertical Industries in Multicloud Environment," in IEEE Transactions on Network and Service Management, vol. 19, no. 4, pp. 4888-4904, Dec. 2022, doi: 10.1109/TNSM.2022.3194078.

This paper proposes a permissioned distributed ledger (PDL)-based blockchain architecture for network management in the telecommunications industry. The focus is on creating a trusted environment for Cloud Service Providers (CSPs) and Mobile Network Operators (MNOs) to manage network services in a multi-cloud setup. The approach is validated through experiments using the Quorum blockchain network, measuring performance metrics such as transaction and block count, write time, and transactions per second. The evaluation results highlight variations in service instantiation time and blockchain metrics, indicating differences in transaction load and speed. The paper concludes by offering recommendations for optimizing the transfer of service orchestrator logs to blockchain networks and addressing observed challenges.

F. Rezazadeh, L. Zanzi, F. Devoti, H. Chergui, X. Costa-Pérez and C. Verikoukis, "On the Specialization of FDRL Agents for Scalable and Distributed 6G RAN Slicing Orchestration," in IEEE Transactions on Vehicular Technology, vol. 72, no. 3, pp. 3473-3487, March 2023, doi: 10.1109/TVT.2022.3218158.

Network slicing allows for the creation of multiple virtual networks tailored to different use cases in 5G and future networks. However, current solutions face scalability issues due to centralized controllers needing a comprehensive view of resource availability. To address this, we propose a hierarchical architecture that manages network slice resources in a federated manner. Using deep reinforcement learning and the Open RAN paradigm, we introduce traffic-aware local decision agents in the radio access network. These agents adapt their resource allocation policy based on traffic dynamics, forming specialized clusters for faster training and reduced communication overhead. Our Federated DRL approach outperforms benchmark solutions by efficiently responding to user mobility patterns and minimizing interactions with centralized controllers.

Artificial Intelligence and Machine Learning solutions to improve communications

C. Casetti et al., "ML-Driven Provisioning and Management of Vertical Services in Automated Cellular Networks," in IEEE Transactions on Network and Service Management, vol. 19, no. 3, pp. 2017-2033, Sept. 2022, doi: 10.1109/TNSM.2022.3153087.

This paper addresses the challenges faced by new-generation cellular networks in supporting a wide range of virtual services with varying performance requirements. It proposes a softwarized 5G network architecture that incorporates ML-as-a-Service (MLaaS) to enable efficient decision making. The MLaaS platform provides pre-trained ML models for network slice subnet sharing and run-time service scaling. Experimental validation using an automotive testbed demonstrates minimal time overhead, while simulations show significant reductions in operational costs, such as up to 40% in CPU consumption and up to 30% in OPEX.

J. Viana, H. Farkhari, L. Campos, P. Sebastiao, K. Koutlia, S. Lagen, L. Bernardo, R. Dinis, "A Convolutional Attention Based Deep Learning Solution for 5G UAV Network Attack Recognition over Fading Channels and Interference", 2022 IEEE 96th Vehicular Technology Conference (VTC2022-Fall), London, United Kingdom, 2022, pp. 1-5, doi: 10.1109/VTC2022-Fall57202.2022.10012726.

This paper proposes a Deep Learning (DL) approach for detecting attacks on UAV networks, considering scenarios with authenticated terrestrial users and attackers in unknown locations. We use two observable parameters available in 5G UAV connections: RSSI and SINR. The developed algorithm is generalizable regarding attack identification.

M. A. Jadoon, A. Pastore and M. Navarro, "Collision Resolution with Deep Reinforcement Learning for Random Access in Machine-Type Communication," 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), Helsinki, Finland, 2022, pp. 1-6, doi: 10.1109/VTC2022-Spring54318.2022.9860949.

This work explores the use of ML tools to learn more efficient random access policies. Conventional random access protocols such as exponential backoff suffer from a high number of collisions and capture effects. In this work, we propose to use multi-agent deep Q-network (DQN) to find a single policy for all terminals to resolve collisions based on binary feedback. The proposed scheme outperforms exponential backoff and provides a better balance between throughput, delay and collision rate.

A. Pelati, M. Meo and P. Dini, "Traffic Anomaly Detection Using Deep Semi-Supervised Learning at the Mobile Edge," in IEEE Transactions on Vehicular Technology, vol. 71, no. 8, pp. 8919-8932, Aug. 2022, doi: 10.1109/TVT.2022.3174735.

In this paper, we design an Anomaly Detection (AD) framework for mobile data traffic, capable of identifying different types of anomalous events generated by flash crowds in metropolitan areas. We state the problem using a semi-supervised approach and exploit the great performance of different Recurrent Neural Network (RNN) models to learn the temporal context of input sequences. Our proposal processes real traffic traces from the unencrypted LTE Physical Downlink Control Channel (PDCCH) of an operative network, gathered during an extensive measurement campaign in two major cities in Spain. The AD framework is designed to perform: i) a-posteriori analysis to understand users' behavior and urban environment variations; ii) real-time analysis to automatically and on-the-fly alert urban anomalies; and iii) estimation of the duration of the periods identified as anomalous. Numerical results show the higher performance of our AD framework compared to classic AD algorithms and confirm that the proposed framework predicts anomalous behaviors with high accuracy and regardless of their cause.

Francesc Wilhelmi, Lorenza Giupponi, Paolo Dini, Analysis and evaluation of synchronous and asynchronous FLchain, Computer Networks, Volume 218, 2022, 109390, ISSN 1389-1286, doi.org/10.1016/j.comnet.2022.109390.

Motivated by the heterogeneous nature of devices participating in large-scale federated learning (FL) optimization, we focus on an asynchronous server-less FL solution empowered by blockchain technology. In contrast to mostly adopted FL approaches, which assume synchronous operation, we advocate an asynchronous method whereby model aggregation is done as clients submit their local updates. Thus, it potentially leads to higher efficiency in terms of communication overhead and idle periods. Results show the synchronous setting leads to higher prediction accuracy than the asynchronous case. Nevertheless, asynchronous federated optimization provides much lower latency in many cases, thus becoming an appealing solution for FL when dealing with large datasets, tough timing constraints (e.g., near-real-time applications), or highly varying training data.

Radio Access solutions

M. C. Tomé, D. Gutierrez-Rojas, P. Nardelli, C. Kalalas, L. C. Pereira da Silva, A. Pouttu, "Event-driven Data Acquisition for Electricity Metering: A Tutorial," in IEEE Sensors Journal, vol. 22, no. 6, pp. 5495-5503, March 2022, doi: 10.1109/JSEN.2022.3147016.

This paper provides a tutorial on the most recent advances of event-driven metering (EDM) while indicating potential extensions to improve its performance. We have revisited the effects on signal reconstruction of (i) a fine-tuned procedure for defining power variation events, (ii) consecutive-measurements filtering that refers to the same event, (iii) spike filtering, and (iv) timeout parameter. We have illustrated via extensive numerical results that EDM can provide high-fidelity signal reconstruction while decreasing the overall number of acquired measurements to be transmitted. Its main advantage is to only store samples that are informative based on predetermined events, avoiding redundancy and decreasing the traffic offered to the underlying communication network. This tutorial highlights the key advantages of EDM and points out promising research directions.

A. E. Amine, J. -P. Chaiban, H. A. H. Hassan, P. Dini, L. Nuaymi and R. Achkar, "Energy Optimization With Multi-Sleeping Control in 5G Heterogeneous Networks Using Reinforcement Learning," in IEEE Transactions on Network and Service Management, vol. 19, no. 4, pp. 4310-4322, Dec. 2022, doi: 10.1109/TNSM.2022.3157650.

The massive deployment of small cells in 5G networks represents an alternative to meet the ever increasing mobile data traffic and to provide very-high throughout by bringing the users closer to the Base Stations (BSs). This large increase in the number of network elements demands a significant increase in the energy consumption and carbon footprint followed by complex interference management. In order to address these challenges, we consider multi-level Sleep Mode (SM) where BS components with similar activation/deactivation times can be put to sleep. We consider a heterogeneous network architecture where small cells can switch to different SM levels to save energy and reduce dropping rate, based on a reinforcement learning. Results show that while offloading users to the macro cell can significantly reduce their delay, dropping rate and the cluster energy consumption, it comes at a cost of decreasing the network energy efficiency up to 5 times compared with the case of no offload.

S. Lagén, X. Gelabert, A. Hansson, M. Requena and L. Giupponi, "Fronthaul Compression Control for Shared Fronthaul Access Networks", in IEEE Communications Magazine, vol. 60, no. 10, pp. 36-42, October 2022, doi: 10.1109/MCOM.001.2100959.

In this paper we focus on fronthaul (FH) compression control strategies for multi-cell multi-user scenarios sharing a common FH link. We propose various methods for sounding reference signal (SRS) handling and analyze different FH-aware modulation data compression and scheduling strategies. Considering a full system setup, including the radio and FH access networks, a numerical evaluation is conducted using ns-3 5G-LENA.

Koutlia, B. Bojovic, Z. Ali, S. Lagen, "Calibration of the 5G-LENA System Level Simulator in 3GPP reference scenarios", Elsevier Simulation Modelling Practice and Theory (SIMPAT), vol. 119, 102580, Sept. 2022.

In this paper we calibrate the ns-3 5G-LENA simulator according to the 3GPP reference results for NR-based outdoor deployments. Moreover, we explore the REM feature provided by the simulator, to ease the calibration process and understand better the radio environment. Results show the resemblance of the simulator performance to that of simulators used as references by 3GPP.

