PROJECT “LOCUS”: LOCalization and analytics on-demand embedded in the 5G ecosystem, for Ubiquitous vertical applicationS

Grant Agreement Number: 871249
(https://www.locus-project.eu/)

DELIVERABLE D1.3

“Project Vision and Roadmap, final version”

Deliverable Type:	R
Dissemination Level:	Public
Contractual Date of Delivery to the EU:	31/10/2022
Actual Date of Delivery to the EU:	31/10/2022
WP contributing to the Deliverable:	WP1 – Project Management
Editor(s):	CNIT, Stefania Bartoletti
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Internal Reviewer(s):	CNIT, Nicola Blefari Melazzi
Short Abstract:	The goal of this deliverable is to improve and update the project vision with respect to the original one presented in the project proposal. This allows also to renew the project roadmap to enhance LOCUS impact.
Keyword List:	Vision, Roadmap, Impact

Executive Summary

The Project Vision and Roadmap is a tool for helping the LOCUS Coordinator and Partners to reach two main aims:

- maintaining a clear vision of the most relevant intellectual and scientific directions in the research performed worldwide within the scope of the project; and
- coordinating the efforts and the activities for pursuing an efficient roadmap and for a proper management of the required actions.

A clear vision and a sound roadmap significantly affect the pace and evolution of the work planned and therefore its capability to move towards both R&D and economic/societal results.

The preliminary version of this document, D1.2, included inputs from authoritative white papers on B5G and 6G, as well as from recommendations of the Advisory Board and authors' own views, which updated the project vision. The Project roadmap has been then improved, based on such trends and Advisory Board recommendations. A subset of recommendations and suggestions coming from the updated vision has been implemented in the last year of the project. In this deliverable, the project vision is updated to reflect the alignment between the LOCUS project and the main trends and guidelines from and for LOCUS stakeholders and target audiences and describes the collective project vision, taking also into account all the work performed by the project, with the aim of offering a legacy for future work.

The deliverable is public and thus can be used to communicate the project vision to the external world and potentially be useful to fellow researchers and professionals.

Version Control Table			
Version N.	Purpose/Changes	Author (s)	Date
1.0	First draft	Andrea Conti	06/12/2020
1.1	Revision	Marco Chiani, Davide Dardari	12/01/2021
1.2	Revision	Nicola Blefari Melazzi	18/01/2021
2.0	Draft for the Final Version	Stefania Bartoletti	20/10/2022
2.1	Revision	LOCUS Consortium for the collective vision	30/10/2022
2.2	Final	Stefania Bartoletti, Nicola Blefari Melazzi	31/10/2022

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1 Introduction

The Project Vision and Roadmap is a tool for helping the LOCUS Coordinator and Partners in maintaining a clear vision of the most relevant intellectual and scientific directions in the research performed worldwide within the scope of the project, as well as coordinating the efforts and the activities for pursuing an efficient roadmap and for a proper management of the required actions.

A clear vision and sound roadmap significantly affect the pace and evolution of the work planned and therefore its capability to move towards both R&D and economic/societal results. With aim of keeping an eye on evolution to adapt the roadmap toward a more useful and impactful research, the deliverable builds on authoritative white papers on beyond 5G and 6G, as well as on recommendations of the LOCUS Advisory Board and on authors' own views.

1.1 List of Abbreviations

ABBREVIATION	FULL NAME
5G	fifth generation
6G	sixth generation
AI	Artificial Intelligence
DOW	description of work
GNSS	global navigation satellite system
LBS	location based services
MIMO	multiple-input multiple-output
ML	machine learning
PVR	project vision and roadmap
RAT	radio access technology
RTLS	real-time location services
SLAM	simultaneous localization and mapping
UWB	ultra-wideband

Table 1-1: Abbreviation List

1.2 Table Index

2 Project Vision and Related Updates and Improvements

2.1 Project Initial Vision

Context-awareness is essential for many existing and emerging applications. Context information greatly relies on location information of people and things. Global navigation satellite systems are denied in indoor environments, current cellular systems fail to provide high-accuracy localization, other local localization technologies (e.g., Wi-Fi or Bluetooth) imply high deployment, maintenance, and integration costs. Raw spatiotemporal data are not sufficient by themselves and need to be integrated with tools for the analysis of the behaviour of physical targets, to extract relevant feature of interests.

