# Beyond 5G Positioning

## *Public report*

Project within Trafiksäkerhet och automatiserade fordon
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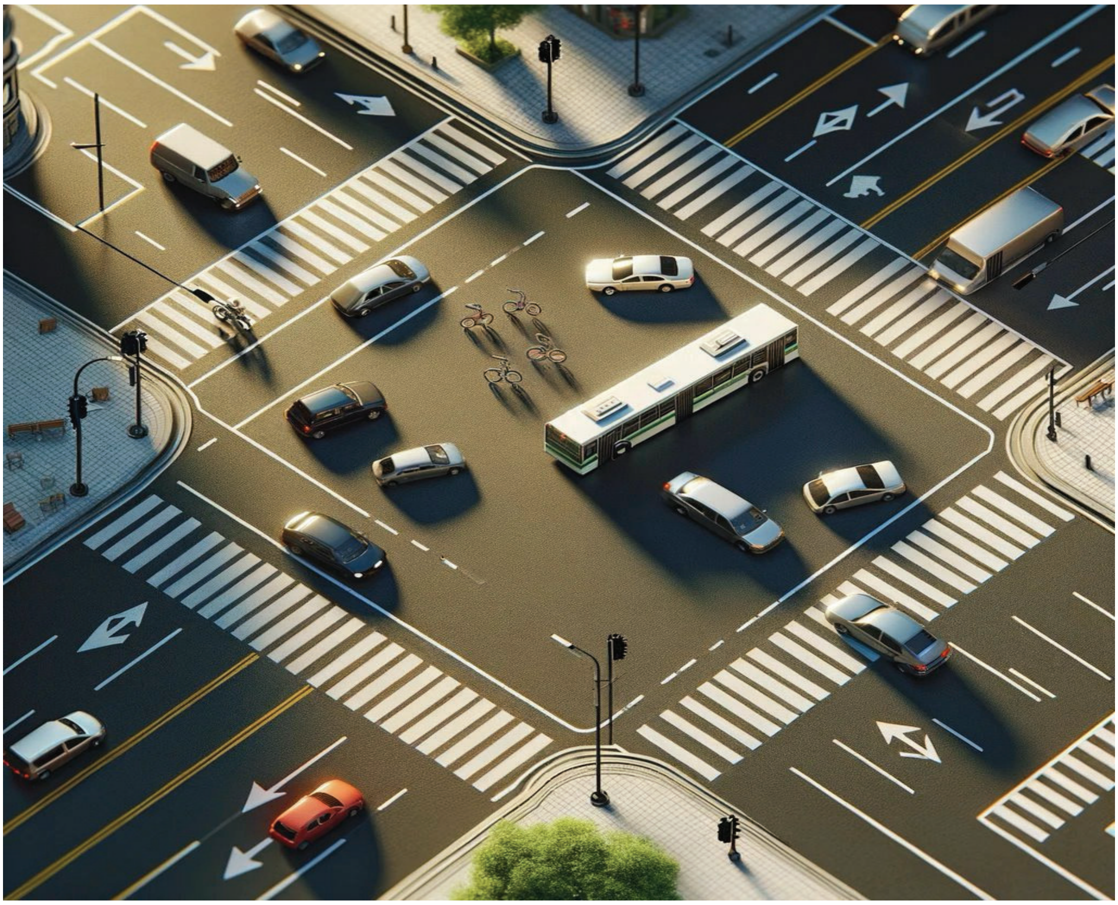

FFI Fordonsstrategisk Forskning och Innovation

## Content



### FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

**For more information:** www.ffisweden.se

# 1. Summary

The Beyond 5G Positioning (B5GPOS) project developed a high-accuracy, low-latency positioning and sensing solution based on beyond 5G radio signals for enhanced road safety. By integrating communication, positioning, and sensing into a single hardware platform, B5GPOS addressed the limitations of current GNSS and sensor-based systems. The project leveraged 5G mmWave and anticipated 6G technologies to support real-time, sub-meter accuracy positioning in urban environments with varying visibility. With contributions from academia and leading industry players, the project advanced methods for channel modeling, waveform optimization, hybrid precoding, and sensor fusion. Demonstrators showed the feasibility of integrated sensing and communication (ISAC), with performance evaluations confirming fundamental accuracy bounds. Key innovations include joint angle estimation with distorted arrays, hybrid precoding strategies, and effective SLAM algorithms for urban mobility. The outcomes have broad implications for semi-autonomous vehicles, infrastructure sensing, and future ITS applications.

