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MARIE SKŁODOWSKA-CURIE ACTIONS

Doctoral Networks (DN)
Call: HORIZON-MSCA-DN-2022

PART B

SpecX

Doctoral Network on
Spectrum Analytics as a Service

This proposal is to be evaluated as:

[DN]

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List of participating organisations

Consortium Member	Short Name	Academic	Non-academic	Awards Doctoral Degrees	Country	Dept./Division / Laboratory	Scientist-in-Charge	Role of Associated Partners
Beneficiaries								
1. IMDEA Networks	[IMDEA]	✓			Spain	Research Department	Domenico Giustiniano	
2. KU Leuven	[KU Leuven]	✓		✓	Belgium	Dept. of Electrical Engineering	Sofie Pollin	
3. Delft University of Technology	[TU Delft]	✓		✓	Netherlands	Department of Software Technology	Qing Wang	
4. Consorzio Nazionale Interuniversitario per le Telecomunicazioni	[CNIT]	✓			Italy	Research Department	Paolo Casari	
5. RWTH Aachen University	[RWTH]	✓		✓	Germany	Mobile Communications and Computing Group	Marina Petrova	
6. Telefonica I+D	[TID]		✓		Spain	TID Research	Andra Lutu	
Associated Partners								
1. NEC Laboratories	[NEC]		✓		Germany	NEC Laboratories Europe	Andres Garcia-Saavedra	Specialised training & hosting secondments
2. Ericsson GmbH	[Ericsson]		✓		Germany	Ericsson Research	Andra Mihaela Voicu	Specialised training & hosting secondments
3. ElectroSense	[ESense]		✓		Switzerland	Research Division	Vincent Lenders	Specialised training & hosting secondments
4. Accelleran	[ACC]		✓		Belgium	Research and Development	Trevor Moore	Specialised training & hosting secondments
5. University Carlos III of Madrid	[UC3M]	✓		✓	Spain	Department of Telematics Engineering	Pablo Serrano	Specialised training & hosting secondments
6. University of Tor Vergata	[UNITV]	✓		✓	Italy	Department of Electronic Engineering	Corrado Di Natale	Specialised training
7. University of Trento	[UNITN]	✓		✓	Italy	Dept. of Information Engineering and Computer Science	Elisa Ricci	Specialised training
8. University at Albany	[AlbanyU]	✓			USA	Department of Computer Science	Mariya Zheleva	Specialised training & Hosting secondments
9. St. Louis University	[SLU]	✓			USA	Department of Computer Science	Flavio Esposito	Hosting secondments

Data for non-academic beneficiaries:

Name	Location of research premises (city / country)	Type of R&D activities	No. of full-time employees	No. of employees in R&D	Web site	Annual turnover[1] (in Euro)	Enterprise status	SME status
Telefonica I+D	Barcelona, Spain	Research	451	256	http://www.tid.es	86.7M	Yes	No

[1] Defined as the total value of sales of goods and services during the last accounting period.

List of SpecX acronyms and abbreviations

2G	Second Generation Mobile network	**JU**	Joint Undertaking
3G	Third Generation Mobile network	**KPI**	Key Performance Index
3GPP	Third Generation Partnership Project	**LICT**	Leuven Centre on Information and Communication Technology
4G	Fourth Generation mobile network	**LPWAN**	Low-Power Wide-Area Network
5G	Fifth Generation mobile network	**LTE**	Long Term Evolution
6G	Sixth Generation mobile network	**MCAA**	Marie Curie Alumni Association
AI	Artificial Intelligence	**MIMO**	Multiple Input Multiple Output
AoA	Angle of Arrival	**ML**	Machine Learning
AR	Augmented Reality	**MSC**	Marie Skłodowska-Curie
BS	Base Station	**MSCA**	Marie Skłodowska-Curie Actions
CBRS	Citizens Broadband Radio Service	**MST**	Management Support Team
COST	European Cooperation in Science and Technology	**NDA**	Non-Disclosure Agreement
COTS	Commercial Off-The-Shelf	**NWE**	Network-Wide Event
CS	Compressive Sensing	**OFDM**	Orthogonal Frequency-Division Multiplexing
CSI	Channel State Information	**PCDP**	Personal Career Development Plan
DAB	Digital Audio Broadcasting	**PM**	Project Manager
DARPA	Defense Advanced Research Projects Agency	**PPP**	Public-Private Partnership
DC	Doctoral Candidate	**PSD**	Power Spectral Density
DCG	Domain Coordination Group	**PU**	Primary User
DESCA	Development of a Simplified Consortium Agreement	**QoS**	Quality of Service
DGC	Doctoral Guidance Committee	**RAN**	Radio Access Network
DMP	Data Management Plan	**RC**	Recruitment Committee
DN	Doctoral Network	**R&D**	Research and Development
DPO	Data Protection Officer	**RDF**	Research Development Framework
DSS	Dynamic Spectrum Sharing	**RE**	Recruitment Event
EC	European Commission	**ReC**	Researcher Council
ECTS	European Credit Transfer System	**REA**	Research Executive Agency
EM	Electro Magnetic	**RF**	Radio Frequency
EMI	Electromagnetic Interference	**RRI**	Responsible Research and Innovation
ETN	European Training Network	**RTDE**	Research, Test, Development and Evaluation
EU	European Union	**SAIFE**	Spectrum Anomaly Detector with Interpretable FEatures
GC	General Coordinator	**SB**	Supervisory Board
GDP	Gross Domestic Product	**SDR**	Software Defined Radio
GDPR	General Data Protection Regulation	**SC**	Scientific Coordinator
gNB	next generation Node B	**SW**	Software
GNSS	Global Navigation Satellite System	**TCCC**	Technical Committee on Computer Communications
GPS	Global Positioning System	**TDoA**	Time Difference on Arrival
GSM	Global System for Mobile Communications	**TRL**	Technology Readiness Level
HR	Human Resources	**TSB**	Technical Steering Board
HW	Hardware	**TSC**	Technical Steering Committee
ICT	Information and Communication Technology	**TX**	Transmitter
IETF	Internet Engineering Task Force	**URLLC**	Ultra-Reliable Low-Latency communication
IP	Intellectual Property	**VR**	Virtual Reality
IPR	Intellectual Property Rights	**WIA**	Wireless Infrastructure Association
IQ	In-phase and Quadrature phase	**WP**	Work Package
ISM	Industrial, Scientific and Medical	**WRC**	Women Researchers Council

1. Excellence

1.1 *Quality and pertinence of the project's research and innovation objectives*

1.1.1 Introduction, objectives, and overview of the research programme

The value of the 5G market will enable $13.2 trillion of global economic output in 2035, and the 5G industry is investing an average of $235 billion annually to allow the continuous expansion and strengthen the 5G technology base[2,3]. Besides, the Internet of Things (IoT) industry, which is in an era of rapid proliferation, expects to have a total potential economic impact of up to $12.6 trillion a year by 2030. In such a context, the ***radio frequency part of the electromagnetic (EM) spectrum*** is a precious and limited resource, essential for wireless communications and the upkeep of economic growth. However, the exponential increase in the demand for broadband wireless communication services is stressing the availability of spectrum to accommodate new services and applications. On the other hand, the ***growth of the EU's telecommunication market is decelerating,*** and further growth critically depends on spectrum availability and its efficient usage[4]. Recently, the NSF in United States has announced a 25 million investment over five years, to build a spectrum innovation centre to "catalyse innovation and support workforce development to solve radio *spectrum challenges* that are critical to the nation"[5]. Also, in the EU, we need to build innovation potential and workforces on the interplay between spectrum and infrastructure for new growth markets. Consequently, this is the right moment to take a step forward, *sensing, monitoring, and processing spectrum* with innovative techniques and tools, and make a significant impact on the future 6G technologies market. To this end, **SpecX provides the required experience and effort to train a workforce of 10 Doctoral Candidates (DCs) in spectrum challenges at the frontier of 6G networks**, to:

Pillar 1: Measure the EM spectrum massively, dynamically and in 3D. Although EM spectrum data collection at a massive scale faces important infrastructure, technical and research challenges. For instance, collecting 2M IQ samples per second over just 2 MHz band with crowdsourced IoT sensors would result in a data rate of 128 Mb/s to upload this data for processing in the core network. As reference, the new proposed broadband definition in US by the FCC for uplink data rate is set to 20 Mb/s. There are key technical opportunities in future 6G networks that can be exploited to tame the spectrum data deluge. Spectrum sensing benefits largely from Software Defined Radio (SDR) technology, which is reconfigurable in nature and will become a critical asset for future network deployments. Edge computing, distributed algorithms, spatial correlation, feature extraction, as well as 3D spectrum sensing, exploiting the crowd, 5G and beyond infrastructure, and Open-RAN (O-RAN) edge, all drive towards the opportunity of designing a scalable, spectrum monitoring infrastructure critically relying on edge computing and distributed big data processing.

Pillar 2: Turning the wireless data deluge challenge in new applications and innovative use of spectrum for future networks. To efficiently understand the EM Spectrum, SpecX proposes to add Artificial Intelligence (AI) capabilities and other more traditional spectrum analysis methods to create insights in spectrum use, detecting anomalies to dynamically scale and orchestrate network resources as the number of devices increase (e.g. massive IoT), localizing non-cooperative mobile transmitters to better allocate resources and 3D predictive coverage mapping by means of aerial base stations. As an example, both telecom operators and non-telecom services using the spectrum (e.g., radio-astronomy, standard frequency and time signals, radars, telemetry, aeronautical radio-navigation, radio beacons, and others), could benefit from the interference and coexistence assessment by SpecX data analytics, the detection of incumbent transmitters on their bands, their emission footprints and localization, out-of-band emissions detection, opportunities for spectrum sharing and collaborative dynamic access of spectrum and achieve mission-critical wireless communication for Industry 4.0. Adding embedded AI capabilities to the radio access and edge networks relieves the communication to the core network due to the local computation and the fact that only pre-processed data, rather than raw data, are computed in the core network.

Pillar 3: Tackling the talent shortage in the EU's spectrum big data market. Dedicated skills are needed to dive into the unexplored big data spectrum, but they are missing. For example, the Wireless Infrastructure Association[6] recently reported a significant skill gap in the telecommunication market, asking for critical training on, first, RF principles and fundamentals and, second, spectrum aspects (allocation, policy, and impact of re-farming). Other critical aspects that face a skill gap are the introduction of small cells and the understanding of connectivity for the IoT. The European Commission sets ambitious goals to increase innovation and competition in the wireless domain by promoting spectrum access *flexibility* (e.g., dynamic spectrum access), but this assumes a sufficient understanding of the opportunities of the spectrum usage. From the cyber-security point of view, it is important

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[2] https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/iot-value-set-to-accelerate-through-2030-where-and-how-to-capture-it
[3] https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/the_ihs_5g_economy_-_2019.pdf
[4] SpectrumX, https://www.strategyand.pwc.com/media/file/Grasping-at-differentiated-straws-v2.pdf
[5] https://www.nsf.gov/news/news_summ.jsp?cntn_id=303454
[6] https://wia.org/wp-content/uploads/WIA_5G_Training-finalweb3.pdf

to monitor the spectrum and protect it from attacks whose aim is to destabilize the communications in a country and negatively impact its economic opportunities. The latter is really a countries' concern when critical communications are compromised not only for aviation or GNSS, but even for the 5G and beyond network, for instance, for ultra-low latency applications such as remote surgery and autonomous cars networks.

In short, the overarching objective of SpecX is to provide high-level training to 10 Doctoral Candidates (DCs) in large-scale spectrum measurement, analysis, and applications in future telecom infrastructure. The goal is to create a research and innovation workforce with transferable skills in radio hardware, cellular network infrastructure, edge computing, data collection, signal processing, deep learning and Artificial Intelligence, data tools to assess, improve and analyse big spectrum data and provide innovative services. This goal will be achieved by a unique combination of hands-on research training designed to provide to the DCs the needed fundamental elements to conduct the research programme, for collecting real spectrum data, analysing it, and developing innovative methods, and create insights and invent new valuable applications. Hands-on in depth-training will be strengthened with non-academic placements, as well as multi-disciplinary, intersectoral, and international cooperation to maximize the employability of DCs and the impact of the project.

Integration and contribution of individual projects in the SpecX research programme. To achieve the SpecX overarching objective and implement and execute the 3 pillars of the project, we have designed 10 DCs projects. The specific science/technology (S/T) objectives (**Obj1**-**Obj10**) are summarized in **Table 1**, with each DC contributing to at least one S/T objective of the overall project. The output from each DC project corresponds to a component in the architectural design presented in **Figure 1**, that also shows the interaction and complementarity of each DC project. SpecX is the first EU research and doctoral training program that aims to build a complete system for spectrum analytics by exploiting sensing, edge computing, machine learning and spectrum analysis for a diverse and innovative spectrum use applications. The proposed conceptual architecture and network components are based on the separation between Radio Access Network (RAN)/O-RAN, edge network and core network in current 5G architectural deployments, further leveraging Service Based Architecture to virtualize the network services over the available physical resources and facilitate links between DC projects.

Table 11. SpecX specific S/T objectives (measurable and verifiable targets shown in **Section 3** and **Table 13**)

WP	Specific Objectives
WP1: Sensing and infrastructure	**Obj1.** To improve the embedded spectrum analysis performed in sensing devices (**Obj1a**, **DC1**), and to design a scalable embedded federated learning framework for spectrum analysis that can run on a few mobile aerial sensors or 1000s connected terrestrial sensors that all have computing constraints (**Obj1b**, **DC1**). **Obj2.** To explore how spectrum sensing techniques can help edge to improve service quality, i.e., anomaly detection, orchestration (**Obj2a, DC2, DC3**), minimize interference, and investigate how edge platforms can help spectrum sensing measurements and services, such as run spectrum sharing auctions/allocations across users (**Obj2b**, **DC2**). **Obj3.** To propose a sensing-based radio access architecture that is capable of identifying spectral and spatial resources at the required time scale and dynamics for 6G applications by interfacing radio access infrastructure to a spectrum-monitoring infrastructure at optimised cost and complexity (**Obj3a**, **DC3**). Compare various radio access infrastructures (O-RAN, 5G core network, Wi-Fi-based) and impact on sensing performance (**Obj3b**, **DC1, DC3**).
WP2: Data Analysis	**Obj4.** To incorporate expert feedback (human-in-the-loop) to a semi-supervised learning framework to improve the state-of-the-art algorithms for anomaly detection (**Obj4a**, **DC4, DC6**). To investigate solutions for adding spectrum sensing and anomaly detection in the O-RAN edge (**Obj4b**, **DC4**). **Obj5.** To build a framework for localizing transmitters at any frequency that do not collaborate for the purpose of localization, only exploiting the waveform structure of transmitters (**Obj5a**, **DC5**) and perform analytics to infer pattern movements of several mobile transmitters (**Obj5b**, **DC5**). **Obj6.** To explore and design new algorithms for building efficient and reliable measurement-based mobile coverage and performance maps (accurately building real-time Radio-Environmental Maps) for 6G network performance optimizations by leveraging the data collected from the terrestrial and aerial nodes (**Obj6a**, **DC6**). Compare predictive 3D methods with real-world data (**Obj6b**, **DC1, DC6**).
WP3: Network applications	**Obj7.** To investigate solutions for orchestration or network resources based on anomaly detection and spectrum sensing (**Obj7a**, **DC4, DC7**). To propose scalable sensing and access frameworks for the massive Internet of Things (**Obj7b**, **DC1, DC9**). **Obj8.** To exploiting mobile cells to satisfy the high and dynamic demands on the wireless capacity (**Obj8a**, **DC8**). To integrate drones for sensing as well as access in converged aerial-terrestrial networks (**Obj8b**, **DC1, DC8**). **Obj9.** To develop electrosmog sensing and forecasting techniques for dense deployments, including smart cities (**Obj9a**, **DC9**). To understand the fundamental limits of sensing with embedded sensors (**Obj9b**, **DC1, DC9**). **Obj10.** To identify the possible risks and threats of using wireless connections for safety-critical applications in Industry 4.0 and develop a systematic approach on how to react on a possible anomaly in the used spectrum for a safety-critical wireless connection (**Obj10a**, **DC4, DC10**). To test the approach in applications such as collaborative robots and autonomous guided vehicles and drones (**Obj10b**, **DC8, DC10**).

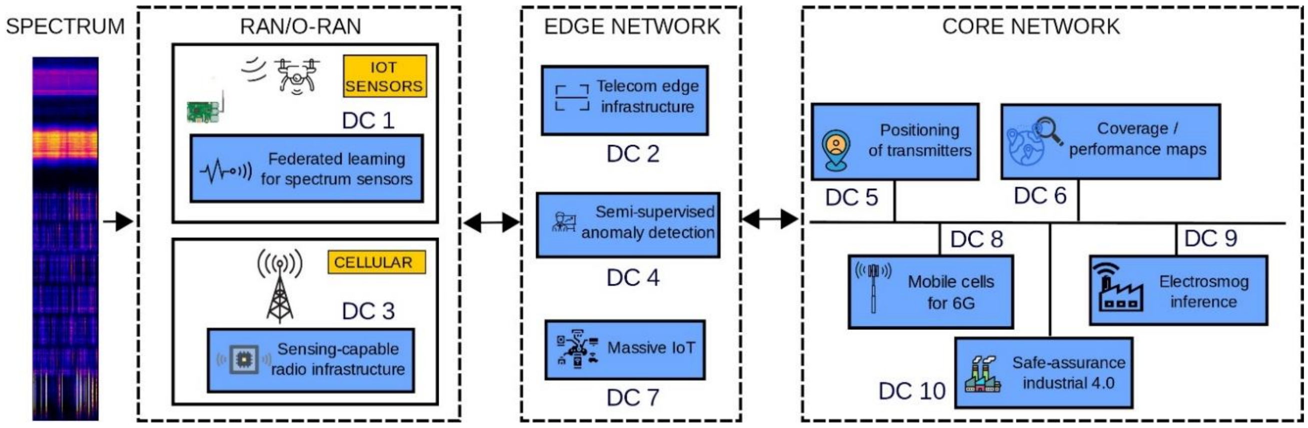

Figure 1. Overview of SpecX's research work and conceptual architecture for their inter-connections.

For instance, standard publish/subscribe interfaces can be implemented to provide location of transmitters as input of electrosmog interference service. It jointly addresses both the fundamental challenges of spectrum sensing and infrastructure, spectrum big data analysis and the application-driven problems, and it facilitates the adoption of solutions designed by each DC. Furthermore, it guides coherent elaboration on implementation and integration of different types of research activities.

The overall implementation work of SpecX is organized in 6 WPs and the 10 DC projects are organised in three research work packages: **WP1**: sensing and infrastructure, **WP2**: data analysis, and **WP3**: applications. SpecX improves physical sensing of the spectrum using distributed signal processing, federated learning and scalable infrastructure in WP1 and derives spectrum insights in WP2. Exploiting the know-how from WP1 and WP2, SpecX targets a range of future application areas of spectrum analytics in WP3. The project participants of SpecX (IMDEA, KU Leuven, RWTH, TU Delft and CNIT) are leading the effort of instrumenting testbed designs for spectrum sensing. This provides unique know-how, prototyping expertise, and testbed facilities to SpecX (as shown in **Figure 2**), allowing application-specific spectrum sensing to be evaluated using wireless sensed data. SpecX combines and strengthens Europe's skills and knowledge base through an intersectoral and interdisciplinary cluster of excellence: SpecX beneficiaries and associated partners are leading members of large EU initiatives, and comprise major telecommunication manufacturers (e.g., Ericsson, NEC), legacy and private operators (e.g., Telefonica), new hardware/system integrators (e.g., ACC), and spectrum analysis experts and stakeholder (ESense, and SpectrumX, AlbanyU, and SLU through USA partners). Necessary S/T skills as well as soft skill to conduct the research in WP1-3 will be acquired through a dedicated program with interdisciplinary training (WP4) and entrepreneurial skills (WP5). Individual S/T skills will further be learnt through research at host institution and secondments at both academic and non-academic partners. The overall management and coordination of the project will guarantee high employability of DCs and high impact of project outputs (WP6).

