5G mobil positionering för fordonssäkerhet

Public report

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Projects within Trafiksäkerhet och automatiserade fordon

FFI Fordonsstrategisk Forskning och Innovation

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1 Summary

Cellular communication signals have always been used for positioning. In particular, operators must satisfy stringent demands in terms of emergency call localization. However, the achievable accuracies were never sufficient for vehicular applications, such as navigation, let alone safety-critical applications. To enable safety-critical automotive applications, a high degree of accuracy and reliability is needed, as well as very low latency. Today, these demands can partially be satisfied by GPS, though not in dense urban conditions. The core idea of this project is to **utilize the high frequency band of new fifth generation mobile signals (so-called 5G mmWave) to provide accurate 3D position and motion information**, especially for challenging urban and suburban scenarios. This project is particularly timely, as its timeline coincides with 3GPP Release 17 and the start of 3GPP Release 18 standardization activities.

The work performed in this project has led to an understanding of the potential of 5G mmWave radio as a complementary positioning and sensing technology for vehicular applications. The project lasted for 2.5 years and are coordinated by Chalmers University of Technology. It includes as academic partner Lund University and as industrial partners Veoneer and CEVT (positioning services), Ericsson (infrastructure part of positioning) and QAMCOM (user part of positioning). The project budget is 13 426 000 SEK, of which 50 % (6 713 000 SEK) is requested from VINNOVA. The outcomes of the work can be utilized by Ericsson to further develop and standardize 5G mmWave positioning; by Veoneer and CEVT in the development of safety-critical services and applications; by QAMCOM to expand expertise in client-side algorithms for positioning; by Chalmers and Lund University to disseminate knowledge in top conferences and journals and to train students in advanced radio-based positioning.

This is the first large project to propose 5G mmWave positioning for safety-critical vehicular applications. The project brings together the important stakeholders (5G infrastructure, 5G UE, services, and applications) with leading experts in academia. The work on requirements, models, algorithms, signals, and architecture, finally culminating in the demonstration will be a world-wide unique achievement that will push the boundaries of cellular positioning and provide important insights and opportunities for all partners.

2 Background

As vehicles are equipped with more automated and connected features, the need for accurate and fast positioning (synonym: localization) has become more imminent. Vehicles rely on a variety of sensors to position themselves in a map and to sense the environment. These sensors commonly include satellite navigation (e.g., GPS) and radar. In addition, situational awareness of a vehicle can be extended beyond the local sensors’ field of view through vehicular communication. Applications range from periodic awareness messages and event-triggered safety messages to platooning and see-through driving. Vehicular communication is currently driven by two competing standards: (i) the WiFi-based 802.11p standards, used in ITS-G5 (Europe) and dedicated short-range communications (DSRC) (USA) provides a flexible short term solution in unlicensed spectrum and has been adopted by major OEMs; (ii) cellular vehicle-to-X (C-V2X) communication, based on 4G and the emerging 5G standard has been the choice for China, and provides a more long-term solution with explicit performance guarantees.

The need for accurate and fast positioning, as well as **timely and reliable situational awareness cannot be met with current technologies**. This is because GPS fails to provide accurate positioning in dense urban environments, where automated and connected services will be most useful. Moreover, ITS-G5 will not be able to provide any performance guarantees and could on the long term be replaced by 5G technology. In any case, whatever the outcome is of the current legislation process, 5G modems are expected to be integrated in future vehicles.

As 5G is currently undergoing standardization and deployment, now is the ideal time to investigate the use of 5G positioning for automated and connected vehicles. The specific properties of 5G at mmWave (large bandwidths, high frequency carriers, large number of antennas) making it a suitable candidate for combined vehicular positioning and communication. However, there have been any studies that demonstrate 5G mmWave positioning in real-world conditions.

In contrast to many other 5G vehicular projects, here we bring together a unique consortium to investigate the potential of 5G mmWave for positioning in several safety-critical vehicular scenarios and thereby guide ongoing standardization. Our project is to answer the core research questions below, and it have significant impact in both vehicular safety and wireless communication, inspiring new services and use cases.

