6G

SHAPING THE 6G VISION: THE i2CAT'S PERSPECTIVE

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EXECUTIVE SUMMARY

The communications industry has set the ambitious goal to deliver 6G networks by 2030. 6G is expected to be a key enabling technology that will help realize the United Nations Sustainable Development Goals (UN SDGs) and the twin green and digital transition envisioned by the European Commission. To meet this ambitious goal, 6G research and development activities have already started.

Delivering 6G entails several significant challenges. Among them, we can highlight two: 1) first, the industrial, academic, and user communities need to converge on a common vision defining the scope and design principles of the future 6G system, and 2) 6G key enabling technologies need to be identified so that their associated research challenges can be properly addressed.

i2CAT, as a research and innovation technology center located in Barcelona and focused on digital technologies, is determined to contribute to building 6G.

Motivated by this context, in this white paper, we introduce i2CAT's view on the future 6G system and we highlight the key technical areas where i2CAT will focus its 6G R&D efforts in the upcoming years. We also describe a set of key R&D assets that will help us maximize the impact of our 6G research. These assets take the form of capabilities, experimental tools, and facilities that i2CAT has developed over recent years through a very strong research, development, and innovation activity around 5G. For example, i2CAT has participated in 16 projects of the European 5G Public Private Partnership, having coordinated three of them, and having acted as technical manager in a further three projects.

We look forward to collaborating with the interested stakeholders in the exciting 6G journey ahead of us!

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01 MOTIVATION

Today is the right time to start thinking about 6G. The massive deployment of 5G technologies has just started and very soon we will witness its whole potential. For that particular reason, we must start thinking about and designing what will come next. Learning from history, we can anticipate that in about 10 years' time – in other words, by the year 2030 –, there will be a new set of customer and market requirements that will call for a next generation of smart networks that can deliver unprecedented new services to satisfy the needs of society.

5G is the first mobile communications technology which has been designed, not only to evolve the Mobile Broadband service, thus offering more capacity to satisfy the never-ending growth of data transfer demand mainly driven by the unstoppable demand for video transmission, but also to offer new services. Indeed, 5G has also been designed to satisfy the requirements of the Internet of Things (IoT), calling for a massive deployment of low-cost and low-energy devices, and emerging services and applications which demand ultra-low latency and very high reliability. This includes connected and automated mobility, e-health, or the vision of industry 4.0, to mention just a few. A common aspect of these services is that they need an extremely reliable communication system; something that previous generations of mobile technologies have not managed to provide.

6G is the next necessary step. 6G is about evolving 5G services to a new dimension, but also about melding the human, physical and digital worlds into a unified system of systems (Figure 1-1). The human world is composed of us, humans, considering a holistic view where humans become not only our bodies, but also our interactions, intentions, moods, feelings, and, ultimately, our intelligence. The physical world encompasses the objects around us which become our homes, offices, cities, factories, roads, etc. Finally, the digital world will become a virtual representation of the human and physical worlds, seen as one big thing, where intelligent agents can make decisions, thus boosting the concept of artificial intelligence and collective artificial intelligence.

Therefore, 6G is about connecting both human and artificial intelligence to ensure that all means of intelligence are connected, and also internet-connected to build a more efficient world where humans will ultimately benefit from unprecedented smart services that will boost our sustainability, well-being, inclusiveness, economy, prosperity and resilience. These novel smart services include, among others:

- **Connected intelligence**: Connecting all sources of artificial intelligence enablers, such as Machine Learning algorithms, across a distributed network/compute infrastructure which will be able to balance and distribute the resources of the system to facilitate a federated learning approach; all this, without human intervention.
- **Digital twinning/control**: The creation of virtual models to replicate the physical world will have the power to monitor and better understand it, optimizing its resources and also anticipating possible misbehaviors, underperformances, or even security threats.
- **Cognition:** The possibility to anticipate and predict human behavior and its intentions will completely disrupt the concept of human interaction and human value in the current society.
- **Immersive experiences**: Making the concept of the Internet of Senses, Internet of Skills, or the Tactile Internet truly possible, will have a significant impact on our lives. The capability to exchange haptic information, visual experiences, and sound in absolute and accurate real time, will allow new ways of remote interaction. A new era of Holoportation and remote control and human interaction is about to start; and 6G will be a key facilitator in this.

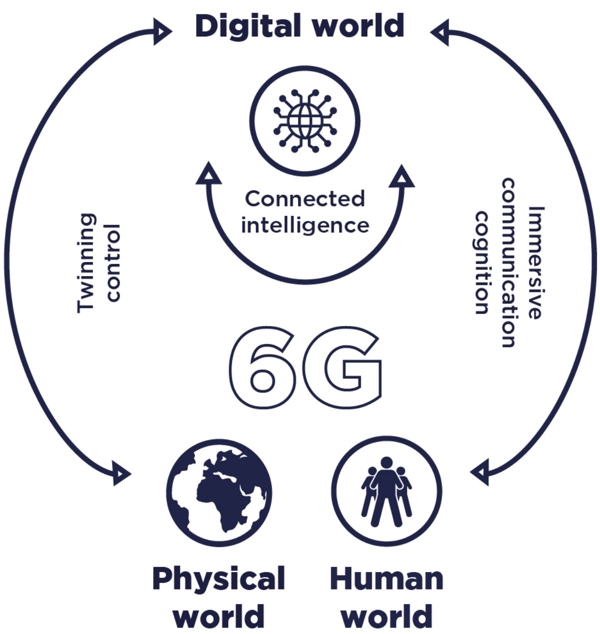

Figure 1-1. 6G vision: melding the human, physical and digital worlds [1]. This is the vision documented by the 5G infrastructure association in the white paper entitled "European Vision for the 6G Network Ecosystem" in June 2021. (Figure 1).