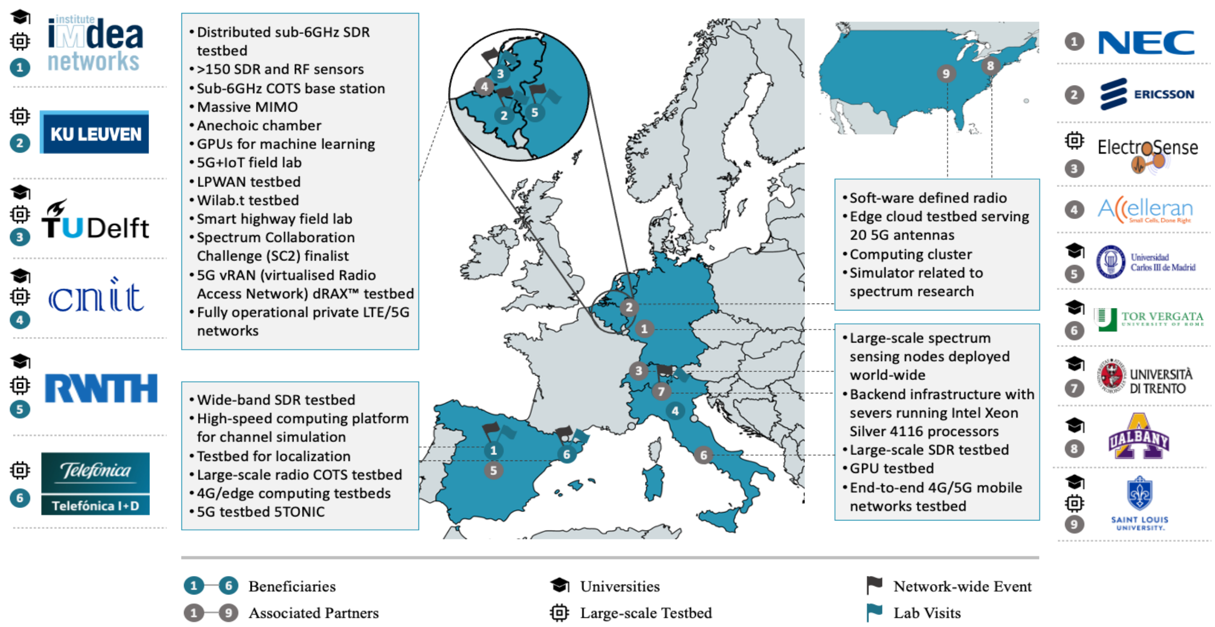

Figure 2. SpecX consortium: an overview of the six beneficiaries and eight associated partners from seven different EU countries and the USA. The infographic highlights the large-scale facilities that allow network-wide measurements with more than 200 nodes and the available hardware.

1.1.2 Pertinence and innovative aspects of the research programme

Traditionally, governmental agencies and international organizations are responsible for regulating, allocating, optimising, and monitoring the usage of the radio EM spectrum. Today's spectrum measurements are mainly performed by the government and telecommunication companies which use expensive and bulky equipment scheduling very specific spectrum campaigns limited in space and time. These approaches are targeting the well-known mobile broadband application for traditional - often frequency division duplex - types of spectrum use. However, traditional ossified spectrum surveys cannot cope with the exponential increase in the number of devices and smaller cell sizes of 5G and future newer generations of wireless networks, given the number of locations that would be needed and the amount of data that would be generated to monitor all bands (licensed and unlicensed) at all locations and time. A *new spectrum monitoring paradigm is needed to sense EM waves for all bands and space locations*, and provide information beyond simple coverage for a single technology or strength maps for a single frequency band. Given the importance of spectrum, several large players or research consortia have attempted to create spectrum monitoring solutions, such as Microsoft's Spectrum Observatory[7], the City-Scape Spectrum Observatory from University of Washington or the Electrosense Initiative in Europe[8] (partner of SpecX), or RadioHound[9] All these solutions, however, face spectrum data deluge, require large investments in deployments to enable a scalable spectrum monitoring density in space, time, and frequency, and fail to give spectrum data insights to stakeholders beyond coverage information.

The roll-out of 5G is starting now in the EU, reusing 4G bands with small cells or other novel 5G access technology such as Massive MIMO, and opening up also new bands in higher frequency bands such as 3.5 GHz. Each of those technologies will result in a more spatial focus of the communication: Massive MIMO, small cells or higher frequency bands. In parallel, novel use cases and types of operators emerge in the context of Industry 4.0 or other scenarios where private networks operate. To manage the coexistence of those local cells and local private networks, operators and users will critically depend on dynamic and predictive spectrum analytics rather than traditional spectrum surveys. These problems have constrained the full deployment of advanced applications. Closing these gaps in terms of spectrum availability and optimization will be essential for achieving the potential of 5G and beyond networks, and to enable new services with a high economic and societal value[10].

Related research projects: The EU has supported different spectrum-related projects where the SpecX beneficiaries were involved in, such as FARAMIR, CREW, Flex5Gware, LOCUS and ORCA, have studied the basic challenges of spectrum sensing and flexible spectrum use, often with a focus on flexible architectures and physical layer techniques. One of the two ambitious Horizon 2020 prizes was awarded in the domain of collaborative spectrum sharing, where the EU aimed to support an innovative and disruptive approach that could enable a significant increase in spectrum sharing and re-use. Other EU MSCA actions typically target network rather than spectrum data analytics. For example, the RISE action DAWN4IoE focuses on network usage and traffic to help network planning, whereas the ITN-EID ACT5G exploits network usage analytics for anticipatory networking and optimization. *SpecX complements these programs by offering a spectrum data rather than a network data point of view*. In fact, this unique vantage point makes it possible to optimize network deployments, configurations, and usage, while also enable new applications. Closer in scope to SpecX, there are also initiatives in the USA, such as DARPA Spectrum challenge and Colosseum[11]. Although instrumental to prove the feasibility of flexible spectrum use, these projects did not venture much into the analysis of spectrum use beyond radio environment or occupancy maps. More recently, SpectrumX in the USA has been awarded 25M$ to build a spectrum innovation centre to "solve radio spectrum challenges that are critical to the nation".

SpecX contains six WPs, including three research WPs (**WPs 1-3**), with clear objectives (**Obj1**-**Obj10**), milestones (**mX.Y**), deliverables (**DX.Y**) and delivery dates, as well as packages related to Training (**WP4**), Dissemination (**WP5**) and Management (**WP6**). In the following paragraphs, we provide a general overview of the S/T WPs. A more detailed S/T description is given in **Section 3**.

SpecX leverages the aforementioned initiatives in EU (where SpecX partners had an active role) and it is inspired by ongoing initiatives in USA. By pooling the resources of the leading manufacturers, network operators, spectrum use organizations and research institutions and universities, SpecX goes beyond spectrum use mapping, and targets disruptive spectrum applications relying on automated, location-aware, accurate and reliable spectrum analytics. This implies devising rich and distributed spectrum *analysis solutions* which can be tailored to the specific requirements of each use case and *implementing* them in the various testbeds available at the project

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[7] http://spectrum-observatory.cloudapp.net
[8] http://electrosense.org [Bold references are own work of the researchers of the SpecX consortium]
[9] https://wireless.nd.edu/research/radiohound-distributed-spectrum-sensing/
[10] European Commission, "Digital Economy and Society Index (DESI)", 2022.
[11] https://www.rfglobalnet.com/doc/northeastern-to-design-the-wireless-networks-of-the-future-0001

beneficiaries. Building the sensing and localization capabilities in future cellular systems provides an unprecedented level of environmental awareness, enhanced by spectrum sensing capabilities in low-cost sensors deployed by everybody at various locations. In itself, this will pave the way towards a new line of spectrum data products and applications, as well as autonomous network control solutions to improve network resilience. The sensing analytics technology will have a tremendous socio-economic impact, as one of the spectrum analytic outcomes is the feasibility of dynamic spectrum sharing, most cost-effective sections of spectrum might be allocated to mobile communications. This will materialize through the advances in mobile network performance, capabilities, reduced cost for operators, and will enable innovation opportunities to develop new services and applications. This will further enable the creation of new spectrum access business models and eco-systems. Finally, the technology will influence society through improvements in manufacturing, transportation, communication, healthcare, and all application innovations it will enable.

Table 2 provides a detailed overview of the scientific progress beyond the state-of-the-art and the research objectives for each of the research paths explored in SpecX for overcoming the identified scientific gaps. Prior experience of SpecX's project partners presents solid foundations for fulfilling the three missions of the project (see **Section 1.1.1**) and is detailed in **Table 2**. At a high level, project partners have been at the frontier of research in the domain of modulation classification[12], anomaly detection[13], transmitter localisation[14]. It is expected that future systems will make more use of technologies that are not ground-based, such as drones used as base stations to provide temporary coverage or capacity extensions[15]. Another example is satellites providing coverage to underserved areas or emergency communications in remote areas. SpecX partners were among the first to measure LTE performance in the sky[16] or design solutions for sensing up to the stratosphere[17]. With the introduction of non-terrestrial networking, another dimension is added to the network planning and anomaly detection problems.

Table 22. State of the art and progress beyond state of the art in SpecX.

	State of the art	Progress beyond state of the art and expected innovation
Project	No spectrum analytics framework exists. Despite the scarcity and importance of the wireless spectrum, **no scalable, large scale spectrum monitoring solution exists.** Most projects focused on physical layer 2D coverage maps, whereas upper layers and feature analysis were studied much less.	**Enabling spectrum analysis for a wide range of future mobile applications (Industry 4.0, 6G, Aerial Networks, Massive Internet of Things)** by developing scalable sensing and telecom edge computing techniques to support application-specific requirements and considering the **edge computing** and **AI** paradigms.
WP1	Existing deep learning works on technology classification, and anomaly detection required **labelled dataset**[18], which is often not available or difficult to acquire. Further, training of deep learning models is executed **centrally** on powerful platforms. Modern infrastructures are equipped with dedicated machine learning processors. This concept, which involves end devices in the process, is termed as **Federated learning**[19].	Perform model training for federated technology classification and anomaly detection 1) with limited labelled data and 2) at the device level with an interplay with the edge in the learning process. Build solutions for federated technology classification and anomaly detection with semi-supervision from the cloud and application experts. A framework that can scale to extreme resource constrained aerial sensors. (**Obj1**)
	Policies for sensor data transmission have focused mainly on optimizing data collection for machine learning model training[20]. Existing edge infrastructures are agnostic with respect to spectrum sensing information in their operations, and **only rely on traditional metrics** such as the number of users, network latency, and service requirement. Also, existing **spectrum sensing infrastructures do not leverage edge** infrastructures to improve spectrum sensing information[21].	Investigate adaptive **policies for the use of edge to favour spectrum data processing and learning**. Design **data-driven policies** that change the **behaviour of the system** based on **spectrum usage events**. Identify and modify the **operational elements of edge infrastructures** that could benefit from the availability of spectrum sensing data to improve quality of service provided to users. **Enhance spectrum sensing techniques** by leveraging the location and computing capabilities of edge infrastructures. (**Obj2**)
	In the literature, different sensing techniques and database approaches have been proposed in the context of cognitive radio and recently in LSA and CBRS deployments[22]. However, these are **quasi-static and slow**, and cannot sustain a seamless operation across licensed and unlicensed bands for many applications in 5G and beyond network deployments[23].	Identify available spectrum resources and potential harmful interference in a **dynamic and agile fashion** across different bands. We aim at designing such functionality in the future RAN (gNBs/APs), exploring both **data-driven and predictive dynamic spectrum allocation and sharing policies**, using sensing data for timely and proactive decision making. (**Obj3**)

[12] **E. Perenda, et al. "Learning the unknown: Improving modulation classification performance in unseen scenarios."** ***IEEE INFOCOM*, 2021.**
[13] **S. Rajendran, et al. "Crowdsourced Wireless Spectrum Anomaly Detection."** ***IEEE Trans. Cognitive Communications and Networking***, **2020.**
[14] **H. Sallouha, et al. "Aerial Vehicles Tracking Using Noncoherent Crowdsourced Wireless Networks."** ***IEEE Trans. Vehicular Technology***, **2021.**
[15] **Deruyck M, et al. "Designing UAV-aided emergency networks for large-scale disaster scenarios." EURASIP J. Wireless Comm. & Net., 2018.**
[16] **B. Bergh, et al. "LTE in the sky: trading off propagation benefits with interference costs for aerial nodes."** ***IEEE Comm. Magazine***, **2016.**
[17] **B. Reynders, et al. "SkySense: terrestrial & aerial spectrum use analysed using lightweight sensing with weather balloons."** ***MobiSys*, 2020.**
[18] T. O'Shea, et al. "Over-the-air deep learning based radio signal classification." *IEEE Journal of Selected Topics in Signal Processing*, 2018.
[19] K. Bonawitz, et al. "Towards federated learning at scale: System design." *Machine Learning and Systems (MLSys)*, 2019.
[20] Y. Roh, et al. "A Survey on Data Collection for Machine Learning: A Big Data - AI Integration Perspective." *IEEE TKDE*, 2021.
[21] **S. Rajendran, et al. "Electrosense: Open and Big Spectrum Data."** ***IEEE Communications Magazine*, 2018.**
[22] R. Tehrani, et al. "Licensed spectrum sharing schemes for mobile operators: A survey and outlook." *IEEE Communications Survey and Tutorials*, 2016.
[23] M. Hoyhtya, et al. "Database-assisted spectrum prediction in 5G networks and beyond." *IEEE Circuits & Systems M*, 2019.

WP2	Existing state-of-the-art anomaly detection frameworks are not specifically optimized for the spectrum sensing domain. SAIFE already introduced a semi-supervised anomaly detection framework with interpretable features and expert feedback[24], but this scheme is still working with synthetic anomalies and has not been verified on **real application data, expert feedback and application-specific anomalies.**	**Interpretable deep learning for spectrum sensing** is, in general, not yet existing in the state-of-the-art. Design a deep learning framework that allows a large number of interpretable features (power, location, frequency, and modulation type) presented to the expert user as features of a detected anomaly. The anomaly detection framework will be **trained by expert feedback,** as well through **automated analysis of network outage events**. (**Obj4**)
	Existing algorithms on localising signal transmitters at any frequency make use of **expensive and bulky hardware** to accurately localize the transmitter. This limits the deployment of the systems to ad-hoc deployment in small and outdoor[25] or are affected by large positioning error[26]. Besides, there is limited effort to estimate the location of emitters completely passively (e.g. without its cooperation).	Distributed IoT and non-coherent sensors will be synchronized **not using GPS but opportunistically using signals** of the environment (LTE, DAB, Mode-S). Study TDoA-based, Doppler-based AoA-based methods that work without cooperating emitters as enablers of signal transmitter localization using non-coherent radio frequency receivers. Infer **pattern movements** with estimated position of multiple devices (**Obj5**)
	Cellular **coverage maps using field measurements** of signal strength currently integrates two components: (i) sampling strategy design, which involves defining a method for collecting a representative and unbiased set of measurements; and (ii) a predicting value at unobserved locations based on the collected measurements. These techniques are technology-dependent and limited in data size.	Leverage the data collected from spectrum sensing infrastructures (e.g., ESense infrastructures) and crowdsource apps and introduce **algorithms to efficiently predict mobile network performance**. Work closely with operators in SpecX to process data on the expected coverage of the radio network. Work towards building novel **anomaly detection approaches and alerting** the radio planning team about potential suboptimal configurations. (**Obj6**)
WP3	Future networks are inherently very flexible and resources can be allocated dynamically based on spectrum insights. Current approaches for **software-defined networking are mainly based on wired networks, and do not extend well to wireless networks**, although we have proposed a vision towards this[27]. Thinking further to the massive wireless Internet of Things, we need scalable and **specific orchestration frameworks**, e.g., as we considered for BLE[28].	Employ multi-band spectrum data to infer the status of distributed massive Internet of Things deployments, including overuse, communication issues, and anomalies. Orchestrate the deployment of status inference functions across the network, in a way to optimize computational resource usage intensity, promote fair energy consumption, and alternate optimally between spectrum sensing and spectrum usage. (**Obj7**)
	Emerging 5G and beyond systems are characterized by multi-tier networks, high heterogeneity, and density of devices, which are making necessary innovative spectrum sharing and interference management solutions[29]. However, there is still a general **lack of practical implementation of 3D spectrum sharing**, mainly because of over-reliance on 2D coverage planning, and the lack of predictive 3D spectrum use models[30]. Spectrum sharing in mobile networks have been limited to the self-band assigned to a certain operator for bandwidth split between services.	Design **advanced 3D spectrum access rules** to be easily programmed and executed on aerial wireless nodes, for testing in real deployment of collaborative mechanisms for increasing the level of autonomy of ground-air coexisting systems. **Exploit the movement of BSs** (mobile cells) to satisfy the high and dynamic demand on wireless capacity. Study how to provide pervasive and reliable 5G+ service **without overprovisioning** the number of fixed-location BSs (**Obj8**). Exploit spectrum insights from scalable light-weight anomaly detection and technology classification (**Obj1**) towards **dynamic 3D spectrum sharing**.
	While lack of reliable information is one of the main drivers behind the public concern regarding 5G radiation, we see few solutions for massive, large scale electrosmog measurement. For exposure analysis, state-of-the art still critically relies on **bulky and expensive measurement approaches** that can only be done by measurement experts and in limited locations[31]. Furthermore, due to the complexity of its physical layer, measuring the exposure from 5G base stations is challenging[32].	We have shown that reliable measurements are possible with cheap SDR solutions[33], and will build fundamental limits on 3D sensing with such radios. **Measures to improve reliability and to perform radiation analysis of dynamic 5G networks and beyond will be investigated** (**Obj9**). By exploiting scalable and lightweight (3D) technology classification (**Obj1**), accurate sensing with lightweight sensors enhanced with collaborative spectrum insights, will be realised. For instance, uplink/downlink radiation will be separated through technology classification.
	In current Industry 4.0, wireless connections are mainly chosen based on their energy efficiency or data speed. However, without considering external spectrum anomalies either from intended or non-intended electromagnetic interference (EMI), **the safety and dependability of the wireless connections** will be **highly uncertain.** Some knowledge about EMI resilience for safety is already available[34].	**Spectrum anomaly detection, and the response methods,** will be a crucial component of **safety-critical systems** in **industry 4.0, autonomous systems, etc.** By using spectrum anomaly detection, the safety and dependability of wireless industry 4.0 networks will drastically increase. We will use multi-protocol sensors, cognitive networks, flexible OFDM, etc., to avoid interference between the spectrum anomaly and the wireless connection. (**Obj10**)

[24] S. Rajendran et al., SAIFE: Unsupervised Wireless Spectrum Anomaly Detection with Interpretable Features. *IEEE DySPAN*, 2018
[25] J. Schmitz, et. Al. Real-time indoor localization with TDOA and distributed software defined radio: demonstration abstract. *ACM/IEEE IPSN*, 2016.
[26] M. Khaledi, et. al. "Simultaneous power-based localization of transmitters for crowdsourced spectrum monitoring." *ACM MobiCom*, 2017.
[27] J. Santos, et al. "Breaking Down Network Slicing: Hierarchical Orchestration of End-to-End Networks." *IEEE Comm. Magazine*, 2020.
[28] Y. Murillo, et al. "SDN on BLE: Controlling Resource Constrained Mesh Networks." *IEEE ICC*, 2019.
[29] E. Hossain, et al. "Evolution toward 5G multi-tier cellular wireless networks: An interference management perspective." *IEEE TWC*, 2014.
[30] M. Akhtar, et al. "Synergistic spectrum sharing in 5G HetNets: A harmonized SDN-enabled approach." *IEEE Communications Magazine*, 2016.
[31] L. Chiaraviglio, et al. "Massive Measurements of 5G Exposure in a Town: Methodology and Results." *IEEE Open Journal of the Comm. Society*, 2021.
[32] S. Adda, et al. "A Theoretical & Experimental Investigation on the Measurement of EM Field Level Radiated by 5G Base Station." *IEEE Access*, 2020.
[33] Y. Ben-Aboud, et al. "Electro-Smog Monitoring Using Low-Cost Software-Defined Radio Dongles." *IEEE Access*, 2021.
[34] J. Waes, et al. "Resilience of Error Correction Codes against Harsh Electromagnetic Disturbances: Fault Mechanisms." *IEEE Trans. on EMC*, 2019.