3 Purpose, research questions and method

The purpose of this project is **to develop techniques that achieve positioning errors down to 1 meter level with the support of a 5G system's communication** capacity by cross-industrial cooperation among academia and large as well as small companies that excel in telecommunications and vehicles safety. Additionally, we aim to a rapid introduction of software and hardware components in the automotive safety area to show the real-world and real-time performance of the proposed approaches.

To fulfill the research purpose, we formulate several research questions:

- Q1 *What are the requirements to meet the automotive industry's safety standards and other services utilizing redundant and/or additional positioning functions?*
- Q2 *Can 5G mmWave signals provide sufficient positioning accuracy to serve a variety of vehicular safety use cases?*
- Q3 *What kind of models and algorithms are suitable?*
- Q4 *What are the designs and architectures to support these use cases and applications?*
- Q5 *Where should the processing occur and what are the trade-offs?*
- Q6 *How should signals be designed to enable the best possible positioning performance under latency and bandwidth constraints?*
- Q7 *How do these models, methods, designs, and architectures behave in real-world operating conditions?*
- Q8 *What are the main technical challenges for large-scale deployment?*

To answer these questions, we decomposed the problem into sub-problems, which are tackled in different work packages (WPs). Veoneer leads WP1 (WP1: Requirement analysis and User Case definitions), which will determine use cases and requirements, as an input to other WPs. Lund University coordinates WP2 (WP2: Channel characterization and modeling for 5G mmWave positioning) including the measurement and modeling activities. Chalmers University of Technology coordinates WP3 (WP3: Algorithms) focusing on channel estimation and positioning algorithm development, based on the models from WP2. Ericsson coordinates WP4 (Data flow and solution architecture) and WP5 (Cellular reference signal design), which deal with architecture and signal design, respectively. Finally, Veoneer coordinates WP6 (WP6: Validation and testing), which plans and tests the solutions developed in WP3-5 by applying well adapted use cases to validate the solution. A demonstrator is used to demonstrate the end results, including real-time processing and commercial 5G base station for positioning.

4 Target

The project goals are to develop expertise around 5G mmWave radio positioning and sensing for vehicular applications, as well as the realization of a demonstrator. Moreover, the project aimed to further develop and standardize 5G mmWave positioning and safety-critical services and applications. The specific goals (SG) of this project are as follows:

- SG1: *Formulate requirements and use cases in 5G mmWave positioning for automotive safety.*
- SG2: *Collect 5G mmWave measurement data for the purpose of building models, gaining insight into the radio signals, and validate methods.*

- SG3: *Derive and evaluate algorithms for positioning and mapping, both for relative positioning (through D2D communications without a base station) and absolute positioning (with one or more base stations).*
- SG4: *Propose a solution architecture, investigate integration with cellular communication architecture, deployment effects, trade-offs of user-side processing vs core-side processing, positioning methods for the proposed architecture.*
- SG5: *Design dedicated reference 5G signals for the purpose of 5G mmWave positioning for automotive safety, contributing to 3GPP release 17.*
- SG6: *Validate and test a subset of the considered methods, signals, and architecture for an exemplifying use case.*

The work towards these goals has been reported in the project's deliverables and can be summarized as follows.

- SG1: We have defined system-level requirements to meet the automotive industry's safety standards and other services with positioning function.
- SG2: We have performed a dedicated measurement campaign involving with both dedicated measurement hardware and the devices used for the demonstration.
- SG3. Based on the geometric channel models, we have designed efficient low-complexity algorithms for positioning and mapping.
- SG4: We have proposed a novel positioning system architecture based on cellular system and signals. However due to a change in focus of the 3GPP standards, work was shifted from this goal towards SG6.
- SG5: We have investigated optimal spatial signal designs, based on the reference signal decided in 3GPP release 16.
- SG6: Finally, we have successfully built a demonstrator and validated the key ideas of the project.

Further details are provided in Section 5.

We have also contributed to global knowledge on 5G mmWave positioning. In particular, based on the understanding of the insight of the positioning and communications, we have successfully identified new research areas such as integrated sensing and communications, joint radar and communications, which have enriched the worldwide and cross industry and academic collaborations. We also contributed to the development of channel models. The results from this project can be utilized to improve standards and products for cellular based positioning and vehicle safety.