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i2CAT'S VISION: FUTURE 6G (META) ARCHITECTURE

The European Vision for the 6G Network Ecosystem white paper [2] identifies seven key technical areas that will underpin the design of the future 6G system, namely:

1. **Network Architecture and Control**, defining the future architecture of the 6G system.
2. **Edge and Ubiquitous Computing**, expanding the 5G edge compute vision towards a cloud continuum that spans from the cloud to the smart device.
3. **Radio Technology and Signal Processing**, including disruptive wireless technologies such as Reconfigurable Intelligent Surfaces (RIS) and Integrated Sensing and Communication (ISAC).
4. **Optical Networks**, to sustain energy efficient Tbps transmission networks.
5. **Network and Service security**, embedding security and trustworthiness as native primitives of the 6G system.
6. **Non-Terrestrial Communication**, integrating terrestrial and satellite networks to deliver truly ubiquitous coverage.
7. **Device and Component enhancements**, required to scale up radio communications to Tbps speeds and to decrease the energy footprint of the ICT infrastructure.

Figure 2-1 illustrates the key 6G technical areas identified in the 6G European vision white paper [1], highlighting in orange the technical areas that will be prioritized by the 6G research of i2CAT. The i2CAT vision in each of the highlighted areas will be described in the following chapters of this white paper.

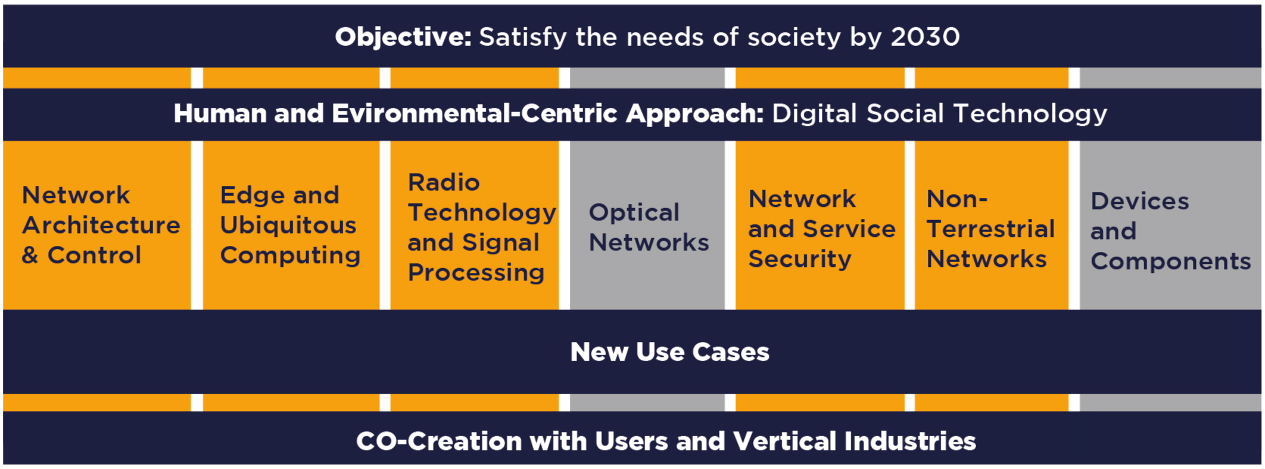

Figure 2-1. 6G technical innovations identified the by European 6G vision white paper. i2CAT priorities highlighted in orange.

Building on the previous key technical areas, a preliminary view on the overarching 6G system architecture has already been agreed on the more than 30 companies contributing to the European 6G vision white paper [2]. This preliminary overarching architecture is illustrated in figure 2-2, where we can see that the evolution of the 6G system is split in two clearly distinct layers.

In the lower part of figure 2-2 we observe a composable multi-party and multi-tenant resource pool. This resource pool represents a clear departure from the 5G infrastructure model where, despite adopting the principles of softwarization and virtualization, the 5G network is still confined to a single administrative domain offering primarily a connectivity service defined over the Radio Access Network (RAN) and Core Network (CN) domains. The 6G resource pool will natively aggregate multiple administrative domains, with infrastructure resources contributed to the common 6G pool by Mobile Network Operators, hyperscalers, private network domains, local edge providers or vertical domains. The aggregated 6G resource pool will thus not be limited to RAN and CN domains, but will natively include terminals, transport networks, computation and sensing as additional composable resources, consumed according to novel business models and Service Level Agreements (SLAs).

A Unified Controllability layer, depicted in the middle of figure 2-2, is required to abstract the complex aggregated 6G resource pool into easy-to-consume ephemeral infrastructure resources, where service isolation and SLA enforcement is guaranteed.

Finally, in the upper part of figure 2-2, we observe the service layer, where the 6G mobile network functions of a particular provider can be understood as a communication service instantiated over the aggregated 6G resource pool (Service A in figure 2-2). Additional novel services, not limited to communication, will also be instantiated over the 6G resource pool, alongside the mobile communication services.

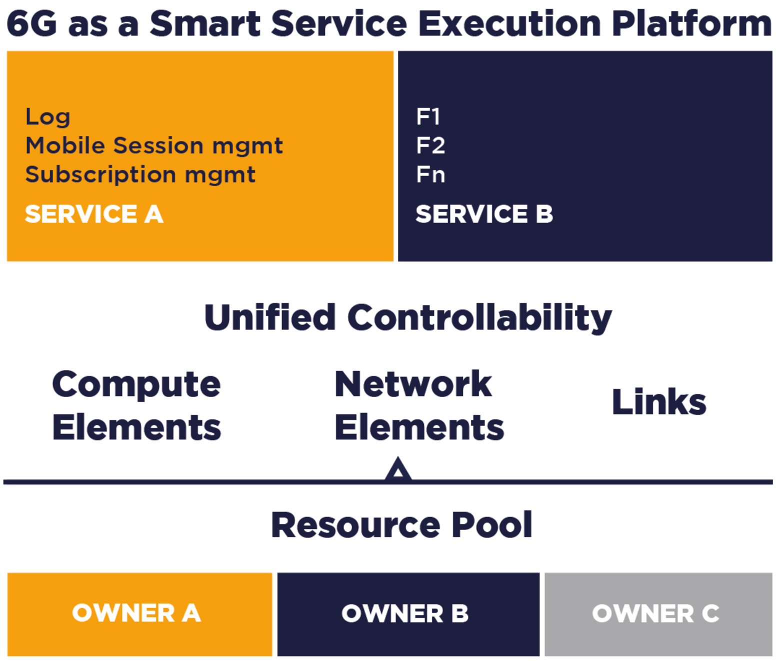

Figure 2-2. Preliminary view of the 6G system architecture by the European 6G vision white paper.

i2CAT's current work in beyond 5G systems is well aligned with the European vision of the 6G system architecture. Multi-tenancy and resource isolation in 5G systems was investigated in the 5GCity project [3]. Integration of public and private 5G networks supporting delivery of end-to-end services across domains is being investigated in the 5G-CLARITY project [4]. Autonomic resource discovery across administrative domains using blockchain is being investigated in the 5GZORRO project [5]. These ongoing works position i2CAT in an excellent place to contribute to the definition of the European 6G vision.

