Annual

2023

Report

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Annual

Report

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Editorial

Ana Isabel Pérez-Neira
Director

Empowering Sustainability in Telecom: CTTC Leading the Way

In the ever-evolving landscape of telecommunications, innovation is not just a buzzword; it's the lifeblood that propels industries forward, connecting people, businesses, and societies in ways once deemed impossible. At the forefront of this innovation stands the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), a beacon of excellence in research and development in Catalonia and beyond.

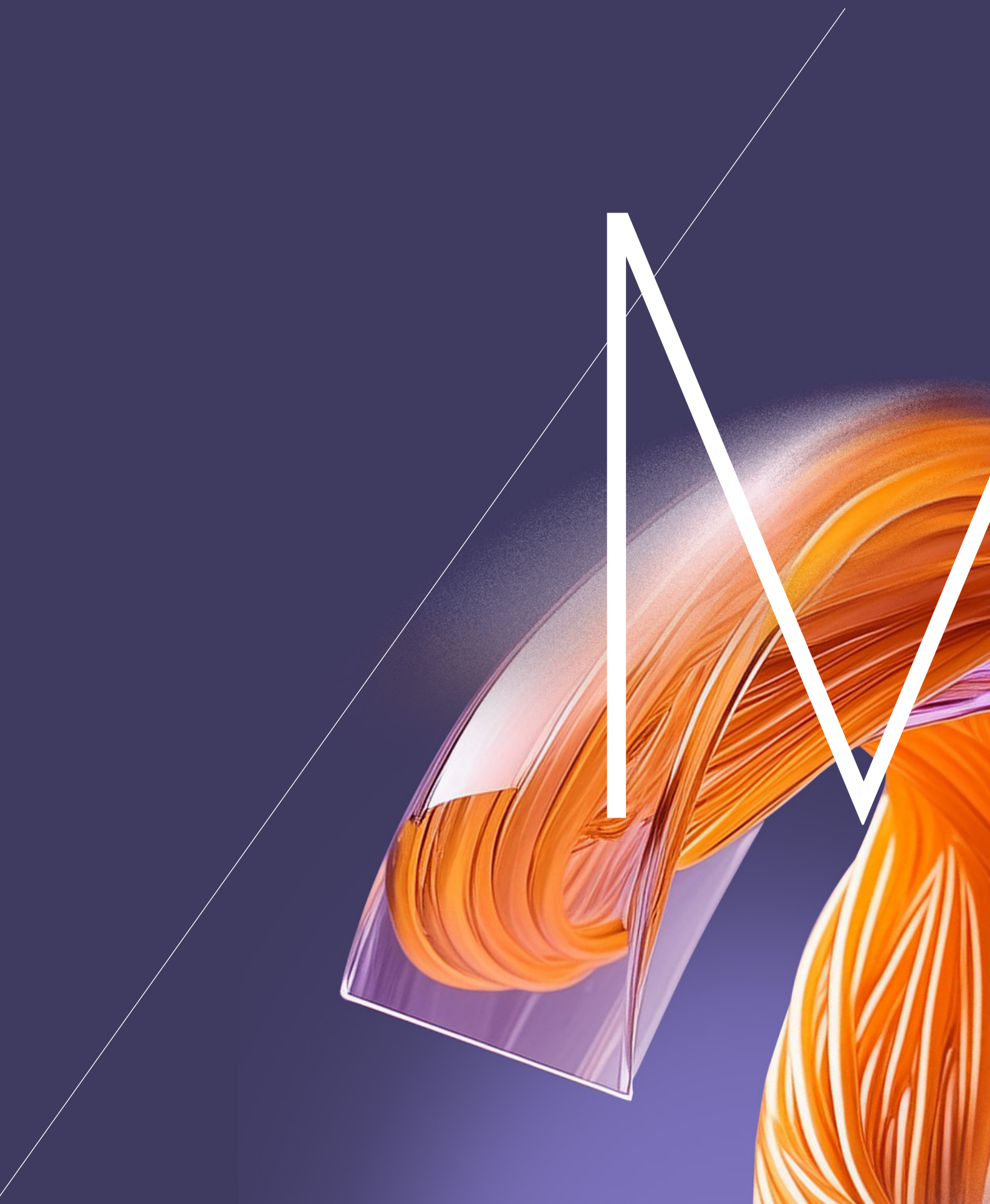
CTTC's commitment to advancing telecommunications technologies is unparalleled. With a multidisciplinary team of 117 (17 % more than in 2022) researchers (with a 30% increase in the number of PhDs), engineers, and visionaries, CTTC drives groundbreaking research across a spectrum of areas, from wireless communications to networking, sensing, and beyond. Just only in 2023, 9 PhD Thesis were defended at CTTC (a 200% increase with respect to 2022). By fostering collaboration between academia, industry, and government institutions, CTTC serves as a catalyst for transformative change, turning cutting-edge ideas into real-world solutions.

One of CTTC's core strengths lies in its ability to anticipate future challenges and opportunities in the telecommunications sector. In an era marked by 6G in the horizon, with the Internet of Things (IoT), and artificial intelligence, CTTC is at the forefront of driving innovation in these areas, shaping the digital infrastructure of tomorrow. Its publications have a steadily increasing impact factor of 5,92 (15% superior to that in 2022 and 25% to that in 2020). Through pioneering research projects, such as the development of advanced wireless technologies, spectrum management strategies, and intelligent networking protocols, CTTC has obtained a total income of 13,5 M euros (40% higher than in 2022), and a total self-funding of 72,25%. CTTC is growing and among other aspects it is renovating and enlarging its experimental facilities and creating internal programs for growth in women researchers (22% out of the total number of researchers), excellence, and dissemination of our activities among the graduate and undergraduate students.

Moreover, the impact extends far beyond the confines of the laboratory. By actively engaging with industry partners, policymakers, and stakeholders, CTTC ensures that its research not only pushes the boundaries of knowledge but also translates into tangible benefits for society. One relevant example is CTTC's engagement and leadership in the design and development of xG mobile networks (from 3G to 6G) and satellite communications, which have enabled the appearance of new services and new approaches towards the digitalization of vertical industries and commitment towards the global coverage for communication and information networks. CTTC also seeded the way for global challenges, such as sustainability of such networks. Some of the early projects in Horizon 2020 pioneered the work beyond green communications to a holistic approach for sustainable and "reasonable" communications, inducing new research challenges into EU research and innovation programs.

All these achievements are thanks to CTTC people, who understand that innovation knows no bounds, and with CTTC leading the way, the possibilities are endless.

Mission & Vision



Mission

Our mission is set to:

/ Push the boundaries of excellence in knowledge and technologies in telecommunications and geomatics: design relevant innovations for the digital society of the future.

/ Be a bridge between academia and industry, regionally and world-wide.

Vision

/ Be a **world-wide lighthouse** in terms of scientific and technological relevance and leadership in the fields of information and communication technologies and geomatics.

Approach

Our DNA resides in:

/ Providing a good balance between experimental engineering know-how (championed by our testbeds) and excellence in research.

/ Fostering talented personnel composed of experienced permanent researchers holding PhD degrees (the highest percentage) and temporary staff. Both focused on research and development, with no teaching obligations but encouraged to participate in specialized training through tutoring and mentoring.

Technology at the Service of Society

As stated in our vision & mission, CTTC pursues technology and knowledge advances with the ultimate goal to serve to societal needs, by the articulation of scientific excellence and increase in the competitiveness of the industrial ecosystem through innovation and technological development.

There is clear evidence that telecommunication technologies have been one of the key technologies driving the rapid evolution (revolution for some) of society. They have revolutionized the way we communicate and socialized, having a strong impact on employment and economic activity, educational, cultural, or recreational activities, to cite a few.

Beyond their clear benefits, we are also aware of the challenges ahead. One of them being the increased concern on the sustainability threats associated with the constant growing demands for higher data rates, processing and learning power, number of devices, etc. All highly energy greedy.

We foresee **environmental sustainability and energy efficiency**, together with security and integrity, being a key prerequisite to drive societal and business value from communication systems. Likely, the next generation of communication, information and sensing networks will progressively abandon the performance maximization paradigm in 5G to focus on the value for society, environment, and economy. These values will necessarily include efficient network realization (with a clear reduction on the energy consumption per bit, as well as a radical operative cost reduction due to automation), novel digital services (with distributed AI applications in large scales) and enhanced connectivity (in particular, in terms of geographical coverage). The research strategy of CTTC is configured in order to generate provable effects along these values, that is to generate impact in terms of connectivity, new services and sustainability.

For these accomplishments, CTTC leverages on its role as key player in Europe in the definition of 5G and 6G communication systems and its leadership on the sustainability of such networks. This is evidenced by its long record track of participation in Horizon 2020 and Horizon Europe projects and, specifically, those under the umbrella of the 5G Public-Private Partnership (5G-PPP) and the Smart Networks and Services Joint Undertaking (SNS-JU).

Throughout Horizon 2020 (2014-2020), CTTC participated in a total of 43 projects, for a total funding of 19.2M€. This represents the top 1.1% in terms of funding for all categories of participants, namely, large industries, SMEs, academia, etc. CTTC's participation was particularly intense in the 5G-PPP partnership. In this area, the centre was involved in and/or led 20 projects, for a total funding of 10.8M€. Notably, CTTC acted as project coordinator in very successful 5G-PPP projects such as 5GCroCo, MONB5G, TERAFLOW, SANSA or MARSAL. As a result, CTTC ranked sixth (top 0.8% in terms of funding) among all categories of participating institutions. Also, it ranked the second R&D centre in Europe and the first in Spain in terms of funding and number of projects awarded. In this line, the momentum gained in 2023 with the participation in 11 R&D projects from the first two calls of Horizon Europe (2021-2027) from the 6G JU SNS Workprogramme (total funding of 5 Meuro), allows the CTTC to continue to play a major role in the definition of the future **xG communication systems**. Very importantly, this includes the participation in HEXA-X II, the 6G flagship project of the JU; and one project, 6G-REFERENCE, which is coordinated by the CTTC. CTTC also contributes to the definition of 6G communication systems through the execution of industrial R&D projects with key players like Nokia Bell Labs, Telefonica, META, Huawei or Apple.

Very relevant are also the projects focusing on the specific aspects of **sustainability in the context of AI and communication networks**. From early contributions in 2013, "HetNets Powered by Renewable Energy Sources: Sustainable Next-Generation Cellular Networks," in IEEE Internet Computing, to the coordination of MSCA ETN SCAVANGE, one of the first European projects on Sustainable 5G Mobile Network and pioneer raising awareness on the need for multidisciplinary training of telecom researchers in sustainability; CTTC has acquired solid expertise in energy efficiency and eco-friendly solutions, being well position to rethink sustainability challenges. A recent example is the GREENEDGE, funded under European Excellence Science MSCA, in which CTTC, as technical coordinator, continues to dwell into the environmental impact of mobile networks to tame the growing carbon footprint, by addressing the new challenges of ML/AI based edge computing services and exploiting renewable energy resources. Conceiving novel and green-by-design machine learning algorithms to be used within edge mobile computing platforms is one of the key contributions.

Besides, CTTC aims to have an impact on policies that revert to the European and national development strategies by being very active in terms of R&D policy making in these areas (details are provided in following sections).

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 2023, the members' representatives are:

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

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

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

SR. JOAN GÓMEZ I PALLARÈS
Director General for Research

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

SR. MARC DARDER SOLÉ
Head of Technical Cabinet at the Department of Territory

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

Generalitat de Catalunya

UPC UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

UNIVERSITAT RAMON LLULL

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.

In 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

Nine research units configure the current organizational research structure of CTTC.

They organize their research interests and focus from an institutional freedom of research paradigm but fostering collaborations.

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 focus 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-efficient, 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 sustainability**

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

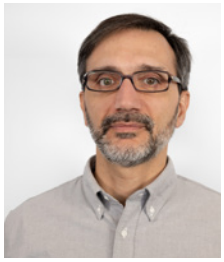
Dr. Jesús Gómez
Head of ISPIC

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. Miguel 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 define 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.