1.2 *Soundness of the proposed methodology*

1.2.1 Overall methodology

SpecX's unique approach to hands-on research and training on spectrum and telecom infrastructure challenges hinges on building up a reference spectrum analysis infrastructure in Europe that can handle the deluge of spectrum data. The research methodology of SpecX is set up in the following way: i) the DCs will be exposed to training activities covering both the domain of the WP they primarily work on and the two complementary domains, resulting in a broad knowledge base across the three domains, which is the key for cross-domain collaborations. For instance, training on crowdsourced spectrum sensing will be applied to anomaly detection framework of spectrum data; ii) All research in the project will be related to common reference architecture (see **Figure 1**) and applications (see WP3) identified and used by all domains. For instance, exploitation of existing signals as references of opportunity for data processing will avoid actively transmitting signals in the scarce spectrum resources for the purpose of localization, which will be used as output for further network analysis by other DCs; iii) Selected technology components developed during the project will be integrated in one or more proof-of concept demonstrations spanning across the three domains. The setup will be challenged by feedback from leading infrastructure vendors (Ericsson, NEC) or new players (ACC), legacy operators (Telefonica). By cooperating with the USA partners (University at Albany and St Louis University), we ensure the European reference infrastructure is also globally relevant. In what follows, we describe the innovative aspects of the methodology in each of the three technical WPs.

WP1: Sensing and infrastructure [M7-M42]

Spectrum sensing results in massive amounts of data, several orders of magnitude more than what is generated by other types of IoT sensors such as temperature and humidity. The sensors acquiring this data are the first in line to process them and obtain the relevant features for further analysis. Ideally, the big data system is perfectly scalable which means that adding more sensors, allows more compression and richer feature computation[35], which means that the total amount of data scales gracefully with network density. More practically, coordination will be achieved, through distributed methods such as federated learning where algorithms are trained across multiple decentralised edge devices (**Obj1b**), or centrally (**Obj3**), where sensors get centralized information about common transmitters. Edge computing, where more and more data is analysed in the edge instead of in the cloud, is a hot topic of investigation for big data analysis. This is especially essential for spectrum sensing, as the amount of spectrum data is simply too large (a sensor working at 10M samples/s of 8 bit generates 7 Terabit per day) to be processed in a centralised fashion. The current approach in, e.g. Electrosense[8], is centralised data gathering and processing, but this does not scale to thousands of sensors. Tools are needed that allow reducing that Terabit/day to valuable spectrum insights generated locally at the sensor itself, or at the edge for a small group of sensors. SpecX will bring computing close to the sensors, improving response time, increasing scalability, reducing the hardware cost per sensor, and saving network bandwidth between sensors and backend. In this domain, Telecom providers can play a key role for the success of this technology, as they can provide the locations for deployment of edge devices and are currently in the phase of deploying them for next-generation mobile networks. This WP will then design edge analytics infrastructure that uses Telecom infrastructure (**Obj3**), by analysing the compute resources available and the size of the data flow from the sensor to cloud. Two different Telecom infrastructures will be considered by **DCs 2-3**, one consisting of the traditional view on the RAN and core network architecture (with Ericsson) and one focusing more on a disaggregated view (O-RAN with ACC), with the goal of generating insights for improved resource sharing (**Obj2**). Furthermore, **DC1** will explore and propose solutions on how to add local machine learning acceleration on the sensor itself. Our current models will be compared against federated learning methods, and the algorithms themselves will be trained to take local computing constraints into account (**Obj1**). **DC3** will then explore the case-study of interfacing radio access nodes of a Telecom infrastructure to a spectrum-monitoring infrastructure, to access and process spectrum data in advanced cellular network deployment under a controlled cost primarily with the goal of optimizing the capabilities to identify spectral and spatial resources dynamically at the required time scale for 6G applications (**Obj3**).

WP2: Data analysis [M7-M42]

SpecX introduces data insights that can be accessed by several emerging applications, some of which are explored in WP3. First, machine learning/deep learning algorithms are a core topic in SpecX, and WP2 will provide mechanisms to process data from the infrastructure. The accuracy of machine learning algorithms incorporating human-in-the-loop for the semi-supervised learning framework developed in WP1 will be studied for anomaly detection (**Obj4**). Second, WP2 will enable the capability of localizing wireless transmitters using low-cost IoT spectrum sensors. The work will challenge past work that considered unfeasible to reliably localize transmitters

[35] **Y. Zeng et al., "Adaptive Uplink Data Compression in Spectrum Crowdsensing Systems", IEEE Dyspan 2021.**

without a wired synchronization network system on low-cost spectrum sensors and will rather uses reference wireless signals available in the air. In turn, this will enable the opportunity to infer pattern movements of mobile devices transmitting at different frequencies (licensed and unlicensed), which is not possible with today's methods (**Obj5**). The third objective of the WP2 is to increase the availability in space and frequency of a measurement-based spectrum coverage database by leveraging the data collected from the spectrum sensors (**Obj6**). In order to fulfil these objectives, **DC4** will study how machine learning algorithms can be improved in terms of accuracy by adding a new input source knowledge based on expert feedback. **DC5** will design and implement a framework to localize signal transmissions emitted by any transmitters and extract temporal signal features computed on the edge and perform inference of location patterns. By last, **DC6** will go beyond traditional coverage maps that focus on a single spectrum band or technology and build reliable measurement-based mobile coverage maps spanning the whole spectrum using data extracted by multiple low-cost RF receivers. These real-world observations of the spectrum usage play an important role to understand the most efficient way to use the EM spectrum.

WP3: Network applications [M7-M42]

Spectrum knowledge will be the key enabler for the emerging disruptive technologies that not only demand very high QoS requirement in terms of spatial data rate (Gb/s/m^2) and latency (<5ms), but also operate in challenging environments with high 3D mobility and dynamics. This WP develops solutions to meet the requirement of four key applications: network orchestration for the massive Internet of Things, drone networks for Enhanced Mobile Broadband, reliability for Industry 4.0, and Electrosmog measurements for Smart Cities and societal awareness. Mobile broadband has been evolving from using low-frequency bands to high-frequency bands to meet with the increasing demands for wireless capacity. In the latest 5G standards, the frequency band is extended to 7.125 GHz[36]. Although 5G can provide a high data rate, it has several challenges: 1) non-line-of-sight links can significantly reduce the achieved data rate; 2) the cell radius of a 5G BS is only about 100-300 meters, which requires denser deployment than 4G. Furthermore, the cost of a 5G BS is 3 times of a 4G BS[37]. These are increasing investments in 5G infrastructure significantly. Meanwhile, the 5G spectrum license cost is exceptionally high. In addition, the demand for 5G service (such as AR/VR) changes dynamically in the time domain. This fact makes it wasteful to devote an ultra-high investment on an ultra-dense, geo- and spectrum-fixed 5G infrastructure, and extremely costly for a single operator to occupy a certain 5G frequency band in a particular area. With perfect spectrum knowledge of a particular area made available to multiple operators, BS could be instantiated dynamically and spectrum accessed by multiple operators in an optimized manner. In Industry 4.0 applications, such as collaborative robots and autonomous guided vehicles, safety is the greatest concern. The stability and dependability of a wireless connection depend strongly on the EM environment. Hence, measures need to be taken to ensure the dependability according to the intended EM environment. The spectrum knowledge can be used as a trigger to warn about the occurrence of a possible interferer and its location. Besides, realizing smart cities are demanding high-performance wireless connections and sensing where spectrum analytics plays an important role. In this WP, **DCs 7-10** will contribute to increasing the spectrum utilization efficiency in terms of Gb/s/m^2 bits/secs and resilience for 6G networks. **DC7** will optimize the management of available spectrum portions using anomaly detection for the massive Internet of Things (**Obj7**). **DC8** will exploit mobile cells to satisfy the high and dynamic demand on the wireless capacity to improve the coverage (**Obj8**). **DC9** will contribute to citizen science and smart cities by focusing on techniques to provide Electrosmog measurements and patterns using low-cost spectrum sensors (**Obj9**). **DC10** will work on securing the wireless connections in Industry 4.0. **DC10** will identify the possible risks and threats of using wireless connections for safety-critical applications in Industry 4.0, develop a systematic approach on how to react to a possible anomaly in the used spectrum for a safety-critical wireless connection, and finally, apply and test the developed approach in industry-oriented case studies (**Obj10**).

1.2.2 Integration of methods and disciplines to pursue the objectives

The SpecX approach is inherently multidisciplinary in nature: knowledge of signal and data processing, machine learning, wireless hardware design but also spectrum applications will be of integrated in a new wireless infrastructure that connects the research of DCs as presented in **Figure 1**, and builds a spectrum measurement reference facility in Europe, in cooperation with vendors, operators and other players. The scope is wide, as reflected in the topics of the three technical WPs and the different topics of the DC projects, spanning from spectrum sensing hardware to edge and cloud processing architectures; and also, from large scale spectrum measurements to telecom applications; going from advanced cybersecurity technology for anomaly detection to citizen science and Electrosmog; going from signal processing to AI; going from traditional ground-based infrastructures to aerial nodes. Each DC has a primary attachment to one of the technical WPs (WP1-3) according to its main research domain, but also has secondary associations which are developed during secondments to facilitate innovative

[36] In addition, mmWave bands between 24 GHz and 40 GHz will be in 5G networks.
[37] http://www.chinadaily.com.cn/a/201908/09/WS5d4d0d24a310cf3e35564d5a.html

methodologies required when considering a complex problem from different angles. Quality of the interaction is guaranteed by at least one secondment conducted at another organization actively contributing to the secondary WP. Real data will be measured in a real infrastructure, and true interaction between all the stakeholders is mandatory to achieve the target 10 S/T objectives and the overarching goal of SpecX.

1.2.3 Gender dimension and other diversity aspects

There are no gender issues regarding the content and use cases of the research in SpecX. The main reason is that the analysed activity in the spectrum are caused by radios, and the languages used by radios are defined in standards and protocols that are gender-neutral. By ensuring diverse teams surrounding all DCs, we ensure that there is a diverse view on the technology use cases. Furthermore, when designing future applications, an inclusive team is needed to ensure that the selected applications are of interest to all individuals. Hence, to achieve the best possible results, a diverse team will be constructed, with both female and male researchers, from different parts of the world. Finally, data from each country will have different properties, that relate to the deployment of telecom infrastructure, penetration of the technology in society, and overall usage patterns. We will make sure that the opinions of all individuals are incorporated into the research agenda. All partners further implement the above inclusive approach through comprehensive gender equality plans[38], that promote equality throughout all relevant steps of the work life, from hiring to payroll equality, promotion, roles, opportunities, and decisions. Besides, as part of SpecX's plan on Responsible Research & Innovation (RRI), soft-skill training 2 will cover *gender aspects*, aiming to eliminate discrimination based on gender and diversity, while providing participants with the knowledge and skills to ensure the effective implementation of gender equality.

1.2.4 Open science practice

SpecX will systematically share knowledge and tools as early and widely as possible in the process. *Open science* best practices with the academic community, such as open peer-review, making research papers early available, or sharing code publicly or even open-source, is already practised by the consortium and will be continued. With respect to spectrum analysis, the crowd-sourced initiative of the partner organization Electrosense will be involved, and through this network, yearly workshops, datathons and other co-creation activities will be established. Note that, through Electrosense, all gathered data is already shared with the public, and a lot of existing deep learning spectrum analysis tools are already made open source in this context. Through Electrosense, data is gathered via crowdsensing, which means that everybody can participate in gathering data. The methods for data gathering are also fully publicly documented. All software to analyse the code is also open-source. Datathons will be organised, fully open, where all researchers can take part in the design of new data analysis methods, and give input to the existing data monitoring tools. From the experience we have with Electrosense, this *open way of spectrum data gathering and analysis will be further developed.* By focusing on the electrosmog monitoring application, which is of interest to the broad public, *initial experience with social science* will be developed. By liasing with initiatives in the USA (one of the partner organizations, University of Albany, is part of SpectrumX in USA), we will also consider *reproducibility of spectrum analysis*, as methods and datasets can be compared across regions. With respect to *Open Access*, we will mainly benefit from Zenodo as the main repository of the project, where *all publications will be made open immediately after publication* in the green open-access form. For selected publications, top-tier open access journals or gold open access opportunities will also be leveraged. A wealth of preprint versions of all papers will also be posted on public websites and advertised on our social media, in order to obtain early feedback from peers and interested stakeholders. Together with Zenodo, other OpenAIRE-compliant repositories will be used by different partners to comply with their internal dissemination policies (e.g., the OpenAIRE-compliant DSpace at IMDEA, https://dspace.networks.imdea.org/ and Lirias repository at KU Leuven, https://lirias.kuleuven.be).

1.2.5 Research data management and management of other research outputs

The work of SpecX will be driven by experiments, testbed prototyping, and measurements. Therefore, a large number of labelled and unlabelled datasets, such as spectrum IQ samples, spectrum statistics, will be collected. In addition, SpecX data also includes the developed algorithms. In SpecX's datasets, we will ensure that the data collected will be anonymized and processed according to General Data Protection Regulation (GDPR) requirements and European Data Protection Supervisor (EDPS) recommendations. SpecX data management plan will be consulted with IMDEA's Data Protection Officer (DPO), Maria Cumbreras, in charge of discussing and communicating all the potential ethical issues of the work and the mitigations. Additionally, the chair of the ethics committee at IMDEA Networks will contribute to the supervision of the ethical aspects of the project. SpecX's data will be stored privately on the reliable and secure clouds that are widely used at the beneficiaries, such as KU Leuven's OneDrive, TU Delft's Surfdrive, and IMDEA's Box share system, for initial processing and formats

[38] E.g., https://www.cnit.it/2021/09/28/piano-per-la-parita-di-genere-cnit-gep/

unification, following the specifications that will be detailed in **D6.3** (Data Management Plan (DMP)) and updated during the project based on needs for extensions and/or corrections. We will use **standard formats** to store the data, such as CSV and MAT, making it **interoperable** for external users. The private clouds that will be used in SpecX have a few Terabytes of storage, which is more than enough for SpecX **data size**. Subsequently, SpecX's datasets will be made open source by storing them on IEEE DataPort free service or other similar ports, and linking them on SpecX's Zenodo repository to ease their **accessibility**. Taking into consideration the IP protection that will be defined in the consortium agreement, SpecX's algorithms will be made open access on Gitlab and GitHub for **reusability** and maximize the impact of research outputs. Moreover, we will use a fixed naming and versioning convention, and further ensure the datasets are discoverable by providing Digital Object Identifiers (DOIs) to make the data generated by the project **findable** and traceable. A Creative Common License scheme is adopted to reuse the data generated in the project. DCs are trained on data management locally by each doctoral school as well as in the SpecX network-wide event, NWE (Soft-skill training 5 in **Table 3)**.

1.2.6 Artificial Intelligence (if applicable to the proposal)

DCs 1, 4, and 7 use different artificial intelligence[39] to carry out their individual research projects. More specifically, DC1 exploits federated learning to design a scalable computing framework for spectrum analysis with sparse aerial sensors or dense terrestrial sensors. DC4 studies how to incorporate expert feedback into a semi-supervised learning framework for anomaly detection that could run on embedded devices. DC7 exploits various learning techniques to find the orchestration policies for computation task allocation. SpecX will devote efforts for designing **robust learning techniques** for different application scenarios. For example, the global model training and inference in federated learning with exiting aggregation strategies, such as FedAvg, are vulnerable to the data quality issues, latency of communication and heterogeneous data distributions across the devices, affecting the robustness of the learning. In SpecX, we will design a novel aggregation strategy that enables the central server to weigh the contributions of clients. Our framework can guide the global model learning to converge faster through the appropriate selection of gradient updates, which saves the communication cost but also improves the robustness of the learning model.

1.3 *Quality and innovative aspects of the training programme*

1.3.1 Overview and content structure of the doctoral training programme

Size of DN programme. SpecX provides unique system-oriented training to 10 DCs, nurturing a new generation of innovators thanks to internationally recognized researchers with broad experience in research, training, and participation in EU, national, and industry-sponsored projects. With the intensive involvement of industrial beneficiaries and associated partners (TID, NEC, Ericsson, NEC, ESense, ACC), the DCs will obtain in-depth knowledge and skills in spectrum sensing and its key emerging applications. This interdisciplinary and intersectoral training is an essential component of each DC's PhD. The 10 DCs (**Table 12**) are distributed over six beneficiaries in five countries (**Figure 2**, Spain: IMDEA and TID; Belgium: KU Leuven; Netherlands: TU Delft; Italy: CNIT; Germany: RWTH). Additionally, nine associated partners (four companies and five universities), represent six countries (Belgium: ACC; Germany: NEC (vendor), Ericsson (vendor); Italy: UNITN and UNITV; Switzerland: ESense; Spain: UC3M; USA: AlbanyU and SLU).

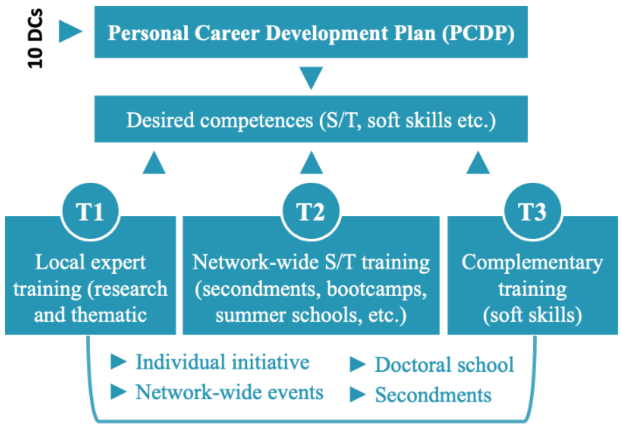

Figure 1. Schematic diagram of the training types.

A personalised training approach. The training block diagram is given in **Figure 3**. SpecX's personalised approach ensures that each DC is trained not only on SpecX's required competences, but also on her/his personal background and aspirations. The training programme consists of four elements: *(1) individual self-assessment*, conducted after recruitment by each DC under guidance of the Doctoral Guidance Committee (DGC, incl. supervisor and co-supervisors, see **Table 12**). This identifies skills, expertise, and competences that must be developed by each DC, both for successful completion of their research project and for their future professional career; *(2) Personal Career Development Plan (PCDP)*, formulated according to each individual self-assessment. The PCDP comprises each DC's training and career needs, incl. training on transferred skills, advising and teaching, planning for publications, and conference attendance. The DGC discusses the PCDP regularly, aligns the process with each local doctoral school, and adapts it if necessary. The PCDP also serves as a reference point for the training leaders

[39] https://ec.europa.eu/futurium/en/system/files/ged/ai_hleg_definition_of_ai_18_december_1.pdf

to monitor the training progress regularly; *3) tailored training programme*, developed by the DCs based on the PCDP and under the DGC's guidance. The training programme consists of: **(T1) expert training through research** in each DC's individual project and the collaborations with other DCs (cf. **Section 3.1.1**). **(T2) network-wide S/T training** (with ECTS credits) through workshops, summer school, and S/T secondments. All courses on S/T training give the DCs the needed fundamental elements to conduct the research programme. **(T3) complementary training** in generic and transferable skills, partly individual, partly through the host doctoral school, network-wide activities and secondments, following a comprehensive researcher development Framework (see **Figure 3** and **Table 5**). Finally, *(4) yearly progress assessment* of the research and training evolution, evaluated based on a proven, multi-level progress monitoring strategy (see **Table 14**).

(T1) Expert training through research (**Figure 3**). The research training has been described in **Section 1.1.1** and is discussed in detail on a per-DR basis in **Section 3.1.4**. Such research training in SpecX complies with the interdisciplinary training needs for professionals working in the ICT area. All individual projects have well-defined research topics and include soft-skill training. While DCs are funded for 36 months according to the DN requirement, most of the beneficiaries come from countries where the duration of PhD studies is above 36 months, e.g., 3+/4+ years in Spain/Belgium. SpecX's beneficiaries have committed to support the DCs for the additional period, through other national/international/industrial funds (except for CNIT, because the PhD studies in Italy last for three years), such as the internal funds C2 of KU Leuven, Dutch NWO short-term funds XS, etc.