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i2CAT'S FOCUSED 6G RESEARCH CHALLENGES

CLOUD CONTINUUM

The vision of the 6G cloud continuum is to expand the computational resources that sustain digital services from the cloud, provided by today's hyperscalers, and the 5G edge, provided by Mobile Network Operators (MNOs), to computational resources available at the very edge of the network composed by a plethora of smart devices.

To enable the 6G vision of interconnecting ubiquitous intelligent agents requires moving from the centralized cloud infrastructure of today, to a fully distributed computational substrate that can support the AI/ML pipelines that will underpin future 6G services. This distributed computational substrate cannot be provided by a single stakeholder, as is the case in today's cloud or edge resources; it requires a federation of resources offered by different stakeholders, including MNOs, private networks, local edge providers, and smart devices particular to specific vertical domains. Orchestrating the provisioning of cloud native services over this distributed computational substrate in a similar manner as network services are orchestrated on top of today's Network Function Virtualization (NFV) infrastructures, is the main challenge to be solved by the 6G cloud continuum vision. Figure 3-1 illustrates the expected structure of the 6G cloud continuum highlighting the different domains from smart device to the cloud.

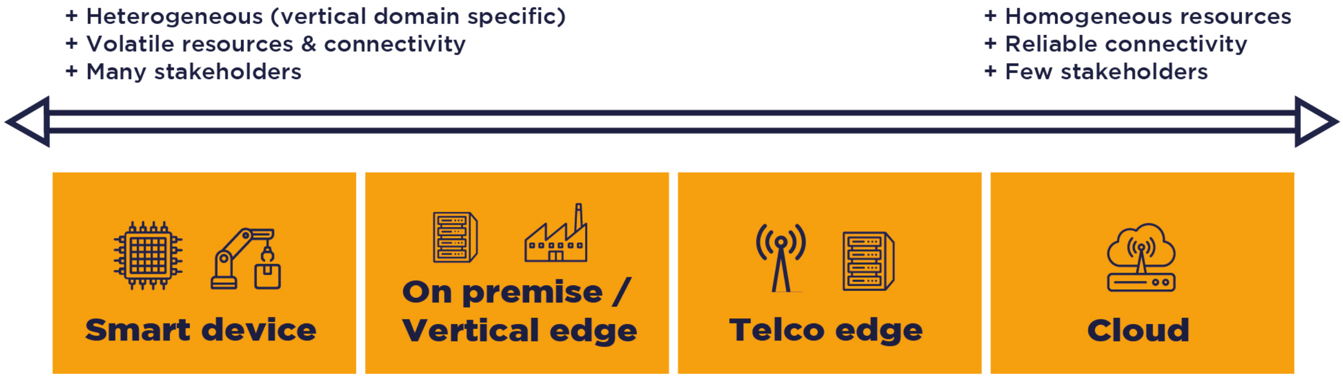

Figure 3-1. Structure of the 6G cloud continuum.

The vision of the 6G cloud continuum poses significant research challenges. First, given the heterogeneity, volatility, and high number of devices, orchestrating computational resources in the smart device domain becomes more challenging than in traditional edge or cloud computing environments. Second, the multi-stakeholder nature of the 6G cloud continuum requires distributed and auditable mechanisms for resource discovery, trust establishment and SLA monitoring. Third, it is essential to abstract service developers from the inherent complexity of the 6G cloud continuum providing stable development Application Programmable Interface (APIs) that can work across different domains. Fourth, another key challenge is to minimize the carbon footprint of the distributed cloud continuum infrastructure. AI/ML is a key transversal technology to address the previous research challenges.

i2CAT is well positioned to contribute to the design of the future 6G cloud continuum given its previous work on 5GZORRO, where a distributed marketplace for compute, radio and spectrum resources is being built based on a private blockchain [5]. In CARAMEL, i2CAT developed a virtualized V2X stack, running on both the infrastructure (MEC) and in the vehicle [6], and which can be used to enable instantiation of new ML-powered services running in the car (smart device). In 5GCity and PLEDGER i2CAT deployed a distributed cloud continuum testbed in Barcelona, integrating computational resources at MEC and extreme edge (streetlamps and street cabinet) sites, alongside 5G and V2X connectivity [7].

INTELLIGENT OPEN NETWORKS

The 6G Intelligent Open Network is a novel mobile network architecture that extends the use of disaggregation, Service Based Architecture (SBA) and AI/ML beyond 5G networks. The adoption of these concepts in 6G networks is expected both in the RAN and in the Core Network.

RAN disaggregation will evolve from the current O-RAN architecture [8] towards a fully cloud native SBA-based RAN, including both User Equipment (UE) functions and base station functions. The application of cloud native and SBA concepts to the RAN will allow the speedy provision of highly customized network slices tailored to specific services, outgrowing the 5G view of predefined eMBB, URLLC, mMTC and V2X slices, towards a system where a high number of customized network slices coexist over a shared resource pool. The definition of service-based interfaces, which can be easily consumed by other RAN services, beyond what exists in O-RAN today, is essential to enable customizations of the air interface, both in the user and the control planes, reducing the need for standardization and speeding up the time to market for new features.

The Core Network in 6G is expected to evolve towards a unified core that extends the 5GC in two main directions. First, the unified 6G core should incorporate additional network domains such as the transport network, including the NTN segment, new access technologies, and additional administrative network domains (network-of-networks). Second, the unified 6G core will smooth the boundary between the network and the application domains, which will both be based on cloud native services, thus allowing the spin of application-specific core networks on demand.