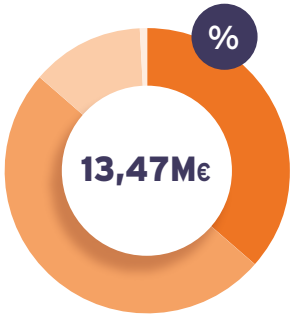
Research activities focus on the following topics of interest:

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

Facts & Figures

Projects

Total income



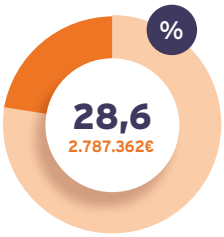
Income distribution

27,7% Core Funding
61,7% Competitive Funds
6,6% R&D Services
3,9% Other

Total own-raised funds

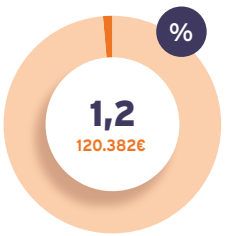
~9,7M€

R&D projects

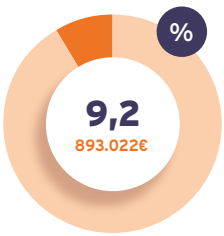


EUROPEAN ADMINISTRATION

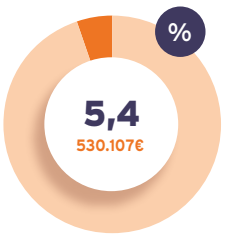
SPANISH ADMINISTRATION



CATALAN ADMINISTRATION



DIRECT R&D CONTRACTS



OTHER

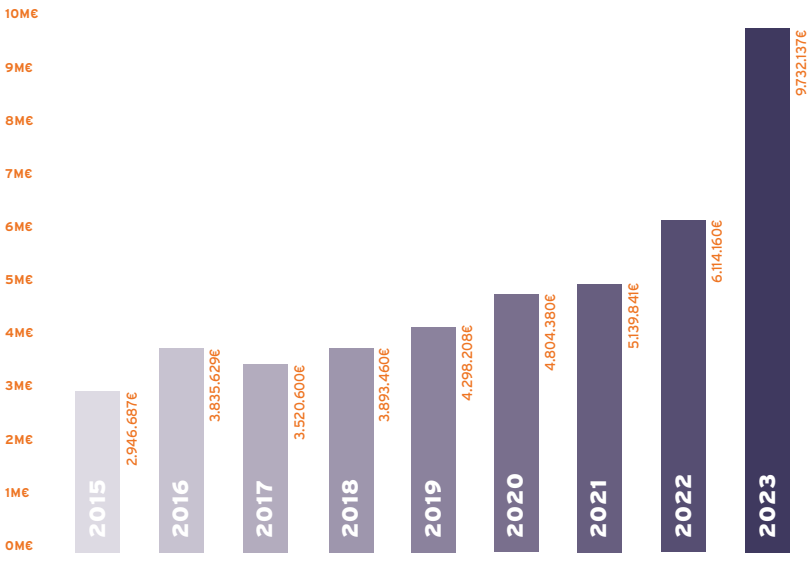
Project distribution

35 30% European projects

53 45% National projects (Spanish + Catalan)

30 25% Industry projects

Income evolution (raised own funds)



59%
INCREASE
(AVERAGE GROWTH RATE/YEAR ~17,5%)

Horizon Europe: results from first calls

17 NEW PROJECTS
7 M€ CTTC's total funding

5 M€ UNDER THE UMBRELLA OF THE 6G SNS-JU.

Funding received within the Smart Networks and Services (SNS) call 2022:

The CTTC was in the upper 2% percentile among all categories of participating institutions.

At the European level

1st R&D center

2nd out of all the Spanish institutions

At the Spanish level

Scientific publications

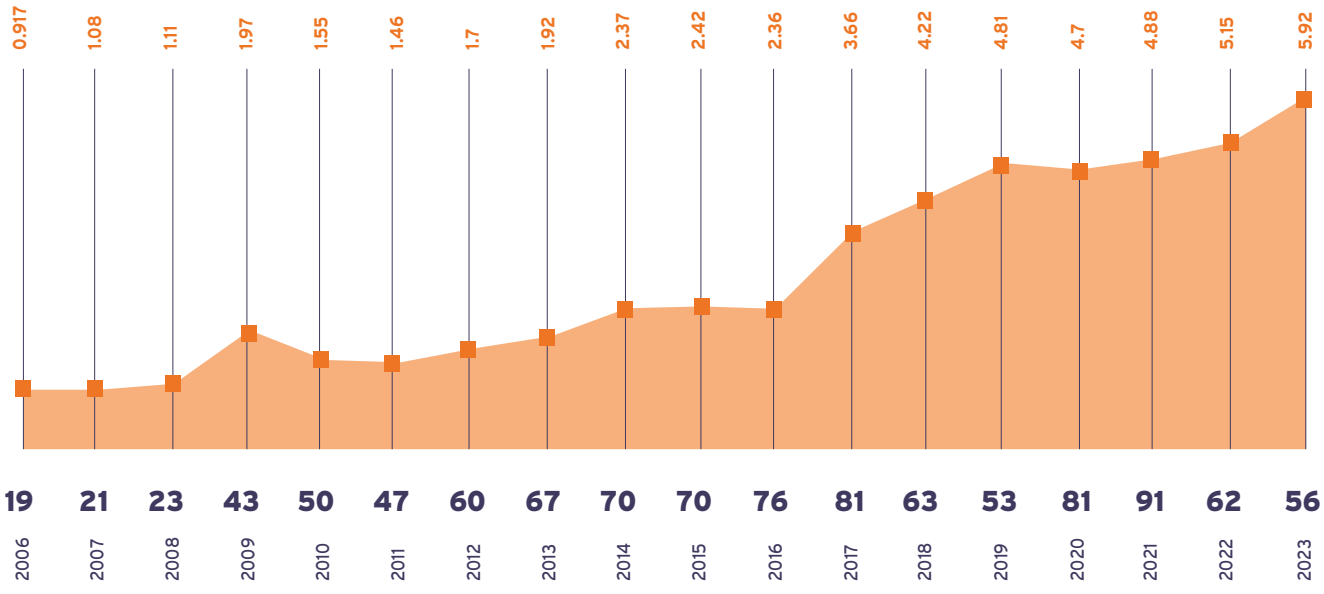
Number of Scientific Publications

56 Journals (indexed)
73 Conferences

68 % FIRST QUARTILE

5,92 AVERAGE IMPACT FACTOR

Evolution of the average impact factor (Indexed journals)



Number of indexed journals Average Impact Factor

All publications are accessible in open-access

Knowledge & technology transfer

1 spin-off

LAND AND STRUCTURE DEFORMATION
Detection. Monitoring. Prediction
geokinesia.com

GEO KINESIA

▶ **Granted patents in force**

28

NEW COMMERCIAL PRODUCT

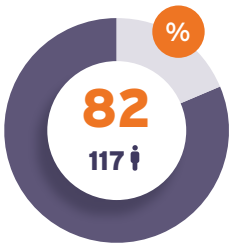
GNSS-SDR embedded SoC hardware accelerators (IP core)

▶ **Industry innovation**

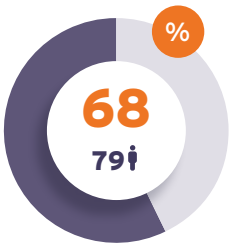
20

Staff

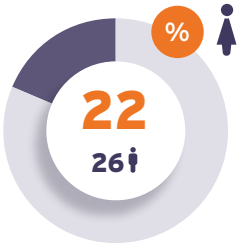
▶ **Details of team members**



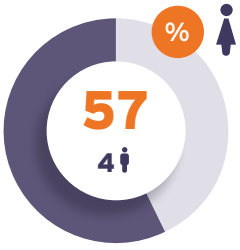
OF RESEARCHERS



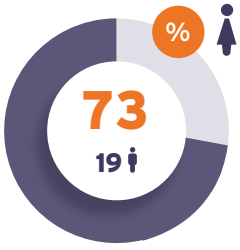
OF DOCTORS



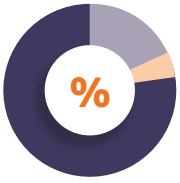
OF WOMEN (IN RESEARCH)



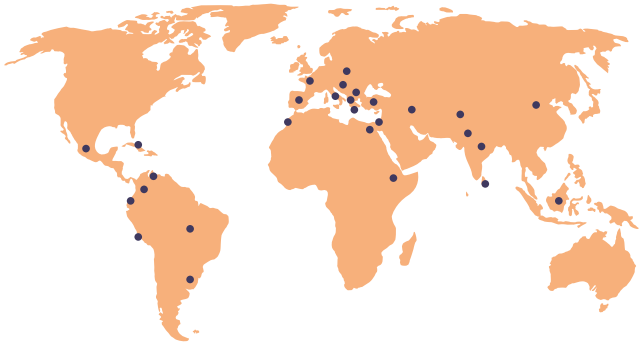
OF WOMEN (IN MANAGEMENT)



OF WOMEN (IN ADMIN & SUPPORT)



18% Admin & Support
82% Research
5% Management



28 Different nationalities

49% Spanish
51% Non-Spanish

▶ **R&D Personnel distribution**

RESEARCH DIRECTOR **R4**

SENIOR RESEARCHER **R3**

RESEARCHER **R2**

RESEARCH TRAINEE **R1**

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

2023 was particularly intense in the acquisition of experimental infrastructure and conditioning of new spaces. Thanks to the support of the UNICO's program within the frameworks of the "Plan de Recuperación, Transformación y Resiliencia" and of the "Mecanismo de Recuperación y Resiliencia", funded by the Spanish Government and the European Union-NextGenerationEU, CTTC will significantly enhance its testbeds and equipment in the areas of:

- **Non-terrestrial communication and its integration with terrestrial networks**
- **Packet Optical Networks and services**
- **Mobile networks and services**
- **Radio Access**

More specifically, we are acquiring new equipment that will allow direct access to GEO and LEO satellite links, including radio and optical communication technologies, from CTTC laboratories. This will allow end-to-end satellite transmissions, including relays and integration with terrestrial networks. Enhancement of the professional satellite channel emulator for NGEO scenarios will be also acquired, providing a powerful tool for 6G developments.

Experimental infrastructure is also being upgraded to include security aspects. In particular, Quantum Key Distribution systems are being integrated into the Packet Optical Networks and Services Lab as well as in the non-terrestrial communication infrastructure. The optical domain is also being extended to allow testing open-source solutions (white-boxes) in 6G fronthaul and backhaul disaggregated and distributed network deployments.

Significant upgrades are being developed to provide an end-to-end xG network innovation and experimentation platform for mobile and radio access networks. This includes capacities to generate digital twins, to experiment new services under heterogeneous equipment and the flexible integration into a softwarization network framework (from access to core network orchestration, slicing, edge/distributed computation) that allows to evaluate new service deployments into a close to commercial network framework. The radio access infrastructure is being enhanced with commercial 5G base stations and prototypes such as reconfigurable modular intelligent extra-large antenna systems that will allow experiments on communication and sensing capabilities. The wireless communication framework is also complemented with AI/ML high performance computing equipment.

CTTC's experimental infrastructure is integrated into 7 testbeds and additional general-purpose facilities.

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 deploying 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 combine 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.
Besides the testbeds [https://www.cttc.cat/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. Inspired 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/

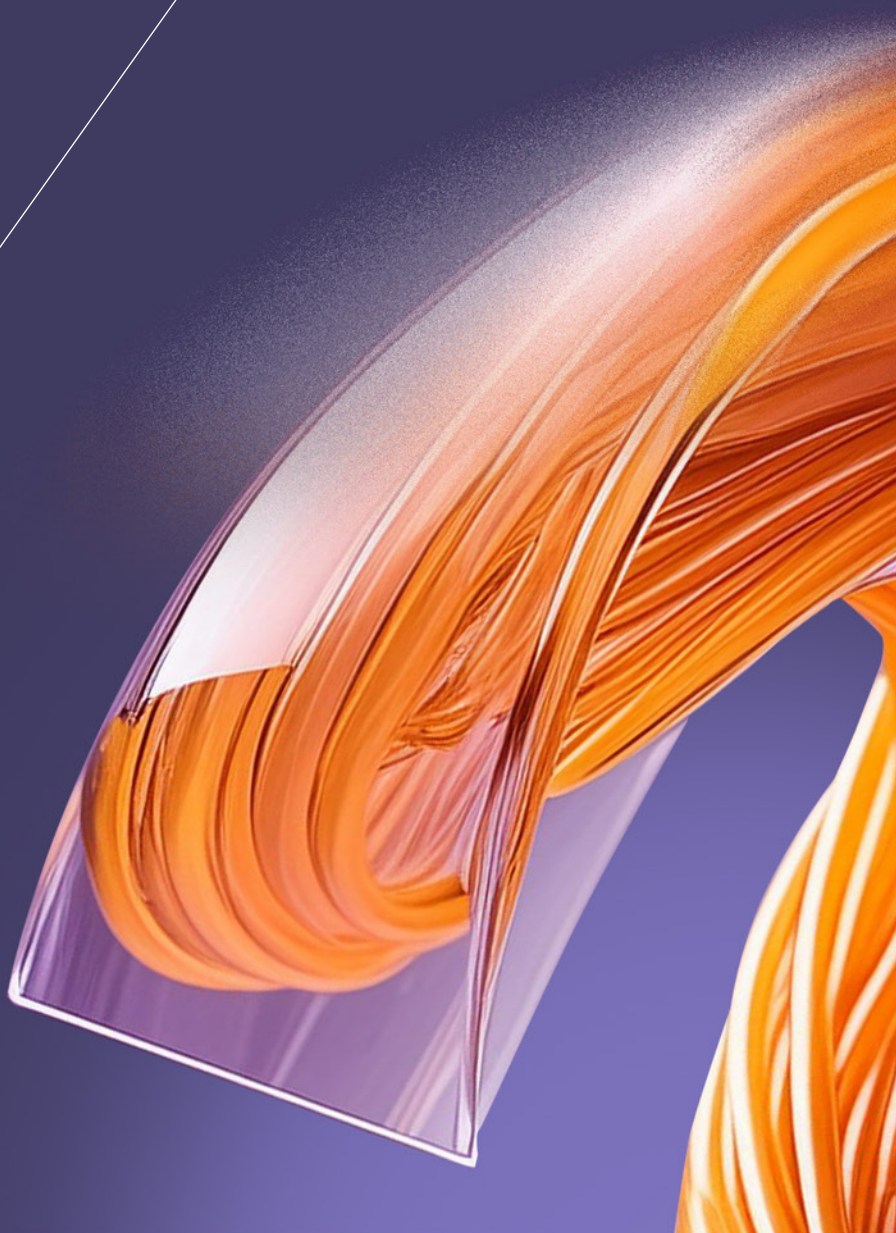
5GLENA – ns-3 modules for LTE/LTE-A and 5G network simulation according to standards defined by 3GPP, https://5g-lena.cttc.es/. A new video introduces the simulator main features and applications https://www.youtube.com/watch?v=PM1c4Vf_DSA

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 used by the professional and educational community. The continuous timely effort to upgrade the software modules has positioned 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 small terrain deformations with high sensitivity; 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 post-processing of GEOKINESIA PSIG® output or any other software that returns interferometric measurements for an improved management and classification of such detected deformations.