(T2) Network-wide S/T training (**Figure 3**). SpecX's advanced network-wide S/T training builds upon the specific research expertise of participating partners to stimulate an interdisciplinary training environment. SpecX plans seven *workshops* (**Table 3**). Besides, SpecX organises a *Summer School* on the "Emerging paradigms for next-generation wireless networks and the enabled digital societies" (**M24**, Italy) and a dedicated *Symposium* on "Spectrum analytics as a service for future digital societies" (**M42**, Spain). Both events are organised with a strong intent to attract industry attendance and are all open to external participants.

Network-wide workshops. These workshops contribute to the training of DCs in multiple aspects: (1) DCs receive 11 S/T trainings given by experts, offering a genuinely *interdisciplinary programme*, including wireless networking (telecommunications), SDR prototyping (system engineering), machine learning (computer science), data protection (ethics/privacy), and standardisation (together with further topics such as technology integration, patenting, marketing, economics, and policy). In addition, 12 complementary trainings on soft skills integrate smoothly into the VITAE Research Development Framework (RDF, see **Table 3** and **Table 5** for details). These soft-skills trainings are provided by the experienced Doctoral Schools of the participating organisations and by experienced researchers. (2) DCs present their work on their individual projects: this provides opportunities for the DCs to communicate their research to interdisciplinary, intersectoral, and international internal (and external) participants. (3) DCs are highly involved in the workshops' organisation, to gain organisational and logistics experience. The S/T and the soft-skills training are open to external applicants. Besides, the meetings of the Supervisory Board (SB) and the WP teams are co-located with these workshops to reduce travelling overhead and carbon footprint. The typical programme of such network-wide workshops is available in **Table 4**.

Kick-off event/workshop. The kick-off meeting takes place in Madrid (**M8**), attended by the full consortium, including at least one representative per associated partner and all 10 DCs. The kick-off meeting will present the overarching goal of SpecX and organise a "SpecX-networking" session where DCs discuss their future visits with their secondment supervisor. The DCs will visit IMDEA's 5TONIC Lab, associated with S/T training *on "Trends in EU research for 5G+ networks"*, which provides the foundational knowledge to start their individual projects. In addition, DCs receive combined one-day training on "*Spectrum analytics as a service for future wireless networks*" and *"Prototyping and building up spectrum sensing testbeds*".

Summer school. In **M24**, SpecX organises the summer school "*Emerging paradigms for next-generation wireless networks and the digital societies*" in Trento (Italy). It consists of 15 lectures, each lasting 60 minutes, covering technical paradigms and trends from interdisciplinary ICT areas that can enable next-generation wireless networks, e.g., integration of terrestrial wireless and satellite communications, ultra-dense cellular networks, reconfigurable hardware, enhanced optical wireless interfaces, networked visible light communications, intelligent networking, enablers of fully immersive user experience, etc. The invited lecturers are experts in these fields, affiliated with SpecX's participating organisations and/or coming from other institutions. Besides the DCs, the summer school is open to interested PhD students, postdocs, and senior researchers, with a limited number of 30 seats. All young researchers can present their work during the demo and poster sessions.

Symposium. In **M42**, SpecX organises a dedicated symposium on "*Spectrum analytics-as-a-Service for future digital societies*", where DCs will present their research results. In addition, a job fair is organised as an ideal talent/job hunting opportunity, with the participation of 5TONIC members such as Telefonica, Ericsson, NEC, and other invited companies such as IMEC and ACC.

(T3) Complementary trainings (soft skills) (**Figure 3**). SpecX puts a significant effort into nurturing the complementary skills of the DCs. A number of soft-skill training events have been planned (see **Table 3**). These trainings are designed based on the VITAE RDF, and cover all the four domains of this comprehensive framework (from domain **RDF.A1** to **RDF.D3**), rather than providing a disparate set of ad hoc trainings (see **Table 3**). The four domains are: (a) knowledge and intellectual abilities, (b) personal effectiveness, (c) research governance and organisation, and (d) engagement, influence and impact (see **Table 5**). The 12 soft-skills training are compulsory for all DCs. Besides, each DC also receives further technical and individual training during the planned secondments according to each research project. Finally, depending on needs and interests, each DC can select additional soft skill training initiatives integrated with the domains **RDF.A1-D3**. Some of these are on a per-DR basis through online courses (e.g., Coursera), others are provided through the doctoral school of the host unit. The individual training programmes of the DCs hosted by universities are embedded in the local doctoral schools (**Table 12**). Here, "individual" means that each fellow has to compose a tailored mixture of courses, complying with the DC's background and interests, and in agreement with the PCDP. The doctoral schools provide training courses to increase the DCs' scientific expertise and skills. These courses may pertain to the domain of the DC, to adjacent scientific fields (interdisciplinary research), or to research in general. All schools have accepted to mutually recognise one another's training programmes (including the ECTS credits of network-wide events).

Table 3. Main network-wide training events and contribution of beneficiaries

	Main Training Events & Conferences	ECTS[40]	Lead	Month
1	• **SpecX kick-off meeting** in Madrid (IMDEA's auditorium), Spain, including a "SpecX-networking" session to detail all the planned secondments (1 day) • **Site Visit** to 5TONIC lab, one of Europe's foremost 5G digital innovation centres. The visit includes the **S/T training** on "Trends in EU research for 5G+ networks", by Prof. A. Banchs (1 day) • **S/T training** "Spectrum analytics as a service for future wireless networks: state of the art, challenges, and applications", by Prof. D. Giustiniano and Prof. S. Pollin, who are experts on spectrum sensing and analytics, in Leuven, and "Prototyping and building up spectrum sensing testbeds", by Dr. R. Calvo (University of Ray Juan Carlos, Madrid) and Dr. V. Lenders (ESense) (1 day) • **Soft-skill training 1:** "How to come up with great research ideas", by Prof. P. Casari (**RDF.A2**) and "The art of excellent doctoral research", by Prof. J. Widmer, author of 30+ papers in top venues, e.g., MobiCom, CoNEXT, Infocom (**RDF.A1**); **S/T training** on GDPR: "Privacy-oriented software development: from general concepts to real horror stories", by Prof. N. Vallina, in Madrid (1 day) • **Soft-skill training 2**: "Responsible Research and Innovation (RRI), open access, ethics, scientific integrity, and gender aspects", by IMDEA R&D office (**RDF.C1**), in Madrid (1 day)	2 credits (report to be written)	IMDEA	**M8**
	• **Network-wide workshop** in Leuven (1 days) • **Site visit** to KU Leuven's WaveCore Lab **and** Software Defined Radio Lab, incl. a **S/T training** on "Privacy-enhancing technologies", by Prof. C. Diaz, who is expert on privacy protection, and **Soft-skill training 3**: "Our experiences in PhD studies", by Dr. T. Claeys and Prof. Q. Wang (**RDF.B1**), in Leuven (1 day) • **Mid-term meeting** between REA and SpecX consortium, incl. all beneficiaries (scientists-in-charge and all DCs), and associated partners, in Leuven (hence, close distance to Brussels) (1.5 day) • **Soft-skill training 4:** "Teamwork and interpersonal communication skills", by KU Leuven HR (**RDF.D1**), **Soft-skill training 5**: "Good research practice and data management", by Dr. A. Lutu (**RDF.C2**), and **S/T training** on "Dual use/export license training", by KU Leuven R&D (1 day)	2 credits (report to be written)	KU Leuven	**M13**
3	• **Network-wide Workshop** in Delft (EWI building), the Netherlands (2 days) • **Site visit** to DIoT lab, incl. **S/T training**: "Future challenges in wireless communication networks and 5G/IoT Field Test", by Prof. F. Kuipers and Prof. Q. Wang (TU Delft) (1 day) • **Soft-skill training 6**: "Time management & self-management for PhDs" by TU Delft HR (**RDF.B2**) (0.5 day), and **Soft-skill training 7**: "Entrepreneurship and elevator pitch with real investors", covering subjects such as creating a business plan, market research, product/market fit, fund raising, investor pitch deck, among others; by ACC, and TU Delft (two real investors will be invited for this training) (**RDF.D3**) (2 days)	2 credits (report to be written)	TU Delft	**M18**
4	• **Network-wide workshop** in Trento, Italy (1 day) • **Mid-term progress review meeting (intra-SpecX consortium)** in Trento, Italy (1 day) • **SpecX Summer School**: "Emerging paradigms for next-generation wireless networks and the digital societies" with speakers from non-academic organisations (e.g., TID, Ericsson, ESense, ACC, and NEC) of the SpecX consortium as well as other invited well-known experts (Prof. Suman Banerjee from Wisconsin University (USA), Dr. Bozidar Radunovic, Microsoft), in Trento (3 days)	3 credits (report to be written)	CNIT	**M24**
5	• **Network-wide workshop** including visit to Telefonica R&D, in Barcelona, Spain (2 days) • **Soft-skill training 8**: "Creative problem solving for researchers", by the Scientific team at Telefonica R&D (**RDF.A3**), in Barcelona (1 day) • **Soft-skill training 9**: "IPR & patent training" (**RDF.A1**) and **S/T training** "Open-source software", by Telefonica legal department, in Barcelona (1 day)	2 credits (report to be written)	TID	**M30**

[40] The ECTS credits have been agreed upon by the SpecX participating organisations. The DCs will also take other local PhD training courses to accrue enough ECTS credits for PhD graduation.

	• **Soft-skill training 10**: "Career orientation and development, and research in industrial organisation", by Telefonica HR (**RDF.B3**) and Dr. A. Lutu, in Barcelona (1 day)			
6	• **Network-wide workshop** in Aachen, Germany (2 days) • **S/T training on** "Pattern Recognition and Data Analysis", by Prof. P. Patras from University of Edinburgh (also co-founder of Net AI), and **S/T training on** "Machine learning in dynamic spectrum management and wireless networking", by Prof. M. Fiore (IMDEA), in Aachen (2 days) • **Soft-skill training 11**: "From research to impact", by R&D of RWTH Aachen (**RDF.D2**) (1 day)	2 credits (report to be written)	RWTH	**M36**
7	• **Symposium** on "Spectrum analytics as a service for future digital societies", in IMDEA, with planned job fairs, and in cooperation with 5TONIC members, in Madrid (3 days) • **Soft-skill training 12**: "Grant writing for individual fellowship after the PhD: successful stories", by invited IMDEA's Alumni (**RDF.C3**) (1 day); Closing **Network-wide workshop** with plans to maintain SpecX network, in Madrid (1 day)	3 credits (report to be written)	IMDEA	**M42**

Table 4. Typical programme for network-wide workshops (see topics detailed in **Table 3** and locations in **Figure 2**)

Day	Board/Meeting	Who?	Organisers
Mon	AM: DC presentations from WP1 and WP2 (6 DCs)	DCs + Supervisors of all DCs + Representatives industrial associated partners + MST	Host + MST
	PM: DC presentations from WP3 (4 DCs)		Host + MST
Tue	AM: TSC meeting (WP presentations by WP leaders WP1-3)	Technical Steering Committee (TSC) members	Host + MST
	PM: SB (WP presentations by WP leaders WP4-6)	SB members	Host + MST
	(PM: Recruitment Committee)	RC members	Host + MST
	(Research/Women Council + Lab visits for DCs + Guest lectures by world-leading experts + topics chosen by DCs)	DCs (obligatory)	DCs + Host
Wed -Fri	Social interaction event for DCs	DCs (obligatory) + Supervisors (optional)	Host
	S/T training + Soft-skill training	DCs (obligatory) + Supervisors (optional)	Host
	Industry/site visits	DCs (obligatory) + Supervisors (optional)	Host

An evaluation questionnaire will be distributed at the end of each training event. This will allow i) for feedback on the organisation and outcomes of each event towards improving the next one, ii) get suggestions for topics to cover in future schools (e.g. gaps between research and training), iii) to draw statistics related to the attendance outside/inside the network and the age and profile of participants.

1.3.2 Role of non-academic sector in the training programme

The five non-academic institutions of SpecX actively contribute to the training. The industrial beneficiary TID recruits one DC, provides S/T & soft-skills training, and organizes a lab visit to Telefonica facilities in Barcelona. TID also hosts secondments for other DCs, as do associated partner ESense (Switzerland), ACC (Belgium), Ericsson and NEC (Germany). TID, Ericsson, and IMDEA are part of 5TONIC lab (one of Europe's foremost 5G and beyond digital innovation centres) in Madrid, and will offer lab visit. Likewise, the industrial associated partners NEC, Ericsson, ESense, and ACC also provide industry secondments and/or complementary S/T and soft-skills training (**Table 3**). Further, each DC has at least one non-academic supervisor in her/his DGC (**Table 12** and **Section 3**). There is a strong industrial drive behind the SpecX consortium, as *the involved companies are leading vendors* (e.g., Ericsson, NEC) *or leading operators* (e.g., TID, ACC) *in the telecommunications area*. Together, they will drive, facilitate, and deploy the real-world integration of SpecX's results. The non-academic participants are strongly involved in the Summer School and the closing symposium. From the interaction with industrial partners, the DCs will learn a non-academic, problem-solving, and innovation-oriented approach to research and development, resulting in a full rounded understanding of both research and industrial impact.

Table 5. SpecX soft-skill training based on the VITAE RDF, focusing on the DCs' employability and skill development

Domain	Domain A: Knowledge and intellectual abilities			Domain B: Personal Effectiveness			Domain C: Research governance & organisation			Domain D: Engagement, influence and impact		
Description	The knowledge, intellectual abilities and techniques to do research			The personal qualities and approach to be an effective researcher			Knowledge of the professional standards and requirements to do research			The knowledge and skills to work with others to ensure the widest impact of research		
RDF Subdomain	A1. Research method	A2. Cognitive abilities	A3. Creativity	B1. Personal qualities	B2. Self-management	B3. Career development	C1. Professional conduct	C2. Research management	C3. Funding and resources	D1. Working with others	D2. Communication	D3. Engagement and impact
Soft skill Training at Network event	See NWE1&5, **Table 3**	See NWE1, **Table 3**	See NWE5, **Table 3**	See NWE2, **Table 3**	See NWE3, **Table 3**	See NWE5, **Table 3**	See NWE1, **Table 3**	See NWE2, **Table 3**	See NWE7, **Table 3**	See NWE2, **Table 3**	See NWE6, **Table 3**	See NWE3, **Table 3**
Institutional organiser	IMDEA	CNIT	TID	KU Leuven	TU Delft	TID	IMDEA	TID	IMDEA	KU Leuven	RWTH	TU Delft & TID

1.4 *Quality of the supervision*

In SpecX, each DC has a dedicated supervisor and at least two co-supervisors as outlined in **Section 6**. During secondment, the DCs will be co-supervised by both the home and hosting institution. A core element in the supervision process is the PCDP which will be created jointly by the DC and the supervisors in the first two months of the incorporation of the DC and will be updated regularly thereafter.

1.4.1 Qualifications and supervision experience of supervisors

In line with the European Charter for Researchers, all chosen main supervisor within the SpecX consortium are experts (with an average H-index >30), have ample experience in intersectoral/interdisciplinary collaboration, and a strong track record with PhD supervision (the total number of PhDs supervised and under supervision is about 149), and commitment to offer all required support (**Table 12**)**.** The supervisor has a mentoring role: she/he provides a roadmap of the research, gives career advice, sharpens the entrepreneurial spirit, supports professional development and informs on the practical issues related to the individual project.

1.4.2 Quality of the joint supervision arrangements

SpecX provides joint supervision, forming the Doctoral Guidance Committee (DGC) Members (**Table 12)**. All DCs will be supervised by: i) a Full or Associate (Research) Professor or Senior Researcher from their hiring institution, along with a second co-supervisor; ii) a local supervisor during their secondment. Industrial partners will actively contribute to DCs supervision, as each industrial partner will host at least one DC on subjects in line with both the project, and company priorities, implying that DCs' progress monitoring will include a formal industrial component throughout their PhD (**Table 14**). Besides, where appropriate and if allowed by the rules from each doctoral school, industrial members will be invited to serve in the PhD juries of the DCs.

2. Impact

2.1 *Contribution to structuring doctoral training at the European level and to strengthening European innovation capacity*

SpecX is fully compliant with the doctoral training structure of the EU (following the "Salzburg II Recommendations & Principles" for Innovative Doctoral Training) and it contributes to further strengthening European collaborative research. SpecX aims to be at the frontier of innovation, contributing to the strategic orientations of the Horizon Europe plan. In this context, spectrum scarcity and spectrum utilization inefficiency is a fundamental impediment toward achieving the **EU digital strategy**[41] of a post-pandemic scenario. From a technological standpoint, this project is conceived in a unique moment, when the trend towards network densification (smaller cells), the ever-increasing number of connected mobile devices (Massive IoT), and the transition towards 6G technologies will exacerbate the network operation complexity and amplify the operators' need to efficiently use the limited radio spectrum resources. The SpecX Doctoral Network aims at answering this challenge by strengthening the next generation of wireless networking systems at the EU level, thus contributing to the **Europe Mission** to make Europe fit for the digital age. SpecX's view is fully in line with the EU's target for the digital decade and 2030[42], by training highly skilled digital professionals with know-how to implement secure and performant sustainable digital infrastructures. Spectrum availability measurements, reutilization, and flexibility are also key objectives of the European Vision for the 6G Network Ecosystem[43]. Finally, SpecX contributes to the **UN's Sustainable Development Goals**, and in particular to goal 8 ("*Decent work and economic growth*", by helping preserve and optimize a strategic resource for the economy such as the EM spectrum) and goal 9 ("*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*", as a better managed EM spectrum improves resilience against crises).

2.1.1 Meaningful contribution of the non-academic sector to the doctoral training

Secondments: There are five non-academic members within SpecX, including one beneficiary and four associated partners, which will actively contribute to the training programme. Each DC performs two secondments, of which at least one is intersectoral (academia to industry and vice-versa), to broaden the DC's understanding of both the academia and the industry sectors, as well as to put each DC in contact with different working strategies and organizations at different institutions. The secondment timing is pre-agreed so as they position at the best timing for each DC's research. Additional technical and transferable skills training is performed during secondments to the non-academic sector, and adapted to the individual needs of the DC project.

Supervision and Mentoring: Each DC is supervised by a DCG composed of experienced researchers from both the academic and the industrial sector, thus ensuring supervision quality and diversity. At a high level, one DC is

[41] European Commission Digital Strategy, https://ec.europa.eu/info/publications/EC-Digital-Strategy_en
[42] https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/696189/EPRS_BRI(2021)696189_EN.pdft
[43] https://5g-ppp.eu/wp-content/uploads/2021/06/WhitePaper-6G-Europe.pdf

directly recruited by non-academic beneficiaries, while non-academic members will be co-mentoring and supervising the 10 DGCs, the industrial supervision of secondments, and the inter-sector mobility of the research training, thus largely contributing to the quality insurance of the doctoral training.

Research and Transferable Skills: SpecX offers network-wide S/T and soft-skill training through workshop-style professional development sessions with active engagement from the non-academic sector, see **Section 1.3**. The planned lab visits and co-located workshops at the facilities of the non-academic beneficiary gives the DCs a unique opportunity for direct exposure to cutting-edge technologies in telecommunication (the 5TONIC lab at TID/IMDEA). The composition of the consortium includes strong interactions with both worldwide vendors (Ericsson and NEC) and large EU operators (TID), and renowned SME (ACC, Electrosense) guarantees a public/private-sector collaboration in the research training with the acquisition of key skills needed in both sectors, including entrepreneurial skills. Per the DOC-CAREERS II Collaborative Doctoral Education report[44], SpecX puts emphasis on doctoral theses carried out with interaction between academic and non-academic sectors. Besides intersectoral employability for the DCs, and their education into the business world, this will constitute an advantage for EU research labs in industry, closing the gap with respect to doctoral education in US research labs.