Figure 3-2 depicts a high-level diagram of the envisioned 6G Intelligent Open Network, where all RAN, Core, Transport and Application Components are instantiated as cloud native functions distributed across different multi-stakeholder resource domains, with an inter-cloud service bus component allowing communication between microservices in different resource domains. Network and application functions are colored according to the service they support, and an end-to-end data layer is used to gather the necessary telemetry, logs and traces that enables the necessary AI/ML cognitive management.

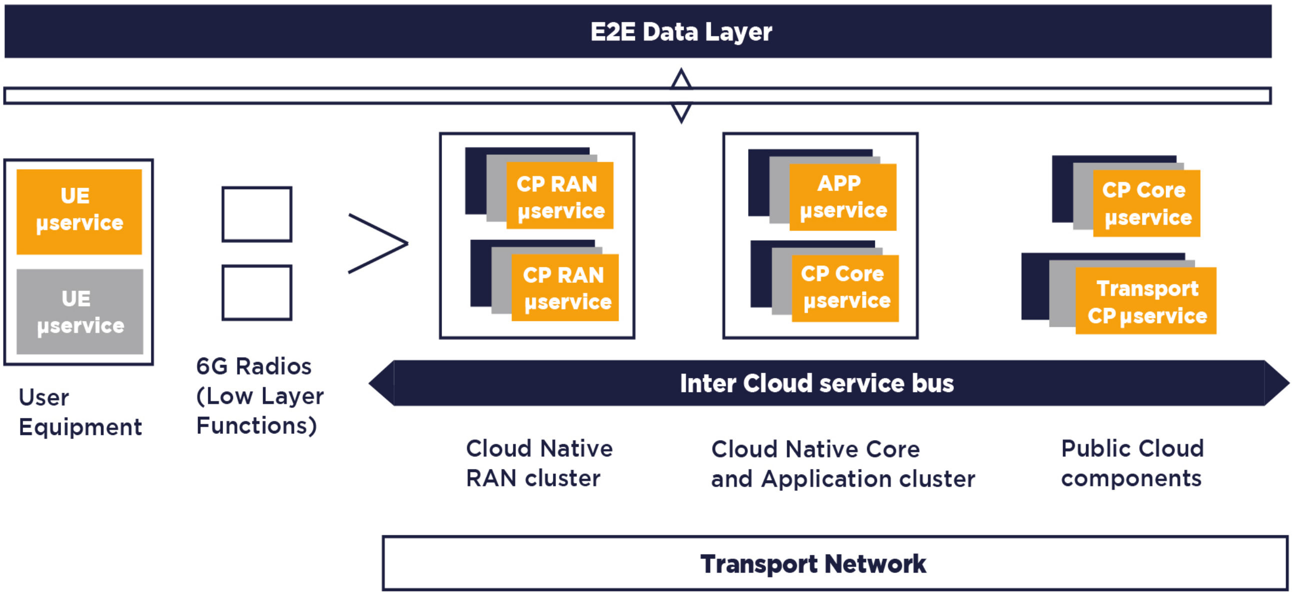

Figure 3-2. 6G Intelligent Open Network concept.

Several research challenges need to be addressed to bring the 6G Intelligent Open Network concept to reality. First, the monolithic virtual RAN (vRAN) implementations used in 5G networks need to be rearchitected to embrace cloud native principles and to allow easy composition of customized RAN interfaces. Second, AI/ML powered autonomous software agents that can discover and consume intent-based APIs offered by other system services need to be designed to realize the concept of the unified 6G core, and to optimize the use of spectrum, by brokering negotiations and SLA enforcements across mobile network stakeholders.

Given its previous work in 5G-PPP, i2CAT is well positioned to contribute to the design of the 6G Intelligent Open Network concept. In the 5G-CLARITY project, i2CAT contributed to the design of an Intent Engine, which allows a private network operator to provision network slices using a natural language-based interface [9]. In Affordable5G i2CAT developed an ORAN non-real time Radio Intelligent Controller (RIC) manager that allows the discovery and management of xAPPs from multiple vendors in a homogeneous way [10]. In the project 5GZORRO, i2CAT led the definition and demonstration of a blockchainbased spectrum sharing use case [5].

NON-TERRESTRIAL NETWORKS (NTN)

The vision of the Non-Terrestrial Networks (NTN) in the 6G architecture is to augment the terrestrial network with aircraft and spacecraft systems, to support current terrestrial infrastructure and to provide additional services. Specifically, this network is composed of satellites orbiting in different altitudes (i.e., in LEO, MEO, and/or GEO), High-Altitude Platforms (HAP) and Unmanned Aerial Vehicles (UAV) that are interconnected in a 3D multi-layered network (Figure 3-3). The relevance of this network segment is undoubtedly gaining momentum in the evolution towards 6G as a complement to terrestrial wireless, providing ubiquitous access, offloading capabilities to edge devices, and providing alternative routing paths, among other advantages.