R&D Projects



6G has been one of the main drivers in a significant number of the 2023 active R&D projects. Capitalizing our expertise in mobile network design, developments towards next generation systems (xG) continue to reflect in the R&D collaborative work with key players (from manufacturers, operators and system integrators to vertical services, industries and administrations). 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.

BEYOND SUSTAINABLE COMMUNICATIONS

CTTC is leading a pioneer approach on pervasive intelligence for and beyond sustainability. Based on AI and pervasive cyber-physical systems for the development of a new information and communication technologies paradigm, we are rethinking sustainability approaches and evolving telecom technology towards more rationalized network infrastructures and use.

Pervasive and Sustainable Intelligence internal project, focus on solutions suitable for advancing towards a truly pervasive and liquid AI enabling edge devices, regardless of their available resources, to accomplish training and inference with the same accuracy of cloud AI without harming our environment. For doing so, we propose to investigate on highly efficient learning methods using model compression, reservoir and neuromorphic computing and combining them with distributed/decentralized and collaborative data/client selection algorithms to reach the minimum energy consumption and maintain high accuracy and good generalization properties.

GREENEDGE aims at mitigating the carbon footprint of Information and Communication Technology (ICT), with focus on AI-based and edge computing systems. This requires a set of new skills and multidisciplinary training. During 2023, our training program realised two doctoral schools. The first one in Paris (at CEA) performed seminars on neural network architecture search, extended reality services, explainable AI and invited expert speakers also to discuss about the directions toward a sustainable transition and how digital technologies should be reshaped in this respect. The second one, which took place at the University of Oulu, focused lectures on soft-skills such as business development and entrepreneurship, together with a visit at VTT industrial facilities for printed electronics.

From a research perspective, we worked on energy-aware optimization for federated learning processes. In particular, studying user-centric approaches in which the participation in the training process is decided directly by the clients in a collaborative fashion with the ultimate goal to reduce the energy consumption, while maintaining high privacy preservation and high accuracy of the learning tasks. Such approach represents an interesting step forward to human-centric AI. In another study, we investigated the usage of similarity metrics to measure data redundancy in federated learning, establishing the foundations for our activities on representation learning and reasoning for increasing the energy efficiency of learning systems.

VERGE is building three fundamental pillars: the "edge for AI", namely an edge-to-cloud compute continuum design unifying the lifecycle management and closed-loop automation of cloud-native applications, MEC and network services; the "AI for edge", namely an AI-powered portfolio of solutions for intelligent management and orchestration; and the "security, privacy and trustworthiness of AI-based models at the edge", providing a suite of methods to protect AI models against adversarial attacks, increase their explainability and reliability, and ensure data privacy. We are developing an O-RAN architecture blueprint to expose radio unit parameters and edge application analytics to an ML-driven micro-orchestrator, whose goal is to jointly manage the radio and compute resources to adaptively reduce the latency and energy footprint of the radio unit towards a more sustainable lifecycle operation. This work is ongoing and interactions with partners like Intel, BSC and Nearby Computing are foreseen.

DEFINING xG: NETWORK ARCHITECTURE & OPTICAL COMMUNICATIONS

Given the nature of core and transport network segments challenges, optical communications play a significant role, together with the tools already introduced in 5G such as network slicing, edge computing or network softwarization leading the boom of open-source network solutions in which CTTC has played a leading role in European and national projects.

MonB5G focused on the smart, flexible, and automated management of 5G and 6G network resources using artificial intelligence (AI). The project implemented AI-based mechanisms for zero-touch management and orchestration of a large number of network slices, enabling self-configuration, self-monitoring, self-healing, and self-optimization capabilities without 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. The concept of "network slicing" refers to the division of a virtual network infrastructure into multiple customized and independent segments and the suitable allocation, per use case, of network resources to efficiently serve different requirements. Each network slice, assisted by AI, ensured the seamless operation of demanding applications that require high capacity and low latency, in addition to the provision of reliable and high-quality services, the use of AI enhanced infrastructure security and improved energy efficiency of networks. The decentralized autonomic network management and orchestration proposed by MonB5G enables telecom and service providers to optimize their resource usage thus reducing both CAPEX and OPEX paving the way to offer new innovative 5G and 6G services at lower costs to consumers.

HEXA-X-II advanced the capabilities of optical networks with a focus on enhancing orchestration, awareness, and connectivity. Key activities included the practical demonstration of intent-based networking to simplify the management of end-to-end services in packet optical networks via cloud-native SDN orchestration. The project introduced location-awareness techniques into the networking fabric, which is critical for improving service delivery and network performance. Additionally, the researchers developed methods to group intent-based connectivity services, which are expected to aid in the efficient allocation and management of network resources, catering to the dynamic requirements of modern communication systems.

FLEX-SCALE included the development of disruptive optical networking approaches that enhance scalability while prioritizing energy efficiency. CTTC worked on TeraFlowSDN, a framework for controlling space division multiplexing (SDM) and wideband optical networks, aiming to meet the demands of the emerging 6G era. It was also explored the pivotal role of optical networking as the backbone for 6G transport, focusing on multi-granular control combining wavelength, waveband, and spatial switching. This multi-faceted control approach is essential for optimizing the high data rates and low latency required by 6G applications. Additionally, we developed a hierarchical energy-aware monitoring framework designed to improve the sustainability of packet-optical networks. This framework is vital in reducing the environmental impact of network operations and ensuring that future optical networking infrastructure can adapt to the increasing demands of data traffic while maintaining a low carbon footprint.

ALLEGRO advanced in aspects related to the coexistence of quantum and classical channels in the network infrastructure as well as SDN control plane requirements and architectures for optical networks, and well as transceiver solutions adopting innovative photonic technologies; this includes addressing advanced use cases involving slicing of the optical transport network, the introduction of advanced telemetry, the accounting for in line amplifiers along with physical layer impairment extensions and the usage of digital twins.

DEFINING xG: INTEGRATING THE SPACE SEGMENT

Non terrestrial communications projects continue enriching the expertise acquired over 20 years of work in satellite communications and space telemetry and telecommand, expanding the activities towards the integration of terrestrial and non-terrestrial networks (NTN) in 6G systems.

6G-NTN focuses on the study of 6G satellite communication systems. By addressing the terrestrial and non-terrestrial unification air-interface unification, the project aims to design and test new techniques for next standardized 3GPP Release 21 systems.

TRANTOR aims to provide in-orbit validation of pre-6G concepts to be demonstrated at CTTC premises. They involve the use of real satellite systems provided by Hispasat. Concepts such as multi-connectivity will be demonstrated together with the emulation of a LEO satellite.

MFSK4LDR has studied non-coherent receiver architectures for deep-space communications (telemetry and telecommand) including modulation, coding and data frame schemes in very challenging scenarios that involve extremely low link budgets, very large Doppler dynamics, and other channel distortions. The analyzed scenarios for the proposed transmission and receiver schemes are associated with envisioned spacecraft operational modes in future space missions such as the joint NASA-ESA Ice Giants mission that plans to observe Uranus and Neptune. Space missions typically involve different operational modes, such as the entry-descent and landing phase, safe and survival operational mode, or when the spacecraft navigates close to the Sun or is affected by strong solar scintillation conditions, all imposing diverse communication requirements. Within the project the receiver was implemented considering novel software implementations that can support real-time operations.

EVOLVING RADIO ACCESS WITH THE AID OF AI

CTTC's mathematical and theoretical knowledge is constantly used in R&D projects, including the integration of Machine Learning and Artificial Intelligence algorithms into the communication framework. In this sense, not only ML and AI have been integrated into our daily activities to enhance communication networks and solutions, but also, we have brought our mathematical expertise in statistical inference, signal processing, information/digital communication/network theories to address ML problems.

EmMAC2 aims to demonstrate the viability of task-specific MAC protocol learning by means of (deep) multi-agent reinforcement learning (MARL) techniques. The focus is on learning the layer 2 signaling for Discontinuous Reception (DRX), a power saving technique that allows for intermittent transmission interspersed by sleep periods. The work consists in experimental validation of different variants of MARL algorithms and architectures designed for the purpose of learning to transmit MAC Control Elements (CEs) for the proper timing of sleeping periods in DRX. These MARL-based DRX algorithms are compared against their conventionally designed, rule-based counterparts specified in 3GPP standards.

6GAINA aims to contribute algorithmic innovations towards the realization of a truly AI-native air interface for 6G communication systems. Several key enabling technologies for next-generation radio systems are studied in 6G-AINA, namely distributed computation over the wireless medium, AI/ML algorithms such as multi-agent deep reinforcement learning, as well as software-defined localization and positioning. The deepening of our understanding and the tailoring of these tools for advancing high-performing communication systems, is the centerpiece of the 6G-AINA research roadmap.
In particular, we leverage AI/ML algorithms to improve multi-antenna rate-splitting and non-orthogonal (MIMO-RSMA/NOMA) multiple-access schemes, extend current proposals of deep learning-based coded modulation and waveform designs, as well as to enhance the accuracy, sustainability and bandwidth efficiency of extremely large antenna arrays and cell-free massive MIMO networks. The project combines and applies these techniques to build prototypes of AI-native radio system components and validates their performance by proof-of-concept implementations on an experimental platform. For the experimental part, the project relies on modern laboratory equipment. This includes powerful GPU-equipped workstations and software-defined radio modules for over-the-air validation of AI/ML physical-layer algorithms, as well as, for localization and synchronization, a very mature testbed for software-defined radio GNSS positioning (GNSS-SDR).

EterComp focuses on over-the-air computation as an emerging paradigm for distributed computation and communication in the context of wireless data aggregation and federated learning. The key idea is to exploit synergies between the laws of physics (superposition principle of electromagnetic waves) and computation targets (linear combination of signals) such that the air interface can be exploited as an analog computer. To mitigate inaccuracies of this analog operation, the EterComp project investigates hybrid digital/analog coding techniques to make over-the-air computation reliable.

FREE6G investigates machine learning-based cell-free networks for 6G, innovating with ML-driven 6G cell-free access, mmWave fronthauling, elastic edge for zero-perceived latency and blockchain for RAN multi-tenancy. Work focuses in three main areas: a) the combination of innovative cell-free and hybrid MIMO technologies for the RAN and Fronthaul domains integrating Open RAN; b) developing fully elastic edge cloud and dynamic slicing support for the wireless domain, aiming at zero perceived latency in MEC applications. We provide self-driven orchestration and management of communication, storage and computational resources in an integrated way, offering an agile reconfiguration framework of accelerated virtualized functions hosted in FPGA-based SoC devices used across the telco continuum; and c) address the implications of multi-tenant infrastructures in security and privacy, when considering a holistic framework for end users and tenants.

DELIVERING IMPROVED APPLICATIONS THROUGH 5G

We have continued to deliver improved 5G network solutions to verticals and services.

DARLENE investigates how cutting-edge augmented reality (AR) technology can be deployed to help law enforcement agencies (LEAs) and first responders make more informed and rapid decisions, especially in situations where time is of the essence. DARLENE combines innovative AR smart glass technology and powerful computer vision algorithms with 5G network architectures to allow agile processing of real-time data by LEAs even in high-pressure situations. Some of the achievements are the design of a 5G private network architecture for Augmented Reality (AR) and Artificial Intelligence applications; the implementation of a low-latency 5G network for computation offloading of edge AI services; and the integration of 5G into DARLENE system (TRL 6) to support its use cases, e.g. "X-ray vision". The developed end-to-end DARLENE pipeline includes: AR glasses capturing video data and connected to a wearable compute node via WiFi; a WEarable Compute Node (WECN) intelligent agent enabling on-site video analysis and offloading to edge nodes via 5G. The WECN also provides authentication and encryption of the data flows; a private 5G network providing connectivity between wearable compute nodes, edge nodes and the cloud; an edge computing node that analyses the video images and sends them back over the 5G network to the AR glasses which render the results for a proper visualization; and a portable cloud that contains a 5G and MEC orchestrator, a virtualized 5G core network, and the security and authentication server-side software.