2.1.2 Developing sustainable elements of doctoral programmes after the end of the DN funding

SpecX is committed towards a sustainable cooperation scheme that extends beyond the financed project duration, converting the network into a long-term and structured training programme, which involves all SpecX participants, their future PhD students, and postdocs. The elements that are sustainable include i) Training programmes at local or network-wide level; ii) Cooperation and secondment opportunities; iii) Transferable skills training offering; iv) Researchers recruitment according to the code of conduct for the recruitment of researchers. Moreover, DCs will join the Marie Curie Alumni Association (MCAA) to extend their network and interact with scientists with common research interests. Through the strong prior, ongoing and future research interactions, the creation of long-lasting training structures is fully realistic.

To achieve the above targets, the partners of SpecX will: (1) seek the creation of a workshop series co-located with a top conference on "Emerging paradigms for next-generation wireless networks and the digital societies" with SpecX researchers as steering members; (2) seek the establishment of a COST action on spectrum sensing and analytics for next-generation wireless networks; (3) apply for EU and industrial funding on follow-up projects, e.g., Horizon Europe calls in the "Digital, industry and space" work programme and future calls supported by the Smart Networks and Services (SNS) Joint Undertaking; (4) formalise joint programmes among the partners, e.g., joint PhD programmes or Erasmus programmes for master student exchange.

2.2 *Credibility of the measures to enhance the career perspectives and employability of researchers and contribution to their skills development*

SpecX will unleash the potential of emerging network applications that require a new telecommunication paradigm that will be integrated into a 6G ecosystem. The DCs will become the leaders of this transition. As noted in a report from project beneficiary Telefonica[45], in the last decade, *telecom sector revenues in Europe decreased by 29%, while in the United States they have increased by 20%*. In this context, training of DCs will help the EU industry recover its leadership in wireless communication through their competitive advantage. Also, highly ranked EU universities employing the DCs will acquire talented human resources trained at and capable of cutting-edge research on a broad set of technologies, thus clearly improving their **employability**.

Boosted by the industrial, business and entrepreneurship training, the DCs will actively contribute to the start-up eco-system. These new actors created in EU will have great potential for quick take-up in new disruptive markets created for solutions that enable flexible spectrum sensing and analytics. This multi-faceted exposure of the DCs to different environments and concepts will offer them a competitive advantage over other researchers and engineers specialized in a single domain. Besides, DCs will participate in job fairs and their skills will be demanded by the knowledge-based economy. These elements are part of two network-wide events organised in collaboration with industry partners in SpecX at **M18** and **M42**.

Table 6. S/T individual skills development of DCs (refer to **Table 3** for S/T training for all DCs, and **Table 5** for Transferable skills.

DC	Primary S/T domain (at host institution)	Secondary S/T domain (during secondments)	DC	Primary S/T domain (at host institution)	Secondary S/T dmain (during secondments)
DC1	IoT, neural networks, prototyping, computation	Data analysis, network co-existence, aerial sensing	DC6	Big data, measurements, end user exp., wireless coverage	Algorithms, anomaly detection, prototyping

[44] Collaborative doctoral education in Europe: Research partnership and employability for researchers - DOC-CAREERS II project, shorturl.at/ciot3

[45] European leadership in connectivity requires collaboration and consistency within the regulation, https://www.telefonica.com/en/communication-room/blog/european-leadership-in-connectivity-requires-collaboration-and-consistency-within-the-regulation/

DC2	Edge infrastructure, physical sensing, algorithms	Measurements, anomaly detection, prototyping	DC7	Computation tasks, IoT, orchestration, ML	Optimization, analytics, anomaly detection
DC3	Algorithms, prototyping, modelling	Physical sensing, resource allocation	DC8	Aerial sensing, modelling, connectivity	Prototyping, coverage map mobile cell performance
DC4	Neural networks, algorithms, anomaly detection	Federated learning, edge computing	DC9	Algorithms, measurements, prototyping,	Physical sensing, prototyping
DC5	Algorithms, localization, prototyping, physical sensing	Modelling, IoT, measurements, analytics	DC10	Wireless applications, safety	Measurements, prototyping

Skills development. SpecX will greatly contribute to the skills developments in different domains. DCs are provided with transferable skills acquired through training, including business development in ICT and career orientation skills in both academia and industry (see **Table 5**). S/T training at consortium level is complemented by individual skill developments. In particular, as highlighted in **Table 6**, DCs will acquire knowledge in new disruptive methods and algorithms, encompassing physical communications, edge computing, big data, neural networks, and network applications of spectrum data.

2.2.1 World-class, interdisciplinary training programme

The SpecX consortium has carefully selected experts from European institutions with a long-standing expertise in diverse research and training domains such as networked systems, wireless networking, communication system engineering, signal processing, security, etc. This guarantees the DC exposure to top-notch scientific environments and research. Each DC handles her/his own ambitious research project while being part of an interdisciplinary environment and having access to unique cutting-edge testbeds and facilities (see **Section 4**). During the network-wide workshops, additional S/T trainings and complementary soft-skills training are provided, with an emphasis on entrepreneurship skills and product-oriented innovation. The soft-skills training is integrated in the unique VITAE RDF framework, which allows to plan, promote, and support the personal, professional and career development of the SpecX researchers in 4 key domains (**RDF.A1-D3**), in view of maximising future employability (**Section 1.2.1** and **Table 5**). The training acquired at a participant's institution is formally recognised by the other participants in the context of the PhD programmes of the different doctoral schools. This mutual recognition allows the DCs to collect credits for their own doctoral programmes by performing secondments, attending network-wide workshops, conferences, and training sessions at different participant institutions.

2.2.2 Career paths in industry, academia and the public sector

The training of SpecX is specifically designed to develop and hone the skills of DCs through a comprehensive and diverse knowledge on fundamental and applied research. DCs will be supervised to achieve the high academic standards of our doctoral degree granting institutions, which have the high standing objective of publishing in top journals and conferences in their respective fields and achieve impact in the scientific community and the society. DCs will work with the final user in mind, leading to innovators that can nail down the source of the scientific breakthrough; while being always aware that, their work should benefit society and respect RRI principles. For all DCs, network-wide training and secondments will be the place where they will be encouraged to explore the tie-ins between each other's projects, enhance inter-domain research, and leverage the most recent advancements in the state of the art, further developing the objectives at the time of the proposal submission, thus acquiring both broad and deep knowledge to succeed in their careers. Associated partners (from both academia and industry) will be involved in the development of the DCs project and skills from their conception, helping to strengthen and amplify the contribution of the DCs beyond the scientific merits.

The training of SpecX DCs is inter-domain, covering the necessary communication engineering and computer science fundamentals with focus on delivering pragmatic solutions in several key industrial domains (e.g., mobile broadband, industry 4.0, massive Internet of Thing, etc.). SpecX will invest a significant effort through the training events on developing soft skills such as handling leadership roles, improving oral and writing presentation skills for different stakeholders, including real investors that will be invited during the training programme (see **Table 3**). SpecX DCs will be highly employable in various academia, industries, or public government bodies. As wireless is a basic societal need, Europe will require highly trained researchers that are both the next leaders in EU telecommunication networks and the ultimate experts to reproduce the toolkits acquired during the SpecX program in new successful yet challenging initiatives, thanks to the transferable skills of the research and training programme and the uniqueness of the challenging projects covered by each DC. Given the solid analytical training, the topics in fundamental science covered within the network, and the publications in international top conferences and journals to present research work, all DCs will be able to pursue careers in academia and research institutes. The talented researchers of SpecX will master emerging technologies, and, furthermore, through direct and deep exposure with industry, will also acquire transferable skills to apply them in practical challenges of interest for industrial environments with shorter term cycles from research to innovation. SpecX DCs will also be a unique human resource for governmental bodies, including the European Commission and national regulators, that need expertise in new emerging sectors to forge and guide EU's policies/regulations and strategic investments.

2.3 *Suitability and quality of the measures to maximise expected outcomes and impacts, as set out in the dissemination and exploitation plan, including communication activities*

A non-exhaustive list of already identified **target groups** consists of: ***(i)*** MSCA DNs and former ETNs Networks; ***(ii)*** industry (technology developers, experts, etc.) delivering technology that benefits economy and society at large, and consortia of other EU projects which gather and share knowledge and tools for the development and use of novel solutions for digitalisation of key sectors of European economy; ***(iii)*** institutions and regulatory bodies (national & international) impacted by the potential need of redesign standards and regulations, as well as public authorities, policymakers who regulate the spectrum allocation and adopt new technologies to accelerate the transition to the digital economy; ***(iv)*** specialised media and science journalists to reach the general public; ***(v)*** general public, e.g., EU citizens, and associations who will be informed about applications that can run using spectrum analytics; ***(vi)*** private and public funding institutions for innovation and investors to bring solutions to the market; ***(vii)*** academic, research, and technology organisations actively contributing to 6G technologies.

For each target group, SpecX has set specific activities and means to reach them during the duration of the project, as described in **Table 7**, and beyond the duration of the project, with expected outcomes and long-term impacts detailed in **Table 8a, b and c**.

Table 7. Communication and dissemination target groups, activities & means to reach them and related output (as the basis for the Communication & Dissemination Plan and the Exploitation Plan).

Target groups	Main activities & means to reach them	Outputs
Internal communication (for sound project implementation)		
DN Network (beneficiaries + associated partners) & REA project officer	• DCs' PCDPs, DC progress presentations, RTDE progress reports stored on the project intranet (password-protected) • Periodic, Mid-term and Final reports, Communication & dissemination Plan, Exploitation plan, DMP, Minutes of WP and SB meetings, Financial overview reports (on Intranet) • Email (for email-hygiene all subject headings to start with [SpecX] with mailing lists depending on the target group)	Reports and presentations are assessed and monitored by (depending on report & presentation type) Supervisors, DGCs, WP leaders, S/T Coordinator, GC, MST and SB, REA Project Officer
External communication (for awareness and impact generation)		
Industry and other EU projects	• Institutional communication through bulletins and websites of all project partners, creating maximum leverage • Project website (**D5.5**) • LinkedIn "Company Page" for SpecX • Communication kit (Project flyer, presentation) at EuCNC	Project start: 1 Project flyer Regular posts: 1 Post per month in LinkedIn; 1 Post per month on Website Project End: 1 Brochure about project results + presentation Expected reach: 5K people
Policy makers, public bodies including regulatory agencies	• White paper presenting main project's achievements • Talks at events organized by national regulatory agencies (e.g., BIPT in Belgium)	3 standards to be agreed on 3 tests to be financed
Specialised media and science journalists to reach the general public	• Press releases (TechCrunch, Wired, etc); SpecX video (**D5.6**) • Interviews (TV, radio, newspapers, magazines; e.g., Prof. Pollin is frequently cited in De Standaard or VRT News, with respect to 5G and spectrum issues.)	3 press releases, 2 video presentations, 5 interviews Expected reach through online newspapers: 10K people
General public	• Project website featuring blogs, news and press items, etc. • Open Days, European Researchers' Night, Science Week, Science is Wonderful, and local events such as the Arenbergfeest in Belgium • SpecX animation video (**D5.6**); Blogs shared on social media.	50 posts/news on web – Expected reach: 5K people 20 participations in events – Expected reach: 5K people 10 Videos – Expected reach: 50K 3 posts/month on social media (Twitter) – Expected reach: 15K people
Dissemination of SpecX DC research results (for maximum take-up of new knowledge and exploitation of results)		
Industry target groups and funding institutions to bring to market	• SpecX Summer School and Symposium (**D4.3**) • Job Fair and Exhibition showing DCs' results	20 External Industry participants >6 DCs recruited by companies 1 prototype per DC, 5 patents filled
Academic, research, and technology organisation	• SpecX Summer School and Symposium (**D4.3**) • Peer-reviewed publications at prestigious conferences and journal (MobiCom, INFOCOM, ToN, TWC, TMC, etc.) and journals (**D5.1-D5.4**); Open Access research data.	40 Peer-reviewed conference/journal/demo/poster papers (4 per DC) 150 Attendees in major conference events such as MobiCom

2.3.1 Plan for the dissemination and exploitation activities, including communication activities

SpecX pursues a fully integrated outreach (internal and external), dissemination and exploitation strategy, which is summarised in **Table 7**. The key metric is to ensure visibility and impact (the 3rd column, **Table 7**). The different components of this strategy are discussed below. They are performed by **subtask 5.1** (dissemination and outreach) and **subtask 5.2** (exploitation) of **WP5**.

Dissemination of the research results: The dissemination targets academic and industrial sectors through various channels (**Table 7**). Every DC has the opportunity to present results at the network-wide events (twice per year). All results are published in international peer-reviewed journals and conferences, after careful consideration of protecting intellectual property rights (see **Figure 4**). Following Horizon Europe's open-access policy and respecting RRI principles, the consortium ensures that all peer-reviewed publications of SpecX are deposited in the Zenodo open-access repository (https://zenodo.org). Together with Zenodo, other OpenAIRE-compliant repositories will be used by different partners to comply with their internal dissemination policies (e.g., the DSpace at IMDEA, https://dspace.networks.imdea.org/, and the repository at KU Leuven, https://lirias.kuleuven.be). Dissemination also includes publications at top conferences (e.g., ACM MobiCom, IEEE INFOCOM), where DCs present their latest findings, demos/posters, and source code/data published in repositories. For other SpecX dissemination channels, please see **Table 7**.

Exploitation of results and intellectual property: The SpecX exploitation strategy (**Figure 4**), developed and monitored through the Exploitation Plan (**D5.1-5**, see **Section 3**) contains four routes, each of which is assessed per DC project. The DCs are actively involved in pursuing exploitation routes and continuously update the exploitation section in their Research, Training, Dissemination and Exploitation progress report. *For this, they are guided by their main supervisors and non-academic supervisors* (DGC, **Table 13**) and continuously trained through the SpecX entrepreneurial soft-skills training (**Table 5**). The four exploitation routes are: (**EX1**) Dedicated (bilateral, national, and EU) follow-up projects targeting a higher Technology Readiness Levels (TRL)[46], including the EU EIC Pathfinder and Accelerator programs; (**EX2**) industrial implementation, e.g., TUD drone-hosted mobile cells for 6G (DR8); IMDEA Electrosmog inference with low-cost spectrum sensors (DR9); patenting of breakthrough results (all DCs work on innovative projects beyond the state-of-the-art with potential for filing patents) and (**EX4**) spin-off creation, e.g., KU Leuven's federated learning for aerial and terrestrial spectrum sensors (DR1); RWTH's sensing-capable 6G radio access infrastructure (DR3). In **Table 13**, we present the possible exploitation routes per DC (cf. the last row of each DC description). *An experienced exploitation manager (Dr. J. Widmer, IMDEA) has been appointed, with the aim to work with the GC and SC to commercially exploit all breakthrough results*, irrespective of the training goals. Moreover, 5TONIC at IMDEA/TID holds a 5G start-up competition to which the consortium members are encouraged to participate. These hubs will help DCs creating disruptive business models and establishing strategies to search for investors. All consortium members have identified some background knowledge (patents, know-how, data, software, scientific studies, methods, material held prior to the project) to be contributed to the project at the proposal stage and further during the execution. In addition, the search of patents related to the research project of each DC did not reveal any relevant patent impeding our "freedom to operate" and the exploitation of SpecX's results.

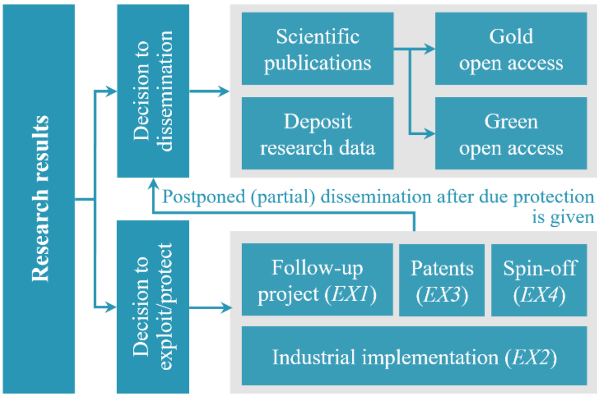

Figure 2. SpecX exploitation and dissemination strategy.

Communication activities (Table 7)

SpecX website and outreach. SpecX targets several activities to significantly increase the visibility of SpecX's output. The main public engagement activity (targeting professionals, media, and the public) is the development of SpecX website which is focused on the DCs' research, training and results in the field of spectrum analytics as a service. In the first phase of the project, the website contains short videos to introduce challenges using spectrum analytics to enable exciting futuristic applications and the way they can dramatically change people's life. As DCs produce results, short videos targeting the general public will be posted in the website to promote the main achievements. In addition to the DCs blogging on SpecX website about their research, the SpecX MST develops and maintains a LinkedIn Company page. Furthermore, the consortium exploits the opportunities of Open Days at each institution to introduce SpecX to the public with presentations, demos and posters, e.g., the European Researchers' Night, Science Week, Science is Wonderful, among the UE events, as well as local events, such as ICT Days at UNITN and T3chFest at UC3M. The objective is to reach a physical and online attendance at the talk/booth between 100 and 1000 people per event (depending on the size and duration of each of them). We will reach more traditional media such as radio and TV (e.g., La 2 in Spain via IMDEA/TID and RAI in Italy via

[46] https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

UNITN) to promote DCs' results, supported by the Communication Manager of each partner. For instance, IMDEA has appeared in the last year 3 times on the national TV.

SpecX project videos. Before **M13**, a short video about SpecX and its 10 S/T objectives is produced together with all the 10 DCs. Then, on **M42**, a video on the results is updated by all the DCs, guided by their supervisors and the exploitation manager. SpecX consortium has ample experience with outreach using videos: for example, KU Leuven's video clips about the project OmniDrone (www.omnidrone720.com), which totalled several thousand views; TU Delft will leverage their connections with regional and national broadcasters to showcase early results and publicise security vulnerabilities for early public awareness; IMDEA has a local channel for regular research updates that is streamed on YouTube.

2.3.2 Strategy for the management of intellectual property, foreseen protection measures

SpecX manages IPR in line with EU requirements for MSC actions (www.iprhelpdesk.eu). Introduced background knowledge owned by the beneficiaries is made freely available to the DCs as needed for their research. Foreground and side-ground knowledge in SpecX (including theoretical and practical results) is owned by the DCs and beneficiaries that generate it. Joint ownership is regulated by the Consortium Agreement. All DCs are obliged to share their scientific articles with the consortium before submitting them for publication. SpecX results are reviewed (leaders: Dr. A. Saavedra (NEC) and Dr. A. Lutu (TID)) to assess their exploitation potential. This balances timely scientific dissemination with patenting and protection, possibly leading to commercialisation, follow-up projects, and the creation of spin-off companies (see **Figure 4**). Upon a decision to disseminate, SpecX makes results available to the scientific community in a gold or green open access fashion, with highlights in lay language for the general public through the network's website and social media. Protectable knowledge and early outcomes will be stored in protected non-public repositories, and access granted to each person/entity that holds rights to it. Typically, this includes all research contributors, including those that provided access and guidance to cutting-edge research facilities to experiment and prototype a new technology. The Supervisory Board supervises IPR controversy resolution based on the Consortium Agreement. The Consortium Agreement will be based on the latest version of the MCARD-HEU model template provided by DigitalEurope and will be agreed by the partners before the Grant Agreement is signed. SpecX partners have a history of joint collaborations, and also joint inventors both at EU and international level (e.g., J. Widmer, IMDEA, and P. Casari, UNITN). The corresponding knowledge and experience gained is shared as part of the DC training.

Industrial partners take an active part in suggesting exploitation venues and in highlighting the commercialization potential of DC ideas. Periodic meetings (every six months, see **Table 3**) enable non-academic consortium members including associated partners to hear the progress of each DC's research, discuss the results, and scout/support exploitation possibilities. The exploitation manager will coalesce SpecX's results of interest for policymakers (e.g., related to spectrum usage, or to illegal radio emission detection in protected bands) and will summarize them in a brochure to be forwarded to the RF regulation authorities of the member states.