5 Results and goal achievement

In this section, we report on the results achieved related to each of the goals, as well as any deviations (both positive and negative).

SG1

To achieve SG1, Veoneer coordinated Workpackage-1 (WP1: Requirements analysis and Use Case definition). The requirements on system-level to match the expected accuracy, latency and robustness for urban vehicle safety applications are specified. The requirements are also exemplified with selected use-cases. For the requirements of cellular positioning system, we have identified the operational environment challenges for the system and transformed the application requirements to technical requirements on radio and client. This includes the cellular operational environmental parameters such as urban infrastructure, indoor/underground, and weather conditions. Theoretical analysis and numerical simulations are also conducted to assess the requirements. Business case analysis as well as the influence of the architecture aspects are also studied. All these studies can be found in D1.1, D1.2, and D1.3.

Deviations: no deviations have been reported

SG2

In terms of SG2, Lund University led the Workpackage-2 (WP2: Channel characterization and modelling for 5G mmWave positioning). The literature review of the state of the art in models for 5G mmWave positioning has been conducted. Particularly, most of the 5G mmWave models are established for communication system performance evaluation, which are not detailed enough for positioning purposes. The related work is summarized in D2.1. With the identified gap, a dedicated measurement campaign involving one vehicle communicating with a base station in an urban scenario has been performed. Based on the data collected, the statistical geometric channel model has been established and validated, used for positioning and mapping purposes. In addition, since a beam sweeping strategy is applied, the beamspace measurements and calibrations are conducted at the UE side to get insight on the beams and beamspace channels. Related work has been reported in D2.2. The multipath components of the propagation channel have been also studied with measurement data collected on site, together with the environment recorded. Based on that, the position and map-based geometric properties of the channels are validated and used for real-time localization of the vehicle. The related work has been reported in D2.3.

Deviations: The scope of the work has been slightly modified to focus on the measurements needed to successfully complete the demonstration. Hence, less emphasis has been placed on modeling the channel and more on modeling the devices.

SG3

To achieve SG3, Chalmers University of Technology led the Workpackage-3 (WP3: Algorithms). The main tasks have been the development of the low-complexity channel estimation methods and the simultaneous localization and mapping (SLAM) methods, both with simulated data and measurement data. Specifically, a tensor-based estimation of signal parameters via rotational invariance techniques (ESPRIT) has been initially exploited. Based on the statistics of the geometrical channel parameter estimations, the localization of the vehicle with angle and delay measurements is performed. The SLAM methods based on Poisson multi-Bernoulli mixture (PMBM) filter has been developed to show good localization and mapping performance. The preliminary methods and results are reported in D3.1. In addition, both the BS and the UE sides adopted the beam sweeping strategy, and the corresponding beamspace ESPRIT-based approaches for high dimensional channel estimation and high accurate localization are developed. The proposed methods enjoy almost linear complexity, and the analytical channel estimation and localization performance has also been conducted. A good match of the analytical results and the numerical results has been demonstrated. Meanwhile, multiple variations of the PMBM filter-based approaches for SLAM have been developed, to further reduce the computational complexity for real-time localization and mapping purposes. These studies can be found in D3.2. Moreover, together with the measurement campaigns, the estimated beam pairs between the BS and the vehicle have been derived. The low complexity beamspace ESPRIT approaches are utilized to resolve the multipath components, producing the angle and delay estimates for real-time localization. Using the associated GPS data, together with the estimated angle and delays, the location and the orientation of the transmit antenna array at the BS are calibrated. Due to the limited knowledge of the BS beams, a low complexity localization algorithm with limited measurements is developed. The meter level localization accuracy has been achieved based on the real-time measurements.

Deviations: The scope of the work has been slightly modified since the project consortium decided to not consider device-to-device communication (since it was not considered in standardization). Instead, the focus has been on device-centric positioning.

SG4

The work towards SG4 was led by Ericsson in WP4 (Data flow and solution architecture). The project proposed possible deployments and evaluation settings for exploring positioning solutions and evaluating them, with and without sensor fusion. Two deployments suitable for positioning purposes have been advocated. Also, three studies for exploring positioning solutions have been proposed. These studies have been evaluated with agreed deployments and evaluation parameters. A variety of performance criteria were proposed. These findings have been reported in D4.1. The work in WP4 then shifted to contributing to the demonstrator, for which a network-centric architecture was proposed, to minimize latencies. The discussions in SG4 has resulted in a paper on semi-passive positioning. A survey paper on vehicular positioning is under preparation.