# 2. Sammanfattning på svenska

Projektet Beyond 5G Positioning (B5GPOS) har utvecklat ett högprecisionssystem för positionering och sensorer baserat på radioteknik från 5G och kommande 6G. Syftet har varit att öka trafiksäkerheten genom att förbättra fordonens förmåga att lokalisera sig själva och andra objekt, även i komplexa urbana miljöer där GNSS inte är tillförlitligt. Lösningen bygger på samverkan mellan kommunikation, positionering och sensorsystem i en enhetlig platform. Projektet har kombinerat forskning och industriell utveckling inom områden som radiovågformoptimering, hybrid-precoding, sensorfusion, och SLAM (Simultaneous Localization and Mapping). Genom praktiska demonstrationer har vi visat att radiobaserad sensing och positionering kan fungera med hög tillförlitlighet. Särskilt fokus har lagts på att möjliggöra tjänster för avancerad förarassistans och skydd för oskyddade trafikanter som fotgängare och cyklister. Resultaten har visat att det är möjligt att nå sub-meter noggrannhet och låg latens, vilket är avgörande för tillämpningar inom autonoma fordon och smart infrastruktur. Projektet har också bidragit med insikter kring standardisering, datasäkerhet och arkitektur-krav för att möjliggöra framtida implementering av sådana system.

# 3. Background

The B5GPOS project was initiated to address limitations in current vehicular positioning and sensing systems, particularly in urban environments where GNSS often fails due to poor satellite visibility and multipath effects. With the automotive industry's shift toward automation and connected mobility, the need for reliable, high-accuracy positioning and environment perception has become critical.

Traditional positioning methods, including GNSS and local sensor systems (e.g., radar, LiDAR, cameras), suffer from issues such as blockage, signal degradation, and lack of synchronization. These limitations reduce the effectiveness of advanced driver-assistance systems (ADAS), traffic management, and vulnerable road user (VRU) protection.

At the same time, 5G networks offer promising capabilities, including low latency, high bandwidth, and precise timing, which can be exploited not only for communication but also for positioning and sensing. The B5GPOS project aimed to leverage and extend these capabilities by exploring how 5G and beyond (6G) technologies could be integrated into a unified framework for communication, positioning, and sensing-as-a-service.

The project builds upon prior work from the 5GPOS project (FFI project 2022-0164), expanding its scope with improved hardware, novel sensing algorithms, and system-level demonstrations. Key application domains identified include vehicle-to-everything (V2X) communication, cooperative perception, VRU protection, and autonomous driving support.

# 4. Purpose, research questions, and method

**Purpose**
The main purpose of the B5GPOS project was to investigate and demonstrate how integrated communication, positioning, and sensing capabilities (e.g., using beyond 5G technologies) can enhance vehicular safety, automation, and situational awareness. The project aimed to provide accurate and low-latency positioning and sensing in real-time, even in challenging environments such as urban intersections or under non-line-of-sight (NLOS) conditions.

**Research Questions**
1. How can radio-based sensing and positioning be improved through the use of 5G mmWave and future 6G waveforms?
2. What are the trade-offs between infrastructure-based and vehicle-based positioning and sensing approaches?
3. Can hybrid analog-digital precoding and beamforming be optimized for simultaneous data communication and high-resolution sensing?
4. What are the integration challenges and interface requirements for deploying positioning and sensing as a network service?
5. How can these technologies be fused with existing sensors (e.g., GNSS, radar, camera) to provide robust and trustworthy data for safety-critical applications?