B. Bojovic, Z. Ali, S. Lagen, "ns-3 and 5G-LENA Extensions to Support Dual-Polarized MIMO", Workshop on ns-3, June 2022.

In this paper, we propose, implement and evaluate models for ns-3 and the nr module to enable Dual-Polarized MIMO (DP-MIMO). The proposed extension supports multiple antennas for DP-MIMO with spatial multiplexing of two streams, by exploiting dual-polarized antennas and their orthogonality under line-of-sight conditions, as it happens at high-frequency bands. Additionally, we propose and evaluate an adaptive rank adaptation scheme.

Novel device technologies

A Wang, L Lei, E Lagunas, A I Perez, S Chatzinotas, B Ottersten, "Joint Optimization of Beam-Hopping Design and NOMA-Assisted Transmission for Flexible Satellite Systems," in IEEE Transactions on Wireless Communications, vol 21. no. 10. pp. 1-1 January 2022., doi: 10.1109/TWC.2022.3170435.

Next-generation satellite systems require more flexibility in resource management such that available radio resources can be dynamically allocated to meet time-varying and non-uniform traffic demands. Considering potential benefits of beam hopping (BH) and non-orthogonal multiple access (NOMA), we exploit the time-domain flexibility in multi-beam satellite systems by optimizing BH design and enhance the power-domain flexibility via NOMA. In the paper, we investigate the synergy and mutual influence of beam hopping and NOMA. We jointly optimize power allocation, beam scheduling, and terminal-timeslot assignment to minimize the gap between requested traffic demand and offered capacity. In the solution development, we formally prove the NP-hardness of the optimization problem. Next, we develop a bounding scheme to tightly gauge the global optimum and propose a suboptimal algorithm to enable efficient resource assignment. Numerical results demonstrate the benefits of combining NOMA and BH, and validate the superiority of the proposed BH-NOMA schemes over benchmarks.

M Caus, M Shaat, A I Perez, M Schellmann, H Cao, "Reliability Oriented OTFS-based LEO Satellites Joint Transmission Scheme," 2022 IEEE Globecom Workshops, pp. 1406-1412 January 2022, doi: 10.1109/GCWkshps56602.2022.10008593.

This paper investigates a dual satellite transmission scheme with coherent reception. The receiver has a single synchronization circuit and is locked to only one of the satellites. Beam-centric pre-compensation techniques are considered in the paper. The cooperation area in which coherent reception is feasible is characterized analytically. The application of precoding to the orthogonal time and frequency space (OTFS) waveform is considered to counteract the residual offsets, which result from the displacement of the receiver from the selected reference point. Numerical evaluations show that the dual satellite scheme improves the system spectral efficiency as well as the link reliability in comparison with the single satellite transmission scheme.

W. Li, N. Bartzoudis, J. Rubio Fernández, D. López-Bueno, G. Montoro and P. L. Gilabert, "FPGA Implementation of a Linearization System for Wideband Envelope Tracking Power Amplifiers," in IEEE Transactions on Microwave Theory and Techniques (IF 4.381).

This article focuses on FPGA prototype implementation aspects of an envelope tracking power amplifier digital predistorter system for wideband energy efficient 5G and B5G terminal devices. The real-time implementation works for 200 MHz bandwidth signals covering x3 DPD bandwidth expansion (i.e., 614.4 MHz FPGA baseband sample rate).

D. López-Bueno, G. Montoro and P. L. Gilabert, "Training Data Selection and Dimensionality Reduction for Polynomial and Artificial Neural Network MIMO Adaptive Digital Predistortion," in IEEE Transactions on Microwave Theory and Techniques (IF 4.381).

This article proposes training data selection methods and dimensionality reduction techniques that can be combined to enable relevant reductions of both polynomial and neural network adaptive MIMO digital predistorters to reduce the training time and implementation complexity in 5G and B5G base station radios and increase their energy efficiency and sustainability.

Llamas-Garro I., Brito-Brito Z., Mira F., De Melo M.T., Kim J.-M. "Microwave Spoof Surface Plasmon Sensor for Dielectric Material Characterization" IEEE Sensors Letters. Vol 6. No. 5. January 2022.

A microwave planar resonator sensor design supporting spoof surface plasmon waves is used for wafer dielectric characterization. The proposed circuit guides the microwave as a surface wave across the metal signal line, from port to port of the device. The surface wave effectively interacts with the sample being measured, placed on top of the planar sensor. The sensor is used to discriminate between wafers with different dielectric permittivity and thickness. Simulation and measurements demonstrate that the proposed spoof surface plasmon resonator sensor can be used to create a high sensitivity sensor for dielectric material characterization.

Maciel-Neto J.O., Fernandes G.D.F., Cavalcanti G.O., Llamas-Garro I., Kim J., Fontana E., "Prospects for developing pressure and tactile sensors based on surface plasmon resonance" IEEE Sensors. Vol 22. No. 19. pp. 1-1 January 2022.

This work examines the prospects of using the surface plasmon resonance (SPR) effect in the Otto configuration for pressure and deformation sensing. An open Otto chip device was employed, and the chip was characterized by reflectometry-based profilometry. The results indicate that the technique is feasible for either pressure or tactile sensing applications.

Navigation, positioning and geomatic solutions

Hernandez-Pajares, M, Olivares-Pulido, G, Graffigna, V, Garcia-Rigo, A, Lyu, H, Roma-Dollase, D, de Lacy, MC, Fernandez-Prades, C, Arribas, J, Tisropoulos, Z, Schmidt, M, Goss, A, Erdogan, E, van Evert, FK, Blok, PM, Grosso, J, Spaltro, E, Dominguez, J, Lopez, E, Hriscu, A. "Wide-Area GNSS Corrections for Precise Positioning and Navigation in Agriculture," Remote Sensing. Vol 14. No. 16. January 2022.

This paper characterizes, with static and roving GNSS receivers in the context of precision agriculture research, the hybrid ionospheric-geodetic GNSS model Wide-Area Real-Time Kinematics (WARTK), which computes and broadcasts real-time corrections for high-precision GNSS positioning and navigation within sparse GNSS receiver networks.

Barra, A., Reyes-Carmona, C., Herrera, G., Galve, J. P., Solari, L., Mateos, R.M., Azañón, J. M., Béjar-Pizarro, M., López-Vinielles, J., Palamà, R., Crosetto, M., Sarro, R., Cuervas-Mons, J., Monserrat, O., (2022), "From satellite interferometry displacements to potential damage maps: A tool for risk reduction and urban planning", Remote Sensing of Environment, Vol. 282.

This paper, which has been published in the most prestigious remote sensing journal, describes a procedure to transform the raw satellite radar observations in potential damage maps. Such maps can be used for urban planning purposes.

Fernández-Tejedor, M.; Velasco, J.E.; Angelats, E. Accurate Estimation of Chlorophyll-a Concentration in the Coastal Areas of the Ebro Delta (NW Mediterranean) Using Sentinel-2 and Its Application in the Selection of Areas for Mussel Aquaculture. Remote Sensing. 2022, 14, 5235.

This paper is focused on chlorophyll-a estimation in shallow coastal areas. The study concerns the coastal areas of the Ebro delta using Sentinel-2 remote sensing imagery. The methodology proposed provides a tool to the shellfish aquaculture industry of this important area.

Luzi, G., Barra, A., Gao, Q., F. Espín-López, P., Palamà, R., Monserrat, O., ... & Colell, X. (2022). A low-cost active reflector and a passive corner reflector network for assisting landslide monitoring using multi-temporal InSAR. Remote Sensing Letters, 13(11), 1080-1089.

This paper describes the characteristics of a C-band Active Reflector developed at CTTC, which has been tested in an experimental campaign in the Andorran Pyrenees. This device is important to monitor vegetated and forested areas, where it is not possible carry our standard interferometric radar observations.

Soriano-González, J., Angelats, E., Martínez-Eixarch, M., Alcaraz, C. (2022). Monitoring rice crop and yield estimation with Sentinel-2 data. Field Crops Research, 281, 108507.

This study evaluates the potential of Sentinel-2 to monitor the dynamics and evolution of rice fields in the Ebro Delta growing area. Sentinel-2 demonstrated strong capabilities for studying the crop performance of rice fields and must be considered in the development of new strategies for the management of rice-growing areas.

Technology Transfer & Industrial Collaboration

Spin-offs

After the constitution of CTTC's spin-off GeoKinesia, S.L in July 2020, during this 2022 CTTC has continued with the research collaboration addressing and supporting 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 2022, CTTC presented the "AgentTAG" solution to the 10th program edition of GINJOL, resulting in an award with financial support. This solution has been submitted for protection by the European Patent "SENSOR, SENSOR SYSTEM AND METHOD FOR GAS DETECTION", Patent ID: EP23382387. The AgentTAG solution relates generally to the field of sensors, and in particular, to an improved small, low-cost planar wireless sensor for sensing gases. Stand-off detection of toxic chemical compounds, such as nerve agent gases, is critical for security. Traditionally, nerve agent detection is performed using optical wavelengths and there are several technologies available, which include mass-sensitive sensors, field-effect transistors, chemicapacitors, and chemiresistors. The main difference between the above-mentioned technologies and the one being proposed in AgentTAG, is the use of microwave circuits and signals for the detection of the nerve gas. Advantages of the proposed technology include the possibility of using the microwave signals for sensing and wireless sensor data transmission, simultaneously. Microwave sensors can be made with low-cost in the form of sensor tags (e.g. wearable or conforming tags).

