Gemensam radar och kommunikation för nästa generations fordonsapplikationer

Public report

Project within Trafiksäkerhet och automatiserade fordon
Author Henk Wymeersch
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FFI Fordonsstrategisk Forskning och Innovation

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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

Summary

Modern vehicles are equipped with a variety of sensors to provide real-time situational awareness and communication technologies to gather information beyond the local sensors' field of view. Among these sensors, radars play a critical role due to their robustness in different weather conditions and high accuracy. However, the uncoordinated signals emitted by radars can lead to mutual interference, with the risk of reducing the availability of ADAS functions. Interference can be mitigated by coordination, which requires low-latency inter-vehicle communication.

The core idea of this project was to enable vehicular radar to perform a dual role by providing joint radar and communication (JRC). This JRC system aimed to deliver faster, more reliable, and higher-rate communication links compared to standard technologies while simultaneously ensuring interference-free radar operation. This approach was timely, as JRC was being considered in the evolution of radar and 3GPP communication standards. Thus, the project had the potential to make significant impacts in both areas.

The specific goals of the project were:

1. **Specify use cases for JRC**: Identifying scenarios where JRC can significantly improve vehicular safety and communication.
2. **Development and demonstration of on-vehicle JRC chipsets**: Creating hardware that integrates radar and communication functionalities.
3. **Exploration of automotive JRC in the context of 5G and beyond**: Investigating how JRC can be optimized with current and future communication technologies.
4. **Development of link-level and network-level models and simulators**: Enabling rapid testing and prototyping of software solutions.

The work has led to a deeper understanding of JRC in an automotive context for tailored use cases and made progress toward a JRC automotive prototype. The project lasted for 30 months (including 6 months extension) and involved academic partners (Chalmers University of Technology and Halmstad University) and industry partners (Volvo Car Corporation, AB Volvo, Magna, Gapwaves, Chalmers Industriteknik, and Comnisens).

In terms of impact, this project aimed to disrupt the automotive sensor market by providing a cost-effective, integrated JRC solution. Such a solution would enhance vehicular safety, reduce interference, and improve communication reliability, benefiting the Swedish automotive industry and its suppliers. Additionally, the project contributed to the Agenda 2030 goals by promoting good health and well-being, quality education, and innovation in industry and infrastructure.

This report provides an overview of the background, purpose, and results from the project. To complement the report and broaden the reach and understanding of the entire project, we have prepared a 30-minute video presentation. This presentation introduces the project

partners, outlines the main goals, describes the methodologies employed, showcases the developed JRC solutions, summarizes the outcomes and discusses the road ahead. The video is uploaded to Youtube and can be accessed here.

Sammanfattning på svenska

Moderna fordon använder olika sensorer för realtidsövervakning och kommunikationsteknik för att samla in information utanför det lokala sensorns synfält. Radarer är särskilt viktiga tack vare deras noggrannhet och tålighet i olika väderförhållanden, men deras okordinerade signaler kan orsaka störningar och säkerhetsrisker. Detta projekt syftade till att integrera radar- och kommunikationsfunktioner (JRC) i fordon för att förbättra hastighet, tillförlitlighet och störningsfri radaroperation. Genom att utforska och utveckla JRC i samband med 5G-teknologi, skapade projektet ett prototypchipset och avancerade modeller och simulatorer för snabb testning. Under 24 månader samarbetade akademiska institutioner (Chalmers och Högskolan i Halmstad) och industripartners (Volvo Car Corporation, AB Volvo, Magna, Gapwaves, Chalmers Industriteknik och Comnisens) för att förbättra fordonssäkerhet och kommunikationspålitlighet, vilket också stöder de globala målen för Agenda 2030.

Background

Modern vehicle safety and comfort systems relied heavily on individual sensors and communication devices, such as radar, cameras, cellular modems, and global navigation satellite systems (GNSS) with inertial measurement units (IMU). Each of these components required its own processing units housed in physically separated boxes connected by extensive cabling. The rapid development of Advanced Driver Assistance Systems (ADAS) and Autonomous Driving (AD) created a need for multiple data sources to form a comprehensive perception of the vehicle's surroundings. This situational awareness was crucial for aiding drivers (ADAS) or the vehicle itself (AD) in making safe driving decisions.

However, the integration of numerous on-vehicle sensors and communication devices presented challenges, including limited situational awareness in complex traffic conditions, radar interference from uncoordinated signals, high communication latency, lack of suitable communication protocols, and high costs. To address these issues, the project (referred to as the RADCOM2 project in this report) aimed to develop a solution that combined radar and communication functions (i.e., JRC) in a single system. This integration promised to enhance vehicular safety, reduce interference, and improve communication reliability by utilizing minimal resources in terms of cost, material, energy, and spectrum usage.