**Methodology**
The project followed a multi-disciplinary approach with the following key components:

***Waveform and Channel Modeling:*** **Development and analysis of 5G and beyond waveform characteristics for positioning accuracy and channel behavior in urban settings.**

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| *Signal Processing & Algorithm Design:* **Design of signal processing techniques for Angle-of-Arrival (AOA) estimation, joint detection of sensor distortions, hybrid precoding, and low-complexity channel estimation.** |
| *Sensing & SLAM:* **Investigation of sensing methods using both user-centric and network-centric paradigms; integration of mapping and tracking methods such as Bayesian SLAM.** |
| *System Architecture & Interface Specification:* **Definition of service architectures, including logical and electrical vehicle architecture and standard-based interfaces (ETSI, 5GAA).** |
| *Demonstrations and Testing:* **Field trials using enhanced UE and BS hardware platforms, testing various use cases like intersection awareness, VRU detection, and high accuracy positioning.** |
| *Performance Benchmarking:* **Use of theoretical bounds (e.g., Cramér-Rao Bound) to predict and validate performance outcomes under realistic constraints.** |

# 5. Objective

The primary objective of the project was to develop and validate technologies for integrated positioning and sensing based on 5G and future 6G radio signals, enabling enhanced vehicular safety and automation. The project aimed to demonstrate a working system capable of providing:

| # | Name | Description | Status |
|---|---|---|---|
| 1 | Achieve Sub-Meter Positioning Accuracy | The project aimed to deliver positioning accuracy better than 0.1 meters, even in challenging urban and NLOS conditions. This level of precision is essential for safe and efficient operation of autonomous vehicles and advanced driver assistance systems (ADAS). | The objective was partially achieved. The project achieved less than 2~3 meters (in order of meters) with a commercial base station and B5GPOS user equipment, and 0.1 m in controlled experiments with a dedicated channel sounder. |
| 2 | Enable Low-Latency and High-Reliability Communication | By leveraging 5G mmWave and beyond, the system targeted latencies below 200 milliseconds for positioning updates and sensor data sharing. Low latency ensures that safety-critical applications can respond in real time to changes in the environment. | The objective was not achieved. The project is around 0.5 Hz update rate. But the reliability is very good. |
| 3 | Develop Integrated Sensing Capabilities | B5GPOS sought to extend traditional communication infrastructure to also perform environment sensing, i.e., detecting objects and road users that may not carry any communication devices. This integrated approach offers radar-like capabilities using standard 5G infrastructure. | The objective was not achieved. |
| 4 | Implement Multi-Sensor Fusion Techniques | A key goal was to combine data from GNSS, onboard vehicle sensors (e.g., radar, cameras), and network-side sensing into a unified perception model. This fusion approach improves system robustness, especially in areas with limited visibility or sensor occlusion. | The objective was achieved. |
| 5 | Design Scalable Interfaces and Service | The project focused on defining practical interfaces for vehicle and infrastructure integration, consistent with standards such as ETSI’s | The objective was achieved. |

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|---|---|---|---|
| | Architectures | Collective Perception Service (CPS) and 5GAA frameworks. These interfaces support flexible deployment across OEMs, telecom providers, and public infrastructure. | |
| 6 | Real-Time Processing with Ultra-Low Complexity | Algorithms were developed to function under real-time constraints while minimizing computational burden, making them suitable for integration into embedded and power-constrained hardware platforms. This objective supports practical deployment in commercial-grade systems. | The objective was achieved. |
| 7 | Robustness Under Imperfect Synchronization and Hardware Impairments | The project investigated how synchronization errors and hardware non-idealities affect sensing and positioning accuracy. This led to the development of resilient signal processing techniques that maintain performance despite practical system limitations. | The objective was achieved. |
| 8 | Refined Interface Models for Sensor Fusion and Vehicle Integration | Significant effort was invested in understanding how sensing and positioning data can be securely and efficiently integrated into vehicle logical and electrical architectures. The models also address trust, responsibility, and safety in data exchange between vehicles and networks. | The objective was achieved. |

These objectives were aligned with the FFI program's focus on sustainable road transport and vehicle innovation, specifically within its sub-program for connected and automated vehicles.

# 6. Results and deliverables

The main results have been reported in the project's 18 internal deliverables.