Industrial Collaboration

CTTC is strongly committed to the realization of industrial R&D projects too. One of the most significant recent milestones was the consolidation of CTTC as a 5G/B5G/6G expert with the award of 25 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 all the R&D projects, accounting for a total budget of more than 22 M€. This program is an excellent opportunity to strengthen the collaboration with the national industry and private sector, boost the development of own 5G/B5G technology and help Spain to be one of the leaders on the development of 6G in Europe. During this 2022, CTTC has secured the participation in its 25 R&D projects of key partners from the national industry (among which we highlight ATOS, Cellnex, Ericsson, Hispasat, Idneo Technologies, Inster, Keysight, and Telefonica) and, also, very relevant and active companies from the SME domain (such as 5COMM, Aragon Photonics, E-lighthouse, Integrasys, LuxQuanta, Optare, Naudit, Nearby-Computing, SRS, Telcaria, TTI Norte, WorldSensing).

It is also worth noting that the internationalization level of this activity is very high, with more than 75% of income being generated abroad. Notably, this includes strategic contracts with large companies like META/Facebook (advanced 5G network optimization techniques for a massive use of AR/VR/XR techniques), HUAWEI (5G fronthaul compression strategies for next-generation Radio Access Networks), Nokia Bell Labs (AI methods to enable autonomous wireless nodes to negotiate new protocols without human intervention), KDDI (multi-layer wavelength division multiplexing over SDM neworks), Septentrio (performance evaluation of tightly-coupled sensor fusion algorithm for positioning and navigation), or GMV (prototyping of radio resource management schemes for satellite communications).

Testbeds & Experimental Facilities

CTTC's testbeds and experimental facilities are one of CTTC most relevant assets. Thus, resources are devoted each year to extend experimental infrastructure and better condition the experimental spaces. One of such actions in 2022, is the extension of the Packet Optical Networks and Services Lab to enhance the ADRENALINE® testbed with passive optical access segment and edge computing enhanced features. The refurbishment of the space was accompanied by the connection of CTTC buildings by means of high-velocity and high-capacity dedicated optical fiber, which provides highly customized service connectivity between CTTC's testbeds and laboratories. Other renovations were initiated to substantially improve the fabrication workshop and rearrange some of the laboratories.

Once more the testbeds, laboratories, and research platforms, managed by specialized research personnel, have been a key resource for the realization of flagships R&D projects, such as the ones started in 2022 under the Horizon Europe program or the Spanish UNICO I+D. They also are fundamental to delivering competitive results in industrial direct contracts.

This infrastructure may be grouped in three areas of activity,

- NETWORK ARCHITECTURE
- RADIO ACCESS
- NAVIGATION & POSITIONING

The ADRENALINE® and EXTREME® testbeds are specifically designed for the deployment and assessment of network architectures, focusing on the transport and core network. They offer the capacity of developing, testing and validating solutions for network management, control and orchestration, as well as advanced transport solutions and end to end services. This infrastructure, fully developed at CTTC, relies on several labs and allows to deploy both physical and virtual network functionalities with advanced computing capabilities at both edge and cloud. They have been fundamental in the development and proof-of-concept of 5G solutions and in positioning CTTC as a key partner for 5G transformation and 6G development.

We also contribute to the CERCA Facilities with the "**xG Programmable Networks Testbed**"

CERCA GINYS

Addressing the **radio access** segment and wireless transmission are the GEDOMIS®, CASTLE® and IoTWORLD® testbeds. GEDOMIS® is a generic demonstrator for intelligent Software Defined Radio (SDR) platforms and edge computing, highly customizable to develop transceiver prototypes that combines hardware and software implementations. The space segment is integrated into the experimental infrastructure from CASTLE®, which combines a cloud-based access simulation platform for different radio standards with 5G over-the-air tests (sub 6GHz and mmWave front ends) and an end-to-end satellite communications link with access to a geostationary satellite for hybrid satellite-terrestrial network experimentation. To explore radio-based solutions for monitoring and smart management the IoTWORLD® provides an end-to-end testbed for the internet of things and its evolution to pervasive intelligence and cyber physical systems.
Complementary to the communication experimental facilities, we devote specific testbeds to address **navigation and positioning** technologies. GESTALT® is a global navigation satellite system testbed for the design and prototype testing of GNSS receivers. It hosts the open-source SDR receiver "GNSS-SDR" developed by CTTC and a common processing platform for GNSS signals, which is complemented with commercial receivers for reference performance measurement and other test equipment for the measurement and analysis of positioning and navigation solutions. Additional digital signal processing capabilities, sensors and controlled environment allow testing hybrid positioning solutions based on sensor fusion (UWB, INS, LIDAR, odomotry, cellular, ...) beyond outdoor positioning. For the analysis of the navigation systems, CTTC features GEMMA Navigation® testbed composed of different software modules for trajectory validation and optimal trajectory determination.

Additionally to the testbeds we continue to offer advanced simulation software and simulation environment for telecommunications and geomatics. Leaning on an open-source software approach, we are committed to transferring our knowledge, contributing to the research and innovation community and reinforcing CTTC leadership and expertise in open SW and open-standardization:

GNSS-SDR® – Is an open-source Global Navigation Satellite Systems software-defined receiver fully developed and maintained by CTTC. 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/

5GLENA – ns-3 modules for LTE/LTE-A and 5G network simulation according to standards defined by 3GPP, https://5g-lena.cttc.es/. A new video introduces the simulator main features and applications [link to youtube channel/video].

As ETSI Teraflow SDN task force chair, CTTC contributes to the development of cloud native SDN controller for 6G xHaul transport networks downloadable from https://tfs.etsi.org/.

These solutions have received 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, system level analyst for LTE/LTE-A/5G -especially on mobility and spectrum sharing/coexistence solutions- and software network solutions for micro-service based, cloud-native and carrier-grade SDN controllers, integrated with virtual and edge computing frameworks (NFV, MEC).

Other software packages are not open source but can be used 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; ADA (Active Deformation Area) Tools includes 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.

Corporate Events

CTTC participated as an exhibitor in international trade fairs such as the **Mobile World Congress** (MWC), the **IoT Solution World Congress** or the **Smart City Expo World Congress**. The booths are instrumental for showcasing CTTC technologies, testbed and demo portfolio. At MWC22 in particular, CTTC presented to the visiting authorities and potential partners, a number of results from on-going R&D projects and showcased demos of (i) 3D constellations for 6G designed by AI; (ii) log management in NFV Service Orchestration; (iii) how 5G-LENA, the open-source ns3 simulator developed by CTTC, can be used in V2X scenarios and for radio environmental mapping activities.

CTTC also participated in the corresponding **brokerage event** and signed a **Memorandum of Understanding** with the **Korea Testing Laboratory** on the occasion of the MWC. At the IoT Solutions World Congress CTTC showcased a solution for increasing driving safety based on vehicular communications (V2X), while the presentations at Smart City Expo brought a delegation from Colombia to visit CTTC and explore possible collaborations.