Purpose, research questions and method

The purpose of this project was to develop a JRC system for automotive applications to enhance vehicular safety and efficiency. By integrating radar and communication functionalities into a single system, the project aimed to mitigate issues related to radar interference, improve situational awareness, and provide reliable, low-latency communication links. This innovation was expected to lead to safer and more efficient driving experiences, contributing to the advancement of autonomous driving technologies and improved traffic management.

Research Questions

1. How can joint radar and communication (JRC) systems improve the situational awareness and safety of modern vehicles?
2. What are the specific use cases where JRC can significantly enhance vehicular communication and radar functionalities?
3. How can JRC technology be integrated and optimized within the framework of current and future 5G communication standards?
4. What are the technical challenges and potential solutions in developing on-vehicle JRC chipsets that ensure interference-free operation and reliable communication?
5. How can the performance of JRC systems be effectively modeled and simulated at both the link-level and network-level to facilitate rapid testing and prototyping?

Method

The project adopted a comprehensive approach divided into several work packages to achieve its goals.

- Initially, critical traffic scenarios and use cases that would benefit from JRC technology were identified. These use cases informed the development of performance and hardware requirements.
- Subsequently, the project focused on the development and evaluation of a distributed antenna co-packaged mmWave transceiver front-end platform capable of beamforming above 100 GHz. This involved creating prototypes of JRC chipsets and testing them in real-world conditions.
- To support system-level simulations, models of the hardware components and the JRC channel were developed, incorporating non-linear effects and antenna characteristics. These models were validated through experiments and used to refine the design requirements. The project also evaluated the compatibility of JRC technology with current and future 5G standards, developing novel waveforms and detection methods to optimize performance.
- Finally, a full system simulator was created to integrate the findings from all work packages, enabling the evaluation of JRC technology in realistic automotive scenarios. Hardware demonstrations on actual vehicles were conducted to validate the system's performance and uncover potential issues, guiding further refinements and practical applications.

Objectives

The primary objectives of the project were to advance the development of JRC systems for automotive applications, addressing critical challenges and unlocking new capabilities in vehicular safety and communication. The specific objectives were as follows.

#	Name	Description	Status
1	Specify Use Cases for JRC	Identify and define specific scenarios where JRC technology can significantly enhance vehicular safety, communication, and overall driving experience. This involved detailed analysis of traffic situations and requirements for advanced driver assistance systems (ADAS) and autonomous driving (AD) functionalities.	The objective was achieved.
2	Development and Demonstration of On-Vehicle JRC Chipsets	Design and create hardware that integrates radar and communication functionalities into a single chipset. This objective aimed to demonstrate the feasibility and benefits of JRC technology through the development of a prototype chipset that could be tested in real-world conditions.	The objective was partially achieved.
3	Exploration of	Investigate how JRC technology can be optimized and integrated within the framework of current 5G and	The objective was achieved.

	Automotive JRC in the Context of 5G and Beyond	future communication standards. This involved evaluating the performance of JRC systems with 5G waveforms and exploring potential enhancements for beyond 5G technologies.	
4	Development of Link-Level and Network-Level Models and Simulators	Create advanced models and simulators to represent the performance of JRC systems at both the link-level and network-level. These tools were essential for rapid testing, prototyping, and validation of JRC solutions, enabling detailed performance analysis and optimization.	The objective was achieved.
5	Enhance Situational Awareness and Safety	Develop JRC systems that provide a more comprehensive and accurate situational awareness by integrating radar sensing and communication. This objective focused on improving the detection, tracking, and classification of objects, reducing interference, and ensuring reliable communication even in challenging conditions.	The objective was achieved.
6	Cost-Effective Design for Mass Market:	Ensure that the developed JRC technology is cost-effective, compact, and energy-efficient, making it viable for widespread adoption in the automotive industry. This involved the use of advanced manufacturing techniques and materials to keep costs low while maintaining high performance and reliability.	The objective was achieved.
7	Standardization and Interoperability	Contribute to the development of international standards for JRC technology, ensuring interoperability between different vehicles and communication systems. This objective aimed to facilitate the integration of JRC systems into existing and future vehicular communication frameworks.	The objective was partially achieved.

In summary, of the 7 objectives, the project achieved 5, while 2 were only partially achieved. In terms of objective 2, the project was not able to develop a complete integrated solution, but rather components of that integrated solution. This was because of lack of available components and equipment, which in turn are a consequence of global supply chain disturbances. In terms of objective 7, the consortium did not make specific contributions to international standards. However, partners have followed ongoing evolution in several standards development organizations (SDOs), namely 3GPP and ETSI.

Results and deliverables

The main results have been reported in the project’s 14 internal deliverables.