## WP1: Models and Fundamental Performance Prediction

| D1.1 Preliminary models |
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| The scope of Deliverable D1.1 is centered on laying the foundational system and signal models necessary for implementing and evaluating 5G mmWave positioning using a single base station. It presents a comprehensive architecture involving base station (BS) and user equipment (UE) models, signal processing mechanisms, and geometric relationships essential for position estimation. The deliverable also introduces preliminary validation through experimental setups, including signal acquisition, synchronization, and channel estimation using real-world vehicular scenarios. Initial findings from field trials are used to refine the assumptions and requirements for future algorithm development, providing insights into the limitations and practical considerations of real-time 5G positioning under realistic conditions. |

| D1.2 Channel characteristics for detailed positioning and sensing |
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| The scope of this deliverable includes simulation-based investigations of how complex urban objects, i.e., specifically a corrugated shipping container, affect radio wave propagation at mmWave frequencies. Using HFSS SBR+ simulations, the study evaluates both specular and non-specular (diffuse and diffracted) scattering behaviors under realistic geometries and material assumptions. The findings emphasize the importance of high-fidelity electromagnetic modeling for understanding multipath, reflection, and diffraction effects that influence positioning and sensing performance in vehicular environments. These results contribute to accurate channel modeling needed for algorithm development in later stages of the project. |

| D1.3 A Geometry based stochastic channel model for beyond 5G positioning and sensing |
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| The scope is to experimentally analyze and model how physical features of urban environments, such as windows, walls, and other structural elements, interact with mmWave signals to form multipath components (MPCs). The deliverable introduces a high-resolution channel sounding setup and uses SAGE-based parameter estimation, clustering, and tracking to identify and follow MPCs over time. The core contribution is a geometry-based stochastic modeling approach that links these observed MPCs to real physical objects, mapping their behavior spatially and temporally. This helps characterize the lifetime, visibility, and evolution of clusters, which are essential for developing accurate mmWave positioning and sensing systems. The results demonstrate how windows and building materials influence both backscatter and reflection, forming a strong empirical foundation for multipath-assisted localization and realistic ray-tracing simulations. |

| D1.4 Fundamental bounds for beyond 5G positioning and sensing |
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| The scope is to define theoretical performance limits for localization, sensing, and tracking using beyond-5G radio signals. This includes deriving Cramér-Rao Bounds (CRBs) under various system configurations, such as hybrid precoding, monostatic and bistatic sensing, and scenarios with imperfect synchronization or hardware impairments. The deliverable explores standard CRBs for estimating user equipment (UE) position, orientation, clock offset, and sensing parameters (delay, Doppler), as well as misspecified CRBs that quantify performance degradation due to model mismatches or practical impairments (e.g., near-field propagation, RIS pixel failures). Posterior CRBs are also considered for dynamic systems like SLAM, assessing joint estimation of UE trajectories and environmental maps. Overall, this deliverable provides insights into optimal system design and algorithm feasibility across realistic and constrained deployment settings. |

## WP2: Methods and signals for beyond 5G positioning and sensing

| **D2.1 Report on architectural and protocol alternatives to support 5G and beyond 5G positioning and sensing** |
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| This deliverable focuses on exploring and evaluating various architectures and protocols to enhance positioning and sensing services in 5G and future 6G networks. The document examines different sensing modalities, including monostatic, bi-static, and multi-static sensing, and addresses mobility support for tracking both connected and non-connected objects. It discusses architectural enhancements, such as decentralized solutions for reduced latency and improved scalability, and highlights key technical components like new frequency bands, integrated sensing and communication, and evolved protocols. The deliverable also considers requirements for traffic participant safety, privacy concerns, and practical use cases, such as intersection safety, while emphasizing the integration of these technologies into vehicle safety platforms. Overall, it aims to provide a foundation for high-accuracy, low-latency positioning and sensing solutions to support advanced applications like autonomous driving and collaborative traffic safety. |