5GMED demonstrated advanced Cooperative Connected, and Automated Mobility (CCAM) for the automotive sector and railway communication services along the Mediterranean cross-border corridor between Figueres (Spain) and Perpignan (France), enabled by a multi-stakeholder compute and network infrastructure deployed by Mobile Network Operators, neutral hosts, and road and rail operators, based on 5G.
Our activities have concentrated on the use case for Road Infrastructure Digitalization, for which we have developed **EyeGuard**, a solution which integrates HD cameras and IR sensors with advanced machine learning algorithms to enable high accuracy prediction of hazardous events in the road. **EyeGuard** is also equipped with a 5G radio interface and enables real-time transmissions of identified alarms to the central control centre. **EyeGuard** runs on an edge computing node that may be installed in street furniture or vehicles to assist drivers. Field trials are being performed across the Spanish-French border to evaluate the performance of our proposal and gather data for future research. In particular, towards the design of roads digital twin, with the aim of supporting monitoring road traffic, reducing traffic accidents or performing efficient transportation planning and monitoring based on high density air quality parameters.

ACCELERATING SERVICES DEPLOYMENT THROUGH SOFTWARIZATION

Softwarization is present across the entire network and its components: from the devices at the access point to the transport and core segments, including the computation/management levels. Regarding softwarization, open-source approaches have been adopted at CTTC in a wide range of scenarios, leading word-wide initiatives such as GNSS-SDR receiver, 5G-LENA ns3 system level simulator or ETSI TeraFlowSDN controller. The following are examples of specific projects leveraging on such tools.

6G-BLUR targets softwarization brought by flexible service deployment to multiple industries in the form of cloud services and smart decision-making algorithms for efficient end-to-end resource management. It aims to integrate the radio access segment into overall network management, along with the core and transport segments, so as to reach a full end-to-end network management. The final end-to-end architecture has been agreed upon, and multiple Proofs-of-Concept (PoCs) have been defined, involving key players (manufacturers, operators, verticals, ...). They are being used to experimentally validate 6G disaggregated zero-touch mobile network as a service, with two PoCs that demonstrate how the 6G-BLUR architecture can deliver non-public networks (NPN), and dynamic network slices with optimal performance and flexibility on O-RANs. Another key scenario includes joint RAN and transport mechanisms for 6G disaggregated mobile networks, with two additional PoCs on joint fronthaul capacity control/placement, QoS management and flexible functional splits, and NPN cross-validation/optimization through digital twins. At the algorithmic level, the project focuses on the RAN, considering deep-reinforcement learning-based optimization of radio resources in NPNs, optimization of hardware-accelerated distributed units and radio units, and data-driven xApp- and rApp-based O-RAN optimization.

5G-EPICENTRE lays the foundations for an open-standards, end-to-end (E2E) 5G experimentation platform focused on software solutions that serve the needs of public protection and disaster relief. The 5G-EPICENTRE platform enables SMEs and developers to acquire knowledge regarding the latest 5G applications and approaches for first responders and crisis management, as well as to build up, and experiment with their solutions. The experimentation platform is based on an open Service Oriented Architecture (SOA), following the current best Development and Operations (DevOps) practices (e.g. containerization of micro-services), and can accommodate and provide open access to a federation of 5G networks' resources, acting this way as a 5G open-source repository for 5G-enabled PPDR solutions. Furthermore, it incorporates security by design approaches, such as e.g. a trusted data interchange layer safeguarding the security and integrity of the data transferability and services intercommunication between the endpoints and the infrastructure.

DEVELOPING TOOLS FOR CLIMATE CHANGE RISK MITIGATION

RASTOOL, the "European ground motion risk assessment tools", is a project funded by the Union Civil Protection Mechanism, which targeted Civil Protection in Europe. This project, coordinated by CTTC, developed key tools to extract high-level information from the European Ground Motion Service (EGMS) of Copernicus, which is relevant to different levels of Civil Protection organizations. The project highlighted the utility of new tools and procedures to exploit the rich information content of the EGMS products.

WISE, "Wide-Area Sentinel-1 Deformation Classification for Advanced Data Exploitation" focused on the automatic classification of the products coming from the European Ground Motion Service (EGMS) of Copernicus. The project, funded through a Living Planet Fellowship by the European Space Agency, will support an advanced interpretation and exploitation of the EGMS products. The approach tested in 2023 includes different supervised and unsupervised classification techniques.

NAVIGATION AND SPACE APPLICATIONS

SCRIPT, SENER Concept Receiver for Indoor Positioning Techniques, built a technological demonstrator that took advantage of new technological developments in location systems based on wireless technologies, in combination with new techniques for position estimation and data fusion for ubiquitous indoor positioning. The proposed innovative solution was based on mass-market wireless technologies which are complementing GNSS to cover indoor environments: UWB (Ultra-Wide band), that enables fine time resolution, which allows identifying direct path received signal, mitigating multipath effect very effectively; WiFi RTT (Round Trip Time), taking advantage of the widespread use of WLAN access points that allows use of simple infrastructures; Bluetooth, which is widely adopted in consumer market and supports AoA/AoD with relatively simple HW; and the CTTC's GNSS-SDR receiver, expanded to include high-sensitivity algorithms in signal acquisition.

GNSS-FLEX addresses the design and implementation of a national GNSS receiver that overcomes the limitations in dynamics of existing products on the market and adds new functionalities currently not available, with a level of technological maturity suitable for its commercialization as a product ready for technology integrators (Original Equipment Manufacturer, OEM). The development of a proprietary GNSS receiver also integrates an Inertial Measurement Unit (IMU) to optimize the fusion of inertial, magnetic, and satellite sensors, to obtain a positioning solution adaptable to a wide variety of applications, including high dynamics of space vehicles. Of course, the system is also fully validated and can be incorporated into all types of vehicles, whether land-based or maritime. In this way, technological independence and the development of proprietary knowledge will be achieved, impossible to obtain with commercial GNSS receivers.

Scientific Publications

Contributions to architectural network design, communication, orchestration and management protocols applied to 5G/6G networks

M. Dalgitsis, N. Cadenelli, M. A. Serrano, N. Bartzoudis, L. Alonso and A. Antonopoulos, "NSFaaS: Network Slice Federation as a Service in Cloud-Native 5G and Beyond Mobile Networks," 2023 IEEE Conference on Network Function Virtualization and Software Defined Networks (NFV-SDN), Dresden, Germany, 2023, pp. 59-64.

This joint work with Nearby Computing and the UPC focuses on a novel cloud-native orchestration framework for network slice federation, allowing to exchange federated service and slice resource templates among operators and thus enabling the continuity of services across different operator domains. This functionality opens the door to a whole new range of applications and services by improving and extending the user experience and by allowing operators to better capitalize and monetize their infrastructures.

R. Vilalta, L. Gifre, R. Casellas, R. Muñoz, R. Martínez, A. Mozo, A. Pastor, D. López, and JP Fernández-Palacios, "Applying Digital Twins to Optical Networks with Cloud-native SDN Controllers", IEEE Communications Magazine. 2023 Aug 28.

The use of Network Digital Twins (NDT) in optical networks is a promising development that can significantly improve network optimization, decision-making, and testing. The proposed architecture that utilizes SDN controllers to deploy NDTs presents a novel approach to achieving these benefits. The virtual representation of the physical optical network provided by the NDT allows for the testing of different scenarios and the validation of specific behaviors before their implementation in the physical network, such as network optimization. This approach can help network operators identify potential issues and optimize the network's performance, resulting in cost savings and improved user experiences.

Fabrega JM, Vilchez FJ, Svaluto Moreolo M, Martínez R, Quispe A, Nadal L, Casellas R, Vilalta R, Muñoz R, Neumeyr C, Lee SY, "Experimental demonstration of a metro area network with terabit-capable sliceable bit-rate-variable transceivers using directly modulated VCSELs and coherent detection", Journal of Optical Communications and Networking. 2023 Mar 1;15(3):A103-13.

Disaggregation in optical networks is particularly relevant to be considered for the deployment of 5G services and towards the support of 6G. Particularly in the metro area network (MAN), this is especially crucial, as is the adoption of suitable photonic technologies enabling dense integration to design a sustainable network architecture. Furthermore, to dynamically allocate the ever-increasing traffic, supporting multiterabit capacity, an optimal usage of the available resources by properly exploiting the multiple dimensions, with programmable and adaptive data plane solutions, is key. In this work, we assess the capabilities of a disaggregated MAN that relies on new photonic devices, node architectures, and sliceable bandwidth/bit-rate-variable transceivers, approaching wavelength division multiplexing and space division multiplexing.

Kosmatos E, Casellas R, Nikolaou K, Nadal L, Uzunidis D, Matrakidis C, Fàbrega JM, Moreolo MS, Stavdas A, "SDN-enabled path computation element for autonomous multi-band optical transport networks", Journal of Optical Communications and Networking. 2023 Oct 9;15(11):F48-62.

This paper reports on the design, implementation, and validation of an SDN control plane for multi-band optical networks with externalized path computation. The SDN control plane relies on extending current open and standard interfaces to support dynamic service management and decoupled path computation services on multi-band optical networks while accounting for physical layer impairments, which is critical for successful service provisioning. We detail the multi-band optical network resource management and optimization engine for transparent and translucent networks. The system is experimentally validated in a 22-ROADM BT network with emulated hardware showing the performance of the control plane and the considered workflows.

E. Zeydan, J. Baranda, J. Mangues-Bafalluy and Y. Turk, "Blockchain for Network Service Orchestration: Trust and Adoption in Multi-Domain Environments," in IEEE Communications Standards Magazine, vol. 7, no. 2, pp. 16-22, June 2023, doi: 10.1109/MCOMSTD.0003.2200014.

In the coming years, blockchain technologies will be used in a variety of industries, including telecommunications. In this article, due to strict governance of telecommunication infrastructure, we propose a blockchain supported architecture, based on a permissioned distributed ledger scheme, for a network management and orchestration platform. The main goal is to create a trusted environment for multiple-stakeholders, such as Cloud Service Providers, a Mobile Network Operator, Vertical Service Providers, Legal and Regulation Authorities, and Responsible Ministry so that the life cycle of automated vertical network services can be managed securely and transparently in a multi-cloud and multi-domain environment.

B. Bakhshi, J. Mangues-Bafalluy, and J. Baranda, "Multi-provider NFV network service delegation via average reward reinforcement learning", Comput. Netw. 224, C (Apr 2023). https://doi.org/10.1016/j.comnet.2023.109611

In multi-provider B5G networks, service delegation enables administrative domains to federate in provisioning NFV network services. Admission control in selecting the appropriate domain for service deployment, without prior knowledge of service requests' statistical distributions, is fundamental to maximize average profit. This paper analyzes a general federation contract model for service delegation in various ways. First, under the assumption of known system dynamics, we obtain the theoretically optimal performance bound by formulating the admission control problem as an infinite-horizon Markov decision process and solving it through dynamic programming, which is used as a benchmark to evaluate practical solutions. Second, Reinforcement Learning is applied to practically tackle the problem when the arrival and departure rates are not known.

5G Radio Access and applications

B. Bojovic, S. Lagén, K. Koutlia, X. Zhang, P. Wang and L. Yu, "Enhancing 5G QoS Management for XR Traffic Through XR Loopback Mechanism," in IEEE Journal on Selected Areas in Communications, vol. 41, no. 6, pp. 1772-1786, June 2023, doi: 10.1109/JSAC.2023.3273701.

In this paper, we propose and study extended reality (XR) loopback mechanisms that adapt the XR traffic to the instantaneous 5G network conditions by exploiting XR application feedback. We propose various XR loopback algorithms, strategies, and parameters' configurations and study their impact on the 5G end-to-end performance. We conduct extensive simulation campaigns by building realistic end-to-end 5G network scenarios with 3GPP mixed XR traffic setups. Results show that the proposed XR loopback mechanism can boost XR performance by adapting to 5G network conditions, while keeping the XR QoS requirements under control. We provide various insights and practical directions on XR loopback design that allow us to take full advantage of the 5G network capabilities and progress toward 5G-Advanced network design.

S. Lagén, X. Gelabert, L. Giupponi and A. Hansson, "Fronthaul-Aware Scheduling Strategies for Dynamic Modulation Compression in Next Generation RANs," in IEEE Transactions on Mobile Computing, vol. 22, no. 5, pp. 2725-2740, 1 May 2023, doi: 10.1109/TMC.2021.3128700.

In this paper, we consider a multi-cell multi-user scenario with a shared fronthaul (FH) link across multiple cells and we focus on optimizing the resource allocation and modulation compression of each user, in a centralized and dynamic manner, aiming to maximize the air interface performance subject to the shared FH capacity constraint. The problem is formulated as a convex optimization problem, which allows deriving the optimal resource allocation and modulation compression per user. Then, we evaluate the proposed FH-aware scheduling methods against baseline holistic strategies over an end-to-end dynamic 5G NR system-level simulator based on ns-3. Under a tight available FH capacity, results show gains that vary from 16% to 567% in different percentile statistics of the user-perceived throughput.

A. Larrañaga, M. C. Lucas-Estañ, S. Lagén, Z. Ali, I. Martinez, J. Gozalvez, "An open-source implementation and validation of 5G NR configured grant for URLLC in ns-3 5G LENA: A scheduling case study in industry 4.0 scenarios", Journal of Network and Computer Applications, Volume 215, 2023, 103638, ISSN 1084-8045,

To analyze the capability of 5G and beyond networks to support time-critical services in digitalized factories of the future, this work presents the first implementation of Configured Grant (CG) (defined by 5G NR to reduce the latency in the uplink and support URLLC services) in the open-source ns-3 5G-LENA simulator. To validate the implementation of CG, we analyze the latency performance that can be achieved using CG with different scheduling policies in Industry 4.0 scenarios. The results show that the latency values achieved with CG in 5G-LENA match with those reported by previous analytical studies. In addition, this study shows the importance of efficiently using radio resources to reduce the latency experienced and meet the requirements of critical services.