2.4 *The magnitude and importance of the project's contribution to the expected scientific, societal and economic impacts (project's pathways towards impact)*

The advent of 6G will cause a tremendous paradigm shift in the way networks are designed, with novel transceiver designs and software network solutions that enable and drive more efficient deployment, provisioning and management of verticals. In this context, we expect SpecX to generate positive and consistent outcomes and long-term impacts as described next.

2.4.1 Expected scientific impact

SpecX will allow obtaining insights from spectrum data and analytics, creating new knowledge for more efficient spectrum management and coexistence of next generation applications for both telecom and non-telecom users of the spectrum, and create the foundations for exploring new technological solutions originated from the core research WPs of SpecX. Academic, research and technology organizations working on the latest 6G technologies will be the first adopters of SpecX solutions. SpecX is aligned to Horizon Europe strategic plan 2021-24: SpecX help propel the EU's innovation capacity along with the "Digital, Industry and Space" chapter of the Horizon Europe work programme and the calls in 6G and Smart Networks supported by SNS Joint Undertaking, which will allow for cross-fertilizations with these initiatives. **Table 8a** details the main expected outcomes and long-term impact and maps them to target groups presented in **Section 2.3**.

Table 8a. Expected outcomes and long-term impacts for target groups with expected scientific impact

Target groups	Expected outcomes – Awareness and use of SpecX output - during the project and 1 year after its end	Expected long-term impacts – Consequence of people using output - years 2 to 6 after the project's end

Academic, research, and technology organisation	Talented postgraduates in core topics for 6G networks; advancement of the state of the art by each DC will generate citations and visibility. Workshop series co-located with top conference on with SpecX researchers as steering members and joint programmes among the partners.	*Scientific impact*: Achieved in the domains of novel sensing, infrastructure, data analysis and applications within academia organizations working on the latest 6G technologies. Education of new generations in the fields covered by SpecX. *Magnitude*: >10,000 researchers exploiting knowledge and data generated. *Importance*: Europe back at the forefront of 6G.
Other EU projects	Cross-fertilization with other EU projects; contribution to the Horizon Europe calls ("Digital, industry and space" work programme) and to shaping the 6G Smart Networks and Services (SNS) roadmap.	*Scientific impact:* Formation of new EU projects from the results of SpecX, providing impact both to research and economy. Preparation for early market adoption of 6G by the end of the decade. *Magnitude:* Impacting >10,000 researchers. *Importance:* New projects further develop SpecX technologies.

2.4.2 Expected economic/technological impact

SpecX outcomes after the project will contribute to boost the spectrum utilization efficiency for next generation radio technologies. European vendors and large operator will improve their competitive position through the following actions: i) the project will provide a comprehensive solution that can be applied to all verticals, with EU players that will drive the exploitation of new market sectors, ii) the strong presence of EU telecommunication stakeholders (e.g., NEC, Ericsson, TID, and ACC), combined with leading EU research institutions with a broad research portfolio in spectrum analytics, will channel real-world problems as well as current and future market needs into concrete research actions, iii) SpecX participants TID, NEC and Ericsson already contribute to telecommunication standards, including 3GPP (e.g., NEC, Ericsson) and IETF (e.g., TID and Ericsson), and SpecX will leverage the comprehensive and diverse know-how acquired by the DCs during the project, and the global reach of its key market players (the large companies of the consortium) to shape the global standards that determine how SpecX spectrum analytics will be used in future 6G networks. Economy will be fostered by SpecX results through the exploitation and communication strategy of the project, attracting funding for start-ups, and income through license fees through the interaction with potential investors and contributing to industry standards, and then indirectly influencing the economy growth via the introduction of disruptive products that will be part of the 6G ecosystem. **Table 8b** details the main expected outcomes and long-term impact.

Table 8b. Expected outcomes and long-term impacts for target groups with expected economic/technological impact

Target groups	Expected outcomes – Awareness and use of SpecX output - during the project and 1 year after its end	Expected long-term impacts – Consequence of people using output - years 2 to 6 after the project's end
Private regulatory bodies	SpecX technologies will contribute to standards' setting, recommendations, and new regulations at European (ETSI) and international level (3GPP, ITU).	*Economic/technological impact:* will facilitate the introduction of SpecX solutions in real deployments at worldwide scale, thanks to the global reach of our industry partners. *Magnitude*: 300 policymakers working with the project's policy recommendations. *Importance*: Shaping the industry, fostering wireless services. Impacted verticals worth several € bn.
Funding institutions to bring to market	Engagement in start-up competitions (including EIT Jumpstarter). Attracting funding for start-ups; Generation of license income for filled patents; testing of advanced prototypes in realistic settings (advanced TRL).	*Economic/technological impact:* new business models/market opportunities for telecommunication infrastructure & digital economy. Startups from projects of DCs will gain market share. *Magnitude*: 2,000 entrepreneurs and innovators. *Importance*: Increasing competitiveness of EU in start-ups, closing the gap in number of tech start-ups vs US.
Industry	5G infrastructure market is projected to reach USD 47,775 million by 2027, (67.1% CAGR)[47]. Contribution to standards and research prototypes will be leveraged for generating new revenue streams.	*Economic/technological impact:* Creation of new business models towards pre-6G products (shorter term) and 6G (longer term) infrastructure. *Magnitude:* 100% of EU ICT companies (vendors and operators). *Importance:* New market segments from SpecX solutions. European companies holding critical IP; increasing growth of EU telecom providers.

2.4.3 Expected societal impact

SpecX will be a stepping stone to radically improve future wireless networks by natively embedding and extensively applying spectrum data intelligence in the whole network stack. Public regulatory bodies will receive input from SpecX already during the project duration and will be able to improve policies for spectrum regulation, and guidelines for potential improvements in the network to maximize its utilization efficiency. SpecX will inform decision making for involved actors in complex scenarios as a result of the introduction of new infrastructures and methods that comply with new regulations. The knowledge of electrosmog measurements that are collected by SpecX will provide guidelines for new policies, while objectively reporting the electromagnetic exposure. **Table 8c** details the main expected outcomes and long-term impact.

Table 8c. Expected outcomes and long-term impacts for target groups with expected societal impact

[47]Source: https://www.marketsandmarkets.com/Market-Reports/5g-technology-market-202955795.html

Target groups	Expected outcomes – Awareness and use of SpecX output - during the project and 1 year after its end	Expected long-term impacts – Consequence of people using output - years 2 to 6 after the project's end
Specialised media and science journalists + general public	Awareness of SpecX through the communication activities presented in Section 2.3.3 will generate media coverage and interests of the public in emerging ICT technologies.	*Societal impact:* Adoption of new wireless technologies and applications for reliable and sustainable digitalisation of the economy. The public will be engaged by exploiting the knowledge of electrosmog measurements, so future networks can report objectively on electromagnetic field exposure. *Magnitude*: All EU citizens. *Importance*: Greater citizen wealth and involvement.
Public regulatory authorities	SpecX technologies will be delivered as brochures and demonstrators to national RF regulation authorities, introducing measurements to monitor the spectrum & architectures to better use spectrum.	*Societal impact:* New disruptive policies will be introduced by national spectrum regulators to monitor the usage of the spectrum and maximizing its utilization efficiency. *Magnitude*: All EU countries. *Importance*: Increased efficiency of public resource usage/value. Improve profit of spectrum license for many € bn.

3. Quality and Efficiency of the Implementation

3.1 *Quality and effectiveness of the work plan, assessment of risks and appropriateness of the effort assigned to work packages*

3.1.1 Work Packages (WP) list

Table 9. Work package (WP) list

WP	WP Title	Start Month	End Month	Activity Type	Lead beneficiary	DC Involvement
WP1	Sensing and infrastructure	M7	M42	Research	RWTH	DCs 1-3
WP2	Data analysis	M7	M42	Research	TU Delft	DCs 4-6
WP3	Applications	M7	M42	Research	KU Leuven	DCs 7-10
WP4	Training	M7	M48	Training	IMDEA	All DCs
WP5	Dissemination, outreach, and exploitation	M1	M48	Dissemination	IMDEA	All DCs
WP6	Management and recruitment	M1	M48	Management	IMDEA	All DCs

3.1.2 Description of Work Packages

Table 10. WP Description (only the recruiting beneficiaries are reported, other participant involvement is shown in Tables 4 and 13)

WP1	**Sensing and Infrastructure**	**M7-42 DCs 1-3**
Lead beneficiary	**RWTH**	**Recruiting beneficiaries: KU Leuven, CNIT, RWTH**

Objectives: To improve the performance of spectrum analysis in embedded sensing devices and design a scalable embedded federated learning framework for spectrum analysis that can run on computing-constrained sensors (Obj1). To explore how spectrum sensing techniques can help improve service quality and investigate how edge platforms can support spectrum sensing measurements and services (Obj2). To propose a sensing-based radio access architecture that can identify spectral and spatial resources at the required time scale and dynamics (Obj3a). To compare various radio access infrastructures and their impact on sensing performance (Obj3b).

Task 1.1: IoT connectivity and machine learning (ML) hardware acceleration (KU Leuven, Obj1, DC1)
DC1 will first design the core system and ML accelerator. The work will investigate available platforms for deep learning acceleration, considering as requirement the capability to enable extra compression or knowledge extraction on the sensor itself at reasonable cost per device. This trade-off needs to be investigated. How much of the pipeline can run locally, what are the features that should be communicated and what should be combined in the cloud? Second, the internet connectivity and meshing strategy will be designed, studying how multiple data streams can be combined inside the network for extracting spectral knowledge.

Task 1.2: Advance edge infrastructure for spectrum sensing (CNIT, Obj2, DC2)
DC2 explores and designs an edge infrastructure to maximize and perform the computing close to spectrum sensors improving the quality of service to the final user (anomaly detection, spectrum sharing policy, etc.) (Obj2). **DC2** will investigate how to integrate spectrum sensing techniques and systems with the telecom edge infrastructure and identify the elements (algorithms, applications, architecture, etc.) that can be optimized using information available from spectrum sensing. **DC2** focuses on managing the edge infrastructure to provide spectrum sensing and sharing algorithms to determine the optimal way of computing and sharing spectrum resources from an architectural point of view and therefore enhance the total capacity of the network (Obj2).

Task 1.3: Sensing-based radio access architecture (RWTH, Obj3, DC3)
DC3 studies and designs new architectures and algorithms to dynamically manage spectrum resources by leveraging the 5G network infrastructure. **DC3** will interface gNB and IoT spectrum sensing nodes, investigating methods that efficiently use the transceiver design and protocol functionalities of gNBs for the problem of wideband and distributed sensing across gNBs. By keeping the cost and complexity reasonable, **DC3** will study the benefit of identifying and tracking available spectrum resources in licensed and unlicensed bands, and potential harmful interference in a dynamic and agile fashion across different bands, facilitating multi-tier access and increasing spectrum utilization in time, frequency and space. Prototypes will be implemented for performance assessment.

Deliverables: D1.1-D1.3 for **DCs 1-3** (see Table 11)

Connection to other WPs: Anomaly detection, localisation, and coverage mapping (WP2); mobile cells for 6G networks and spectrum-awareness empowered wireless systems for Industry 4.0 application (WP3).

WP2	**Data Analysis**	**M7-42 DCs 4-6**
Lead beneficiary	**TU Delft**	**Recruiting beneficiaries: TU Delft, IMDEA, TID**

Objectives: To incorporate expert human-in-the-loop feedback into a semi-supervised learning framework to improve the state-of-the-art algorithms for anomaly detection and to investigate solutions for adding spectrum sensing and anomaly detection in the O-RAN edge (Obj4). To build a signal transmitter localization framework that does not collaborate with the target devices for the purpose of localization (**Obj5**). To design new algorithms for building efficient and reliable measurement-based mobile coverage and performance maps for 6G network performance optimizations by leveraging the data collected from the terrestrial and aerial nodes (**Obj6**).

Task 2.1: Scalable anomaly detection computing framework for IoT spectrum sensors (TU Delft, Obj4, DC4)
DC4 studies and proposes strategies for embedded processing on the sensor or federated learning in a local group of edge sensors with the ambition to keep as much generic spectrum anomaly detection information as possible. The main objective of the feature computation is the compression of the massive amounts of sensed data. optimized for the specific purpose of detecting anomalies, in addition to improving privacy or other non-technical characteristics of the crowd-sourced spectrum sensing framework. The generic and scalable anomaly detection framework will work over all bands but can detect band-specific anomalies.

Task 2.2: General-purpose non-cooperative signal transmitter localisation (**IMDEA**, **Obj5**, **DC5**)
The localization of signal transmitters typically assumes that there exists a network synchronization mechanism and that the transmitters cooperate with the localization process. **DC5** studies system-oriented algorithms that will remove these hypotheses and make use opportunistically signals of the environment (LTE, DAB, Mode-S, etc.) to provide time synchronization at the receiving network, without actively sending any signals to the intended target device, and extracting temporal features of the signals that only exploit the waveform structure of the transmitter to be localized. **DC5** will then extend the framework to infer movements of several target devices, considering impairments from the receiving network, such as frequency and bandwidth of observation.

Task 2.3: Geo-statistical analysis of spectrum data for coverage/performance maps (**TID**, **Obj6**, **DC6**)
DC6 explores and designs new algorithms to build efficient and reliable measurement-based mobile coverage and performance maps, by using large spectrum dataset collected by sensors of SpecX network. DC**6** creates mobile coverage and performance maps for any technologies (e.g., 4G/LTE, 5G) in different areas and times. DC**6** will also work closely with operators within the Telefonica corporation (e.g., O2 UK, Movistar Spain). By contrasting the expected radio coverage of the network with the actual experience of the end-user (from mobile apps), DC**6** will work towards building novel anomaly detection approaches that can alert radio planning teams about potential suboptimal configurations.

Deliverables: **D2.1-D2.3** for **DCs 3-6** (see **Table 11**)

Connection to other WPs: ML HW acceleration, anomaly detection, edge sensing (WP1), applications-oriented deployments (WP3)

WP3	**Applications**	**M7-42**	**DCs 7-10**
Lead beneficiary	**KU Leuven**	**Recruiting beneficiaries: CNIT, TU Delft, IMDEA, KU Leuven**	

Objectives: To investigate solutions for the orchestration of network resources based on anomaly detection and spectrum sensing and to propose scalable sensing and access frameworks for massive Internet of Things (**Obj7**). To exploit mobile cells to satisfy high and dynamic demands on wireless capacity and integrate drone-based sensing and access in converged aerial-terrestrial networks (**Obj8**). To develop electrosmog sensing techniques for dense deployments in smart cities, and to understand the fundamental limits of sensing with embedded sensors (**Obj9**). To identify the possible risks/threats related to wireless connections for safety-critical applications in Industry 4.0, to develop a systematic approach on how to react to a possible anomaly in the used spectrum for a safety-critical wireless connection, and to test the approach in applications such as collaborative robots and autonomous vehicles/drones (**Obj10**).

Task 3.1: Orchestration and anomaly detection for massive IoT (CNIT, Obj6, DC7)
DC7 investigates how to employ radio sensing algorithms to infer the status of distributed, heterogeneous massive IoT deployments, based on the joint analysis of spectral information. **DC7** specifically focuses on algorithms for signal feature extraction, anomaly detection and signal classification (object of investigation in WP1). Different spectrum sensors could estimate different spectrum anomalies due to interference, etc. **DC7** evaluates orchestration policies for computation tasks that can optimize the accuracy of the anomaly and classification algorithms.

Task 3.2: Mobile cells for 6G networks (TUD, Obj8, DC8)
DC8 studies how to exploit the movement of BSs (mobile cells) to satisfy the high and dynamic demand on wireless capacity, not only in the time domain but also in the 3D spatial domain. The BSs can be relocated by robots/drones to predefined locations that have the capabilities (such as power and fiber/wireless backhaul) to host BSs, or are directly hosted by robots that can move freely on the ground, or by drones. The awareness of the spectrum knowledge and coverage map in the surroundings (the research of **DC6**) plays an important role here. With further information on the location of the users, **DC8** will study how to properly place and configure the mobile cells to satisfy the dynamic demands on wireless capacity. All in all, **DC8** studies how to provide pervasive and reliable 6G service without the need to deploy a vast number of geo-fixed BSs.

Task 3.3: Electrosmog inference and forecast (IMDEA, Obj9b, DC9)
DC9 studies innovative tools – based on IoT sensors and large-scale crowdsourcing initiatives to massively deploy a set of low-cost Electromagnetic Field (EMF) probes over the territory. **DC9** will develop reconfigurable IoT spectrum sensors with embedded software capabilities to collect EMF measurements. Innovative low-complexity algorithms that can run on embedded sensors with bandwidth smaller than the one of 5G and beyond transmitters will be designed and evaluated. Innovative techniques will be then applied by **DC9** to forecast the EMF exposure and patterns over short and medium periods of time.

Task 3.4: Spectrum-awareness empowered wireless systems for Industry 4.0 applications (KU Leuven, Obj10, DC10)
DC10 studies systematic approach, based on the spectrum anomaly detection, to ensure a dependable wireless connection which is robust and low-latency. **DC10** will develop a methodology on how the whole safety-critical wireless interconnected system should react in case an anomaly is detected. For this, **DC10** will start from the latest developments in run-time safety assurance, EMI risk management and self-adaptive systems. **DC10** and **DC8** will share knowledge and insights on achieving reliable wireless networks. The research of **DC6** will help realize the project of DC**10**. The developed methodology can be used not only in Industry 4.0 localized networks, but also in private 5G+ networks for safety-critical applications.

Deliverables: **D3.1-D3.3** for **DCs 7-10** (see **Table 11**)

Connection to other WPs: Signal feature extraction, anomaly detection and signal classification, accurate beamforming and scalable CSI estimation (WP1); Convergence of ML and edge computing (WP2).

WP4	**Training**	**M7-48**	**DCs 1-10**
Lead beneficiary	**IMDEA**		

Objectives: To closely follow-up on and support the training programmes of the 10 DCs.

Description: The training programme is described in details in **Section 1.2**. The main tasks of this WP are: to follow up on and support local expert training; to organise network-wide S/T and soft-skills training during 7 events (in cooperation with MST); to follow up with PCDP writing and updates, to be performed in particular during WP5 Consortium meetings during 7 network-wide events.

Deliverables: **D4.1-4.14** (see **Table 11**)

WP5	Dissemination, outreach and exploitation	M1-48	DCs 1-10
Lead beneficiary	**IMDEA**		

Objectives: To expand the visibility and exploitation of spectrum analytics as a service. To coordinate dissemination of the research results to peers and general public. To exploit the research results, run for innovation competitions and develop business cases.

Task 5.1: Dissemination and outreach (IMDEA + all other beneficiaries and partners)
The SpecX consortium drafts the "dissemination and communication plan" at the beginning of the project. Then, the plan is executed, monitored, and updated when necessary, in accordance with the guidelines from the EC.

Subtask 5.1.1: Academia and industry. SpecX disseminates its achievements to the academia and industry mainly through peer-reviewed papers at very good journals and conferences. Besides, the 10 DCs will develop demos and present them at flagship conferences to increase the visibility and impact of SpecX and its research results.

Subtask 5.1.2: Communication and public engagement. SpecX communicates to the general public the importance of spectrum sensing and analytics for future digital societies, and the contributions of SpecX in achieving a sustainable and powerful spectrum analytics service. The consortium leverages the website of SpecX, twitter, innovation competitions, and interviews to achieve this target.

Task 5.2: Exploitation (KU Leuven + all other beneficiaries and partners)
The exploitation strategy is detailed in Section 2.3.2 and Figure 4. It is developed at two levels: (1) Each partner exploits its own research; (2) the SpecX consortium exploits the research results as a whole unit, coordinated by IMDEA, following the IP procedures defined in the Consortium Agreement. An exploitation plan is developed within 12 months after the start of the project, and will be updated annually. From the second year on, the 10 DCs are highly involved in the evolution of the exploitation plan. Funds are reserved by each beneficiary for possible patenting of the research outcomes. Exploitation covers the four exploitation routes (cf. Section 2.3.2), which are actively designed for each DC topic, together with the DCs and their industrial (co-)supervisor.