| **D2.2 Report on intermediate methods on detection and estimation, as well as tracking and mapping** |
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| The scope of this deliverable focuses on advancing signal processing and waveform optimization techniques to enhance positioning and sensing capabilities in 5G and beyond 5G (B5G) systems. The scope includes optimizing radio waveforms, designing hybrid precoders for positioning, and addressing challenges like hardware impairments and distributed MIMO arrays. It explores efficient channel parameter estimation, joint angle-of-arrival (AOA) estimation with distorted sensor detection, and localization methods such as downlink UE positioning with known environments and RTT-based techniques at sub-6 GHz and mmWave frequencies. The deliverable also investigates tracking and mapping of passive objects and connected users in dynamic urban scenarios, leveraging Bayesian methods and sensor fusion to improve accuracy and reliability. Additionally, it examines sensing modalities (mono-, bi-, and multi-static) and integrates AI-aided approaches, aiming to bridge theoretical advancements with practical demonstrators for future wireless systems. |

| D2.3 Report on final methods on detection, estimation, tracking, and mapping |
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| This deliverable focuses on refining and implementing advanced signal processing techniques for real-time localization, tracking, and environmental mapping in 5G and beyond 5G (B5G) systems. The scope includes a comprehensive SLAM (Simultaneous Localization and Mapping) signal processing chain, covering beam sweeping, FPGA-based preprocessing, low-complexity channel estimation (e.g., FLEX method), snapshot localization, and dynamic tracking algorithms. It evaluates both static and dynamic scenarios, addressing challenges like clock offsets, orientation mismatches, and non-line-of-sight (NLoS) conditions. The deliverable integrates multi-sensor data (e.g., GNSS, RTK) and leverages rich multipath components to enhance accuracy. Additionally, it aims to validate methods through experimental evaluations, ensuring robustness for applications such as vehicular tracking and urban navigation. The final output includes real-time tracking chains and global coordinate visualization, bridging theoretical advancements with practical implementations. |

## **WP3:** UE Demonstrator Hardware

| D3.1 HW requirement specification and final requirement specification |
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| This deliverable outlines the technical and functional requirements for the B5GPOS User Equipment (UE) demonstrator, focusing on its hardware and system integration. The scope includes detailed specifications for the UE's front-end module, such as the mmWave receiver (24.25-29.5 GHz) with dual-polarized 32-element antenna arrays, beamforming capabilities (±45° azimuth/elevation), and analog baseband interfaces. It also covers the back-end Xilinx RFSoC platform, data handling (e.g., 491.52 MS/s IQ sampling, 10 Gb/s data transfer), and power consumption. Key deliverables include receiver performance metrics (e.g., noise figure, EVM), antenna patterns (beambook for 26.7 GHz), and interoperability requirements between the RF front-end and Xilinx platform. The final specification ensures the UE meets demonstrator goals for high-accuracy positioning and sensing in 5G/B5G networks, validated through experimental evaluations. |

| D3.2 Antenna module design review |
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| This deliverable focuses on evaluating the design and performance of the RFM12 antenna module, including simulations of active S-parameters and gain patterns for different scan angles (e.g., (0°, 0°), (30°, 0°), and (15°, 15°)) and polarizations (± 45°). It assesses key metrics such as beam steering efficiency, polarization performance, and comparative analysis with the proven BFM02801 antenna module. Additionally, the review covers the PCB stack-up design, detailing layer materials, thicknesses, and dielectric constants to ensure optimal RF performance and signal integrity. The deliverable aims to validate the antenna module's compliance with technical specifications, including impedance matching, radiation efficiency, and mechanical integration, ensuring readiness for prototyping and testing in the B5GPOS demonstrator. |

| D3.3 Antenna module HW ready |
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| This deliverable confirms the completion and delivery of four fully assembled EVK (Evaluation Kit) modules from Sivers, marking the hardware readiness of the antenna module for the project. This deliverable signifies that the physical implementation of the antenna module, including all RF components, beamforming capabilities, and interface connections, has been successfully realized and is now available for integration and testing within the B5GPOS demonstrator system. The hardware has undergone necessary design validations to ensure it meets the project's specifications for mmWave operation, polarization performance, and mechanical robustness, enabling subsequent phases of system verification and experimental evaluation. |

| **D3.4 Integrated UE hardware system** |
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| The deliverable focuses on the complete assembly and integration of the User Equipment (UE) hardware components, building upon the specifications outlined in D3.1 (UE Specification). This deliverable ensures that the antenna module, RF front-end, Xilinx RFSoC platform, and associated interfaces (e.g., baseband, power, and control connections) are fully integrated into a functional hardware system. It verifies that the UE meets all technical requirements for mmWave operation, beamforming, and data processing, enabling real-world testing and validation within the B5GPOS demonstrator framework. The scope includes system-level validation of performance metrics, interoperability, and compliance with project objectives for high-accuracy positioning and sensing applications. |