LOCUS is improving the functionality of 5G infrastructures to: i) provide accurate and ubiquitous location information as a network-native service; ii) derive more complex features and behavioural patterns out of raw location and physical events; and iii) expose them to applications via simple interfaces. Localization, together with analytics, and their combined provision "as a service", will greatly increase the overall value of the 5G ecosystem, allowing network operators to better manage their networks and to dramatically expand the range of offered applications and services. The current freedom to act on 5G system design, and availability of software network paradigms and AI techniques, uniquely combine in this historical moment to make it possible to radically improve the future network by endowing it with accurate on-demand localization and analytics.

LOCUS will showcase its solutions in the framework of three scenarios: Smart Network Management based on Location Information of 5G equipment; Network-assisted Self-driving Objects; People Mobility & Flow Monitoring, including emergency services.

The initial vision of the project, originally presented in a first submission of the LOCUS idea to the European Commission in November 2016 and then again in March 2019, in the proposal of the current project, is still fully valid in terms of scientific interest, technology developments, market prospects, and user needs. Particularly important is the integration of RAT-dependent and RAT-independent solutions for high-accuracy localization even in harsh wireless environments, such as indoor.

Quoting and extracting from our original document:

> *"The overall Location Based Services (LBS) and Real-Time Location Systems (RTLS) market is poised to significantly grow in the near future...However...as much as 60% of the global LBS revenues have so far been taken by very few leading players, namely major US and Chinese over-the-top companies... that rely on global satellite systems technology and on their own custom over-the-top technologies, and seek relatively little "active"*

> *assistance from the network infrastructure, even if they do rather gather information about cell towers and Wi-Fi nodes that the mobile client can detect.*
>
> *While this can be sufficient for non-critical and loose-time-scale/loose-accuracy LBS services, it is inadequate for addressing several important situations and for unleashing a wealth of business opportunities, e.g.: i) critical spatiotemporal applications (e.g., emergency handling, self-driving objects) demand for ubiquitous availability (including indoor), higher accuracy (up to a few centimetres level) and ultra-low-latency response time (order of milliseconds, e.g. for vehicle navigation); ii) applications like logistics and production (e.g., factories, seaports, etc.): in these cases, both indoor and outdoor accurate positioning is required; iii) application areas like smart cities, smart venues/stadiums, e.g. for retail, define an area that can deliver higher revenues to operators as well as to the respective vertical entities...*
>
> *Only technologies deeply integrated in the mobile network ecosystem may provide the functionality needed to support such use cases, as opposed to the aforementioned loose overlay approaches... This situation is definitely not the result of a lack of interest in localization and context awareness technologies...Rather, we believe that the heart of the matter resides in the fact that, so far, localization aspects (and especially business exploitation of both localization information and derived knowledge...) have never been considered first-class citizens in the network evolution, but have rather been addressed as a valuable, but still aside, add-on to the main communication services that emerging networks are called to provide."*

The situation depicted above is the main reason why LOCUS aims at natively incorporating, within the network infrastructure, tools and application programming interfaces needed to enable and foster the location/context-based services, together with powerful business analytics. We envision that localization and related analytics should be fully integrated in the cellular world: the 5G network and its evolution, both in the short and in the long term, should address not only communication but also localization and sensing functionality. As for feasibility, there is still available freedom to act on the 5G system specification (and of course on beyond 5G systems) and the availability of novel software network paradigms and AI techniques uniquely combine in this historical moment, making it possible to radically improve 5G networks by endowing them with on-demand localization and dedicated analytics.