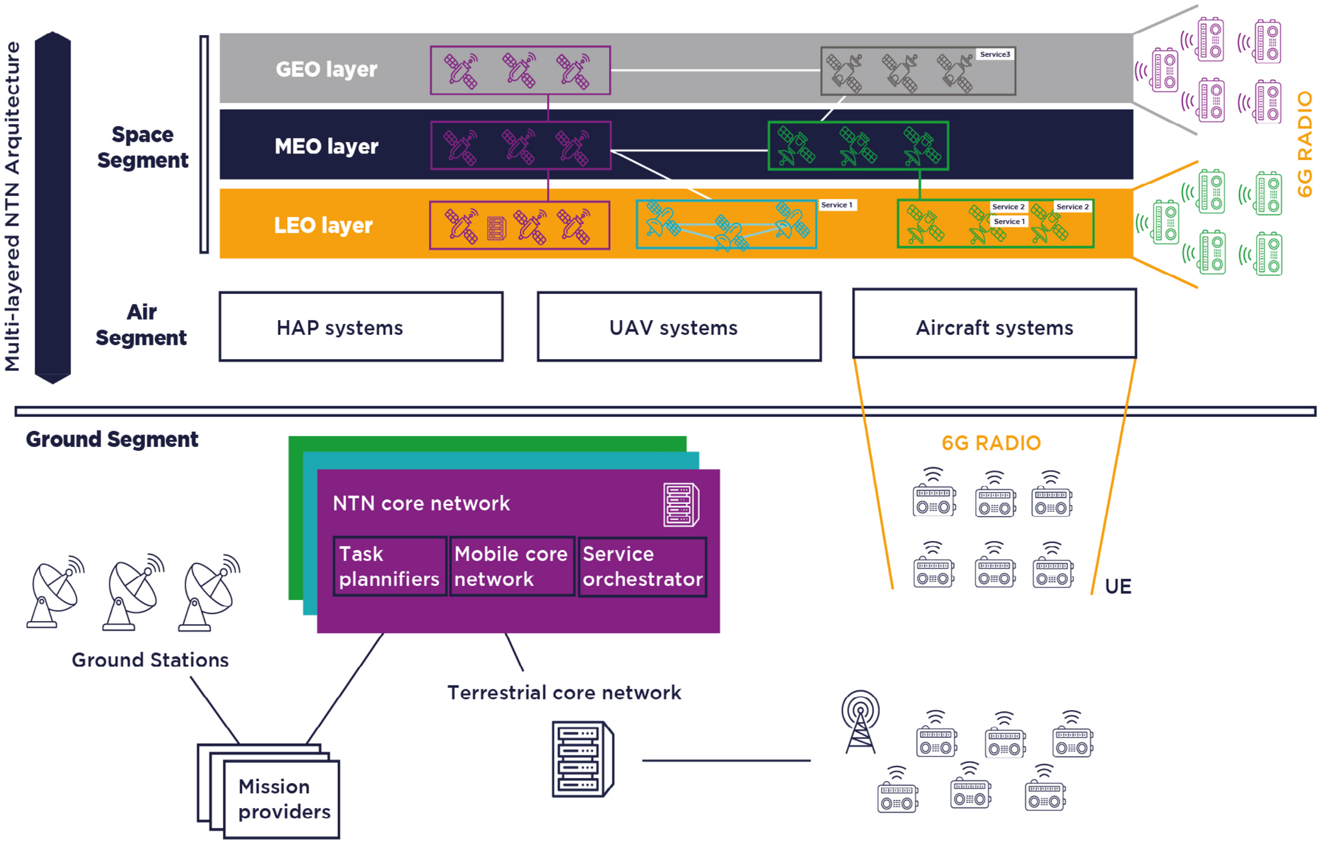

Figure 3-3. Representation of 6G NTN architectures and their challenges.

The NTN architecture is characterized by a group of features that are relevant to delivering 6G services. The large coverage area of spaceborne and high-altitude telecommunications systems enhances service continuity, in case it is not being ensured by terrestrial infrastructure. Furthermore, this coverage boosts the network capacity by serving a myriad of end-users with a single satellite spot. Finally, the orbit trajectory of a satellite allows service ubiquity to be reached across the entire globe, being able to provide services in remote and typically inaccessible areas. Despite these features, NTNs are characterized by being a temporary network, in which links between systems are established and lost over time, remaining stable during lapses of time.

The integration of NTNs with the terrestrial infrastructure opens significant research challenges. First, the enhancement of current 5G core networks to manage the dynamic non-terrestrial infrastructure poses novel challenges, such as intermittent connectivity, and temporal unavailability of the network, among others. Second, the orchestration of space networks as an integral part of the 6G system following the Function-as-a-Service paradigm and using mechanisms to converge non-terrestrial and terrestrial networks. Third, the management of different services in a highly distributed scenario calls for proper service provisioning techniques in order to provide service assurance. To this end, dynamic network slicing and resource allocation are key functionalities to be deployed across the end-to-end network. Fourth, the interaction of heterogeneous systems in the NTN poses challenges in terms of optimal data routing approaches. This novel mechanism must address challenges like heterogeneous communication technologies, heterogeneous system capacities, network disruption and fragmentation, and standardization processes. Among these challenges, AI/ML is a key transversal technology that can be applied in each domain, such as routing approaches, by providing predictive capabilities to support it.

i2CAT is well positioned to contribute to the design of NTN and their integration in the future 6G architecture given its previous work in the Sat5G project, where it integrated communication satellite operations into 5G by defining optimal satellite-based backhaul and traffic offloading solutions [11]. Furthermore, i2CAT is participating in the development of a 5G core network that integrates satellite platforms with NarrowBand-IoT sensors [12]. Additionally, i2CAT is deploying sensors over the Catalan region that connects with a 3U CubeSat to retrieve data from the territory, such as soil moisture, and humidity, among others [13].

1. Smart surfaces

Meta-surfaces are comprised of a few layers of planar structures that can be built using lithography or nano-printing (light and low-cost electronics) suitable for seamless integration into walls, ceilings, etc.

Smart surfaces are particularly attractive due to their passive nature and seamless integration into walls, ceilings or building glass. They can be used to reduce the number of base stations needed in future 6G deployments (particularly in highly crowded, difficult to reach and/or sensitive areas) and their corresponding energy consumption.

Reconfigurable Intelligent Surfaces (RIS) apply controllable transformations into impinging radio waves:

- RISs for enhancing signal reception (constructive combination)
- RISs for privacy/security to avoid signal leaking (destructive combination)

Figure 3-4. Illustration of a RIS-enabled smart factory deployment.

A major challenge for the successful integration of smart surfaces in 6G systems is the complexity of their dynamic configuration.

In order to be fully effective, RIS need to be reprogrammable at very fast time scales (milliseconds or less) and in coordination with traditional RAN tasks such as power control or radio scheduling.

To date, however, smart surfaces have been tested in isolated environments for specific applications (e.g., secure communications, non-orthogonal multiple access, or over-the-air-computation) without considering coordination with related NFV network functions.

Future 6G deployments will have to consider RIS as an integral element of their automated systems operations.

2. Integrated Sensing and Communications

Integrated Sensing and Communications (ISAC) systems are a paradigm change where the previously competing sensing and communication operations can be jointly optimized via the shared use of a single hardware platform and a joint signal processing framework.