## WP4: Validation and demonstration

| **D4.1 Implementation design** |
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| The deliverable encompasses the integration and interconnection of various hardware components and interfaces for the B5GPOS system. This includes the implementation of data interfaces such as 10 Gb Ethernet and CAN FD, power interfaces like 12V DC and 220V AC, and components like the Zynq RFSoC, BFM02803 modules, GPS receivers, power inverters, and leisure batteries. The design also involves coordinating inputs from multiple stakeholders, including Lund, Chalmers, Ericsson, Sivers, VCC, QAMCOM, and Magna, ensuring seamless communication and power distribution across the system. The diagram highlights the modular and interconnected nature of the implementation, focusing on both functionality and scalability. |

| **D4.2 Demo system integrated and mounted on vehicle** |
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| The scope of D4.2 involves the physical integration and installation of the B5GPOS system onto a vehicle, ensuring all hardware components (such as the Zynq RFSoC, BFM02803 modules, GPS receivers, and power systems) are properly mounted and interconnected for real-world testing. This includes validating data interfaces (e.g., 10 Gb Ethernet, CAN FD) and power distribution (e.g., 12V DC, 220V AC) in a dynamic vehicular environment. |

| **D4.3 Test measurements performed and data delivered to WP2** |
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| The scope of deliverable D4.3 involves conducting real-world data collection using the B5GPOS system mounted on a vehicle, focusing on dynamic and static positioning, |

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| sensing, and channel characterization in both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. Despite technical challenges such as a malfunctioning radio module and suboptimal synchronization, the team collected nearly 4 TB of raw data over two days, including scenarios like pedestrian detection, bicycle tracking, and vehicle movement. This data, processed by Qamcom, was delivered to Chalmers and Lund for further analysis in WP2, validating the system's performance in diverse urban environments and supporting the development of GNSS-independent positioning and sensing capabilities. |

| **D4.4 Live demonstration** |
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| The scope of deliverable D4.4 involves showcasing the B5GPOS system's real-time positioning and sensing capabilities during a live event on May 27, 2025, despite unforeseen challenges such as adverse weather conditions forcing the demo indoors into Ericsson's garage, which hindered GPS reception critical for synchronization and tracking. Despite extensive preparations, including a full day of setup and troubleshooting, the team was unable to run the demo live due to technical limitations. Instead, they presented pre-recorded data from earlier measurements, allowing visitors to examine the hardware setup and understand the system's functionality. The event concluded with additional offline data recordings, highlighting the system's potential while underscoring the challenges of real-world deployment in suboptimal conditions. |

## WP5: Positioning and sensing services

| **D5.1 Typical use-case and application descriptions** |
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| This deliverable is to define and analyze automotive safety services and applications that benefit from enhanced positioning, sensing, and communication capabilities, particularly in the context of Beyond 5G (B5G) and 6G evolution. This includes identifying use cases such as lane assist, turn assist, and protection of vulnerable road users (VRUs), while evaluating how redundant positioning data and network-based sensing can improve accuracy (< 0.1 m), latency (< 200 ms), and situational awareness in real-time traffic scenarios. The deliverable also explores multi-domain applications, such as traffic management and distributed warnings, using standardized V2X messages (e.g., CAM, DENM), and addresses system architecture considerations, including bi-static/multi-static base station setups for radar-like sensing. Additionally, it examines business cases, data ownership, privacy concerns, and the integration of sensing services into vehicle solutions, aiming to bridge gaps between 5GPOS and B5GPOS with advanced hardware (e.g., dual polarization, improved clock stability) and future-oriented demo setups. |

| **D5.2 Service interface description for defined applications** |
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| The scope of D5.2 focuses on defining and standardizing the interfaces and protocols for integrating Beyond 5G (B5G) positioning, sensing, and communication services into automotive applications, particularly for autonomous driving and cooperative intelligent transport systems (C-ITS). It builds on the use cases from D5.1, addressing information exchange protocols (e.g., ETSI’s Collective Perception Service and SAE standards), logical and electrical vehicle architectures, and the fusion of external sensor data with ego-vehicle estimates. The deliverable explores challenges such as uncertainty |