2.2 Updated Project Vision (First Year)

The LOCUS initial vision and the main LOCUS objective are still very actual and fully in line with the future evolutions of the network toward 6G. As a matter of fact, the recently published "6G white paper on localization and sensing"[1] makes exactly the same point:

> *"In contrast to 5G and earlier generations, (in 6G) localization and sensing will be built-in from the outset to both cope with specific applications and use cases, and to support flexible and seamless connectivity... Typically, wireless networks are praised for their communication features alone, while their inherent localization and sensing benefits are overlooked."*

Going further, the same white paper also identifies key technologies to provide improved, and even revolutionary functionality to empower new or enhanced localization and sensing use cases. We briefly report here such technologies because we believe that they are of significant interest and also because they are the result of a cooperative effort of researchers in the field coming from different institutions and countries. It is to be noted that authors of such white paper include also researchers involved in LOCUS[1]:

- ***RF spectrum for future localization and sensing systems****: allocate services across channel bandwidths which are at least five times larger compared to 5G, above 100 GHz, will bring the following advantages: i) signals do not penetrate objects, thus there is a simpler relation between propagation paths and environment; ii) larger bandwidths and higher frequencies lead to better performance; iii) shorter wavelengths imply smaller antennas, which can be packed in smaller devices in large numbers; iv) high-rate communication links simplify exchanges of maps.*
- ***Intelligent Reflective Surfaces****: they further enhance the performance of localization and sensing, e.g., enabling tracking/surveillance applications in NLOS communications and autonomous localization, and providing additional technical opportunities, such as exploiting the wavefront curvature, which allows the reduction of the number of reference nodes required to provide positioning information.*
- ***Beamspace processing for accurate positioning****: beamspace channel response contains spatial information of not only the link ends but also the interacting objects/humans in between; it can be exploited also for localizing and tracking active mobile users in a changing environment and even device-free targets (with very high resolution, if performed at high frequencies).*
- ***Machine learning for intelligent localization and sensing****: AI and, specifically, machine learning are required to solve the complex and dynamic problems arising in the above presented situations.*

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[1] C. de Lima, D. Belot, R. Berkvens, A. Bourdoux, D. Dardari, M. Guillaud, M. Isomursu, E.-S. Lohan, Y. Miao, A. N. Barreto, M. R. K. Aziz, J. Saloranta, T. Sanguanpuak, H. Sarieddeen, G. Seco-Granados, J. Suutala, T. Svensson, M. Valkama, H. Wymeersch, and B. van Liempd (Eds.). (2020). ***6G White Paper on Localization and Sensing*** [White paper]. (6G Research Visions, No. 12). University of Oulu. https://arxiv.org/abs/2006.01779 .

As regards possible opportunities and use cases, the white paper identifies the following, after having once more highlighted that "*localization, sensing and communication must all coexist, sharing the same time-frequency-spatial resources in the envisioned 6G systems*".

- *THz imaging with very high resolution;*
- *simultaneous localization and mapping;*
- *passive sensing using transmitters of opportunity;*
- *active sensing with radar and communications convergence;*
- *channel charting;*
- *context-aware localization systems; and*
- *security, privacy and trust for localization systems.*

Regarding the evolution to beyond 5G and 6G networks, new perspectives were also offered in a dedicated chapter of the "5G Italy Book",[2] co-authored and co-edited by LOCUS partners. This chapter pointed out that:

> *"the mobile network will become more intelligent, with learning mechanisms to modify itself based on users' experience; situation-awareness will lead decision making and networking; this will allow fast and flexible spectrum reallocation, with consequent large bitrates available to the users; other human senses will be communicated, and 3D/holographic type communication will improve the quality of the tele-interaction; users will not necessarily need to bring a smartphone but will benefit of wireless-devices-as-a-service, with distributed devices available to anyone; the devices battery life will be substantially extended."*

Among the technologies that are expected to enable such evolution, the aforementioned chapter includes machine learning & AI, fast dynamic spectrum allocation, wireless energy transfer, free-space optical communications, sub-Terahertz and Terahertz communications, massive MIMO and intelligent surfaces, network intelligence, high-accuracy indoor localization, cybersecurity, network digital twins, enhanced sensing, as well as quantum sensing, communication, computing, and networking.