R. Sedar, C. Kalalas, F. Vázquez-Gallego, L. Alonso and J. Alonso-Zarate, "A Comprehensive Survey of V2X Cybersecurity Mechanisms and Future Research Paths," in IEEE Open Journal of the Communications Society, vol. 4, pp. 325-391, 2023, doi: 10.1109/OJCOMS.2023.3239115.

Recent advancements in vehicle-to-everything (V2X) communication have notably improved existing transport systems by enabling increased connectivity and driving autonomy levels. The remarkable benefits of V2X connectivity come inadvertently with challenges which involve security vulnerabilities and breaches. Addressing security concerns is essential for seamless and safe operation of mission-critical V2X use cases. This paper surveys current literature on V2X security and provides a systematic and comprehensive review of the most relevant security enhancements to date. An in-depth classification of V2X attacks is first performed according to key security and privacy requirements. Our methodology resumes with a taxonomy of security mechanisms based on their proactive/reactive defensive approach, which helps identify strengths and limitations of state-of-the-art countermeasures for V2X attacks. In addition, this paper delves into the potential of emerging security approaches leveraging artificial intelligence tools to meet security objectives. Promising data-driven solutions tailored to tackle security, privacy and trust issues are thoroughly discussed along with new threat vectors introduced inevitably by these enablers. The lessons learned from the detailed review of existing works are also compiled and highlighted. We conclude this survey with a structured synthesis of open challenges and future research directions to foster contributions in this prominent field.

Satellite and Non-Terrestrial communications

I. Leyva-Mayorga et al., "Satellite Edge Computing for Real-Time and Very-High Resolution Earth Observation," in IEEE Transactions on Communications, vol. 71, no. 10, pp. 6180-6194, Oct. 2023, doi: 10.1109/TCOMM.2023.3296584.

In simple terms, when we want detailed pictures of Earth from space, satellites flying closer to our planet take the pictures and send them down to us. These pictures help with things like predicting weather and keeping an eye on the environment. They're also really useful for spotting disasters as they happen, so we can respond quickly.

But sometimes, there's so much picture data that the satellites can't send it all down fast enough, causing a traffic jam of sorts. To fix this, we can make the satellites share the load by passing the pictures between each other. This helps speed things up.

This study came up with a clever way to make this sharing process even better. By using a system called satellite mobile edge computing, they figured out how to send and store the pictures more efficiently. This means we can get more pictures down from space without using up too much energy.

M. Caus and A. I. Pérez-Neira, "FBMC-Based Random Access Signal Design and Detection for LEO Base Stations," in IEEE Transactions on Wireless Communications, vol. 22, no. 3, pp. 2156-2170, March 2023, doi: 10.1109/TWC.2022.3209898.

When we talk about bringing fast internet to far-off places, like remote areas, we're starting to think beyond just ground-based networks. Imagine if we could use flying base stations in space to connect everyone, no matter where they are or what time it is. To make this idea a reality, we need to upgrade the way satellites talk to devices on the ground. Here, researchers have come up with a smarter way for devices to connect to satellites. They've designed a new kind of signal called filter bank multicarrier (FBMC), along with a clever way for devices to detect it quickly. This new signal works better than the usual one because it reduces the chances of interference and makes it easier for devices to find the satellite's signal, even when they're far away or moving fast. What's neat is that this new signal still fits in with the technology used in 5G, so we can use it alongside existing systems without too much hassle. And even though it's fancier, it's not any harder for devices to understand, which means we could see these improvements in action sooner rather than later.

Artificial Intelligence and Machine Learning solutions to improve communications

E. Guerra, F. Wilhelmi, M. Miozzo and P. Dini, "The Cost of Training Machine Learning Models Over Distributed Data Sources," in IEEE Open Journal of the Communications Society, vol. 4, pp. 1111-1126, 2023, doi: 10.1109/OJCOMS.2023.3274394

Federated learning is one of the most appealing alternatives to the standard centralized learning paradigm, allowing a heterogeneous set of devices to train a machine learning model without sharing their raw data. However, it requires a central server to coordinate the learning process, thus introducing potential scalability and security issues. In the literature, server-less federated learning approaches like gossip federated learning and blockchain-enabled federated learning have been proposed to mitigate these issues. In this work, we propose a complete overview of these three techniques, proposing a comparison according to an integral set of performance indicators, including model accuracy, time complexity, communication overhead, convergence time, and energy consumption. An extensive simulation campaign permits to draw a quantitative analysis considering both feedforward and convolutional neural network models. Results show that gossip federated learning and standard federated solution are able to reach a similar level of accuracy, and their energy consumption is influenced by the machine learning model adopted, the software library, and the hardware used. Differently, blockchain-enabled federated learning represents a viable solution for implementing decentralized learning with a higher level of security, at the cost of an extra energy usage and data sharing. Finally, we identify open issues on the two decentralized federated learning implementations and provide insights on potential extensions and possible research directions on this new research field.

A. Aguilar-Rivera, "The unscented genetic algorithm for fast solution of GA-hard optimization problems", Applied Soft Computing, Volume 139, 2023, 110260, ISSN 1568-4946,
This work introduces the Unscented Genetic Algorithm (U-GA), which combines ideas from evolutionary computation and Kalman filters to devise a novel approach to solve GA-hard problems. The approach is justified based on how other Bayesian methods make strong assumptions on data, which could limit their performance in the long run. U-GA applies theory from unscented Kalman filters to relax this assumptions via Monte-Carlo simulation. The algorithm is explained in detail, showing how unscented Kalman filters equations could be adapted for the evolutionary computation framework. In the experiments, the proposed approach is compared to Bayesian optimization algorithm (BOA) and genetic algorithms (GAs) to investigate the strengths and limitations of U-GA. The results show how U-GA attains better performance than the benchmarks, even when the problem size is increased. Also U-GA attained a considerable speed-up (around 400%) when compared with similar methods.

L. Blanco, S. Kuklinski, E. Zeydan (SaS), F. Rezazadeh (SaS), A. Chawla, L. Zanzi, F. Devoti, R. Kołakowski, V. Vlahodimitropoulou, I. Chochliouros, A. M. Bosneag, S. Cherrared, L. A. Garrido, S. Barrachina (SaS), J. Mangues (SaS), "AI-driven Framework for Scalable Management of Network Slices," IEEE Communications Magazine, vol. 61, no. 11, pp. 216-222, November 2023, doi: 10.1109/MCOM.005.2300147
This article describes a scalable solution for orchestrating and managing a massive number of network slices that leverages Artificial Intelligence (AI) techniques to design robust and sustainable networks. To achieve this goal, the proposed approach decomposes the management and orchestration (M&O) plane using separation of concerns and uses AI techniques to automate M&O operations. The M&O automation is achieved through the use of multiple, distributed and AI-driven control loops. The control loops have different goals and may work on the node level, slice level, inter-slice level or orchestration domain level. We also present a case study of using the proposed distributed intelligent components to scale, optimize and improve the network infrastructure. Finally, we briefly describe some challenges and future directions for scalable M&O on the road to 6G.

M. Llobet, M. Cabrera-Bean, J. Vidal and A. Agustin, "Optimizing Access Demand for mMTC Traffic Using Neural Networks," in IEEE Transactions on Vehicular Technology, vol. 72, no. 12, pp. 16834-16838, Dec. 2023, doi: 10.1109/TVT.2023.3294724.
Machine-type communications show unique spatial and temporal correlation properties that often lead to bursty access demand profiles. With the expected large-scale deployment of the Internet of Things (IoT), next-generation mobile networks should be redesigned to manage massive, highly synchronized arrivals of access requests by employing efficient access barring schemes. In this work, we first derived the analytical expression of the optimal Access Class Barring (ACB) parameter as standardized by the Third Generation Partnership Project (3GPP). Secondly, we predict the type and number of accessing devices from measurements acquired by the Base Station (BS) by employing Neural Networks (NNs). These estimates are used to effectively implement the optimal barring scheme, achieving performance results close to the theoretical bound.

D. R. Kumar, C. Antón-Haro and X. Mestre, "RS-Net: Neural Network-Enhanced Receivers for MIMO Rate Splitting Multiple Access," 2023 IEEE Globecom Workshops (GC Wkshps), Kuala Lumpur, Malaysia, 2023, pp. 1964-1969, doi: 10.1109/GCWkshps58843.2023.10464670.
In this paper, we investigate neural network-based channel estimation strategies for point-to-point multi-input multioutput (MIMO) systems. In an attempt to keep computational complexity low, we restrict ourselves to shallow architectures with a single hidden layer. Specifically, we consider (i) fully-connected feedforward neural networks; and (ii) 1D/2D convolutional neural networks. The analysis includes an assessment of the estimation error performance, along with the computational complexity associated to the training and inference phases. Several benchmarks are considered, such as the conventional least squares or (linear) MMSE estimators, and other deep neural network architectures from the literature.

Contributions to mathematical and information theoretical tools

A. Pastore, S. H. Lim, C. Feng, B. Nazer and M. Gastpar, "A Unified Discretization Approach to Compute-Forward: From Discrete to Continuous Inputs," in IEEE Transactions on Information Theory, vol. 69, no. 1, pp. 1-46, Jan. 2023, doi: 10.1109/TIT.2022.3197592.
This paper considers the problem of distributed lossy compression where the goal is to recover one or more linear combinations of the sources at the decoder, subject to distortion constraints. For certain configurations, it is known that codes with algebraic structure can outperform i.i.d. codebooks. For the special case of finite-alphabet sources, recent work has demonstrated how to incorporate joint typicality decoding alongside linear encoding and binning. This work takes a discretization approach to extend this rate region to include both integer- and real-valued sources. As a case study, the rate region is evaluated for the Gaussian case. The resulting joint-typicality-based rate region recovers and generalizes the best-known rate region for this scenario, based on lattice encoding and sequential decoding.

Mobile devices and sensors

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, vol. 71, no. 4, pp. 1781-1792, April 2023.
This a joint work with the UPC funded by HiSilicon (China) focusing on the FPGA prototyping of an envelope tracking system targeting 5G mobile devices that significantly lowers the power consumption of the power amplifier, which in turn extends the lifecycle operation of the handset's battery.

K. Silva dos Santos, GO. Cavalcanti, A. Azevedo, CPD. Silva, MT. de Melo, I. Llamas-Garro, E. Fontana, "Hybrid Microstrip Device for Hydrogen Detection at Microwave Frequencies," in IEEE Sensors Journal, vol. 23, no. 7, pp. 6810-6821, April 1, 2023, doi: 10.1109/JSEN.2023.3244698.
This article describes the analysis, design, and construction of a microstrip device capable of detecting hydrogen at microwave frequencies. The proposed structure is a hybrid microstrip line, 10-cm-long, having part of the copper (Cu) line replaced by a strip of palladium (Pd) film 10-nm-thick. The experimental results, corroborated by the theoretical modeling of the device's response, open the possibility of constructing simple hydrogen sensors by incorporating ultrathin Pd films into planar microwave circuits.

Navigation and positioning

M. Majoral, C. Fernández-Prades and J. Arribas, "A Flexible System-on-Chip Field-Programmable Gate Array Architecture for Prototyping Experimental Global Navigation Satellite System Receivers," Sensors, Vol. 23, no 23, Article number 9483, December 2023, doi: 10.3390/s23239483
Global Navigation Satellite System (GNSS) technology is evolving at a rapid pace. The rapid advancement demands rapid prototyping tools to conduct research on new and innovative signals and systems. However, researchers need to deal with the increasing complexity and integration level of GNSS integrated circuits, resulting in limited access to modify or inspect any internal aspect of the receiver. To address these limitations, the authors designed a low-cost System-on-Chip Field-Programmable Gate Array (SoC-FPGA) architecture for prototyping experimental GNSS receivers. The proposed architecture combines the flexibility of software-defined radio techniques and the energy efficiency of FPGAs, enabling the development of compact, portable, multi-channel, multi-constellation GNSS receivers.

M.A. Gómez, A. Solera-Rico, E. Valero, J. Arribas Lázaro and C. Fernández-Prades, "Enhancing GNSS receiver performance with software-defined vector carrier tracking for rocket launching," Results in Engineering. Vol 19. Article number 101310, January 2023, doi: 10.1016/j.rineng.2023.101310
This work introduced a Vector Tracking Loop architecture applied to track GNSS signals' Doppler shift and its rate, using the open-source GNSS-SDR framework. This leads to a novel real-time, software-defined receiver capable to work with different commercial-off-the-shelf RF front-ends. The proposed implementation was tested in challenging, non-conventional, high dynamics positioning scenarios to obtain the position and velocity vectors of a rotation-stabilized guided rocket. Results show that the algorithm and its proposed implementation are able to provide full signal tracking, even under extremely demanding acceleration profiles.