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| propagation, cybersecurity, and data trustworthiness, while aligning with existing frameworks like ISO 26262 for functional safety. Additionally, it examines centralized E/E architectures and proposes enhancements for integrity, latency, and interoperability in V2X communication, ensuring compatibility with evolving standards from ETSI, SAE, and 5GAA. The goal is to enable seamless integration of network-based sensing and positioning services into safety-critical automotive systems. |

| **D5.3 Positioning service demonstrator** |
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| For D5.3, the focus shifts to showcasing the system's ability to provide accurate, GNSS-independent positioning data in urban environments, supporting applications like autonomous driving and collective perception. This deliverable emphasizes real-time data integrity, collaboration in traffic scenarios (e.g., static/dynamic object mapping), and safety-critical services, demonstrating how the system enhances situational awareness for both human drivers and automated systems. Both deliverables D4.2 and D5.3 align with the broader goal of proving the system's reliability and utility in diverse traffic conditions while enabling future scalability. |

# 7. Dissemination and publications

## Dissemination

| How are the project results planned to be used and disseminated? | Mark with X | Comment |
|---|---|---|
| Increase knowledge in the field | X | New methods for localization and calibration, synchronization, sensing, etc. |
| Be passed on to other advanced technological development projects | X | Chalmers is currently coordinating the WITECH competence center, which involves several partners of the B5GPOS project. |
| Be passed on to product development projects | | |
| Introduced on the market | | |
| Used in investigations / regulatory / licensing / political decisions | | |

## Publications

The project has generated a number of publications in high-impact conferences and journals:

1. Huiping Huang, Tianjian Zhang, Feng Yin, Bin Liao, and Henk Wymeersch, "Joint DOA Estimation and Distorted Sensor Detection Under Entangled Low-Rank and Row-Sparse Constraints," *ICASSP*, 2024.
2. Huiping Huang, Alireza Pourafzal, Hui Chen, Musa Furkan Keskin, Mengting Li, Yu Ge, Fredrik Tufvesson, Henk Wymeersch, and Xuesong Cai, "Joint Near-Field Sensing and Visibility Region Detection with Extremely Large Aperture Arrays," *EUSIPCO*, 2025.
3. Huiping Huang, Musa Furkan Keskin, Henk Wymeersch, Xuesong Cai, Linlong Wu, Johan Thunberg, and Fredrik Tufvesson, "Hybrid Precoder Design for Angle-of-Departure Estimation with Limited-Resolution Phase Shifters," *IEEE Transactions on Communications*, 2024.
4. Alireza Pourafzal, Huiping Huang, Victor Pettersson, Musa Furkan Keskin, and Henk Wymeersch, "FLEX: Low-Complexity 5D Beamspace Channel Estimation for mmWave MIMO-OFDM," *EUSIPCO*, 2025.
5. Lorenzo Italiano, Bernardo Camajori Tedeschini, Mattia Brambilla, Huiping Huang, Monica Nicoli, and Henk Wymeersch, "A Tutorial on 5G Positioning," *IEEE Communications Surveys & Tutorials*, 2024.
6. Musa Furkan Keskin, Silvia Mura, Marouan Mizmizi, Dario Tagliaferri, and Henk Wymeersch, "Bridging the Gap via Data-Aided Sensing: Can Bistatic ISAC Converge to Genie Performance?" *IEEE Radar Conference*, 2025.