Deliverables: D5.1-5.5 (see Table 11)

WP6	Management and recruitment	M1-48
Lead beneficiary	**IMDEA**	

Objectives: To organise the timely recruitment of the 10 DCs. To monitor the process and support the implementation of the project. To monitor the compliance of project partners with their obligations. To collect and review reports and other deliverables and submit them to the European Commission in a timely manner. To protect personal data and assess dual use items. To organise network-wide events and meetings. To manage the experiments within the project.

Description: The structure and methodology of management is detailed in Section 3.2.

Deliverables: D6.1-6.9 (see Table 11)

3.1.3 Deliverables List

Table 11. Deliverables List

Scientific Deliverables						
No.	**Title**	**WP**	**Lead benefi.**	**Type**	**Dissem.**	**Due Date**
D1.1	State of the art review with research progress on Sensing and Infrastructure	1	RWTH	PDE	CO	**M12**
D1.2	Mid-term research progress reports on Sensing and Infrastructure; overview of research activities and the status of the results	1	RWTH	PDE	CO	**M26**
D1.3	Final research progress reports on Sensing and Infrastructure; final work, tools developed, software and results available	1	RWTH	PDE	CO	**M42**
D2.1	State of the art review with research progress on Data Analysis	2	TU Delft	PDE	CO	**M12**
D2.2	Mid-term research progress reports on Data Analysis; overview of research activities and the status of the results	2	TU Delft	PDE	CO	**M26**
D2.3	Final research progress reports on Data Analysis; final work, tools developed, software and results available	2	TU Delft	PDE	CO	**M42**
D3.1	State of the art review with research progresses on Applications	3	KU Leuven	PDE	CO	**M12**
D3.2	Mid-term research progress reports on Applications; overview of research activities and the status of the results	3	KU Leuven	PDE	CO	**M26**
D3.3	Final research progress reports on Applications; final work, tools developed, software and results available	3	KU Leuven	PDE	CO	**M42**
Management, Training, Recruitment and Dissemination Deliverables						
No.	**Title**	**WP**	**Lead benefi.**	**Type**	**Dissem.**	**Due Date**
D4.1-4.4	Annual report on 10 Personal Career Development Plans	4	IMDEA	R	CO	**M12,M24, M36, M48**
D4.5-4.8	Annual report on training activities, presentation of the results of past events and detailed planning of upcoming events **(4 deliverables)**	4	IMDEA	Other	CO	**M12,M24, M36, M48**
D4.9-4.10	SpecX Summer School and Symposium **(2 deliverables)**	4	IMDEA	PDE	PU	**M24,42**
D4.11-4.14	Annual report on secondments, description of the research conducted, tie-ins with the research direction of DCs at the hosting institution **(4 deliverables)**	4	Beneficiaries	R	CO	**M12,M24, M36, M48**
D5.1-5.4	Annual report on dissemination, communication and exploitation results, including review of strategies for target groups **(4 deliverables)**	5	IMDEA	R	CO	**M12,M24, M36, M48**
D5.5	Roadmap for exploitation and long-term impact beyond the project	5	IMDEA	R	CO	**M48**
D6.1	Consortium agreement	6	IMDEA	ADM	CO	**M2**
D6.2	Website (public part as well as internal part (protected area: intranet))	6	IMDEA	ADM	PU	**M2**
D6.3	Recruitment event	6	IMDEA	ADM	CO	**M4**
D6.4	Data Management Plan (DMP)	6	IMDEA	R	PU	**M6**

D6.5	Progress report to the REA	6	IMDEA	ADM	CO	**M13**
D6.6-6.8	Full reports (Periodic Report and Final Report) from the DCs (**3 deliverables**)	6	IMDEA	R	CO	**M14,26,42**
D6.9	Inputs for policy feedback / policy brief	6	IMDEA	ADM	CO	**M48**

3.1.4 Milestones List

Table 12. Milestones list (these are also indicated as "**mX.Y**" in the Gantt chart) (additional S/T milestones provided in DC Tables)

mX.Y	Title	WP	Lead Bene.	Due	Means of verification
m5.1	ADM	5	IMDEA	**M2**	Website on-line
m6.1	Recruit-ment	6		**M3**	20 DC candidates are preselected by core supervisors for the Recruitment Event
m6.2		6		**M4**	10 DCs are selected and recruited by Recruitment Committee
m4.1	PCDP	4		**M8**	10 Personal Career Development Plans are approved
m4.2	ADM	4		**M8**	10 DGCs formally established and approved by SB
m6.3		6		**M13**	Project check: middle-term meeting between REA and SpecX consortium
m6.4	Scien-tific	1-3, 6	Benefi.	**M17**	Formal doctoral school review meeting gives green light to DCs for PhD continuation
m6.5				**M24**	SB S/T evaluation/remediation of individual DCs based on scientific milestone at **M24**
m1.1		1	KU Leuven	**M42**	DC1: Feature extractions in local and telecom edge computation
m1.2			CNIT	**M42**	DC2: Edge computation framework for spectrum sensing
m1.3			RWTH	**M42**	DC3: Efficient methods using transceiver design and protocol of gNBs for spectrum sensing
m2.1		2	TU Delft	**M42**	DC4: Anomaly detection with data fusion of multiple heterogeneous and compressed features
m2.2			IMDEA	**M42**	DC5: Localization and analytics of transmitters assuming static and moving targets
m2.3			TID	**M42**	DC6: Evaluation of proposed coverage map method with real world data from operator
m3.1		3	CNIT	**M42**	DC7: Design an efficient resource allocation scheme using the sensing knowledge
m3.2			TU Delft	**M42**	DC8: Experimental demonstration of the feasibility of mobile cells for 6G networks
m3.3			IMDEA	**M42**	DC9: Electrosmog framework using limited spectrum bands
m3.4			KU Leuven	**M42**	DC10: Safely interconnected wireless system for Industry 4.0

3.1.5 Recruitment Table per beneficiary

Table 13. Track record of main supervisors and Doctoral Guidance Committee members per DC

DC	Recruiting Participant	Planned start & Total Duration (month)	Doctoral Guidance Committee (DGC) Members (formal approval during 1st SB meeting)			Doctoral Schools to deliver the PhD degree
			Main academic supervisor [h-index & # PhDs supervised/ supervising] (Gender: m/f)	Academic co-supervisors (incl. extra members in DGC)	Industrial (co-) supervisors(s) in DGC	
DC1	KU Leuven	M7 & 36M	Prof. S. Pollin [h44 & 38 PhDs] (f)	Dr. R. M. Alonso [KU Leuven]	Dr. A. Voicu [Ericsson]	KU Leuven Doctoral School
DC2	CNIT	M7 & 36M	Dr. S. Bartoletti [h15 & 1 PhDs] (f)	Prof. G. Bianchi [UNITV]	Dr. T. Moore [ACC]	UNITV Doctoral School
DC3	RWTH	M7 & 36M	Prof. M. Petrova [h31 & 11 PhDs] (f)	Prof. S. Pollin [KU Leuven]	Dr. A. Voicu [Ericsson]	RTWH Doctoral School
DC4	TU Delft	M7 & 36M	Prof. K. Langendoen [h42 & 25 PhDs] (m)	Profs. G. Lan and Q. Wang [TU Delft]	Dr. T. Moore [ACC]	TU Delft Doctoral School
DC5	IMDEA	M7 & 36M	Prof. D. Giustiniano [h32 & 14 PhDs] (m)	Dr. G. Santaromita [IMDEA]	Dr. V. Lenders [ESense]	UC3M Doctoral School
DC6	TID	M7 & 36M	Dr. A. Lutu [h16 & 11 PhDs] (f)	Prof. P. Serrano [UC3M]	Dr. V. Lenders [ESense]	UC3M Doctoral School
DC7	CNIT	M7 & 36M	Prof. P. Casari [h35 & 8 PhDs] (m)	Prof. F. Granelli [UNITN]	Dr. A. Saavedra [NEC]	UNITN Doctoral School
DC8	TU Delft	M7 & 36M	Prof. Q. Wang [h20 & 7 PhDs] (m)	Prof. F. Kuipers [TU Delft]	Dr. A. Saavedra [NEC]	TU Delft Doctoral School
DC9	IMDEA	M7 & 36M	Prof. J. Widmer [h52 & 15 PhDs] (m)	Dr. T. Otim [IMDEA]	Dr. A. Lutu [TID]	UC3M Doctoral School
DC10	KU Leuven	M7 & 36M	Prof. D. Pissoort [h17 & 24 PhDs] (m)	Dr. T. Claeys [KU Leuven]	Dr. A. Lutu [TID]	KU Leuven Doctoral School

Table 14. Individual research projects

DC1 [KU Leuven]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D1.1-D1.3, D4.11-D4.14

Project Title and WP(s): Federated learning for aerial and terrestrial spectrum sensors, WP1
Doctoral School Enrolment: KU Leuven Doctoral School

Objectives: To design a complete IoT sensing device capable of both local or connected sensing, in aerial or terrestrial settings, using hardware acceleration for machine learning at the edge. To design a scalable computing framework using federated learning, for spectrum analysis with sparse aerial sensors or dense terrestrial sensors. These applications have computational constraints (e.g., no BS with powerful capabilities involved when considering aerial sensors). To co-optimize the deep learning on the sensors and the telecom edge, for enhanced 3D spectrum use prediction (**Obj1**).

Expected results: Complete wideband sensor design with local computing capabilities at the edge. Scalable spectrum analysis framework using federated learning, allowing local learning with central coordination applicable to sparse aerial and dense terrestrial settings.

Milestones: Wideband sensor design with local feature computation capabilities (**M24**). Federated learning design for sparse or dense settings. Trade-off analysis between local and centralised computation for prediction (**m1.1**) (**M42**).

Planned secondments: 1) Ericsson (non-academic) (4 months, M13-M16): Data analysis and modelling for coexistence of networks based on cellular technologies, with A. Voicu (Key Performance Index (KPI): joint conference paper); **2) RWTH** (4 months, M25-M28): Co-optimization of spectrum prediction with aerial and terrestrial sensors, with M. Petrova (KPI: joint journal paper)

Exploitation potential: Follow-up projects targeting higher Technology Readiness Levels (**EX1**). Prototype commercialisation (**EX4**).

DC2 [CNIT]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D1.1-D1.3, D4.11-D4.14

Project Title and WP(s): Spectrum sensing at the edge, WP1
Doctoral School Enrolment: Doctoral School of University of Rome Tor Vergata (UNIRM)

Objectives: Identification of the elements of edge infrastructures (e.g., resource allocation, anomaly detection, traffic forecast, SW/HW components) that can benefit from the availability of spectrum sensing information. Design of techniques and methods to leverage sensing information for improving the quality of service provided to users. Integration of spectrum sensing methods in edge infrastructure (**Obj2**).

Expected results: Algorithms and architectures to leverage spectrum sensing measurements in telecom edge infrastructure mechanisms (e.g., anomaly detection, user and traffic pattern prediction and orchestration). Algorithms and architectures to support and/or improve spectrum sensing measurements and mechanisms in telecom edge infrastructures.

Milestones: Identification of the elements of telecom edge infrastructures that could benefit from spectrum sensing information. Development of algorithms and architectures for modification/design of the identified elements to improve user quality of service (**M24**). Improvements of spectrum sensing mechanisms leveraging telecom edge infrastructure (**m1.2**) (**M42**).

Planned secondments: 1) ACC (non-academic) (4 months, M13-M16): O-RAN telecom measurements, with T. Moore (KPI: joint conference paper); **2) IMDEA** (4 months, M24-M27): Spectrum sensing with edge infrastructure, with J. Widmer (KPI: joint journal)

Exploitation potential: Follow-up projects targeting higher Technology Readiness Levels (**EX1**). Patents and licensing (**EX3**).

DC3 [RWTH]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: : D1.1-D1.3, D4.11-D4.14

Project Title and WP(s): Sensing-capable 6G radio access infrastructure, WP1
Doctoral School Enrolment: Doctoral School of RWTH Aachen University (RWTH)

Objectives: To study and identify enablers for realizing and integrating a sensing functionality in the future RAN components. Study techniques for both data-driven and predictive dynamic spectrum allocation and sharing. To identify how to integrate spectrum sensing mechanisms in telecom edge infrastructure. (**Obj3**).

Expected results: Energy efficient, low overhead and distributed sensing functionality implemented across radio network elements. Mechanisms and procedures for creating environment knowledge including spectrum and traffic patterns, and sharing the knowledge across the network. Agile resource allocation suited for variety of applications by leveraging short-term sensing and long-term spectrum information.

Milestones: Identification of sensing parameters, storing and processing of the data. Evaluating the accuracy and the complexity of the proposed sensing algorithm (**M24**). Prototyping and performance analysis of the sensing mechanism in a testbed of of-the-shelf APs or SDR-based gNBs. Design and showcasing an efficient resource allocation scheme using the sensing knowledge (**m1.3**) (**M42**).

Planned secondments: 1) KU Leuven (4 months, M12-M15): Design and evaluation of sensing algorithms, with S. Pollin (KPI: joint conference paper); **2) Ericsson (non-academic)** (4 months, M25-M28): Design of a sensing knowledge-based predictive resource allocation scheme, with A. Voicu (KPI: journal paper)

Exploitation potential: Follow-up projects targeting higher Technology Readiness Levels (**EX1**). Prototype commercialisation (**EX4**).

DC4 [TU Delft]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D2.1-D2.3, D4.11-D4.14

Project Title and WP(s): Multi-sensor and multi-band semi-supervised anomaly detection, WP2
Doctoral School Enrolment: TU Delft

Objectives: To improve state-of-the-art algorithms for feature extraction, anomaly detection, and classification. To study how to incorporate expert feedback into a semi-supervised learning framework and how to run the framework on embedded devices. To combine heterogeneous data streams for wideband and narrowband cooperative and non-cooperative sensors (**Obj4**).

Expected results: A strategy for combining data or compressed features from multiple sensors. A framework for creating knowledge such as anomaly detection and classification based on that fused data. A strategy for including expert feedback in the anomaly detection and classification step.

Milestones: Wideband anomaly detection and classification using uncompressed data in the RAN/O-RAN edge. Semi-supervised anomaly detection with expert feedback (**M24**). Anomaly detection using data fusion of multiple heterogeneous and compressed features on embedded devices (**m2.1**) (**M42**).

Planned secondments: 1) ACC (non-academic) (4 months, M13-M16): Algorithm design for federated anomaly detection and classification in the O-RAN edge and on embedded devices, with T. Moore (KPI: joint conference paper); **2) AlbanyU** (4 months, M21-M24): Impact of expert feedback from telecom edge on the semi-supervised learning framework, with M. Zheleva (KPI: joint journal)

Exploitation potential: Follow-up projects targeting higher Technology Readiness Levels (**EX1**).

DC5 [IMDEA]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D2.1-D2.3, D4.11-D4.14

Project Title and WP(s): Non-collaborative positioning of transmitters and patterns of movements, WP2
Doctoral School Enrolment: Doctoral School of Carlos III University of Madrid (UC3M)

Objectives: Design distributed algorithms to localise any wireless transmitter in mobile environments that does not collaborate (passive positioning). Study impact on waveform on positioning accuracy. Design of algorithms exploiting time and Doppler, working with non-coherent receivers. Extraction of analytics from multiple target users (**Obj5**).

Expected results: Algorithms to passively localize radio signal transmitters with measured time, Doppler and angle information. System evaluation of distributed localization algorithms in mobile environment with multiple users. Framework for inferring people movements from non-collaborative localization data.

Milestones: Methods for TDoA localization in embedded platforms using low-cost SDR. Methods for Doppler based localization in embedded platforms for mobile targets using low-cost SDR (**M24**). Localisation and analytics of several transmitters regardless of their band of operation assuming both static and moving targets (**m2.2**) (**M42**).

Planned secondments: 1) ESense (non-academic) (4 months, M15-M18): Design and implementation of localisation algorithms with IQ data collected from Electrosense network at different locations, with V. Lenders (KPI: joint conference paper); **2) RWTH** (4 months, M26-M29): Modelling patterns of movements with IoT receivers, with M. Petrova (KPI: joint journal paper)

Exploitation potential: Follow-up toward higher Technology Readiness Levels (**EX1**). Prototype commercialisation (**EX4**).

DC6 [TID]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D2.1-D2.3, D4.11-D4.14

Project Title and WP(s): Geo-statistical analysis of spectrum data for coverage/performance maps, WP2
Doctoral School Enrolment: UC3M

Objectives: To analyse large-scale data collected from spectrum sensing. To contrast network-side planned radio coverage with the actual experience of the end-users and build anomaly detection approaches, traffic and user patterns forecast, answer what-if questions regarding the network deployment, etc. to help radio planning teams. To design new approaches for building efficient and reliable measurement-based mobile coverage (**Obj6**).

Expected results: Data analytics approaches and estimation techniques for building efficient coverage and performance maps. Anomaly detection and predictions mechanisms approach to detect/predict deviations from the planned/expected radio coverage of real-world operators by contrasting the theoretical coverage with the end-user experience. Novel methodology for building radio coverage maps by controlling the network-side state with end-user measurements (e.g., drive tests from the operator, crowd datasets, etc.).

Milestones: Data analysis to understand the challenges for building reliable coverage maps (**M24**). Algorithm design for building radio coverage maps by controlling the network-side state with end-user measurement. Evaluation of the proposed approach using data from a real-world mobile network operator (**m2.3**) (**M42**).

Planned secondments: 1) UC3M (4 months, M14-M17): Big data analysis from spectrum sensing, with P. Serrano (KPI: joint conference paper); **2) ESense (non-academic)** (4 months, M23-M26): Algorithm for reliable mobile coverage, with V. Lenders (KPI: joint journal)

Exploitation potential: Follow-up projects targeting higher Technology Readiness Levels (**EX1**). Patents and licensing (**EX3**).

DC7 [CNIT]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D3.1-D3.3, D4.11-D4.14

Project Title WP(s): Orchestration and anomaly detection in massive IoT deployments, WP3
Doctoral School Enrolment: Doctoral School of University of Trento (UNITN)

Objectives: To employ radio sensing algorithms to infer the status of distributed, heterogeneous massive IoT deployments, based on the joint analysis of spectral information. To implement orchestration policies for computation task allocation so as to optimize the performance of status inference, also considering the architecture of future RAN infrastructure. To combine principles of network virtualization, optimization, sensor placement, and machine learning in order to achieve the above objectives (**Obj7**).

Expected results: Algorithms and architectures to collect and make sense of distributed RF spectrum sensing data in order to infer the status and orchestrate distributed and massive IoT deployments. Algorithms for management based on inference from the sensed RF data.

Milestones: Lightweight spectrum analytics algorithms for the analysis of jointly sensed RF information, including correlation studies and feature extraction (**M24**). Actuation algorithms to exploit multi-modal RF analytics for orchestration and anomaly detection of massive IoT deployments (**m3.1**) (**M42**).

Planned secondments: 1) SLU (5 months, M11-M15): Optimization and scaling of sensing computation placement algorithms for anomaly detection, with F. Esposito (KPI: joint conference paper); **2) NEC (non-academic)** (4 months, M23-M26): Design of a method to deploy, and test machine learning models in an edge-to-fog continuum for IoT resource utilization, with A. Garcia (KPI: joint journal)

Exploitation potential: Follow-up projects targeting higher Technology Readiness Levels (**EX1**). Patents and licensing (**EX3**).

DC8 [TU Delft]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D3.1-D3.3, D4.11-D4.14

Project Title and WP(s): Drone-hosted mobile cells for 6G, WP3
Doctoral School Enrolment: Doctoral School of Delft University of Technology (TU Delft)

Objectives: To propose an analytical model for the cell planning of drone-hosted mobile BSs based on user location and the coverage and interference map obtained from spectrum sensing, to achieve interference-free and pervasively high data rate for 6G networks in all possible scenarios. To study the trade-off between the physical adaptation (e.g., movement) of the BSs and the degradation of the system performance in mobile user scenarios. To study the impact of the quality of wireless backhaul on the performance of drone-hosted cells in scenarios when a fibre backhaul is not available. To experimentally demonstrate the feasibility of exploiting drone-hosted mobile cells for 6G networks (**Obj8**).