As society evolves towards a deeper digitalization, integrated sensing and communications solutions will become vital in 6G systems, given the unique capabilities it has for acquiring information needed for mission-critical systems such as autonomous driving, emergency services, industry 4.0, e-health, smart cities, etc.

Wireless sensing can:

- Detect movements of humans and objects that modify the wireless signal propagation (e.g., reflection, diffraction and scattering)
- Provide detailed information of the motion and object for digital twin purposes by analyzing the received wireless signal

Figure 3-5. Illustration of a dynamic human skeleton reconstruction by an ISAC system.

Most research has focused so far on dedicated wireless systems, since low-level access to communications information is needed, but very difficult to obtain from already deployed commercial devices. Integrated sensing and communication systems need to be designed for cost-efficiency and sustainability reasons. ML-based approaches might be used to improve ISAC sensing services and address previously considered intractable problems.

i2CAT is well suited to address these challenges given its extensive expertise in those areas, as demonstrated by early research on the properties of smart surfaces [14][15] and in the integrated sensing and communications domain [16][17].

The mega technology trends of 6G such as Open Networks, pervasive AI, and the integration of exponential numbers of connected machines or robots in the communication fabric, present new security threats (Figure 3-6) [18] not considered in previous generations of networks. Open networks, combined with the proliferation of open source softwares and virtualization technologies alone, pose a multi-faceted security challenge. The pervasive use of AI for the purpose of automation and optimization for multiple heterogeneous objectives across all layers in next generation communication, poses a major security challenge for 6G. The boom in data analytics applied to user information for various purposes in open networks raises critical privacy and trust concerns for next generation networks. Furthermore, the perceived availability of Quantum computing in 6G jeopardizes the security of cryptographic algorithms used in Public Key Cryptography, which is a prevalent approach in several security mechanisms of current communication networks.

With such security challenges ahead for 6G, we foresee that 6G security architecture should not only be holistic by design including use of secure disruptive technologies, such as AI and Distributed Ledger Technologies (DLT), but should also consider embedded trust and privacy considerations throughout the communication networks. The 6G security architecture presents the following research challenges:

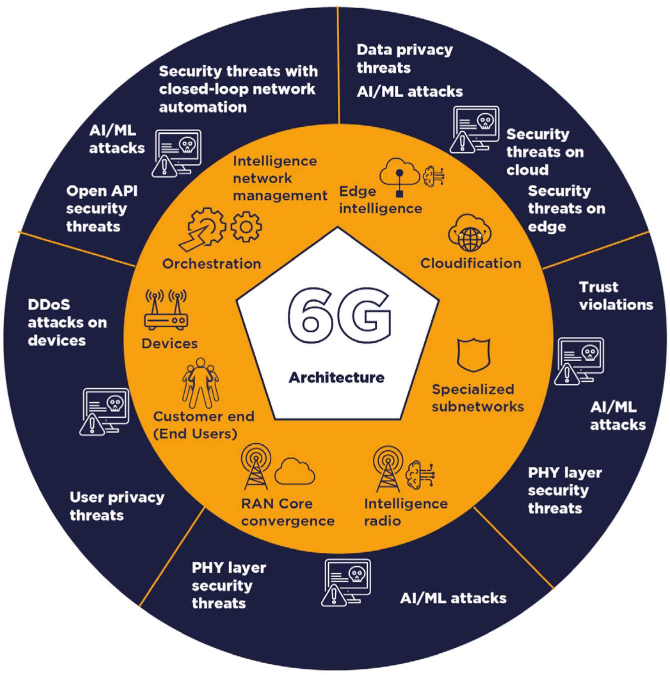

Figure 3-6. 6G security threat landscape.

Trustworthy networks: The exponential increase of security threats foreseen across 6G networks will require networks to be intrinsically trustworthy. That is, the 6G networks should enable embedded and programmable trust that continuously assesses the trustworthiness between network entities and resource, protocol procedures and access policies. One such potential approach is the zero-touch security concept that considers no existing trust inside the communication network thus enforcing dynamic trust establishment as required. Therefore, the Trust modeling, trust policies and trust mechanisms for 6G should consider the zero-touch concept as one of its core principles.

Privacy preservation: The use of big data analysis on a mass scale to drive behaviors, i.e, the Internet of Behavior (IoB), requires extra massive data capture mechanisms posing new security challenges for next generation 6G technologies. For example, tracking services that map behavioral data at scale, impacts directly on citizens' privacy. By 2025, half the world's population is expected to be subject to an IoB commercial or government program. This exponential increase in the demand for data has made data protection and privacy preservation an active research topic, especially for the storage and use of personal data. That is to ensure that the de-identified data sets do not reveal any information leading to identification of the data. For the secure storage and access, the 6G security mechanisms can take advantage of the trust execution environment (TEE) and established authentication and authorization mechanisms. Data anonymization techniques using homomorphic encryption is another way to preserve the privacy of the personal information, while allowing data to be processed.

Secure and trustworthy AI: 5G envisioned the potential of AI being used for automating the detection and mitigation of attacks in the communication networks. However, AI was also used by the attackers to launch more sophisticated attacks. Furthermore, adversarial machine learning (AML) i.e., poisoning of data or modification of AI/ML algorithms to compromise the systems/networks, shadows the gains offered by AI/ML. Therefore, 6G security architecture should consider the use of robust AI/ML in reliable systems by use of digital signatures ensuring use of correct AI/ML techniques and data.

From the several 6G security topics discussed above, i2CAT foresees the following as the main research challenges: the trust management for the wide area across multiple trust domains; software and AI defined security in beyond 5G and 6G; 5G privacy preservation approaches offered to 6G systems; and the development of frameworks to understand the trade-offs between privacy and trust in 6G systems.

i2CAT is well positioned to contribute to the design of the 6G security vision, given its past and current research work. i2CAT is leading the design and development of automated security management and orchestration, addressing continuous detection and mitigation of attacks in 5G networks [5]. i2CAT is also leading the use of AI for enhancing the prediction capabilities for potential threat impact and resilience against sophisticated attacks [6] [19]. i2CAT is also heavily involved in the design and development of privacy toolkits and in-transition data protection focusing on personal data [20]. Furthermore, i2CAT has been involved in the development of particular QKD interfaces, enabling use of QKD for new applications and services [21].