Deviations: The scope of the work has been slightly modified after D4.1 was delivered, since (i) the project consortium decided to not consider device-to-device communication; (ii) there was a need to shift resources to WP6, in order to deliver the demonstration hardware on time.

SG5

To achieve SG5, Ericsson led WP5 (Cellular reference signal design). With WP5, the available signals for positioning in the 3GPP New Radio (NR) system were listed and an initial evaluation of the accuracy of NR rel16 was provided in D5.1. It is shown that using 3GPP scenarios in mmWave frequencies, decimeter-level accuracy is possible using 5G Positioning Reference Signal (PRS) based Observed Time Difference Of Arrival (OTDOA) and an accurately synchronized network. This result should however be completed with a more realistic scenario for the 5Gpos use cases. Work then started on the definition of new signal designs based on spatial shaping, reported in D5.2 (initial results) and D5.3 (published paper).

Deviations: The scope of the work has been slightly modified after D5.3 was delivered to shift resources to WP6, in order to deliver the demonstration hardware on time.

SG6

To achieve SG6, Veoneer has led WP6 (Validation and testing), which included the development of hardware and software in the user device, the integration of the user device into the vehicle (D6.1), the development of the ground truth system, and the integration of the base station in the system. Two validation measurement campaigns were conducted in Lund and in Gothenburg. These provided valuable information to improve the overall system (as reported in D6.2). WP6 ended with a successful demonstration (D6.3) in Lund at the end of the project. A video of the final demonstration is available at https://youtu.be/wAV0_uMpSDo

Deviations: The scope of the work has been slightly modified after D5.3 was delivered to shift resources to WP6, in order to deliver the demonstration hardware on time.

How the results and deliverables serve the FFI objectives

In terms of research and innovation: in this project, better localization accuracy than the GPS localization system[1] has been achieved using 5G mmWave signals. This demonstrates that using the existing and planned 5G cellular infrastructure together with the standard 5G modems with additional software components in the vehicle and base station allows for a rapid penetration of the proposed solution to high accuracy vehicular localization. The positioning features as available in 3GPP standards has been evaluated, supporting the standardization of the 3GPP cellular positioning and communications. In addition, as an important outcome of this project, the measurements and models of the radio channel based on realistic scenarios for automotive use cases, have improved the reliability of our work. Also, several high impact international journal publications and the involvement to international conferences/workshops, has increased the international visibility of our work in this project. All these reflect the achievement of the FFI objective: competitive research and innovation. This project has initiated and involved fruitful cross-industrial cooperation among academia and large as well as small companies that excel in telecommunication and vehicle safety. This interdisciplinary collaboration has led to an increased understanding of both requirements and technical solutions amongst the partners. This can pave the way towards rapid introduction of software and hardware components in the automotive safety area, as well as 3GPP 5G positioning standard improvements, which can be jointly beneficial for operators, device manufacturers, vehicle companies and infrastructure vendors.

[1] Note that very high accuracy GPS positioning can be achieved in some scenarios, e.g., with the use of auxiliary correction information in the form of real-time kinematics (RTK).

6 Dissemination and publication

6.1 Dissemination of knowledge and results

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The project participants have developed expertise in the respective research fields
Moved on to other advanced technological development projects	X	Ericsson has used the outcome of the project as input to further internal research on localization, leading to future contributions to mobile communication standards and products. The project partners have applied for VINNOVA/FFI call in 2022 for a second extension project ("Beyond 5G positioning"), in order to further develop expertise in the robust design and implementation to account for hardware impairments, high mobility, and real-time applications.
Moved on to product development projects	-	
Introduced to the market	-	
Used in investigations/regulations/ permit matters/ political decisions	-	

The project has also benefited from the large eco-system in Sweden related to communication, radar, and positioning. The public project results have been disseminated into larger European projects, such as Hexa-X (https://hexa-x.eu), RISE6G (https://rise-6g.eu), and REINDEER (https://reindeer-project.eu), which increases their chances for higher impact.