2.2.1 Advisory Board recommendations and related actions

The Project vision has been further updated and enriched by the Advisory Board of the LOCUS project, which provided the following recommendations.

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[2] M. Chiani, E. Paolini, F. Callegati, "Open issue and beyond 5G," chapter of "The 5G Italy Book 2019: a Multiperspective View of 5G", M. Ajmone Marsan, N. Blefari Melazzi, S. Buzzi, S. Palazzo Editors, https://www.5gitaly.eu/2019/en/5g-italy-book-2/.Note: M. Chiani is also involved in the project LOCUS.

- Localization technology should include not only 5G New Radio but also the integration with other technologies such as GNSS, Wi-Fi, Bluetooth, UWB, and radar, as well as non-radio technologies such as inertial measurements and vision.
- Consider new approaches to localization that employ machine learning and the probabilistic values of observables rather than the observed measure only.
- Implement a vision in which sensing, communication, and localization all coexist and share network resources.
- Explore the use of bands at higher frequencies (e.g., Terahertz).
- Complement localization with simultaneous mapping of the environment.
- Investigate machine learning/data analytics approaches which exploit the "power of the crowd" in refining the models used for localization and mapping.
- Study of localization/tracking techniques exploiting the waveform curvature in near-field conditions.
- The performance of localization algorithms should be obtained in scenarios described in 3GPP Technical Reports and, when possible, compared also with performance limits.
- Define a network architecture for better exploitation of location information and location-based analytics.
- Define location-based analytics that allow the monitoring of people flows; this is particularly important in emergency situations such as pandemic.
- Investigate how increasing network resources can provide better localization accuracy as well as how an improved localization accuracy can enable a more efficient network management.
- Define a broad set of use cases for verifying location-based analytics obtained with the algorithms developed in LOCUS.
- Implement proof of concepts demonstrators that exploit the developed network architecture in accordance with some of the predefined use cases.

3 Project Activities addressing the Updated Project Vision

The Project activities have been updated, based on worldwide research trends and Advisory Board recommendations. A subset of recommendations and suggestions coming from the updated vision has been already implemented; another subset is left for future work, as described in the following.

In compliance with the Project updated vision, the project consortium has implemented actions listed in the following.

- Investigated and developed techniques for heterogeneous localization using RAT-dependent and RAT-independent technologies.
- Developed localization techniques, including those based on soft information, with preliminary testing by simulation in scenarios defined in 5G technical reports.
- Defined a virtual network architecture for enhanced exploitation of location information and location-based analytics.
- Defined location-based analytics, including one on flow monitoring, and put forth a working group on COVID-19 technological solutions.
- Defined use cases and corresponding network functionalities.
- Study radio-based simultaneous localization and mapping (SLAM) techniques in a 5G ecosystem at millimetre waves.
- Consider the vision in which sensing, communication, and localization all coexist and share network resources, and explore the use of bands at higher frequencies.
- Implement proof of concept demonstrators that exploit the developed network architecture in accordance with some of the predefined use cases.

In summary, LOCUS has been actively working to contribute to make its updated and enriched vision a reality and to contribute to the path towards expected beyond 5G and 6G improvements.

4 Beyond LOCUS

4.1 The Project Consortium Joint Vision Beyond LOCUS

On the occasion of the “Vision of Future Communication Summit” for the Strategic Research and Innovation Agenda (SRIA), the LOCUS consortium worked jointly to propose its vision on the future of cellular tracking systems, which were then presented in the context of the summit by Samsung and which we report in the Section 4.1.1.