A. Moragrega, C. Fernández-Prades, "A Data-Driven Factor Graph Model for Anchor-Based Positioning", Sensors 2023, 23, 5660.
This work presents a data-driven model to perform indoor positioning. The system computes the target position from distance measurements to anchor nodes of know position. The presented algorithm was tested with simulated data and with real-life data. The results showed that the algorithm provides better positioning results than other existing algorithms.

Geomatic solutions applied to Earth Observation

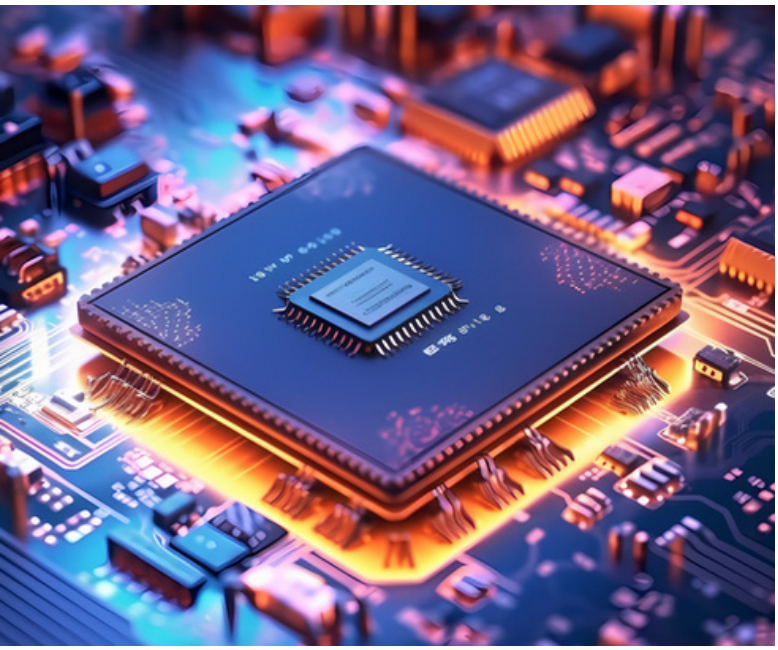
M. Crosetto and L. Solari, "Satellite interferometry data interpretation and exploitation: case studies from the European Ground Motion Service (EGMS)". Elsevier, 2023.
This book is devoted to the interpretation and exploitation of the products from EGMS. The book provides the fundamental information needed to interpret such complex data. In addition, it provides plenty of examples of data interpretation from different fields of application, e.g. subsidence, landslides, settlements, volcanic activity, etc.

R. Palamà, O. Monserrat, B. Crippa, M. Crosetto, G. Bru, P. Ezquerro, M. Bejar-Pizarro, "Radargrammetry DEM Generation using high-resolution SAR imagery over La Palma during the 2021 Cumbre Vieja Volcanic Eruption", IEEE Geoscience and Remote Sensing Letters, 20, pp. 1-5, 2023.
The paper investigates the suitability of DEM generation based on high-resolution Synthetic Aperture Radar (SAR) imagery. The targeted application, i.e. volcanic eruption monitoring, requires imagery also in low visibility scenarios. This is guaranteed by using SAR imagery.

Technology Transfer, Interest Groups and Associations

Spin-offs

GeoKinesia, S.L., established in July 2020, is a spin-off from CTTC that leverages remote sensing techniques based on CTTC's intellectual property and expertise. Utilizing satellite radar images, these techniques enable the measurement and monitoring of deformations across a wide range of scenarios and applications. These include mining operations, detection of urban terrain deformations, risk management related to landslides or subsidence, and maintenance of infrastructure such as roads and train tracks. The satellite-based remote sensing solution allows GeoKinesia to offer services with global coverage. Additionally, CTTC continues to support the company's specific research needs.



IPR protection & New Products

As one of its tools to foster technology transfer, CTTC relies on intellectual property protection through the national and international patent systems, as well as other mechanisms such as industrial secrets and licensing agreements.

2023 represents a step forward with the release of a new hardware product. The new GNSS-SDR embedded System-on-Chip hardware accelerator is available for purchase from CTTC's web https://www.cttc.cat/products/

This IP core, resulting from the leadership of the open-source SDR GNSS receive initiative GNSS-SDR, allows to execute the full capabilities of a GNSS-based positioning system in a lightweight, low-consumption, and small form-factor device in selected System-on-Chip devices via the utilization of FPGA IP cores, ensuring a balance between computational demands and power efficiency for an optimal GNSS signal processing experience.

In addition to its regular IPR activities, such as participating in the GINJOL Patents Fund and monitoring internal invention and innovation opportunities, CTTC began revising its internal IPR policy in 2023. New actions were implemented to enhance technology transfer and IPR exploitation. Specifically, the internal program for Scientific Excellence was extended to include a Business Development specific call. The first call took place in 2023, awarding one Business Development project on smart antenna design for GNSS and two new Scientific Excellence internal projects: Emergent Learning of PHY Layer Functions and Protocols, and Pervasive and Sustainable Intelligence. Adriano Pastore, a recipient of one of the 2023 Scientific Excellence internal projects, also received one of the prestigious Leonardo Fellowships from the BBVA Foundation.

Industrial Collaboration, Interest Groups and Associations

CTTC is strongly committed to the realization of industrial R&D projects. In 2023, CTTC run 31 industrial contracts, with 40% of the industrial contracts corresponding to recurrent customers. This reveals that, on the one hand, CTTC has built a solid reputation as a reliable R&D partner. 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 Apple, Meta, Huawei, Nokia Bell Labs, KDDI, or Telefonica I+D.

CTTC continued to play a major role in the definition of the future 6G communication systems to be deployed worldwide by 2030. This is evidenced by their consolidated leadership as 5G/6G/xG expert with the management and technical lead of the 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". The collaborative work with 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, NearbyComputing, SRS, Telcaria, TTI Norte, WorldSensing) has become a reality in 2023 to boost the development of own 5G/B5G technology and help Spain to be one of the leaders on the development of 6G in Europe. This work will greatly benefit from the UNICO I+D 6G 2023 new projects that shall reinforce experimental infrastructure and secure the acquisition of state-of-the-art equipment supporting xG maturation.

Furthermore, the participation in the 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 that kickstarted this year. 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 also includes the participation in HEXA-X II, the flagship initiative of the JU. The objective of this project is to design a complete 6G communications system with a view to its standardization and implementation. All this is nicely complemented by the 3 additional R&D projects awarded to the CTTC in the second call SNS of the SNS-JU in 2023. One of them, 6G-REFERENCE, which addresses hardware enablers for cell-free coherent communications and sensing is coordinated by the CTTC.

Besides, CTTC has continued to be very influential in terms of R&D policy making. In 2023, CTTC's Director of EU Programmes and Industry Contracts, Dr. Carles Antón-Haro was elected as a Governing Board (GB) member of the Joint Undertaking of 6G Smart Networks and Services (JU-SNS). This GB is composed of representatives of the public (European Commission) and private (6G-IA) sides. It is responsible for the Joint Undertaking's decision-making, including the preparation of the workprogrammes (with an earmarked budget of 900 Meuro for the 2021-2027 period) and funding decisions related to the research and innovation activities under Horizon Europe. The Governing Board also provides strategic guidance and contributes to other EU programmes that are implementing activities in the area of smart networks and services, such as the Connected European Facility 2 Digital, Digital Europe Programme and InvestEU. The Board also adopts the Strategic Development Agenda for pan-European 5G corridors for connected and automated mobility. CTTC is the only representative for all the R&D centers and academia in Europe in the GB. Furthermore, CTTC was also re-elected as Governing Board member of the 6G Smart Networks and Services Industry Association (6G-IA), the private side in the JU SNS. All major equipment vendors, mobile network operators, thriving SMEs, research centers, and academia are represented there. CTTC is currently one of the two representatives of research centers and academia, and has been in this board since 2014. This has allowed the Center to drive the definition of the 6G

R&I Workprogrammes (2021/22, 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. This includes the elaboration of the 66-IA/Next G Alliance Position Paper on "EU-US Beyond 5G / 6G roadmap"; or the 6G-IA Position Paper "Key Strategies for 6G Networks and Services" which followed from CTTC's participation in the 6G-IA Policy Task Force and provides guidance on strategic matters such as technological sovereignty or the sustainability of future communication networks. Furthermore, CTTC has helped establish dialogues with other regions (Japan, Korea) for the analysis of priorities towards the elaboration of the SNS 2024 Workprogramme, and has participated in panel discussions with other R&D funding agencies (NSF, UKRI, DEVCOM, etc). Besides, CTTC has led a number of strategic working groups of the 6G-IA such as the Trials or the Member State Initiatives sub-WG. Additionally, in 2023 CTTC has continued to act as a Steering Board member of NetworldEurope. This European Technology Platform elaborates the Strategic Research and Innovation Agenda (SRIA) on which the SNS-JU 6G R&I 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 where it provides leverage and influence towards the definition of EU priorities in the area of photonic devices and optical networks. CTTC continues to chair the Ground Motion Service Advisory Group of the European Environmental Agency, playing a key advisory role and providing the Agency with expertise in satellite-based interferometry techniques for ground analysis. Starting in 2023, the contract has been renewed for an additional 2-year term.

Complementarily, CTTC researchers were appointed to serve on several boards, steering and technical committees in professional and academic associations.

Standardization is another influential activity through which CTTC is achieving impact. CTTC is actively involved in standardization at the major telecommunication European and global bodies. 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. Some of the leading roles are the leadership of ETSI OSG TeraFlowSDN, 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, as well as encourage adoption of open-source solutions by industry stakeholders. CTTC has also been a founding member (along with Telefonica and other companies) of ETSI's OpenSlice Software Development Group, which is aimed at creating an open-source, service-based operations support system for delivering network slice as a service. Technical contributions were also provided to ETSI Multi-access Edge Computing working group; and the contribution to the roadmap of 6G satellites, from the Satellite Working Group, published in the IEEE International Network Generations Roadmap, from the IEEE Future Network Society.

Other global initiatives aiming at promoting software-defined standards are also led by CTTC, such as the long-term role of Dr. Ramon Casellas as member of the Technical Steering Team at Open Networking Foundation, which oversees the Open Transport Configuration & Control project and is responsible for all technical decisions.

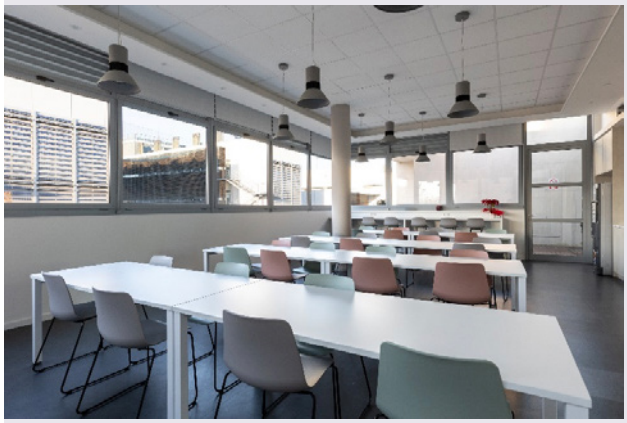
Overall, CTTC's active involvement in standardization efforts demonstrates a commitment to advancing the state of the art in the field and ensuring that research outcomes can be translated into real-world impact.

Quality Standards & New Programs

CTTC has long adopted internal policies to deploy quality standard protocols, ensuring high standards for efficient management of R&D activities, transparent career development, and a stimulating work environment. In 2023, two major quality certifications, UNE 166002 and HRS4R, underwent external review.

For the quality program ensuring efficient management of R&D activities, the adaptation to the new norm UNE 166002:2021 was completed in 2022. The certification renewal was issued by AENOR in 2023 after a successful evaluation of the yearly audit.

Regarding the European HRS4R certification, CTTC entered the Award Renewal Phase after a three-year implementation phase. The external evaluation was satisfactory, demonstrating that CTTC's comprehensive analysis and action plan met all requirements for progress and quality, aligning HR practices with the Charter and Code principles. Consequently, CTTC successfully transitioned into the Award Renewal phase and was granted to keep using the 'HR Excellence in Research' award.



To provide and ensure a favourable work environment, CTTC continued implementing its internal program for improving general-purpose spaces and experimental facilities in 2023. The remodelling of the kitchen and terrace in the B6 building was completed, creating a new networking venue for collaborative project meetings, conferences, workshops, and training schools. This facility has been well-received by staff for regular workday activities, lunch breaks and internal networking events.

Additionally, new meeting rooms were renovated and equipped with advanced virtual facilities, allowing for flexible configurations online, face-to-face and hybrid to suit different event's nature and requirements. These rooms were used extensively in 2023 for training sessions, project meetings, and internal work sessions.

Several efforts were made to expand and improve CTTC's experimental facilities. The fabrication workshop and welding station were relocated to the B6 building, providing significantly larger space and improving working conditions for the PCB assembly and mechanical workshop users.