6.2 Publications

Within this project, 16 deliverables were written (5 deliverables were cancelled, due to shifts in the project priorities). In addition, the project also had a high scientific output, namely 7 journal articles and 10 conference papers have been published/submitted. Additional publications are planned but are not yet available at the time this report was written. The complete list of deliverables and publications is provided below.

Delivered Reports:

1. Automotive safety application requirements (D1.1)
2. Requirements for commercial automotive grade cellular positioning (D1.2)
3. Cellular positioning system requirements and business case analysis (D1.3)
4. Report on literature review and preliminary models (D2.1)
5. Report on measurements campaign (D2.2)
6. ~~Report on positioning-relevant channel models (D2.3)~~
7. Preliminary methods for positioning and mapping (D3.1)
8. Refined methods for positioning and mapping (D3.2)
9. Final methods for positioning and mapping (D3.3)
10. Report on possible positioning architectures. (D4.1)
11. ~~Finalizing positioning architecture and proposing possible different positioning methods. (D4.2)~~
12. ~~Presenting analysis of positioning methods on considered architectures. (D4.3)~~

13. ~~Finalizing positioning methods and architectures. (D4.4)~~
14. Evaluate accuracy and performance to support the selected connected services. (D4.5)
15. Assessment of the rel-16 3GPP standard versus WP2 requirement. (D5.1)
16. List of candidate signals to be evaluated for positioning in uplink, downlink and sidelink. (D5.2)
17. First results of the evaluations. (D5.3)
18. ~~Final results of the evaluations, proposal for new positioning signals (D5.4)~~
19. Vehicle fitted with required hardware support for the developed system (D6.1)
20. Performance validation report (D6.2)
21. Demonstration using selected commercial hardware in vehicle as well as the base stations (D6.3)

Journal and conference publications:

1. Yu Ge, Hyowon Kim, Fuxi Wen, Lennart Svensson, Sunwoo Kim, Henk Wymeersch, “Exploiting diffuse multipath in 5G SLAM,” IEEE GLOBECOM, Dec. 2020.
2. Yu Ge, Fuxi Wen, Hyowon Kim, Meifang Zhu, Fan Jiang, Sunwoo Kim, Lennart Svensson, Henk Wymeersch, “5G SLAM using the clustering and assignment approach with diffuse multipath,” MDPI Sensors, vol. 20, no. 16, pages 4656, 2020.
3. Yu Ge, Fan Jiang, Meifang Zhu, Fuxi Wen, Lennart Svensson, Henk Wymeersch, “5G SLAM with Low-complexity Channel Estimation,” 15th European Conference on Antennas and Propagation (EuCAP), Mar. 2021.
4. Fan Jiang, Yu Ge, Meifang Zhu, Henk Wymeersch, “High-dimensional channel estimation for simultaneous localization and communications,” IEEE Wireless Communications and Networking Conference (WCNC), May 2021.
5. Kamran Keykhosravi , Musa Furkan Keskin, Satyam Dwivedi, Gonzalo Seco-Granados, and Henk Wymeersch, “Semi-Passive 3D Positioning of Multiple RIS-Enabled Users,” IEEE Transactions on Vehicular Technology, vol. 70, no. 10, pp. 11073-11077, Oct. 2021.
6. Ossi Kaltiokallio, Yu Ge, Jukka Talvitie, Henk Wymeersch, and Mikko Valkama, “mmWave Simultaneous Localization and Mapping Using a Computationally Efficient EK-PHD Filter” IEEE 24th International Conference on Information Fusion (FUSION), Nov. 2021.
7. Stefania Bartoletti, Henk Wymeersch, Tomasz Mach, Oliver Brunnegård, Domenico Giustiniano, Peter Hammarberg, Musa Furkan Keskin, Jesus O. Lacruz, Sara Modarres Razavi, Joakim Rönnblom, Fredrik Tufvesson, Joerg Widmer, and Nicola Blefari Melazzi, “Positioning and Sensing for Vehicular Safety Applications in 5G and Beyond,” IEEE Communications Magazine, vol. 59, no. 11, pp. 15-21, Nov. 2021.
8. Ossi Kaltiokallio, Jukka Talvitie, Yu Ge, Henk Wymeersch, Mikko Valkama, “mmWave Mapping using PHD with Smoothed Track Confirmation and Multi-Bounce Suppression,” IEEE International Conference on Communications Workshops (ICC Workshops), May 2022.
9. Musa Furkan Keskin, Fan Jiang, Florent Munier, Gonzalo Seco-Granados, Henk Wymeersch, “Optimal spatial signal design for mmWave positioning under imperfect synchronization,” IEEE Transactions on Vehicular Technology, vol. 71, no. 5, pp. 5558-5563, May 2022.
10. Yu Ge, Yibo Wu, Fan Jiang, Ossi Kaltiokallio, Jukka Talvitie, Mikko Valkama, Lennart Svensson, Henk Wymeersch, “Iterated Posterior Linearization PMB Filter for 5G SLAM,” IEEE ICC, May, 2022.
11. Fan Jiang, Fuxi Wen, Yu Ge, Meifang Zhu, Henk Wymeersch, Fredrik Tufvesson, “Beamspace Multidimensional ESPRIT Approaches for Simultaneous Localization and Communications,” arXiv preprint arXiv:2111.07450, 2022.
12. Yu Ge, Ossi Kaltiokallio, Hyowon Kim, Fan Jiang, Jukka Talvitie, Mikko Valkama, Lennart Svensson, Sunwoo Kim, Henk Wymeersch, “A computationally efficient EK-PMBM filter for bistatic mmWave radio SLAM,” IEEE Journal on Selected Areas in Communications, vol. 40, no. 7, pp. 2179-2192, Jul. 2022.
13. Yu Ge, Hui Chen, Fan Jiang, Meifang Zhu, Hedieh Khosravi, Simon Lindberg, Hans Herbertsson, Olof Eriksson, Oliver Brunnegard, Bengt-Erik Olsson, Peter Hammarberg, “Experimental Validation of Single Base Station 5G mmWave Positioning: Initial Findings,” IEEE 25th International Conference on Information Fusion, Jul. 2022.