4.1.1 The LOCUS Vision of Future Communication (SRIA)

Localization and tracking of users, devices, and vehicles today enable a wide array of applications, from emergency to commercial services and emerging vertical industries. It is now recognized that different applications will need to fulfil stringent requirements over different KPIs (accuracy, latency, reliability, integrity, power consumption, scalability, availability, computational complexity, cost, privacy and security). For example, sub-meter localization accuracy with 5 9’s (99.999%) reliability, very high security and ms end-to-end latency levels are required for some V2X applications, especially safety-critical ones, as well as cm-level accuracy with 5 9’s reliability, ms end-to-end latency levels and high scalability are required for some Industry 4.0 applications in production lines. Utilizing mixtures of technologies including 4G/5G-cellular, Global Navigation Satellite System (GNSS), Terrestrial Beacon System (TBS), WiFi, Bluetooth (BT), Inertial Measurement Sensors (IMS), Ultra-Wide Band (UWB) and mmWaves may be needed to fulfil such requirements. With the deluge of requirements, its multi-dimensional optimization and the usage of different technologies to fulfil such KPIs, proper orchestration of localization will be vital for 6G. At architectural level, extending the 3GPP enhanced Localization Services (eLCS) architecture is a viable option. The Multiple Quality of Service (QoS) class recently included in 3GPP SA2, in which some of the research work was conducted in the H2020 project 5G LOCUS, can support different technologies to achieve varying accuracy levels and reduce the end-to-end latency. When orchestrating RAN options for localization, it is essential to account for the emerging open standards and the challenges from the disaggregation, scalability and cloudification of RAN.

The use of Artificial Intelligence and Machine Learning (AI/ML) to improve localization accuracy is currently receiving a lot of focus, as in the research activities of the 5G LOCUS project. Localization is a focus area in the AI/ML standardization scope in the Rel-18 RAN and SA 3GPP study items, which will enable a systematic communication between the device and the network to enable data collection, training phase, and usage of machine learning models to improve localization KPIs. To reduce the computational complexity, the information load at the network backbone and to improve data privacy and security, federated learning is now emerging as a key solution. Application of federated learning to localization and tracking, especially under stringent latency, privacy and power consumption constraints, will be a key research challenge for 6G. 6G can also play a primary role in location-based analytics, including contact tracing and group movement monitoring. The use of the cellular RAN as a source of localization information will lead to profound interactions between the provision of telecommunication services and their use for positioning. Therefore, network planning, maintenance and operation (e.g., in terms of base station and reflector positions, orientations, bandwidth, etc.) should be addressed considering both localization and telecommunications KPIs via AI/ML techniques.

Radar-like sensing will be widely used in 6G scenarios to detect unconnected devices or objects (e.g., safety-critical vehicular applications). The enhanced resolution of mmWave and wideband signals enables the use of multipath measurements for device-free localization (DFL), the localization of passive objects or unconnected devices based on reflected wireless signals. With DFL becoming safety-critical, these radar-like functionalities can become part of future 3GPP standards, thus effectively combining communication, localization, and radar (a.k.a. joint radar and communication) in a single wireless technology. Device-free sensing and localization introduce further design parameters to the localization problem, including waveform design, range resolution, and clutter removal. The proposed use of Reconfigurable Intelligent Surfaces (RIS) in 6G also opens up new dimensions, including the need for some modifications of time delay and angle-based localization reference signals in RAN.

Other disruptive technological aspects for localization in 6G networks will be the usage of TeraHertz bands for exploiting extremely wide bandwidth, the development of holographic radios for shaping the electromagnetic environment, and the exploitation of quantum mechanical properties for extremely precise and secure quantum sensing, communication, and networking. All in all, 6G and associated technologies present a host of new opportunities and challenges for the optimization of localization and tracking we experience today.