04

i2CAT'S 6G ASSETS AND ECOSYSTEM

5G ASSETS AND SPIN-OFF

Thanks to its wide experience in 5G-PPP projects, i2CAT has developed several technologies to successfully bring research and innovation to the society and the market, with special focus on 5G and its whole ecosystem.

Between 2015 and 2019 i2CAT researchers developed a multi-tenant service and network management platform with Service Level Agreement (SLA) guarantees for 5G private and neutral infrastructures.

These technologies became the seed for our first 5G spin-off Neutroon, constituted in July 2020 and with focus on private networks. Neutroon [22], with i2CAT support, is growing the technology to empower the industry transformation with the adoption of 5G networks.

neutroon

Neutroon offers a management and orchestration software, focusing on a vendor agnostic approach, for heterogeneous and multi-vendor 5G, LTE & Wi-Fi infrastructures. Neutroon's platform is able to provide agile deployment of services on top of such infrastructure. It features hard slicing, being able to isolate physical resources in the RAN, Transport and Compute domains, while providing integrated management of 5G services.

This spin off is just one of the multiple initiatives that i2CAT does to maximize the social and economic impact of the excellent work achieved in research projects.

HOLOPORTATION RESEARCH

The maturity of immersive and interactive technologies, together with the pandemic, have fueled the development of Social Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) platforms. These enable users to meet, immersed or not, in 3D environments, to develop a certain task, such as learning and training, design and engineering, entertaining, etc. These platforms aim to go far beyond the typical mosaic of upper body video representations in video-conferencing platforms. In this context, the promise of social VR is to provide higher levels of realism, immersion and interaction, and steer collaboration through higher levels of (co)presence while overcoming the current limitations of 2D user representations in multi-party conferencing scenarios.

The latest volumetric video (VV) capture developments already enable the recreation of volumetric photo-realistic replicas of humans, which can in turn be inserted in such collaborative 3D environments. Furthemore, we have known for many years [23] that using volumetric photo-realistic representations in immersive environments generate higher levels of Quality of the Interaction (QoI) than CGI-based avatars. Despite that, the current and most known examples of social XR platforms, such as Mozilla Hubs, Facebook Spaces/Horizon or AltspaceVR/Microsoft Mesh, still rely on the use of synthetic avatars (i.e., CGI-generated) to represent the participant users. This is mainly due to the complexity, computational effort and infrastructure requirements needed to achieve higher levels of user representation realism.

As part of its research activities, from its leadership in the VR-Together [24], i2CAT has co-developed HoloMIT (Figure 4-1), an end-to-end system for holoconferencing [25], which allows multiple users to see and interact with each other while immersed in virtual environments; the so-called metaverses. This type of technology will steer new business cases in the near future. As examples of the potential use of this technology, figure 4-2 shows how holoconferencing may serve the cultural sector, enabling remote and gamified visits to museums, while figure 4-3 shows how architectural, design and decoration decisions may be made without the need of a physical deployment, reducing the cost while offering the option for a fast redesign of spaces.

One of the limitations observed in the current social VR solutions, for those using CGI avatars, and also in HoloMIT, is to allow a high number of participating users per session when the canvas in which the users are displayed is not a rectangular video frame anymore (limited by its size and resolution), but a dynamic 3D environment. Thus, i2CAT is already dedicating efforts to solve this problem, in particular designing a VR Multipoint Control Unit (MCU) [26], which will bring the optimizations that videoconferencing MCUs perform in the 2D domain to the 3D domain through a set of key features like fusion of multiple volumetric videos, adjustment of the Level of Detail (LoD) of the participants in the Field of View (FoV) according to their position and distance, and removal of non-visible data, that does not need to be transmitted if it is not finally rendered in any destination.

Figure 4-1. Holoconference among i2CAT members presented during the final review of the VR-Together project where four volumetric users and two remotly located webcam users meet together in a 3D virtual meeting room.

Figure 4-2. Two users exploring together a 3D replica of the Biblioteca Museu Víctor Balaguer.

Figure 4-3. A user exploring different hotel room designs in Interihotel 21, an interior design fair.

6G R&D INFRASTRUCTURE

Through its involvement in the 5G-PPP framework, and its rich local ecosystem, i2CAT has developed a set of 5G and beyond experimental facilities that provide an excellent background to validate future 6G technologies. Figure 4-4 depicts an urban mobility test-bed deployed in Barcelona that features 5G connectivity as well as distributed compute resources deployed across edge data centers, streetlamps and street-cabinets, which represent an excellent arena to validate future 6G deep edge and cloud continuum orchestration mechanisms, as well as future 6G services such as social XR.

Figure 4-4. Urban cloud continuum testbed.

Targeting rural scenarios, i2CAT also deployed a rural 5G testbed in Mora d'Ebre (south of Catalonia), which includes 5G connectivity at both 700 MHz and 3.5 GHz, and edge computing resources supported by mm-wave backhaul links. This testbed provides an excellent resource to validate the ubiquitous connectivity concepts envisioned in 6G, including the integration of terrestrial and satellite networks.