14. Hyowon Kim, Jaebok Lee, Yu Ge, Fan Jiang, Sunwoo Kim, and Henk Wymeersch, "Cooperative mmWave PHD-SLAM with Moving Scatterers," IEEE 25th International Conference on Information Fusion, Jul. 2022.
15. Yu Ge, Ossi Kaltiokallio, Hui Chen, Fan Jiang, Jukka Talvitie, Mikko Valkama, Lennart Svensson, Henk Wymeersch, "Doppler Exploitation in Bistatic mmWave Radio SLAM," accepted in IEEE GLOBECOM, 2022.
16. Alessio Fascista, Musa Furkan Keskin, Angelo Coluccia, Henk Wymeersch, Gonzalo Seco-Granados, "RIS-aided Joint Localization and Synchronization with a Single-Antenna Receiver: Beamforming Design and Low-Complexity Estimation," IEEE Journal of Selected Topics in Signal Processing, DOI: 10.1109/JSTSP.2022.3177925, 2022.
17. Ossi Kaltiokallio, Roland Hostettler, Jukka Talvitie, Yu Ge, Hyowon Kim, Henk Wymeersch, Mikko Valkama, "Towards Real-time Radio-SLAM via Optimal Importance Sampling," IEEE 23rd International Workshop on Signal Processing Advances in Wireless Communication (SPAWC), 2022.

7 Conclusions and continued research

Despite significant challenges due to the COVID-19 pandemic, the resulting change of a project partner, and the need to move many project activities online, the project has achieved most of its goals. It has generated a wealth of knowledge related to 5G mmWave positioning and has reinforced the role of the project partners as worldwide leaders in this technical area.

Real progress has been made towards the practical demonstration of 5G mmWave positioning with a single base station, relying on commercial, but modified hardware and tailor-made signal processing. While the target accuracy could not be achieved, at least meter-level accuracy could be demonstrated, whereas conventional methods would need several base stations to achieve the same performance.

An important outcome of the project are the knowledge gaps that were revealed, in particular related to the gap between theory and experiments. The project consortium is performing ongoing work to bridge this gap and has applied for a follow-up project from Vinnova.

8 Participating parties and contact persons

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