4.1.2 Strategic LOCUS-related Research Areas Beyond 5G

LOCUS partners have identified the following research areas as strategic on the road to 6G:

- Device Free Localization
  - Use of ‘radar-like’ sensing with mm-wave and THz bands.
  - Use of wider bandwidths and pencil beams for precision.
  - Imaging capabilities of THz enables accurate sensing.
- Phase based localization methods
  - Used traditionally in Sat Com but prone to larger delays.
  - NLOS paths in Cellular and other land-based comms, a major obstacle.
  - Use of NR-sidelink and RIS (Reconfigurable Intelligent Surfaces) potentially can overcome these.
- AI/ML techniques in multiple domains

  - From improving accuracy in estimates (post-processing) to extracting more knowledge from the radio environments to aid multiple other applications and processes.
  - Advanced analytics/AI/ML mechanisms combining both network and positioning-derived information (i.e. UE positions, people density/ flows, etc.) for improved network management and network automation.
  - Deep learning approaches for people flow monitoring, e.g. trajectory predictions and mobility profiling, to enable vertical service automation ranging from marketing, smart venue/stadium management to public safety and transportation-related applications.
- 6G Service Orchestration Frameworks
  - native integration of in-network analytics, AI and ML capabilities and services, specifically integrating/evolving the LOCUS solution for (location-based) analytics as a service towards a generalized AIaaS approach
- Energy Efficiency for Smart Building, City and Mobility Applications
  - Applications of localization and data analytics (AI/ML) for the smart buildings and smart cities as well as mobility, in particular for energy efficiency and reducing CO2 emissions

4.2 3GPP Standardization Aspects

As reported in D7.4, looking ahead at 3GPP plans for Release 18 in the final project year, there were several topics both in the RAN NR-pos-enh2 and the SA2 eLCS-phase 3 and Ranging study items that were aligned with the on-going technical work in LOCUS. Among them, the support for NR-sidelink based positioning in both RAN and SA2 is a key topic area. Also, the positioning integrity topic in RAN2 was identified as a technical area with some relevance to LOCUS work. Several technical contributions were made by Ericsson and Samsung (in RAN 1/2 and SA2 respectively), which can be related (at least in part) to the work in LOCUS in these Release 18 study items. Many of the SA2 contributions has a mention of the LOCUS project, as it is the project where some of the related technical work has been carried out. On the one hand, the work of LOCUS is already being seen as input for some of work item in progress, on the other hand, the scientific collaboration between the partners will be carried out even after the end of the project, also for the benefit of the work items in the future.

4.3 6G Infrastructure Association

The 6G Infrastructure Association “Vision and Societal Challenges Working Group” has published in May 2022, i.e., a few months before the end of the LOCUS project, a Whitepaper on “What societal values will 6G address?”. In such a whitepaper, the members of 6G-IA discuss how societal values can complement performance-driven technology development. From published sources, mainly EU-funded ICT-52 research projects, a set of use cases categorized in three use case areas are highlighted to represent new possibilities for 6G. Using these use case areas, they analyse how future technology developments may impact societal key values.

On a technology level, the Whitepaper highlights how the advanced positioning and localization services targeted by 6G networks, via the usage of subTHz frequencies, intelligent reflective surfaces, advanced beam processing, as well as AI-powered techniques will impact on all the three use case areas. Furthermore, network automation and low-latency analytics, which represent another important research area of LOCUS are also included among the main KV enablers. Table 4-1 summarizes the main use case area considered, with KV, KVI, and KV enabler examples. The highlighted KV enablers are those in line with the LOCUS Output.

Table 4-1 Key values mapped to use case areas, related KVIs, and enablers from the 6G-IA Whitepaper "What societal values will 6G address?"

Use case area	KV examples	KVI examples	KV enabler examples
1 Emergency response & warning systems	***Societal sustainability***	*Reduced emergency response times; Increased operational efficiency of interventions in remote areas*	*Flexible network fabric with dynamic network and service orchestration and automation; Mobile ad-hoc networking; TN/NTN convergence*
	Environmental sustainability	*Increased area of protected and surveyed natural habitats and climate preserves*	*Energy-efficient monitoring sensors; Flexible analytics services and network automation; Mobile ad-hoc networking; TN/NTN convergence*
	Personal health and protection from harm	*Increased operational efficiency for saving lives in emergencies; Reduced injuries in PPDR missions*	*Joint communication and sensing; Safe and easy to use XR devices; Network and service automation for low-latency analytics*
	Trust	*Reported confidence in advanced digital devices, systems, and services in critical missions*	*Rugged and robust devices; Secure and trustworthy AI; System E2E privacy and security*
	Environmental sustainability	*Environmental footprint of urban transport of persons and goods*	*Services for coordinating and planning routes; Precise positioning / localization*
	Simplified life	*Access and ease of use of public transport*	*Multimodal interconnectivity services*