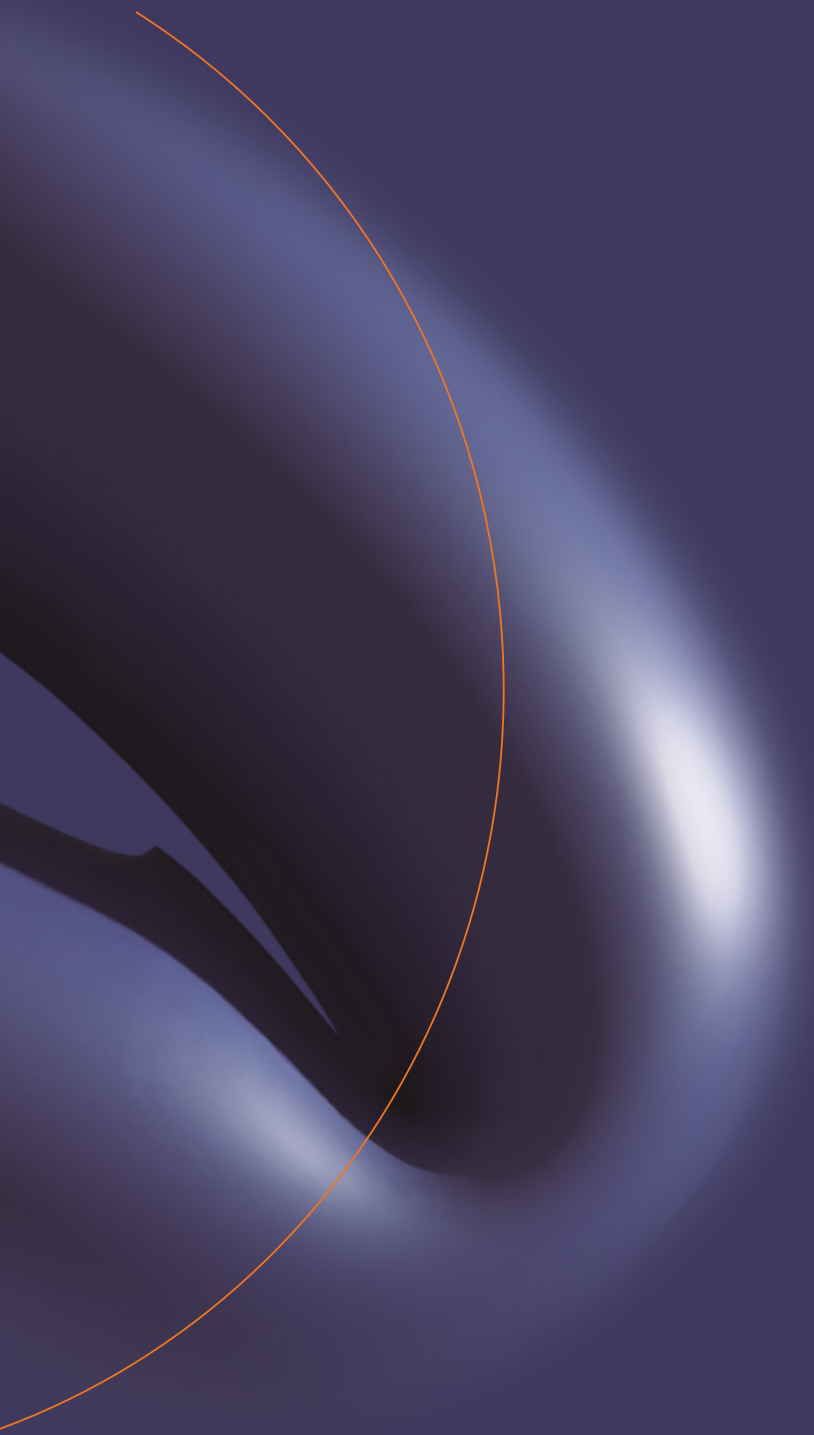
CTTC Day

In 2022 we had the opportunity to organize once more the CTTC Day, which was interrupted due to the pandemic. The CTTC Day held the CTTC Workshop as well as social events. This biannual event aims at gathering all CTTC researchers, so that they can disseminate their technical work and share their ideas with other CTTC colleagues. Several vibrant poster sessions were organized together with invited speakers. This was the second edition of the event, which took place in November 29 at the Sunway Hotel (Sitges, Barcelona). The full program is available at **https://cttcworkshop.cttc.es/**

The workshop hosted two renown invited speakers, along with stakeholders of the local hi-tech ecosystem which had the opportunity to engage with CTTC staff.

The event provided the opportunity for the administration and support staff to also present their activities and to attend specific training and team-building sessions.

Impact, Interest Groups & Associations



In 2022, the Centre Tecnològic de Telecomunicacions de Catalunya has come to play a major role in the definition of the future 6G communication systems. This is evidenced by the fact that CTTC is involved in 8 R&D projects (or nearly one out of four projects) awarded in the first call of the Smart Network and Services Joint Undertaking (JU-SNS) Workprogramme of Horizon Europe. Those projects will bring a total financial support of 3.5 M€ for the CTTC. The topics comprehend a broad set of 6G communication challenges including AI for secure open or ultra-low power network architectures, satellite and terrestrial radio access integration for distributed and ubiquitous services, non-terrestrial networks, flexible and scalable networks, or sustainability and energy efficiency. Notably, this includes the participation in HEXA-X II, the flagship initiative of the JU. The objective is to design a complete 6G communications system with a view to its standardization and implementation. Overall, the participation of CTTC in the first calls of Horizon Europe has resulted in the launch of 11 new projects, with a total funding of 5 M€.

Also, the CTTC has continued to play a very active role in the Governing Board of the 6G Smart Networks and Services Industry Association (6G-IA), the private side in the Smart Networks and Services Joint Undertaking (SNS JU) which builds on an EU contribution of 900 M€ for the 2021-2027 period. All major industrial players from all over Europe are represented in the 6G-IA Governing Board (equipment vendors, mobile network operators), as well as several industrial associations and thriving SMEs. CTTC is one of the two representatives of research centers and academia in this board since 2014. This has allowed the Center to play a very influential role in the definition of the 6G R&I Workprogrammes (2021/22 and 2023/24) which gather the scientific policies and European priorities in the area of SNS. CTTC has also played an editorial role in selected white papers of strategic interest for the EC such as the one entitled 'European Vision on 6G systems'. Additionally, in 2022 CTTC has been re-elected as a Steering Board member of Networld Europe. This European Technology Platform elaborates the Strategic Research and Innovation Agenda (SRIA) in which the SNS-JU workprogramme is largely based. A number of CTTC researchers have had editorial responsibilities in the elaboration of the SRIA.

Besides, CTTC is an elected a member of Photonics 21's Board of Stakeholders which has allowed the Center to provide leverage and influence towards the definition of EU priorities in the area of photonic devices and optical networks. More recently, CTTC has started acting as chair of the Ground Motion Service Advisory Group of the European Environmental Agency. By doing so, the Center plays a key advisory role and provides the Agency with expertise in satellite-based interferometry techniques for ground analysis. Complementarily, CTTC researchers were appointed to serve in several boards and steering committees such as the Technical Steering Team member del Open Networking Foundation, Optical Transport Configuration and Control, or Huawei's European Optical Communication Advisory Board.

CTTC is actively involved in standardization efforts in order to transfer research to products. Being part of several SDOs and having different roles from monitoring to leadership of specific groups from SDOs as ETSI, 3GPP, ITU, ONF or IETF, provides CTTC with a unique perspective on standardization processes and industry needs. Our participation in the ETSI research conference and presenting standardization plans for the new 6G Smart Networks and Services projects can help to ensure that CTTC's research aligns with industry needs and can be implemented in a timely and efficient manner. Additionally, the leadership of ETSI OSG TeraFlowSDN can help to raise awareness about this standardization effort and encourage adoption by industry stakeholders. TeraFlowSDN is an ETSI open source group that focuses on the development of a cloud-native SDN controller to foster innovation in transport networks for beyond 5G and 6G scenarios. Overall, CTTC's active involvement in standardization efforts demonstrates a commitment to advancing the state of the art in the field and ensuring that research outcomes can be translated into real-world impact.

First ETSI TeraFlowSDN Hackfest during the Network X event in Amsterdam, Netherlands, organized by CTTC as Chair of ETSI TeraFlowSDN group

Developing the service to the society, beyond the scientific and technological community is part of our mission. To this respect we continue our collaboration with cities and institutions. An exemple is the partnership with the City of Castelldefels. We supported the Digital Forum "Fòrum Digital de Ciutat" promoted by the City Council of Castelldefels, followed up by a series of meetings to explore further technical assistance towards the development of the Smart City project and its digitalization.

2022 gave us an opportunity to present our recent developments and facilities to the Minister for Research and Universities, the General Director for Research and the General Secretary of the Research and Universities Department.

Quality Standards & Career Development

CTTC has long adopted internal policies to deploy quality standard protocols to ensure very high standards towards an efficient management of the R&D activities, a transparent career development policy and a stimulating and favourable work environment.

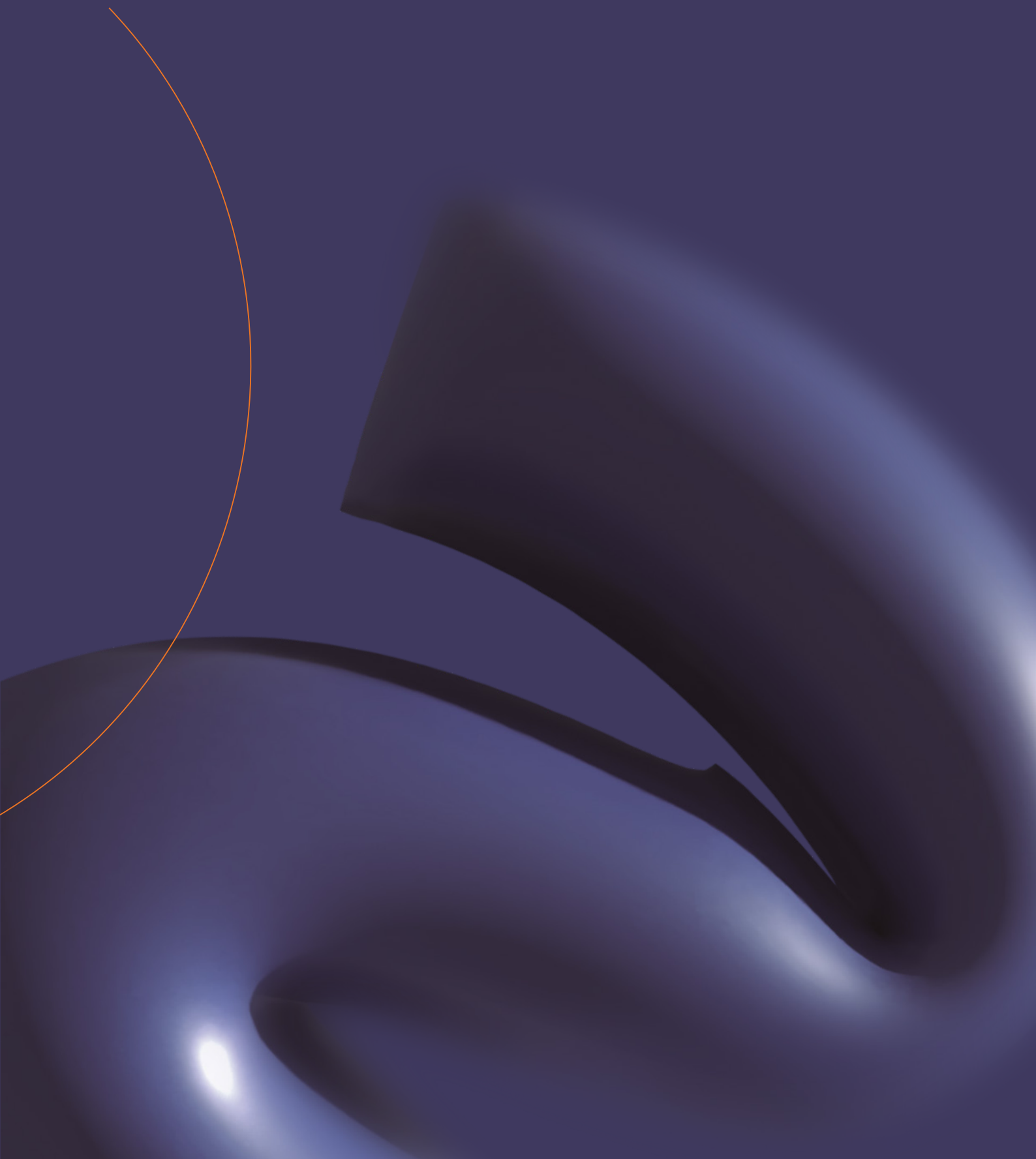
CTTC has been recognized by AENOR with the certification UNE166002:2006, then updated to UNE 166002:2014 and recently updated to UNE 166002:2021 (aligned with the international standard ISO 56002) for R&D Management Systems. This certification has been internally implemented as a group of 12 procedures that are periodically revised and yearly audited. The Direction and Management Team of CTTC are committed to foster high quality research, development and innovation by improving and periodically revising the efficiency of the R&D Management System. CTTC has successfully completed the adaptation to the new norm in 2022, as confirmed in the successfully passed follow-up Audit.