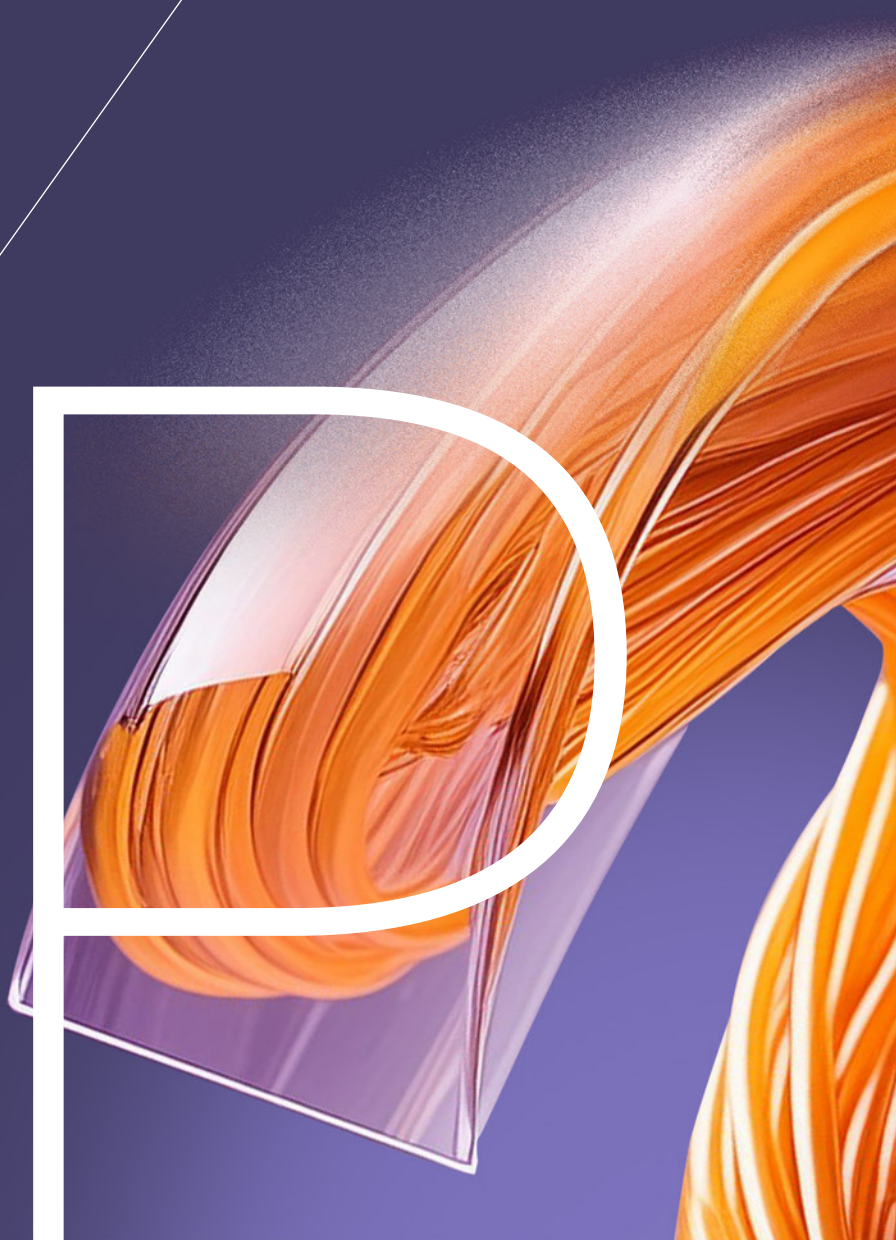
Other actions included the redistribution of some of the existing research laboratories, such as the Space and Resilient Communications Lab and the Signal and Information Processing Lab, which gained significant space.

The expansion of the Packet Optical Networks and Services Lab to include Optical Access and Edge Network capabilities into the ADRENALINE testbed required refurbishing the B6 building lab space and connecting both buildings with dedicated optical fiber for experimental activities and testbeds modules interconnection.

In 2023, several new internal programs were approved to boost talent attraction and promote gender equality. Specifically, the programs "Women in STEM" and "Undergraduate Program" were launched. The "Women in STEM" program allocates a specific budget within the GEP activities to promote women's talent and leadership through grants, mentoring, and communication. This program aims to foster a successful professional life for women in STEM.

The "Undergraduate Program" starts launching the first call for "Young Talent Research Stays" in the first quarter of 2024. These research stays aim to provide financial aid to excellent undergraduate and master's students and introduce them to research and state-of-the-art technology developments in telecommunications and geomatics, providing real contact with the everyday activities of a research centre like CTTC. This program complements the Starting Research Contract introduced a few years ago to bridge the gap between graduation and the first research position, typically associated with a PhD program.

Professional, Scientific, Training & Dissemination Events



CTTC actively participates in a variety of events with the aim of:

- Increasing international visibility
- Fostering new institutional relations and collaboration agreements
- Establishing new R&D partnerships
- Contributing to the training of specialized R&D talent
- Disseminating scientific and technological knowledge and encouraging vocations in science and engineering

CTTC leverages large international congresses in Barcelona to showcase its work to a global audience. Annually, CTTC exhibits at the Mobile World Congress (MWC), IoT Solutions World Congress, and Smart City Expo World Congress. These booths are instrumental in showcasing CTTC technologies, testbeds, and demo portfolios. At MWC23, CTTC presented results from ongoing R&D projects and showcased demos of: cloud-native ETSI MEC Platform as a Service Network Application; management and orchestration of virtualized network services for connected and automated mobility in cross-border scenarios; and AI-designed 3D constellations for 6G.

Beyond the exhibition stand at MWC2023, CTTC organized and moderated a discussion panel on the challenges faced by the Spanish ecosystem in developing 6G and extensively adopting 5G to accelerate digital transformation. This panel, organized within the framework of the Spanish program for the universalization of digital infrastructures for cohesion (UNICO) with the support of red.es, included participation from the State Secretary of Telecommunications and Digital Infrastructures, Dra. María González Veracruz, and industrial partners from UNICO's R&D projects.

At the IoT Solutions World Congress 2023, we showcased a solution developed at CTTC for increasing driving safety. The V2X EyeGuard is an online hazard detection system for driving applications. At the Smart City Expo World Congress 2023, the focus was on sharing our experience on Citizen Science and present recent results on combining technology and Citizen Science to raise awareness about urban air pollution, along with advancements in Cooperative Connected and Automated Mobility and Future Railway Mobile Communications System services.

CTTC has strengthened international relations through several institutional visits to its premises. During 2023 CTTC particularly reinforced links with South America, hosting delegations from Colombia and Chile, aiming to explore collaborative projects to incentivize fair economic growth through innovation and technology transfer. Collaboration agreements were also discussed with Chilean universities. Locally, CTTC has reinforced its impact through a collaboration agreement with the city of Castelldefels, enhancing the city's air-quality monitoring network, which now includes the PMT area and the access of CTTC's researchers to the city open data service that will aid new research developments into low-cost, high-accuracy environmental monitoring technologies and citizen science initiatives. Active participation in PMT networking events led to closer interaction with local ecosystem. CTTC organized one of the Café Networking where the satellite and terrestrial networks integration were exposed, emphasizing the infrastructure and potential synergies with the schools, research centres and companies at the PMT. These interactions spurred further conversations with space communications stakeholders and expand contacts with the Chamber of Commerce of Barcelona and the Baix Llobregat branch.

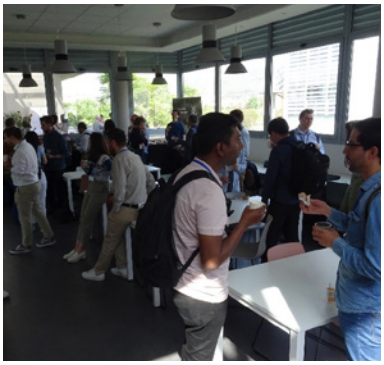
Considering events with specific scientific focus, CTTC hosted the 20th SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference, bringing together researchers and developers in theoretical and experimental fields like Microwaves, Optoelectronics, Wireless Communication, and Photonics Networks.

This biennial workshop, with over 100 attendees and strong industrial partnerships, also provided opportunities for talent attraction and promoting gender and diversity equality.

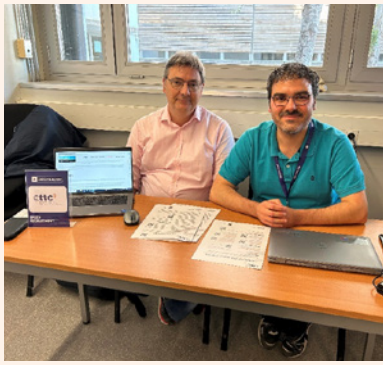
Outstanding students were supported with travel grants to attend the workshop and learnt the career development opportunities in Spain. Interactions with CTTC's senior researchers were facilitated through specific meetings. IMOC2023 was also representative of CTTC's commitment towards diversity and inclusion in research, and cultural exchanges. More specifically, the conference hosted the gender and diversity workshop titled "Talent and career in research: The role of mentoring to foster diversity and inclusion"; and brought an example of Catalan cultural heritage represented by the Castellers.

In 2023, CTTC hosted events of different technical nature involving standardization and training. Examples are the ETSI Multi-access Edge Computing working group meeting MEC#33 and the OSM#15 Hackfest co-located with the OSM#15 Plenary Meeting. These events addressed challenges in open-source developments and advanced the specification of MEC technology for cloud-computing capabilities and IT service environments at the network edge; in environments characterized by ultra-low latency, high bandwidth, and real-time access to radio network information The Hackfest had a more practical flavour, gathering professionals from the Open Source MANO community to address several self-contained challenges like developing small features, writing unit tests, or automating end-to-end tests for use cases. These events are key for the reliable development of open-source and the successful adoption of such open solutions by key players.

On the training side, numerous activities took place. The technical meeting organized within the framework of COST Action CA20120, "Intelligence-Enabling Radio Communications for Seamless Inclusive Interactions" is one example. This event combined invited speakers, technical presentations, and a tutorial by CTTC researchers Josep Mangues and Engin Zeydan who provided hands-on insights into data engineering for networking and applications from the perspective of telecommunication operators.



CTTC also engaged with undergraduate students through student fairs at various universities, offering internships, final studies thesis work and research job opportunities.



Dissemination events targeting primary and secondary school students were expanded within the Science Week framework to include practical workshops. Besides the introduction to CTTC research activity and to the role of engineering researchers, the students from the professional training secondary school could experiment with real indoor positioning solutions, visit research labs and attend a lecture on optical communications.

A citizen science session on how to combat air pollution was delivered in Barcelona.

Additionally, CTTC participated in public initiatives like the "Visions de la Ciència" program from Barcelona's Libraries network promoting informative reflections and discussions in science and technology. In a talk by CTTC researcher Paolo Dini, the implications of Artificial Intelligence for achieving sustainability were discussed leading to an open debate.

PhD Theses

We are proud of our new PhD graduates, which defended their doctoral work in 2023.

Dr. Pol Alemany

Quality of service, security and trustworthiness for network slices

The telecommunications' systems are becoming much more intelligent and dynamic due to the expansion of the multiple network types (i.e., wired, wireless, Internet of Things (IoT) and cloud-based networks). Due to this network variety, the old model of designing a specific network for a single purpose and so, the coexistence of different and multiple control systems is evolving towards a new model in which the use of a more unified control system is able to offer a wide range of services for multiple purposes with different requirements and characteristics.

To achieve this situation, the networks have become more digital and virtual thanks to the creation of the Software-Defined Networking (SDN) and the Network Function Virtualization (NFV). Network Slicing takes the strengths from these two technologies and allows the network control systems to improve their performance as the services may be deployed and their interconnection configured through multiple-transport domains by using NFV/SDN tools such as NFV-Orchestrators (NFV-O) and SDN Controllers. This thesis has the main objective to contribute to the state of the art of Network Slicing, with a special focus on security aspects towards the architectures and processes to deploy, monitor and enforce secured and trusted resources to compose network slices.

Dr. Jesús Soriano

Improving monitoring and management of low-lying coastal areas with Sentinel-2 data: the Ebro Delta showcase

Coastal areas support important ecosystems with great ecological value, giving rise to countless resources increasingly exploited by humans. Understanding the processes occurring in both inland and aquatic ecosystems, as well as their mutual interactions, and with anthropic activities is required. In this line, the new generation of high-resolution multispectral Sentinel satellites (Sentinel-2; S2) extend the capabilities for the integrated monitoring of coastal areas thanks to their spatial and temporal resolutions (up to 10 m and 5 days). However, global remote sensing issues/limitations (e.g., cloud screening, spectral mixing, atmospheric correction) and regional-specific characteristics (e.g., involved ecosystems, economic fabric, interlinkages), make up challenges of diverse nature. The basis of the research presented in this thesis is to explore the potential of S2 for the monitoring of coastal areas, and the associated technical and scientific questions.

The work is focused on the processing of S2 imagery for characterizing Ebro Delta (Spain) coastal features and their dynamics. From atmospheric correction and image pre-processing to data modelling and analysis, a number of technical and scientific challenges have been addressed. The conducted research has been applied to the estimation of phytoplankton biomass at coastal bays (aquaculture), the generation of information on crop dynamics and management (agriculture), the assessment of agriculture runoff disturbance in coastal waters (environmental monitoring), and the characterization of storms' effects on land and water ecosystems (natural hazards). A work that brings the application of satellite image processing to scientists, engineers, coastal managers, and stakeholders by providing results that demonstrate the usefulness of these viable and low-cost techniques for high-quality coastal monitoring.