2 Smart city with urban mobility	***Personal health and protection from harm***	*Injuries in urban traffic*	*Multi-agent supporting network architecture; 3D coverage; Resilient and reliable networks; Joint communication and sensing*
3 Personal health monitoring & actuation everywhere	***Personal health and protection from harm***	*Access to autonomous health monitoring service*	*Medically safe on-body devices with long autonomous operation time; Ubiquitous coverage; Precise positioning / localization; Secure and trustworthy AI; Digital twinning of patient's body*
	Privacy and confidentiality	*Reported user control of medical data for storage/transmission/processing*	*System E2E privacy and security; Decentralized processing / offloading to devices, edge, etc.; Secure and trustworthy AI*
	Societal sustainability	*Average cost saving in health care system per patient*	*System resilience; Ecosystem adaptation and integration; Zero-touch system (re)configuration for minimizing human intervention*

4.4 The Smart Networks and Services Joint Undertaking (SNS-JU)

Under Council Regulation 2021/2085, the Smart Networks and Services Joint Undertaking was established as a legal and funding entity and part of the 10 European Partnerships to accelerate the transition to a green and digital economy in November 2021. In the SNS JU, EU and industrial resources are pooled for the development of Smart Networks and Services. In addition, it encourages alignment with Member States regarding 6G Research and Innovation, and the deployment of advanced 5G networks. An ambitious mission and important EU budget are set out in the SNS JU for the period 2021-2027.

Within the first Work Programme of the Smart Network and Services (SNS) Partnership, among the expected outcomes for the Wireless Communication Technologies, it was mentioned

- *"Wireless technologies and systems capable to meet expected 6G radio capabilities such as Tbps data throughput, sub-ms latency, extremely high reliability, massive mMTC, extreme energy and spectrum efficiency, very high security, and* ***cm-level accuracy localization.***"

Joint communication and sensing was listed among one of the main scopes in this context:

- *"Communication work is complemented by work in the field of location and sensing capabilities for devices. It includes joint radar and communications, with signal*

> *processing techniques for wideband beamforming, or spatial multiplexing, as well as transceivers for higher spectral efficiencies, better power efficiency, faster data converters, high density digital logic, chip-package-antenna co-design, and combination of silicon technologies with III-V technologies. Waveform design can extend to the radar domain to offer the potential for combined radar and communications capabilities. Experimental prototypes are in scope."*

Given the scopes and expected outcomes, it is now clear how some of the LOCUS outputs are perfectly in line with the work program and can be used in synergy and as input to new funded projects.

5 Conclusion

In this deliverable, it is shown how the LOCUS project has pioneered the research area of localization and device-free localization (within the more general definition of “sensing”), not only within 5G, as intended in the proposal writing, but also in all discussions that have continued beyond Release 16 of 3GPP. Furthermore, the project work was ground-breaking for the definition of location-based analytics, which is a new research area that has attracted great interest in the European and international scientific and industrial community, as demonstrated by the new work programmes. During the project lifetime, the LOCUS consortium welcomed proposals from the advisory board and the scientific community outside the project. To this aim, some research activities have been updated and some others have been added. The project results were also timely with respect to the main phases of 5G standardization, with a number of contributions reported in D7.7. Based on these trends, it is clear that the scientific collaborations that have been created and strengthened in the three years of the project, as well as the contributions to the standardization bodies, the project results, and the innovations on a commercial level will continue beyond LOCUS.