In the framework of HR practices with those of the Charter and Code principles, CTTC has been granted to continue to use the 'HR Excellence in Research' award as a provider of a stimulating and favourable work environment for researchers. After a 3-years phase of implementation, the Human Resources Strategy for Researchers (HRS4R) enter the Award Renewal phase. After the assessment undertaken by the EC external experts with a Site Visit in December 2022, the evaluation outcomes evidenced that CTTC comprehensive analysis and action plan meet all the requirements of progress and quality towards aligning HR practices with those of the Charter and Code principles. Accordingly, CTTC successfully passed into the Award Renewal phase.

In synergy with the HRS4R, CTTC is also committed to promoting a diverse and inclusive environment in terms of age, disability, gender, national origin, race, religion, or sexual orientation. The CTTC seeks to increase the presence of women in those areas where they are underrepresented and consider the gender dimension in research, towards improving the quality and excellence of technological and scientific outcomes. To this extent, CTTC has developed and is implementing a Gender Equality Plan (GEP). The general objective is to obtain a more balanced presence of men and women in the Institution, improve working policies towards better reconciling work and family life, prevent discrimination and gender violence, disseminate and inform the staff regarding laws and rules in gender equality, provide training in gender equality, equal access to job post and promotions within the Institution. The actions and measures proposed in the GEP cover work areas such as access to employment, working conditions, promotion and training, prevention and action against harassment, culture, correct use of language and communication. In 2022, in line with the CTTC commitment to protect the safety and health of its staff as well as the rights of people to be respected, a campaign to give awareness on the "CTTC Protocol for preventing and dealing with sexual harassment and sex-based harassment" was performed.

Following the principles of the Charter and Code, a Training Plan is yearly designed based on the results obtained from the annual survey for all staff performed to identify training needs. It is approved by the Direction and the Works Council, resulting in a wide catalogue focused on different types of training (complementary skills, technical knowledge, languages, communication techniques, stress reduction, etc.). A system for the professional career progression/ promotion of personnel has been implemented, according to a defined career path. A mechanism for evaluating the professional category of all new CTTC personnel has also been established through a dedicated Committee which undertook a significant activity in 2022 to promote more than 15 researchers. Except for the R4 categories which were directly appointed by the Director, the promotion followed a bottom-up approach were the RU heads identified potential candidates and encourage their application.

Awards & Acknowledgments



CTTC acknowledges the peer recognition and trust laid up in our colleagues from the different associations, bodies, and panels. Examples of such recognition are highlighted in this report.

As an outstanding example of the mission to strengthen scientific societies and their peer-reviewed publications process, Dr. Xavier Mestre was awarded by the "Outstanding Editorial Board Member Award 2022", granted by the IEEE Signal Processing Society for outstanding editorial board service for the IEEE Transactions on Signal Processing. At European level, Prof. Ana I. Pérez-Neira, CTTC Director, received the fellowship award as 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 honour.

Other excellent technical contributions were acknowledged in the framework of standardization bodies and open-source development initiatives. Representatives of such acclaimed contributions are the "Upstart of the Year" awarded at the Layer123 Network Transformation Awards 2022, London to ETSI TeraFlowSDN initiative chaired by Ricard Vilalta from CTTC, and the "Outstanding Technical Contributor to ETSI OpenSourceMANO (OSM)" awarded to Lluis Gifre for contributing with a new feature enabling integration of ETSI OSM with ETSI TeraFlowSDN.

Best paper awards were granted to the publications:

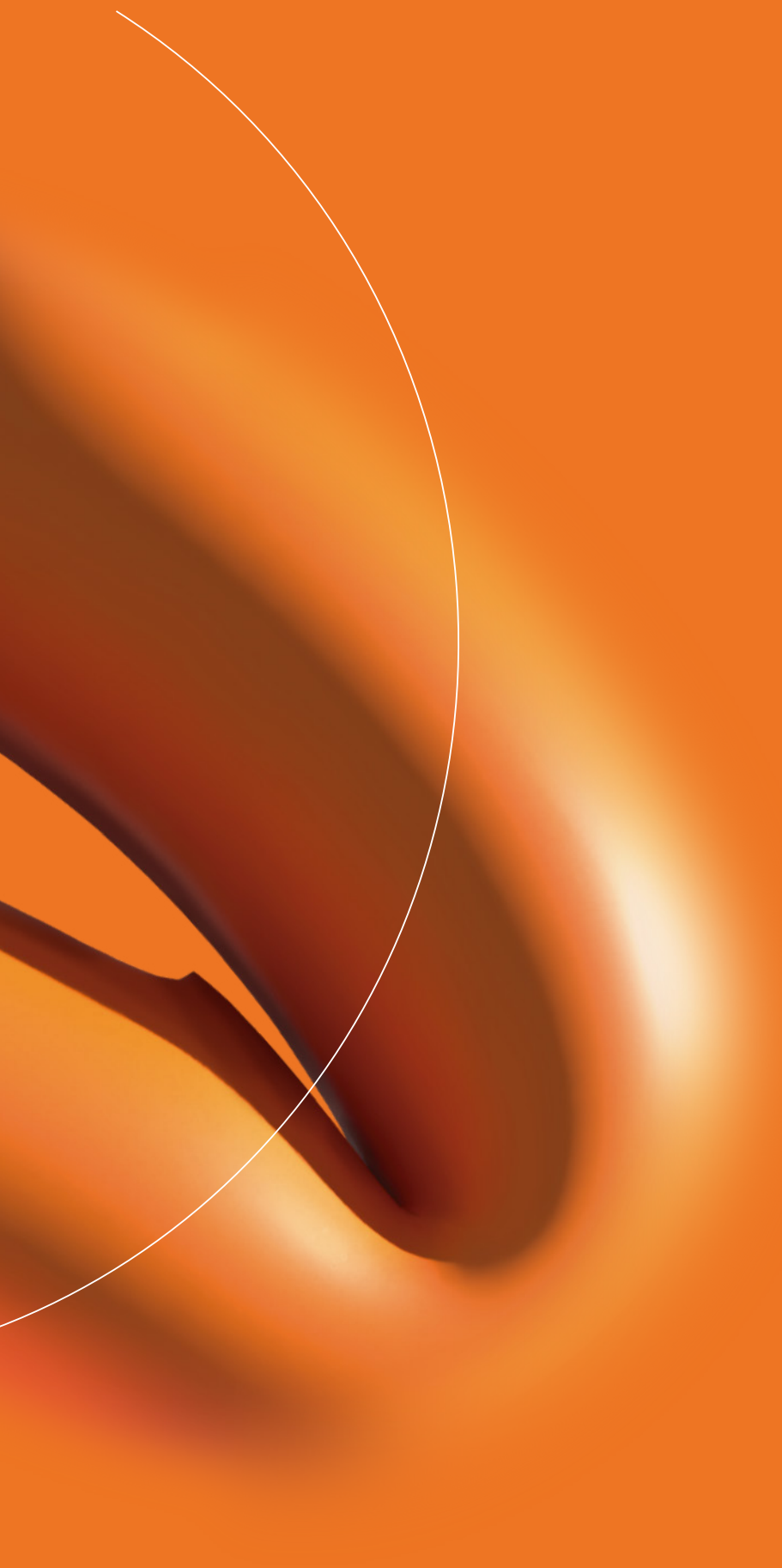
"Testing Uncorrelation of Multi-antenna Signals using Linear Spectral Statistics of the Spatio-temporal Sample Autocorrelation Matrix", authored by P. Loubaton and Xavier Mestre(CTTC), at the IEEE Statistical Signal Processing Workshop, SSP 2021, Virtual Rio de Janeiro.

"UAV Communications in Integrated Terrestrial and Non-terrestrial Networks", authored by M. Benzaghta, G. Geraci, Rasoul Nikbakht (CTTC), and D. López-Pérez, at the IEEE Globecom 2022 flagship conference.

Members of the Services as Networks Research Unit were also prolific in hackathons with several prizes received in 2022.

CTTC continues to encourage pursuing research accreditations from external institutional bodies such as the new awarded Advanced Research Accreditation, granted by the Catalan Agency for the Quality of the University System (AQU) to Dr. Carles Antón-Haro.