Dr. Carlos Manso

Cloud-native orchestration and automation for disaggregated networks

Automated end-to-end operations over transport networks, which are segmented by different technologies and domains, are difficult to operate without direct human intervention. On top of that, datacenter operators are decoupling the software from the hardware, using white-box hardware with open Application Programming Interfaces (APIs), enabling more customization and vendor competition but adding even more complexity. Moreover, the growth of demand by users threatens to exhaust the capacity of Wavelength Division Multiplexing (WDM) optical networks, making Spatial Division Multiplexing (SDM) needed to keep up with capacity demands in the long term.

This PhD Thesis presents different architectures to alleviate these issues. A network architecture to control and orchestrate multi-layer multi-domain disaggregated packet optical networks is presented, based on a Software Defined Networking (SDN) controller, as well as an architecture to control WDM over SDM transport networks. Also, a cloud-native architecture for SDN controllers that can cope with the complexity and size of transport networks is presented, based on the micro-services software architecture, that allows for self-healing infrastructure and independent auto-scaling of micro-services, including a distributed database. The last part presents an architecture that joins the data gathering, training of machine-learning models, and execution, needed to feed data to support multiple operations in the zero-touch management approach.

Dr. David López

Machine learning techniques for adaptive polynomial and neural network digital predistorters

The power amplifier (PA) is a core element in radio transmitters (TXs) to support the required mobile and fixed broadband communication link ranges. However, the PA is a power-hungry and nonlinear by nature device. Under spectrally efficient wideband modulated waveforms with high peak-to-average power ratio, the PA features significantly decreased energy efficiency since power back-off is needed to comply with the transmission quality requirements. Moreover, when employing highly efficient amplification architectures, the added distortion is left as an issue to be addressed at system level. The closed-loop adaptive digital predistorter (DPD) is a key component of the digital front-end (DFE) to counteract the PA nonlinear response under varying conditions and cope with the inherent trade-off between linearity and efficiency.
According to the fifth generation (5G) and beyond communication technologies and proposed radio TX and PA architectures, the DPD may have to deal with strong nonlinearities and memory effects, in-phase and quadrature-phase (IQ) modulator imbalances and dc offsets, PA supply or load modulation distortion, and multi-antenna PA input and output cross talk and beam-dependent effects. These degrade the radio access network energy efficiency, capacity, and the number of potential users due to the increased in-band and out-of-band distortion. The adaptive DPD can overcome such negative impacts but faces relevant obstacles given the increased signal bandwidth and higher speed DPD adaptation requirements. The challenges are twofold. On the one hand, combining massive bandwidth operation together with handling complex multi-dimensional effects may increase exponentially the complexity of the DPD and make it both commercially unaffordable and energy inefficient. On the other hand, the adaptive DPDs need significantly larger training periods to compensate for all the undesired effects.
In line with these challenges, the research presented in this dissertation aims at leveraging on efficiently deployed machine learning (ML) and artificial intelligence (AI) techniques to reduce the computational complexity of DPD modeling and identification at the DFE, guaranteeing well-conditioned and robust DPD estimation, and drastically reducing the DPD training times while meeting performance requirements in complex nonlinear scenarios. To accomplish that, several newly applied and customized ML feature selection and feature extraction dimensionality reduction techniques are combined with novel training data length reduction schemes, to obtain reduced DPD behavioral modeling matrices and input datasets, in single-antenna and multi-antenna adaptive polynomial and neural network predistorters, respectively.

Dr. Yismaw Wassie

Spatio-temporal quality metrics for satellite SAR interferometric data

Unprecedented availability of RADAR images coming from current and future satellite missions for monitoring Earth's surface and its changes over time prompt the development of several interferometric SAR algorithms and methodologies. The widely known Multitemporal interferometric SAR (MT-InSAR) techniques, generally, aim at extracting the temporal evolution of displacements of targets with coherent scattering behaviour from a stack of SAR acquisitions taken from the same area and processed relative to temporal and spatial references. However, from its very nature, SAR data is complex and susceptible to uncertainties accounting for the uncontrolled medium of signal transmission or due to the difficulty (or limited knowledge) of fully representing model parameters. Incomplete representations of modelling parameters, on the other hand, may lead to omission errors and hence an incorrect estimation and interpretation of the displacement timeseries. Which in turn compromises their reliability of the MT-InSAR products in sensitive applications. In line with this, tools making use of estimated phase residuals derived from redundant network of baseline-constrained Sentinel-1 SAR images are developed to formulate threshold-based quality scores as indicators of the reliability of the measurements particularly impacted by phase unwrapping errors. Thereby leveraging the power of the technique for a wide range of applications, including monitoring of natural and anthropogenic phenomenon.

Dr. Eduard Angelats

On hybrid positioning using non-semantic image information

Hybrid or multi-sensor-based positioning has been a research topic actively investigated in the last decade. In this context, the possibility of using information extracted from imaging sensors, for positioning, is very appealing to mitigate the problems that GNSS or INS/GNSS-based trajectories have in terms of robustness and accuracy. On the other hand, different processing workflows, sensor positioning quality or system calibration errors, may also produce even in GNSS-friendly conditions, that multiple geospatial datasets are not properly co-registered. This thesis proposes the use of non-semantic information, this is, the use of a set of geometric entities or features, to improve the trajectory estimation in a multi-sensor-based approach. This thesis covers the mathematical modelling of non-semantic information, implements several hybrid-based trajectory estimation approaches that use this kind of information with the appropriate modelling, and also explores the use of non-semantic features to model the trajectory error modelling. This thesis also presents an approach to improve the determination of Remotely Piloted Aircraft Systems (RPAS) trajectories using open aerial data obtained in the framework of a national mapping project (PNOA), aiming to ensure the geospatial coherence between different datasets.

Last but not least, this thesis presents a seamless indoor-outdoor positioning approach with encouraging results (meter-level accuracy) in several scenarios. This is an open field of research with not widely accepted /adopted solution yet.

Dr. Farhad Rezazadeh

Lifelong AI-driven zero-touch network slicing

The sixth-generation (6G) network's evolution necessitates advancements in algorithms and architecture to transition from an AI-native to an intrinsic trustworthy automation-native system. Network slicing creates multiple virtual networks for diverse service requirements and is a crucial technology for future communication systems and 6G networks. The implementation of network slicing in radio access networks (RAN) is challenging due to the complexity of managing RAN operations. This gap is addressed with zero-touch network slicing, a fully automated management and orchestration scheme, which eliminates the need for fixed contracts and manual intervention. The decision engine, a main component of this technology, employs algorithmic innovation to optimize network resource allocation and handle the challenges of RAN slicing, including energy efficiency, latency, scalability, and trustworthiness. In resource allocation, a joint optimization approach is used to balance energy and latency with service quality. A stochastic Actor-Critic approach is proposed to streamline the learning procedure and reduce the need for hyperparameter tuning in an energy-aware network slicing setup. Additionally, a massive deep reinforcement learning-based actor-learner framework is introduced to tackle complexity issues and control challenges in network slicing.

The temporal variations of traffic demand pose a significant challenge for resource planning and allocation in the RAN domain. To mitigate this, a distributed architecture for RAN slice resource orchestration is proposed, featuring multiple AI-enabled decision agents that perform local radio allocation decisions without a centralized control entity. A federated learning scheme, aligned with the recent development of the Open RAN architecture, is designed to enhance local decision-making capabilities. Despite AI's effectiveness, concerns persist regarding the lack of transparency in deep neural networks, posing risks to reliability and security in network scenarios. This lack of trust prevents telecommunications operators from widely deploying AI models in their networks. To address this, we proposed SliceOps architecture that consolidates explainable ML operations in a standalone slice, offering AI services to other slices.

Dr. Zoraze Ali

AI/ML for multi-technology RAN automation with full and limited infrastructure support

This thesis studies and proposes solutions to some of the most relevant challenges in the Radio Access Network (RAN) management arising from its evolution beyond 5G and towards 6G. The tackled problems are selected due to the increasing inherent complexity with which these technologies come along, which justifies the need for Artificial Intelligence and Machine Learning (AI/ML) techniques. In particular, we identify two axes of complexity: the infrastructure support complexity axis (x-axis), where the complexity varies based on the level of infrastructure support, and the technology complexity axis (y-axis), which captures the complexity variation based on the number of technologies to be operated in a coordinated way. Based on these axes, we define three RAN scenarios: infrastructure-based single-technology, infrastructure-based multi-technology, and limited infrastructure-based single-technology. The main objective is to study these scenarios in depth and identify a set of representative use cases along these axes that can be addressed with AI/ML solutions to automate RAN. In this line, our methodology consists of a three-step approach, using existing and implementing new high-fidelity and standard-compliant simulation models of the open-source ns-3 and 5G-LENA system-level simulators coupled with the proposed AI/ML frameworks.

In the first step, we focus on the two use cases, 1) handover (HO) management and 2) initial Modulation and Coding Scheme (MCS) selection in the infrastructure-based single-technology RAN scenarios. The traditional HO schemes have the drawback of considering only the quality of signals from the serving and the target BS to make a HO decision, which can impact users´ QOE. Also, the initial MCS at the start of the session is usually handled conservatively, i.e., the lowest MCS is assigned to a mobile device that connects to a new BS, impacting its initial throughput. To address these drawbacks, we propose AI/ML solutions prioritizing QoE for HO decisions and optimizing initial MCS allocation using network data. First, we design single-task AI/ML models for each use case, then propose a multi-task framework for addressing multiple use cases concurrently, reducing training costs.

In the second step, we deal with the infrastructure-based multi-access technology scenarios by focusing on the coexistence of License Assisted Access (LAA) and LTE-Unlicensed (LTE-U) with WiFi. These technologies must ensure fair coexistence to operate in the unlicensed spectrum. However, this thesis discovers that the inherent delay in receiving HARQ feedback in the LAA enables it to monopolize the channel, which then degrades neighboring WiFi networks' performance. To solve this, we propose an AI/ML-based scheme that infers feedback without delay. Our scheme achieves a favorable trade-off between WiFi fairness and LAA performance in terms of throughput and latency compared to benchmark approaches. Additionally, we propose a statistical framework to evaluate fairness in LAA and LTE-U coexistence with WiFi, confirming LAA's better fairness over LTE-U's.

Finally, in the third step, we focus on the limited infrastructure-based single-technology RAN scenarios. Without BS, in these scenarios, operations like resource selection and scheduling are uncoordinated, introducing another level of complexity. Specifically, this thesis focuses on vehicle-to-vehicle communication with limited infrastructure, where a roadside unit broadcasts basic information using 3GPP NR-V2X technology. Nevertheless, vehicle resource selection in NR-V2X involves continuous channel sensing, but it consumes more energy. Alternatively, not employing sensing saves energy but increases interference. Hence, an energy-performance trade-off arises. To address this, we propose an AI/ML-based partial sensing mechanism to dynamically balance V2X user performance and energy consumption, surpassing the manual configuration of standard sensing parameters.

Zoraze Ali received his MSc degree in Radio Communication from the Blekinge Institute of Technology, Karlskrona, Sweden. In September 2014, he joined CTTC as a researcher, where he focused on developing novel AI/ML RAN solutions for 4G, 5G, and B5G networks. From 2018 to 2022, he acted as the maintainer and one of the developers of the ns-3 LTE and NR (aka 5G-LENA) modules. In 2020, he received a Networking System Award from ACM SIGCOMM for his contributions to the ns-3 open-source network simulator. He was also the lead developer of the first ns-3 NR-V2X extension published in 2021. Additionally, he delivered training for the ns-3 LTE module and NR-V2X extension at WNS3 workshops in the year 2019 and 2022, respectively. In 2022, he became a standardization manager at Ericsson Sweden, focusing on simulation studies for 3GPP RAN-4. His main interests include wireless communications, AI/ML, and the development of link/system-level simulators for emerging mobile technologies.

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AI/ML for multi-technology RAN automation with full and limited infrastructure support

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PH.D. THESIS

AI/ML for multi-technology RAN automation with full and limited infrastructure support

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2023

Departament d'Enginyeria Telemàtica
UNIVERSITAT POLITÈCNICA DE CATALUNYA

Dr. Roberto Pereira

Clustering large dimensional data via second order statistics: spplication in wireless communications

In many modern signal processing applications, traditional machine learning and pattern recognition methods heavily depend on having a sufficiently large dataset to estimate complex signal structures. However, the definition of sufficient is subjective and problem-dependent. Traditional learning approaches often fail to learn meaningful structures in the cases where the number of features closely matches or exceeds the number of observations, emphasizing the need for strategies that extract meaningful information from high-dimensional settings. This thesis explores the use of Riemannian geometry to assist in the comparison and clustering of high-dimensional data in the form of covariance matrices. Specifically, it investigates the asymptotic behavior of distances between sample covariance matrices by establishing a central limit theorem that allows us to describe the asymptotic statistical law of these distances. A general result is provided for the class of distances that can be expressed as sums of traces of functions applied separately to each covariance matrix. Additionally, it addresses the challenge of consistently estimating the distance between covariance matrices and demonstrates the practical implications of these findings in wireless communications. The aim is to contribute theoretical insights into unsupervised learning mechanisms for the integration and interpretability in wireless networks and signal processing challenges.

We thank you
all our collaborators
and staff to support
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