7. Mauro Marchese, Musa Furkan Keskin, Pietro Savazzi, and Henk Wymeersch, "Disjoint Delay-Doppler Estimation in OTFS ISAC with Deep Learning-aided Path Detection," *arXiv*, 2025.
8. Elizaveta Rastorgueva-Foi, Ossi Kaltiokallio, Yu Ge, Matias Turunen;,Jukka Talvitie, and Bo Tan, "Millimeter-Wave Radio SLAM: End-to-End Processing Methods and Experimental Validation," *IEEE Journal on Selected Areas in Communications*, 2024.
9. Hui Chen, Musa Furkan Keskin, Adham Sakhnini, Nicolò Decarli, Sofie Pollin, Davide Dardari, and Henk Wymeersch, "6G Localization and Sensing in the Near Field: Features, Opportunities, and Challenges," *IEEE Wireless Communications*, 2024.
10. Ossi Kaltiokallio, Elizaveta Rastorgueva-Foi, Jukka Talvitie, Yu Ge, Henk Wymeersch, and Mikko Valkama, "Robust Snapshot Radio SLAM," *IEEE Transactions on Vehicular Technology*, 2024.
11. Ossi Kaltiokallio, Yu Ge, Jukka Talvitie, Elizaveta Rastorgueva-Foi, Henk Wymeersch, and Mikko Valkama, "Bistatic mmWave Mapping in Obstructed Environments Using Double-bounce Signals," *SPAWC*, 2024.
12. Ossi Kaltiokallio, Jukka Talvitie, Elizaveta Rastorgueva-Foi, Henk Wymeersch, and Mikko Valkama, "Integrated Snapshot and Filtering-based Bistatic Radio SLAM in mmWave Networks," *SPAWC*, 2024,
13. Yu Ge, Ossi Kaltiokallio, Yuxuan Xia, Ángel F. García-Fernández, Hyowon Kim, Jukka Talvitie, Mikko Valkama, Henk Wymeersch, and Lennart Svensson, "Batch SLAM with PMBM Data Association Sampling and Graph-Based Optimization," *IEEE Transactions on Signal Processing*, 2024.
14. Yu Ge, Hedieh Khosravi, Fan Jiang, Hui Chen, Simon Lindberg, Peter Hammarberg, Hyowon Kim, Oliver Brunnegard, Olof Eriksson, Bengt-Erik Olsson, Fredrik Tufvesson, Lennart Svensson, and Henk Wymeersch, "Experimental Validation of Single BS 5G mmWave Positioning and Mapping for Intelligent Transport," *IEEE Transactions on Vehicular Technology*, 2024.
15. Hedieh Khosravi, Xuesong Cai, and Fredrik Tufvesson, "Experimental Analysis of Physical Interacting Objects of a Building at mmWave Frequencies," *EuCAP*, 2024.

# 8. Conclusions and future research

The B5GPOS project has successfully demonstrated the feasibility and value of integrating communication, positioning, and sensing functionalities using beyond 5G radio technologies. By developing novel hardware, signal processing algorithms, and architectural models, the project advanced the state of the art in sub-meter accurate localization, low-latency data exchange, and cooperative sensing in complex urban environments. Key achievements include experimentally validated channel models, performance bounds for various localization tasks, hybrid precoding methods, and field-tested proof-of-concept systems for real-time operation.

The results clearly show that radio-based sensing and positioning can provide robust support for safety-critical automotive applications, especially where GNSS and conventional sensors are unreliable. Moreover, the project laid essential groundwork for standardization and commercial deployment of such systems within 5G and upcoming 6G frameworks.

Future research directions include:

- **6G Integration and AI-based Adaptation:** Further exploration of how AI/ML can be applied to optimize signal processing, resource allocation, and fusion in real time, particularly in 6G ISAC scenarios.
- **Large-scale Validation and Standardization:** Continued work is needed to validate B5GPOS concepts in large-scale and diverse real-world deployments, and to contribute findings to standardization bodies such as 3GPP, ETSI, and 5GAA.
- **Resilience and Trust in Perception Services:** As the technology matures, focus should shift toward securing the perception data chain and establishing robust methods for integrity validation and cross-verification across modalities.
- **Edge and Cloud-Based Cooperative Sensing Architectures:** Future research can explore scalable, edge-intelligent architectures that allow infrastructure and vehicles to collaborate in real time for enhanced situational awareness.

The project has paved the way for more intelligent, cooperative, and safe transportation systems. Continued interdisciplinary collaboration between academia, industry, and public stakeholders will be key to realizing these capabilities in commercial applications.

# 9. Participating parties and contact persons

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