Dissemination & Training



Every year we welcome students to CTTC where they can visit our laboratories and testbeds. The visit is combined with a general presentation about a research center like CTTC and the opportunities for a research and engineering career, focusing on the opportunities available in Catalonia; together with more specialized talks that provide examples of the research and development project we carried out. These talks help to contextualize the type of knowledge and skills they would acquire working in the sector and illustrate the type of contribution they can make, or services and solutions they can developed.

The visits are organized both on-demand basis as well as pre-determined dates during events such as "La Setmana de la Ciència".

Besides the visits primarily intended for young students, CTTC hosted dissemination activities such as the instructive itineraries on the atmospheric pollution and the quality of air monitoring technologies that took place in Barcelona during the Science Week. The didactic itineraries were open to the citizenship.


SC22 Setmana de la Ciència

Setmana de la Ciència 22

Viu la ciència de l'11 al 20 de novembre

17 NOV 17:30h a 19:00h

PASSEJADA CONSCIENT PER LA CIUTADELLA

Pg. de Joan de Borbó, 15

Tipus d'activitat: Itineraris didàctics i excursions
Àrea temàtica: Ciència ciutadana
Tipus de públic: Públic general
Orientat: Grups

Eulàlia Parés, Oriol Serra, Mariona Ferrándiz, Rosa Ma Alsina-Pagès
El soroll ambiental i la contaminació atmosfèrica, així com la mala qualitat de les infraestructures verdes, són una preocupació important per a la població europea pel seu impacte en la salut dels ciutadans. L'objectiu final de la passejada conscient que proposem és prendre consciència del paisatge sonor, la qualitat de l'aire i la biodiversitat per a comprendre una passejada predissenyada en una ubicació urbana, als voltants del Parc de la Ciutadella, a Barcelona.

Més informació: Daniella Garcia
93 645 29 00
daniella.garcia@cttc.cat

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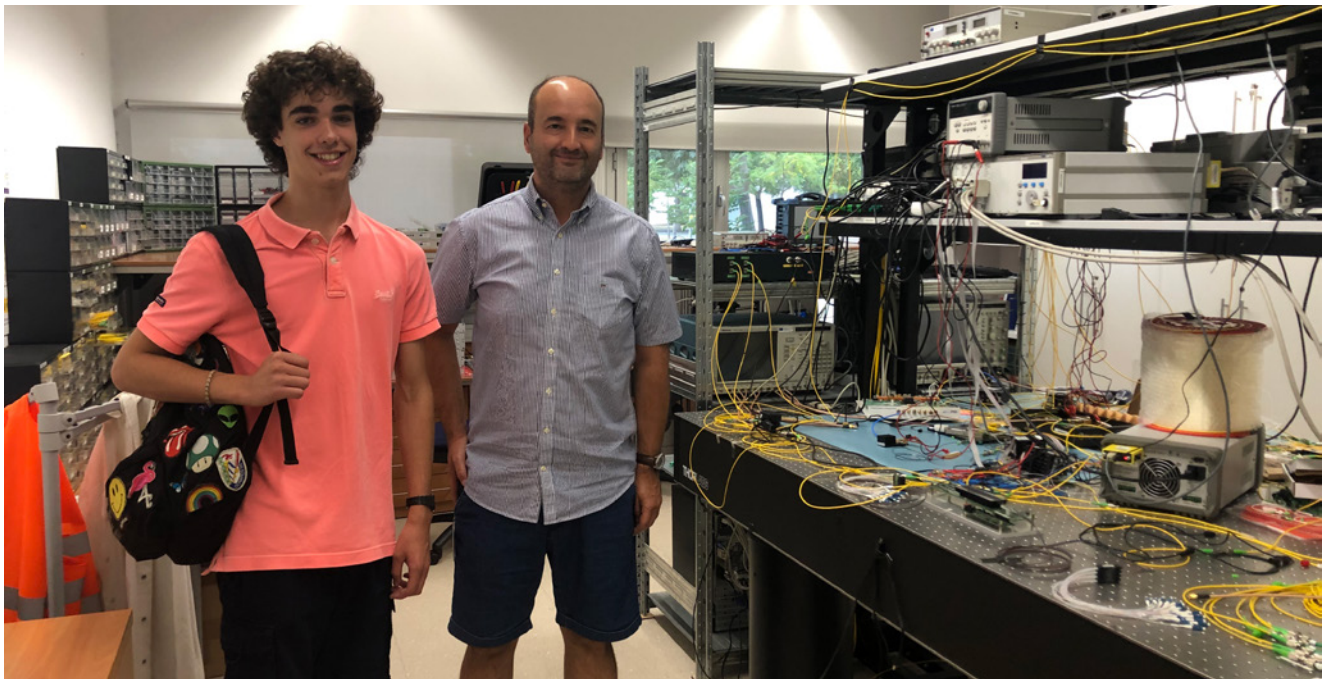
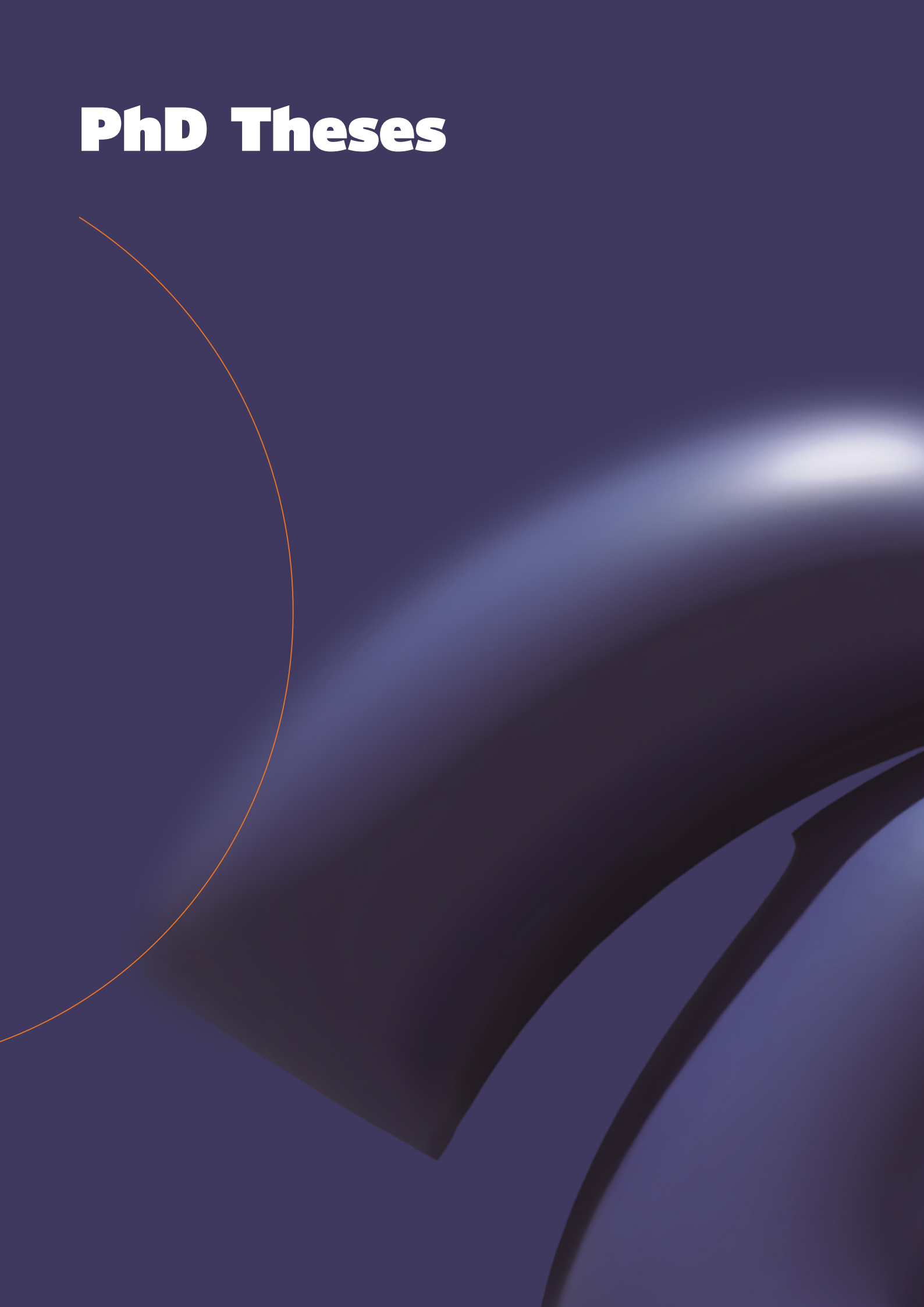


Reinforcing our training mission, we participate as members of ACER, on the program from the Ministry of Education "Premis extraordinaris de Batxillerat". In 2022, we hosted one of the student awardees of "Premis extraordinaris de Batxillerat", who had the opportunity to being exposed to the every-day-work of researchers at different career stages, backgrounds and technical focused during one immersive week. He gathered an initial know-how on our research activities we hope expanded his interest towards his engineering degree.

Other Training Schools were targeted for undergraduate students and early state researchers within the framework of Marie Skłodowska-Curie Actions. CTTC prides this type of training programs which allow us to host brilliant early-stage researchers from different international backgrounds that enrichers our working environment and learning experience. In particular, in 2022 we could physically host the Windmill Training School with a scientific program devoted to novel communication trends and deep learning and other advanced inference mathematical tools; combined with a soft skills program that included several sessions on innovation and ethical and governance aspects of machine learning implementation in the real world. The Greendedge Training School also brought to CTTC experts on machine learning, artificial intelligence and brain-inspired hardware approaches for real-time processing and computing at the edge.