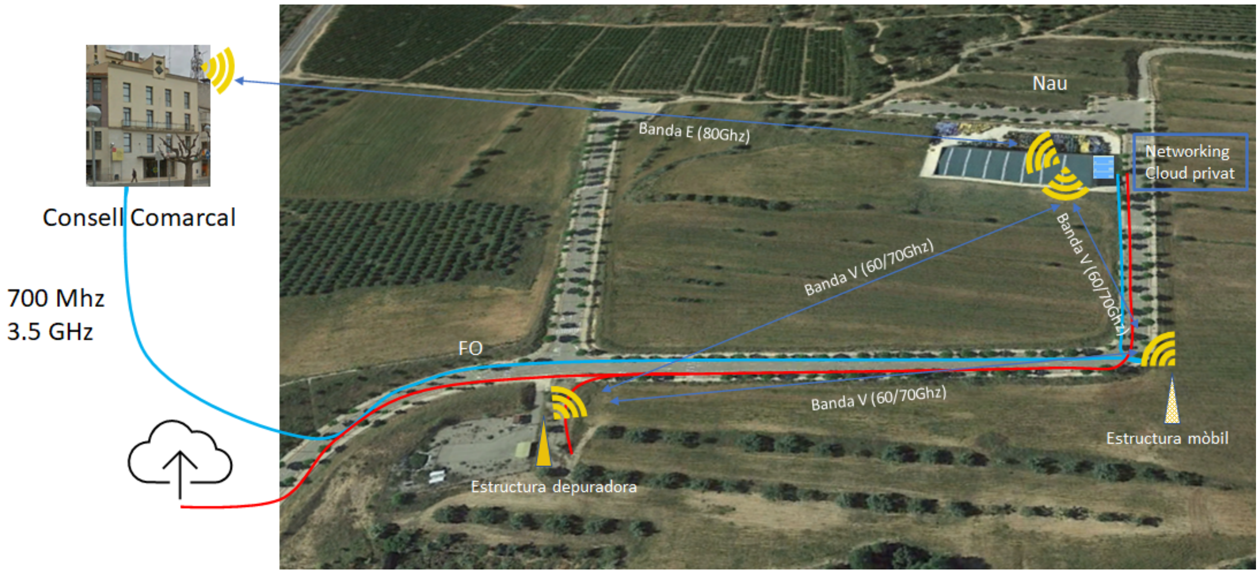

Figure 4-5. Rural 5G testbed.

In addition to the previous testbed facilities, i2CAT continues to expand its testbed footprint with a new 5G node in Barcelona, collocated with the UPC campus, deployed within the Open-VERSO project [27].

In addition to the previous 5G testbeds, as part of the development program in NewSpace activities, i2CAT is currently working in the deployment of different CubeSat missions. These nano-satellite platforms are suitable to deploy in-orbit technology demonstrators and proof-of-concepts. The execution of these missions will enable the demonstration of research developments in the Non-Terrestrial Network (NTN) domain. Specifically, technologies to enable direct-to-satellite IoT, enhancements of core networks for satellite systems, resource allocation and service distribution among satellite constellations, and routing protocols to deploy heterogeneous satellite networks, are the activities planned to demonstrate in these CubeSat missions. These missions are executed as part of the NewSpace strategy of the Catalan Government [28].

To support these missions, it is necessary to have an operational, development and testing ground infrastructure. Therefore, i2CAT has a collaboration agreement with the UPC NanoSat Lab [29] to share infrastructure and use it in different activities. This infrastructure is composed of (1) an ISO-7 cleanroom, (2) a thermal vacuum chamber, (3) a vibration table, and (4) Helmholtz Coil System. Additionally, a S-band and UHF/VHF ground stations (located in the Montsec mountain) are available for these missions. These ground stations are also managed by the IEEC institution [30].

ECOSYSTEM

i2CAT, as a mission-driven research foundation, is a perfect fit for connecting the elements of the beyond 5G & 6G ecosystem. i2CAT has been working closely with the industry, R&D ecosystem, administration, and economic fabric on the development of 5G. Now it is in a great position to facilitate and lead the relationships on the beyond 5G & 6G challenge.

i2CAT has demonstrated its strong commitment to the 5G and beyond 5G research through its participation in 16 5G-PPP projects that will also ground the i2CAT 6G research:

- Phase I: 5G-XHaul (with i2CAT as Technical Manager), CHARISMA (with i2CAT as Project Coordinator), SESAME, SONATA
- Phase II: 5GCity (with i2CAT as Project Coordinator), 5GESSENCE, 5GPicture (with i2CAT as WP leader), SAT5G

- Phase III: 5GZORRO (with i2CAT as Project Coordinator), 5GVictori, 5G-CLARITY (with i2CAT as Technical Manager), 5GCroCo, 5GMED (with i2CAT as Technical Manager), Affordable5G, Smart5Grid, AI@EDGE

i2CAT has been walking alongside industry leaders in the innovation field, working together in competitive and private projects. We have already collaborated with well-known companies through research programs such as those mentioned previously, and also with start-ups that dynamize the ecosystem, such as SatelIoT [31] and Neutroon [22]. We have collaboration agreements, through our board of trustees, with the principal operators in Spain: Vodafone, Orange and Telefónica; with infrastructure operators like Cellnex; and top communication companies such as Fujitsu, Cisco and Juniper, among others. We also have a strong relationship with the state and local administration, through consolidated work with the local government in Catalonia, who we helped in developing their 5G strategy [32], and also with the initiative 5GBarcelona [33] and its members, of which we are partners.

We will continue to work with the ecosystem to define and develop the 5G & 6G, making a difference and bringing the best in research and innovation to society.

05 CONCLUSIONS

It is now time to think about why we need 6G and what it will look like.

The digital and physical worlds are being melded together, and 6G will be a necessary booster for such the virtualization of the physical world, and the physicalization of the digital world.

i2CAT has been very active in the 5G Public Private Partnership (5G-PPP) of the European Horizon 2020 Work Program, participating in 16 research projects, being Project Coordinator in three of them and Technical Manager in a further three projects.

We plan to keep up with 6G under the Smart Networks and Services Joint Undertaking (SNS-JU) within the Horizon Europe R&I program. We have ambitious expansion plans, and we expect to conduct them along with all key stakeholders in the European and worldwide ecosystem.

i2CAT contributes to different areas that we believe are key to making this happen:

- Disruptive Wireless Connectivity
- Reconfigurable Intelligent Surfaces and Wireless Sensing
- Accurate Positioning
- Vehicle to Anything Communications
- Intelligent Open Networks
- Cybersecurity
- Artificial Intelligence
- Non-Terrestrial Networks for 3D Connectivity
- Immersive Technologies
- Digital Social Technologies

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i2CAT Foundation is a CERCA research and innovation center based in Barcelona, spezialized in advanced digital technologies. Since 2003, i2CAT has been committed to designing and building the future digital society by leveraging the knowledge gained from cutting-edge European and local R&D projects in 5G, IoT, VR and Immersive Technologies, Cybersecurity, Blockchain, AI, New Space, and technologies for the Digital Society. The center applies this knowledge in partnership with companies, public administration, academia, and end-users to meet social and business challenges.

The Internet Research Center Barcelona

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