Expected results: A model on cell planning of drone-hosted mobile BSs that can achieve interference-free and pervasive line-of-sight communications in different scenarios. Insights into achievable gain versus overhead on infrastructure, especially drone movements.

Milestones: An accurate model for the cell planning of drone-hosted mobile BSs is derived. Trade-off between BS location adaptation and cell performance (**M24**). Experimental feasibility demonstration of drone-hosted mobile cells for 6G with backhaul considerations (**m3.2**) (**M42**).

Planned secondments: 1) KU Leuven (4 months, M13-M16): Model design of cell planning of drone-hosted mobile BS, with S. Pollin (KPI: joint conference paper); **2) NEC (non-academic)** (6 months, M27-M32): Impact of backhaul links on the mobile cell performance, with A. Saavedra (KPI: joint journal paper)

Exploitation potential: Follow-up implementation into the products of Ericsson and NEC (**EX2**).

DC9 [IMDEA]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D3.1-D3.3, D4.11-D4.14

Project Title and WP(s): Electrosmog inference, WP3
Doctoral School Enrolment: Doctoral School of Carlos III University of Madrid (UC3M)

Objectives: To measure the electromagnetic exposure using low-cost spectrum sensors. To design low-complexity algorithms that can work with IQ signals collected with sensors of bandwidth smaller than the one of the transmitters (such as 5G and beyond). To experimentally test the proposed solution on embedded devices (**Obj9**).

Expected results: Provide quantitative assessment of electromagnetic exposure with low-cost spectrum sensors. Design of analytics for inferring and forecasting the radio exposure. Proof of concept with prototype sensing real transmissions.

Milestones: Fundamental understanding of the limits of electromagnetic exposure measurements with embedded and software-defined spectrum sensors. Comparison of performance with respect to more traditional methods to measure the electrosmog (**M24**). Algorithms that fuse information from several sources to forecast the exposure (**m3.3**) (**M42**).

Planned secondments: 1) KU Leuven (4 months, M15-M18): Design of low-cost algorithms in customized hardware accelerators, with S. Pollin (KPI: joint conference paper); **2) TID (non-academic)** (4 months, M26-M29): Measurement campaign with known transmission patterns of base stations, with A. Lutu (KPI: joint journal paper)

Exploitation potential: Follow-up implementation into the products of ESense (**EX2**).

DC10 [KU Leuven]	PhD: Yes	Start: M7	Duration: 36M	Main deliverables: D3.1-D3.3, D4.11-D4.14

Project Title and WP(s): Safety-assurance of highly dependable interconnected systems in Industry 4.0, WP3
Doctoral School Enrolment: KU Leuven Doctoral School

Objectives: To identify the possible risks and threats of using wireless connections for safety-critical applications in industry 4.0 and drones. To develop a systematic approach on how to react on a possible anomaly in the used spectrum for a safety-critical wireless connection. To apply and test the developed approach in industry-oriented case studies (**Obj10**).

Expected results: Risk analysis of the use of wireless connections in Industry 4.0 and drones. Comprehensive guidance document on how to react to a detected, possibly critical interferer in order to ensure safety and low-latency. Successful application of the systematic approach in an Industry 4.0 private wireless network case study and or drones.

Milestones: White paper on the safety risks of using wireless connections within Industry 4.0. Report describing the generic methodology on how to ensure safety when a possibly critical interferer is detected (**M24**). Demonstration of the methodology on an Industry 4.0 wireless network case study (**m3.4**) (**M42**).

Planned secondments: 1) TU Delft (4 months, M16-M20): Safety case of a drone hosted mobile cell, with Q. Wang (KPI: joint conference paper); **2) TID (non-academic)** (4 months, M25-M28): Methodology demonstration of anomaly detection in mission and safety critical industry 4.0 cases with a. Lutu (KPI: joint journal paper)

Exploitation potential: Follow-up implementation into the products of TID (**EX2**).

3.1.6 Progress monitoring and evaluation of individual projects

SpecX has clearly identified main objectives (**Obj1-Obj10**, **Table 1**), deliverables (**DX.Y**, **Table 11**), milestones (**mX.Y, Table 12**), delivery dates (**Table 11** and **Table 12**) and exploitation routes (**EX1-EX4**, **Figure 4**). This allows for an impartial monitoring of the project progress, both by the project management (MST, SB) and the EC. The governance structure for SpecX (cf. **Section 3.2.1**) allows for quality control at various levels. Moreover, reviews by an external advisory group (to be formed after the kick-off of the DN) will be used to further improve the quality control methods used by SpecX. Furthermore, SpecX uses a **two-level progress monitoring strategy** to evaluate the progress of the 10 individual projects at both the local Doctoral School beneficiary level (cf. 10 DGCs) and the DN project level. DCs will produce different reports to be monitored: (1) A PCDP as a basis for (2) the comprehensive RTDE Progress Report (word doc) that is regularly updated (in view of the DGC; TSC and SB meetings), (3) 3-monthly DC Progress Presentations (slides) which are used for the WP Meetings, (4) shorter Secondment Progress Reports, and (5) Evaluations and surveys reports each time a Secondment or training is completed, which are used for measuring the DC's training satisfaction. The RTDE report covers (1) personal info; (2) S/T progress; (3) Training progress; (4) Dissemination and outreach; (5) Exploitation. All DCs integrate a detailed PhD Work Plan in their RTDE report. SpecX also foresees a genuine involvement of the DCs in the progress monitoring. More details are presented in **Table 16**.

Table 16. Progress monitoring strategy *(TRN: training; C&D: Communication & Dissemination; EXP: exploitation)*

Monitoring level	Frequency	Means of reporting	Who monitors and provides feedback?	Who monitors and provides feedback?	What is monitored? S/T	TRN	C&D	EXP
At beneficiary & Doctoral School level (+secondment level)	Monthly	DC progress report (word doc)	Face-to-face meeting	Main supervisor + co-supervisor(s)	✓	✓	✓	
	4 times (**M16-M28-M40-M54**)	DC RTDE progress report (word doc)	Face-to-face doctoral review meeting	DGC (incl. non-academic supervisor(s))		✓	✓	✓
	Every 2 weeks during secondments	Secondment progress report (word doc)	Face-to-face meeting with secondment supervisor	Secondment supervisor (non-academic ones focus on exploitation)	✓	✓		✓
	Every end of the Secondment	Secondment evaluations survey report	Online survey to be filled by each DC	DGC (incl. non-academic supervisor(s))	✓	✓	✓	✓

At DN project level	Every 5 to 6 months (in between 2 Network-Wide Events) (**M10-15…39**)	DC progress presentation (slides)	WP online meetings (DCs + WP Leader + S/T Coordinator)	WP leader + S/T Coordinator	✓	✓		
			WP meeting (full Network)	WP leader + S/T Coordinator + GC + feedback by other members	✓	✓		
			S/T coordinator feedback meeting (DCs + S/T Coordinator)	S/T coordinator	✓	✓		
	Each 5 to 6 months (at location of network-wide events) (**M8-13-18-24-30-36-42**)	DC RTDE progress report (word doc)	TSC meeting (Part 1)	Technical steering committee	✓			
			SB meeting (Part 2)	Supervisory Board		✓	✓	✓

3.1.7 Implementation Risks

The potential risks in SpecX associated with research, training, etc., are to be managed according to **Table 17**. Any unforeseen risks that manifest are reported immediately to the SB and TSC, depending on the risk. The SB or TSC then meet as soon as possible (also via teleconference) and decide on the appropriate contingency plans.

Table 17. Overview of main risk strategies – contingency plan

Risk domain	Description of risk	WP	Likelihood	Impact	Proposed mitigation scenario
Training	Envisaged experts for lectures not available	5	Medium	Low	Rely on network of SpecX participants to identify alternative speakers, adjust topics of specialised lectures. Links with other projects allow a greater pool of experts.
	Training progress of DC insufficient	5	Medium	Medium	• Short-term intervention by local supervisor and WP5 Leader based on PCDP. • WP5 team to discuss training progress and provide remedial action.
	PhD aborted when funding stops after 36M	5	Medium	Very high	SpecX beneficiaries foresee additional funding for the required time to finish the PhD in accordance with the regular PhD time in the country of origin.
S / T	Delays due to interconnections between DC projects or the inefficient collaboration among some of the DCs	1-3	Medium	Low	All DCs can start their work as soon as they are recruited. Soft-skill training on teamwork is provided during the second network-wide event to ensure smooth collaborations among the DCs. Nevertheless, there is no fundamental interdependence which impedes the progress of the individual DCs. Furthermore, exploration of cooperation opportunities is stimulated so that DCs can build further upon each other's results. IMDEA is in charge of the experiments transfers. In case there are delays in transfer of such results, solutions will be discussed in TSC meetings.
	Technical failure	1-3	Medium	Medium	The TSC meeting seek for case-by-case solutions in case of unforeseen technical failure occurring in the individual projects of the DCs.
	Spectrum sensing architecture not impactful or infeasible	1	Very low	High	Preliminary results, spectrum sensing and data analytics architectures already in place (e.g., Electrosense) show feasibility and great impact of spectrum data analysis. Agile approach will be applied to re-iterate infrastructure & algorithm design.
	Data analytics too complex or ineffective	1, 2	Low	High	Re-iterate feature extraction & learning schemes. Try advanced learning architecture & exchange more data among probes. Incorporate additional expert feedback.
	Slow S/T advancement affects applications	3	Low	High	All S/T objectives are tuned to be feasible for a typical doctoral training. Early in-network dissemination of results will identify (un)feasible approaches.
	Low S/T competence of supervisors	1-3	Very low	Very high	• Participants are thoroughly screened in the project-writing phase. Strong TSC in SpecX to support all supervisors. • Two-level quality control (two-level progress monitoring strategy (**Table 16**).
	Low S/T competence of DCs	1-3	Low	High	• High-profile recruitment methods and events planned; continuous progress monitoring (PCDP, RTDE) through DGC and SB (**Table 16**).
	Conflict Supervisor/DC	1-3	Medium	High	An ombudsperson is appointed to resolve such conflict. An anonymous feedback is in place where DCs can provide confidential comments to ombudsperson.
	Scientific misconduct	1-3	Very low	Medium	All DCs are informed on good practices and correct scientific behaviour. Evidence of scientific misconduct is reported to the SB/WP leader/coordinator and to the host institution, following the regular procedures, to ensure that appropriate actions are taken. Specific training is provided through the VITAE RDF (**Table 5**).
Exploita	IP conflicts	4	Low	High	CA with clear IPR and tech transfer guidelines; Supportive Exploitation Manager in MST; Clear screening method for publishing.
Management	Too ambitious timing for start-up	5/6	Medium	Low	Strict timing foreseen is based on achieved results in previous EU projects. The DGC continually helps tune timing for DCs and SC revises timelines at each NWE.
	Lack of sufficient applicants for DCs	6	Low	Medium	• High-profile recruitment event attracting the best students. Required profiles are indicated per DC position. • Additional targeted communication of vacancies, broadening research topics. • Transfer of candidates from one topic to another
	Not all DCs recruited at Recruitment Event	6	Low	Medium	IMDEA has excellent track record in effective recruitment. During RE: better to leave positions vacant (waiting for better candidates) than to recruit wrong candidates. Clear follow-up strategy: decentralised procedure to fill up vacancies is in place.

	Participant no longer willing to cooperate	6	Low	High	Participants know each other well based on prior joint projects. Stress-tested management structure with clear demarcation of responsibilities, conflict resolution, transparent voting systems, etc. As last measure, a replacement will be sought.
	GC or WP Leader unavailable	6	Low	High	Identification of substitutes prior to the start of the project (e.g., vice GC; vice-WP Leader appointed, being a colleague from the same institute, see **Section 4**).

3.1.8 Supervisory board

The SB consists of the GC (D. Giustiniano), the SC (S. Pollin), the training chairs (A. Lutu and M. Petrova), the WP1-5 Leaders and one representative from each beneficiary. Each beneficiary has one vote in the SB. Each of the associated partners, the ReC, and the WRC also has one representative in the SB but without voting right. The GC chairs the SB. During the SB meetings, an overview of the technical quality, training and dissemination and exploitation is presented by the WP leaders and an evaluation is conducted. An DC recruitment committee is assembled by the SB in **M1**. The SB meeting is organised twice a year along with the 7 network-wide events. An additional SB meeting takes place in **M48** without the network-wide workshop. The SB meeting are also organised for important and urgent decisions, and are carried out through conference calls. Decisions are preferentially made through a consensus procedure. If consensus cannot be made, decisions shall be taken by a majority of two-thirds (2/3) of the votes cast.

Gender aspects: Gender balance aspects are taken very seriously in SpecX (see **Section 1.2.3**). For instance, SpecX has female SC, female training co-chairs. The Recruitment Committee (RC) also has balanced gender. **Note that 3 of the 6 PIs of the beneficiaries and 4/10 of main supervisors are female.** Therefore, as voting right is only for beneficiaries, genders aspects will be duly taken into account any decision**.**

3.1.9 Recruitment strategy

Upon acceptance, the search for suitable candidates starts by internationally publishing ads in platforms such as Euraxess, ResearchGate, LinkedIn, and mailing lists such as TCCC. The basic rule for recruiting the appropriate candidates of the DCs in SpecX is according to normal recruitment strategies, such as previous publications, motivation for research, research/education background, among others. The pre- and final selection will be made in a collective process, led by the **Recruitment Committee** formed by experts with significant prior experience in research recruitment at their groups/institutions. Each applicant can apply for up to three DC openings, in order of preference. During the pre-selection stage, up to 20 candidates will be selected based on the above strategy. Then, they are interviewed in face-to-face meetings (if in EU; the recruiting institution provides traveling and accommodation support), and by conference calls if they are outside of EU. Specifically, the RC selects the DCs following an open, transparent, impartial and equitable recruitment procedure, on the basis of: (1) their scientific skills and the relevance of their research experience; (2) the impact of the proposed training on their careers; (3) the expected benefit of research exchange between the DC's home countries, the institutions and the host of the secondments; (4) in accordance to gender equality and minority rights. The candidates are ranked and a collective decision is made, accounting the order of preference. In this way, a complementary pool of DCs can be selected. All recruitments are in line with the European Charter for Researchers, providing the overarching framework for the roles and responsibilities of both researchers and employers. The Code of Conduct for the Recruitment of Researchers ensures that the selection procedures are transparent and fair. The RC will ensure that no conflict of interest exists in or arises from the recruitment. The recruitment strategy of SpecX fully complies with the definitions of merit from the Code of Conduct. For example, merit should be not measured based only on researcher's grades, but rather based on a complete range of evaluation criteria, such as teamwork, interdisciplinary knowledge, independent thinking, soft skills and awareness of the impact of research. The RC has members of both genders and considers the promotion of equal opportunities and **gender balance** as part of the recruitment strategy. **Special effort will be made to attract female researchers by aiming at recruiting at least one third female DCs.** Among equally qualified applicants, women receive preferential consideration. All DCs are employed on full-time contracts and are enrolled as PhD candidates. DCs are assisted with settling into their new countries and research environments through the Euraxess service for relocation. The DCs are entitled to pension contributions, paid holidays, and other employment benefits as governed by the beneficiaries.

3.2 *Quality, capacity and role of each participant, including hosting arrangements and extent to which the consortium as a whole brings together the necessary expertise*

3.2.1 Appropriateness of the infrastructure and capacity of each participating organisation

SpecX brings together some of the top groups in EU that are on the very forefront of wireless systems with particular focus on the cutting-edge spectrum sensing and analytics research. The details are presented in **Section 4**. Each participating organisation has facilities for supporting their specific research and training, as well as for hosting DCs. Half of the consortium members have unique and large-scale testbeds (see **Figure 2**) and significant expertise in carrying out highly relevant and practical systems research. The facilities can be leveraged by SpecX (DCs) for large-scale and realistic experiments. The SpecX consortium is created also with great care to combine complementary and interdisciplinary expertise spanning all aspects of wireless communication systems including wireless networks (telecommunications), SDR prototyping (system engineering), machine learning and deep learning (computer science), and signal processing (electronic engineering). In addition to complementary partner expertise, the SpecX programme features an extremely high innovation capacity thanks to the participation of institutions that cover the full innovation cycle from scientific discovery (8 academic participants) to test, manufacturing (Ericsson, NEC, and ACC), and finally consumer market (TID). In addition to these innovation partners, SpecX also links with not-for profit organisations such as Electrosense in Switzerland or large and recently established consortia such as SpectrumX in the USA, all with the ambition to strengthen the workforce and knowledge, while being exposed to the latest advancements at worldwide scale. The involvement of the members in major standardization task forces (e.g., 3GPP, IETF) further enhances the aforementioned cycle.

3.2.2 Consortium composition and exploitation of participating organisations' complementarities

SpecX consortium draws its talents from six EU member states, and is complemented by three non-EU members, with long prior experience in joint projects (e.g. IMDEA and KU Leuven have partnered with ESense since 2015). It consists of six beneficiaries (including two non-university beneficiaries) and five industry partners. SpecX's interdisciplinary and intersectoral consortium brings together unique and complementary expertise in all areas of wireless systems, with each participating organisation is fully engaged in the SpecX programme. The SpecX consortium covers the full spectrum sensing and enabled applications from fundamental research (AI-enabled multiband sensing and technology recognition, sparse sensing, etc.) to applied research (applications for mobile broadband, industry 4.0, and massive Internet of Things). The industrial partners are carefully chosen to cover all the essential fundamental and applied research areas of spectrum sensing, e.g., international vendors (Ericsson and NEC), system provider (ACC), and leading operator (TID), while also having overlapping interests (e.g., DC6 Geo-statistical analysis of spectrum data for coverage/performance maps, with involvement of both TID and ESense). The strength of the consortium is reflected by the fact that these partners are involved as coordinators or key partners in several EU or national projects that are complementary to SpecX, e.g., EU ORCA, LOCUS, NATO project SOCRATES and industrial funded project Electrosense, etc. These projects pave the way for the high-quality training of the 10 SpecX DCs. The distinct technical expertise of the consortium is detailed in **Section 6**. Both in terms of the involved organisations and lead supervisors, SpecX includes a premier team of highly respected researchers in spectrum sensing (D. Giustiniano, IMDEA, GC; S. Pollin, KU Leuven, SC; M. Petrova, RWTH and M. Zheleva, AlbanyU), telecom edge infrastructure and intelligence (A. Lutu, TID; P. Casari, UNITN), electrosmog (J. Widmer, IMDEA), wireless networking and embedded AI (Q. Wang, TU Delft), IoT (D. Pissoort, KU Leuven), among others. In terms of guaranteed project management expertise, SpecX is coordinated by IMDEA, which has ample experience in H2020 ITNs.

3.2.3 Commitment of beneficiaries and associated partners to the programme

The six beneficiaries and eight associated partners in SpecX collaborate closely to provide intersectoral and interdisciplinary training to the 10 DCs. The training programme offered by the partners involves: (1) participation in the SB and contribution to the network-wide events, summer school, and symposium (**Table 3**), (2) hosting secondments (**Table 13**), and (3) the industrial supervision of DCs (see DGCs, **Table 12**). Hence, the DCs benefit from the integrative activities between academia and industry by obtaining a full range of trainings, ranging from advanced education to practical applications. Also, the non-academic beneficiaries and partners gain insight into emerging problems, which creates novel initiatives for academic research, and they can use the unique facilities provided by the network. The non-academic partners are exposed to bright researchers and are informed about cutting-edge results, which also allows the non-academic participants to spot potential candidates for recruitment. The Supervisory Board constitutes a prime venue to monitor the commitment of all project members and encourage synergies from research to innovation and exploitation.

3.2.4 Funding of non-associated third countries (if applicable)

No beneficiary resides in a non-associated third country. The travel cost such as flight tickets and accommodation of the associated partners in the USA participating in the NWEs will be reimbursed by beneficiaries that organise the corresponding NWEs, as it will be detailed in the Consortium Agreement. For secondments towards the US associated partners (universities AlbanyU and SLU), we will apply the same rules as for other secondments within EU or associated/third-party countries. That is, the costs of the DCs' mobility will be covered by the beneficiaries that hire the seconded DCs.