PhD Theses



We are proud of our new PhD graduates, which defended their doctoral work in 2022.

Dr. Mohammed Osman

Control Logic Distribution trade-offs in Software-Defined Wireless Networks

The SDN (Software-Defined Networks) architecture separates the data and the control planes of the network. It logically centralizes the control of a network in a central point (SDN controller), which acts as a brain telling each network node how to forward incoming packets by installing the appropriate forwarding rules. One of the main advantages it brings is programmability through this single entity (the logical controller), which network management applications interact with to apply their policies. Agreed upon APIs, the network managers can exploit the full potential of SDN.

This dissertation presents a hybrid SDN scheme that explores the benefits of centralized and distributed operations depending on control communication channel conditions. Our hybrid SDN approach combines both centralized and distributed modes in the same node to form a hybrid control plane architecture. We introduce a local agent in the node that is composed of a monitoring framework to detect reliability of the control communication channel and a decision module that conceive a novel control logic switching algorithm to make a decision whether to operate in a centralized or distributed mode. We evaluate the proposed solution under a variety of unreliable network conditions (e.g., link impairments, control packet loss) to investigate the operational performance of the hybrid SDN during high loss conditions. The experimental results show that the proposed hybrid SDN solution substantially improves the aggregated throughput, particularly when control channel packet loss ratios increase, which in turn keeps the network operational in hard conditions where the centralized SDN would result in a non-operational network.

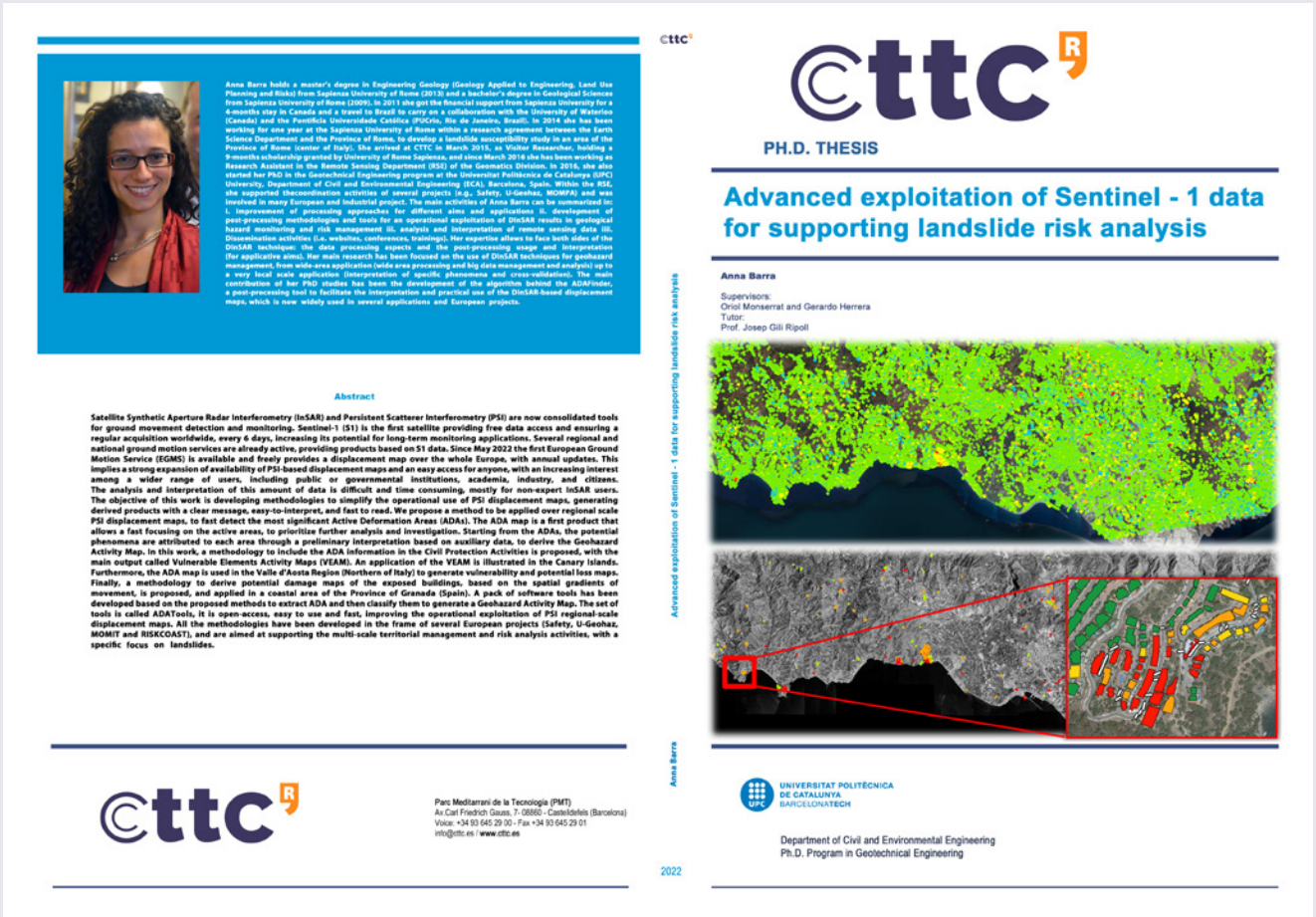
Dr. Anna Barra

Advanced exploitation of Sentinel-1 data for supporting landslide risk analysis

Satellite SAR Interferometry (InSAR) has become an established method for detecting and monitoring ground movements. The availability of free data from the Sentinel-1 (S1) satellite, with its regular global acquisitions every 6 days, has enhanced its potential for long-term monitoring applications. In May 2022, the Copernicus European Ground Motion Service was established, offering freely accessible displacement maps ovevr Europe with annual updates. This has led to a significant increase in the availability and accessibility of InSAR displacement maps, generating greater interest among diverse user groups such as public institutions, academia, industry, and citizens.

This study aims to increase the operational use of InSAR displacement maps by developing methodologies that produce derived products with clear interpreted messages and fast readability. The first method focuses on regional-scale InSAR displacement maps to rapidly extract the Active Deformation Areas (ADAs). The ADA map serves as an initial product that enables quick identification of active areas, allowing to prioritize analysis and investigation. The potential phenomena are then automatically attributed to each ADA based on auxiliary data to derive the Geohazard Activity Map. An example of incorporating ADA information into Civil Protection Activities, yielding Vulnerable Elements Activity Maps, is provided in the Canary Islands. An approach to generate potential loss maps is also proposed through an application in Valle d'Aosta (Italy). Lastly, a methodology for deriving potential damage maps of exposed buildings, based on differential displacements, is presented over an area of the Province of Granada in Spain.

A software toolset called ADATools has been developed. This open-access, user-friendly, and efficient toolset enhances the operational utilization of regional-scale PSI displacement maps. The presented methodologies have been developed within the context of various European projects (Safety, U-Geohaz, MOMIT, and RISKCOAST) and are intended to support multi-scale territorial and risk management activities, with a specific focus on landslides.



Anna Barra holds a master's degree in Engineering Geology (Geology Applied to Engineering, Land Use Planning and Risks) from Sapienza University of Rome (2013) and a bachelor's degree in Geological Sciences from Sapienza University of Rome (2009). In 2011 she got the financial support from Sapienza University for a 4-months stay in Canada and a travel to Brazil to carry on a collaboration with the University of Waterloo (Canada) and the Pontificia Universidade Católica (PUC-Rio, Rio de Janeiro, Brazil). In 2014 she has been working for one year at the Sapienza University of Rome within a research agreement between the Earth Science Department and the Province of Rome, to develop a landslide susceptibility study in an area of the Province of Rome (center of Italy). She arrived at CTTC in March 2015, as Visitor Researcher, holding a 9-months scholarship granted by University of Rome Sapienza, and since March 2016 she has been working as Research Assistant in the Remote Sensing Department (RSI) of the Geomatics Division. In 2016, she also started her PhD in the Geotechnical Engineering program at the Universitat Politècnica de Catalunya (UPC) University, Department of Civil and Environmental Engineering (ECA), Barcelona, Spain. Within the RSE, she supported thecoordination activities of several projects (e.g., Safety, U-Geohaz, MOMPA) and was involved in many European and Industrial project. The main activities of Anna Barra can be summarized in: i. improvement of processing approaches for different aims and applications ii. development of post-processing methodologies and tools for an operational exploitation of DInSAR results in geological hazard monitoring and risk management iii. analysis and interpretation of remote sensing data iii. Dissemination activities (i.e. websites, conferences, trainings). Her expertise allows to face both sides of the DInSAR technique: the data processing aspects and the post-processing usage and interpretation (for applicative aims). Her main research has been focused on the use of DInSAR techniques for geohazard management, from wide-area application (wide area processing and big data management and analysis) up to a very local scale application (interpretation of specific phenomena and cross-validation). The main contribution of her PhD studies has been the development of the algorithm behind the ADAFinder, a post-processing tool to facilitate the interpretation and practical use of the DInSAR-based displacement maps, which is now widely used in several applications and European projects.

Abstract

Satellite Synthetic Aperture Radar Interferometry (InSAR) and Persistent Scatterer Interferometry (PSI) are now consolidated tools for ground movement detection and monitoring. Sentinel-1 (S1) is the first satellite providing free data access and ensuring a regular acquisition worldwide, every 6 days, increasing its potential for long-term monitoring applications. Several regional and national ground motion services are already active, providing products based on S1 data. Since May 2022 the first European Ground Motion Service (EGMS) is available and freely provides a displacement map over the whole Europe, with annual updates. This implies a strong expansion of availability of PSI-based displacement maps and an easy access for anyone, with an increasing interest among a wider range of users, including public or governmental institutions, academia, industry, and citizens. The analysis and interpretation of this amount of data is difficult and time consuming, mostly for non-expert InSAR users. The objective of this work is developing methodologies to simplify the operational use of PSI displacement maps, generating derived products with a clear message, easy-to-interpret, and fast to read. We propose a method to be applied over regional scale PSI displacement maps, to fast detect the most significant Active Deformation Areas (ADAs). The ADA map is a first product that allows a fast focusing on the active areas, to prioritize further analysis and investigation. Starting from the ADAs, the potential phenomena are attributed to each area through a preliminary interpretation based on auxiliary data, to derive the Geohazard Activity Map. In this work, a methodology to include the ADA information in the Civil Protection Activities is proposed, with the main output called Vulnerable Elements Activity Maps (VEAM). An application of the VEAM is illustrated in the Canary Islands. Furthermore, the ADA map is used in the Valle d'Aosta Region (Northern of Italy) to generate vulnerability and potential loss maps. Finally, a methodology to derive potential damage maps of the exposed buildings, based on the spatial gradients of movement, is proposed, and applied in a coastal area of the Province of Granada (Spain). A pack of software tools has been developed based on the proposed methods to extract ADA and then classify them to generate a Geohazard Activity Map. The set of tools is called ADATools, it is open-access, easy to use and fast, improving the operational exploitation of PSI regional-scale displacement maps. All the methodologies have been developed in the frame of several European projects (Safety, U-Geohaz, MOMIT and RISKCOAST), and are aimed at supporting the multi-scale territorial management and risk analysis activities, with a specific focus on landslides.

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PH.D. THESIS

Advanced exploitation of Sentinel - 1 data for supporting landslide risk analysis

Anna Barra

Supervisors:
Oriol Monserrat and Gerardo Herrera
Tutor:
Prof. Josep Gili Ripoll

Advanced exploitation of Sentinel - 1 data for supporting landslide risk analysis

Anna Barra

2022

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Department of Civil and Environmental Engineering
Ph.D. Program in Geotechnical Engineering

Dr. Biljana Bojovic

Cellular and Wi-Fi technologies evolution: From complementary to competition

This PhD thesis studies how wireless technologies have been evolving over a decade from 4G to 5G and studies how IEEE and 3GPP technologies have grown from being two complementary families of technologies to being competitors. First, the thesis focuses on radio resource management for the standalone operation of Wi-Fi in unlicensed and LTE in licensed spectrum. We anticipated the now fundamental machine learning trend by working on machine learning-based radio resource management solutions to improve LTE and Wi-Fi operation. We study small cell deployments aimed at improving the spectrum efficiency in licensed spectrum, reproducing small-range scenarios typical of Wi-Fi settings. As IEEE and 3GPP technologies continued evolving over the years, they have become competitors in the unlicensed spectrum. In this line, this thesis studies coexistence scenarios, in which LTE needs to be designed to coexist with Wi-Fi fairly, and NR, the radio access for 5G, with Wi-Fi in 5 GHz and WiGig in 60 GHz. Unlike LTE, which was adapted to operate in unlicensed spectrum, NR-U is natively designed with this feature, including its capability to operate in unlicensed in a complete standalone fashion, a fundamental new milestone for cellular. In this context, we consider that these two technological families are no longer targeting complementarity but are now competing, and we claim that this will be the trend for the years to come. To enable the research in these multi-RAT scenarios, another fundamental result of this PhD thesis, besides the scientific contributions, is the release of high-fidelity models for LTE and NR and their coexistence with Wi-Fi and WiGig to the ns-3 open-source community.

Biljana Bojović received her Master of Science Electrical and Computer Engineering degree in 2008, and her PhD thesis defense is scheduled for January, 12th 2022. In 2007, she won a student internship grant from Schneider Electric DMS (Novi Sad, Serbia), an R&D company for smart grid solutions, and after graduating she continued to work in the same company as a software engineer on smart grid systems integrations. In 2007, she was in a training and collaboration 3-month visit at Siemens (Minneapolis, Minnesota). In September 2009, she joined CTTC as a researcher. In 2012, she carried out a short-term research visit at (NET labs at RWTH University of Achen, Germany. In 2013, she was during 6 months a visiting researcher at the Qualcomm Institute at the University of California, San Diego (UCSD). Since 2015, she has been a research engineer at the Mobile Networks (MONET) Department at CTTC working on different industrial research projects focusing on 4G, 5G, and 5GI technologies for unlicensed spectrum, i.e., LAA, LTE-U, and NR-U. She is one of the leading developers of the 5G-LENA simulator. She is the principal author of the LAA and LTE-U modules of ns-3. She is also a maintainer and one of the developers of the LTE and spectrum modules. She was a mentor of GSoC for the ns-3 simulator on two occasions, in 2017 and 2019. She held a tutorial on the ns-3 LTE module at the ns-3 workshop (WNS3) in 2016 in Seattle, Washington. She also gave a tutorial on the 5G-LENA simulator on CONFTELE 2021. Moreover, she conducted various tutorials for industrial clients (Interdigital in 2019 and Cannon in 2020). In 2020, she received a Networking System Award by ACM SIGCOMM for her contributions to ns-3 open source network simulator. According to Google Scholar, in 2021, her h-index is 14, and her i10-index is 17. She participated in 12 research projects, most of which were industrial with some of the key players in the wireless industry, such as with Wi-Fi Alliance, SpiderCloud, Interdigital, US federal agencies (LLNL, NIST), and Meta (previously Facebook). She is co-author of one patent application filed with Interdigital (US20200314906A1). Her main research interests include wireless communications, cellular networks, radio resource management, QoS management, IEEE/3GPP coexistence in unlicensed spectrum, IEEE/3GPP convergence, spectrum sharing, and O-RAN.

Abstract

This PhD thesis has the characteristic to span over a long time because while working on it, I was working as a research engineer at CTTC with highly demanding development duties. This has delayed the deposit more than I would have liked. On the other hand, this has given me the privilege of witnessing and studying how wireless technologies have been evolving over a decade from 4G to 5G and beyond. When I started my PhD thesis, IEEE and 3GPP were defining the two main wireless technologies at the time, Wi-Fi and LTE, for covering two substantially complementary market targets. Wi-Fi was designed to operate mostly indoor, in unlicensed spectrum, and was aimed to be a simple and cheap technology. Its primary technology for coexistence was based on the assumption that the spectrum on which it was operating was for free, and so it was designed with interference avoidance through the famous CSMA/CA protocol. On the other hand, 3GPP was designing technologies for licensed spectrum, a costly kind of spectrum. As a result, LTE was designed to take the best advantage of the spectrum while providing the best QoE in mainly outdoor scenarios. The PhD thesis starts in this context and evolves with these two technologies. In the first chapters, the thesis studies radio resource management solutions for standalone operation of Wi-Fi in unlicensed and LTE in licensed spectrum. We anticipated the now fundamental machine learning trend by working on machine learning-based radio resource management solutions to improve LTE and Wi-Fi operation in their respective spectrum. We pay particular attention to small cell deployments aimed at improving the spectrum efficiency in licensed spectrum, reproducing small range scenarios typical of Wi-Fi settings. IEEE and 3GPP followed evolving technologies over the years: Wi-Fi has grown into a much more complex and sophisticated technology, incorporating the key features of cellular technologies, like HARQ, OFDMA, MU-MIMO, MAC scheduling, and spatial reuse. On the other hand, since Release 13, cellular networks have also been designed for unlicensed spectrums. As a result, the two last chapters of this thesis focus on coexistence scenarios, in which LTE needs to be designed to coexist with Wi-Fi fairly, and NR, the radio access for 5G, with Wi-Fi in 5 GHz and WiGig in 60 GHz. Unlike LTE, which was adapted to operate in unlicensed spectrum, NR-U is natively designed with this feature, including its capability to operate in unlicensed in a complete standalone fashion, a fundamental new milestone for cellular. In this context, our focus of analysis changes. We consider that these two technological families are no longer targeting complementarity but are now competing, and we claim that this will be the trend for the years to come. To enable the research in these multi-RAT scenarios, another fundamental result of this PhD thesis, besides the scientific contributions, is the release of high fidelity models for LTE and NR and their coexistence with Wi-Fi and WiGig to the ns-3 open-source community. ns-3 is a popular open-source network simulator, with the characteristic to be multi-RAT and so naturally allows the evaluation of coexistence scenarios between different technologies. These models, for which I led the development, are by academic citations, the most used open-source simulation models for LTE and NR and have received fundings from industry (Ubiquisys, Wi-Fi Alliance, SpiderCloud, Interdigital, Facebook) and federal agencies (NIST, LLNL) over the years.

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Cellular and Wi-Fi technologies evolution: From complementarity to competition

Biljana Bojović

2022

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PH.D. THESIS

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Biljana Bojović
Advisor: Dr. Lorenza Giupponi
Tutor: Prof. Miguel Soriano Ibáñez

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We thank you all our collaborators and staff to support CTTC's mission. Their commitment has delivered more than 20 years of fruitful research, innovation, and training.

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