Scope of the 14 deliverables

D1.1 Use case description

This document defines various use cases that will benefit from the improved performance of JRC systems in fleet management and automotive safety. Building on scenarios from earlier FFI projects, it details additional cases, particularly for trucks in typical traffic and special environments like mines. Key use cases include "Do Not Pass Warning," where vehicles share hazard data to improve detection of hidden pedestrians, and "Electronic Emergency Brake Lights," which enhance emergency braking signals with precise communication. Other scenarios cover overtaking maneuvers, pedestrian detection despite radar interference, directed communication with specific targets, autonomous valet parking, parking assistance, combined communication and sensing, platooning, wireless bridging of vehicle combinations, ad-hoc wireless networks, and vehicle-to-cloud management. These use cases will guide the project's work packages, helping define hardware and software requirements and validating JRC technology through simulations and real-world tests, ultimately enhancing traffic safety and vehicular communication.

D1.2 Report on Performance and Hardware Requirements

This document outlines the performance and hardware requirements for joint radar and communication (JRC) systems, focusing on future commercial applications beyond project prototypes. The requirements align with the use cases specified in the RadCom2 Use Case Definitions document. For front-looking radar, key parameters include a frequency of 140 GHz, a range of 0.1 m to 300 m, and a resolution of 0.05 m for range and ±1 km/h for velocity. The system also features a 100° field-of-view for both azimuth and elevation, a radar frame rate of 30 Hz, and a communication capacity of 100 Mbit/s with a 20 ms latency. Beam steering capabilities extend to ±50° in both azimuth and elevation. The corner or parking radar has similar specifications but with a maximum range of 200 m and a wider azimuth field-of-view of 150°. Both radar types emphasize robust performance in various automotive scenarios, ensuring reliable detection, communication, and minimal interference. These requirements guide the development of JRC systems that enhance vehicular safety, efficiency, and integration with 5G standards, contributing to the advancement of autonomous driving technologies.

D2.1 mmWave Frontend Transceiver Chipsets with RoF Interconnection

This deliverable presents the development and testing of mmWave frontend transceiver chipsets and Radio over Fiber (RoF) interconnections for the RADCOM project. The chipsets were developed using the 130nm SiGe BiCMOS process, featuring high-speed HBTs with impressive ft/fmax values. The transmitter and receiver chipsets include advanced components like frequency quadruplers, LO driver amplifiers, and power amplifiers, achieving notable performance metrics such as a 10 dB conversion gain at 140 GHz and 20 dB gain for the receiver with 10 dB image rejection. The data transmission tests demonstrated successful QAM modulated signal transmission with low bit error rates using a polymer microwave fiber. Additionally, the project addressed the challenge of phase-coherent LO signal distribution for beamforming radar modules by proposing an RoF LO distribution solution utilizing commercially available optical-electrical transceiver modules. These modified SFP modules showed suitable frequency response, supporting up to 100-meter connections. The promising results indicate that these transceiver chipsets will be effectively used in radar demonstrators, with continued development of beamforming radar modules in future work packages.

D2.2 Single Channel Antenna-in-Package (AiP) Module

This deliverable details the development of a single-channel Antenna-in-Package (AiP) module using the 130nm SiGe BiCMOS process. The AiP module integrates a transceiver chipset with a waveguide interface, enhancing the performance for radar and communication applications. The project achieved significant advancements by developing a manual process to reduce the substrate thickness of the MMIC chip, improving transition performance. A metal split block waveguide structure was used to house the MMIC, showing promising results in conversion gain and port matching during testing. Additionally, a cost-effective multiple layer waveguide (MLW) technology was introduced, demonstrating comparable performance to traditional approaches with significantly reduced manufacturing costs. The MLW-based receiver prototype exhibited a 3-dB conversion gain with a baseband bandwidth above 5 GHz. These innovations contribute to the robustness and efficiency of joint radar and communication systems, essential for automotive safety and fleet management applications.

D2.3 RoF AiP Transmitter Module as Beamforming Front-End Demonstrator

AiP module was developed with beamforming antenna with 1x8 array configuration, which is capable for 1 dimension beam steering. Four receiver channels are used with phase adjustment receiver side beam steer can be achieved. XFP modules are suggested for local oscillator distribution at below 10 GHz then the frequency multipliers are used for up converting LO for Dband mixer operation. Power splitting was done at fiber end in optical domain. With 8 dBm LO driven at 7 GHz, the XPF receiver side only provide -2 dBm output after O/E conversion. This poor power delivery requires extra power Amplifier to reach multiplier input power threshold. The RoF topology, selection of components and testing results was given in D2.3. The RoF approach of LO signal distribution is investigated, however, the insufficient driving power of RoF module made it less effective as demonstration solution.

D2.4 RoF AiP Transceiver Module as Radar Front-End Demonstrator

Given the testing result of D2.3, radar front end still used similar beamforming structure, however, PCB based LO distribution was used in the demonstrator. The fundamental LO generation was designed jointly with four channel LO distribution on the same PCB board and LO was then connected via RF cables to four frequency multipliers to steer different receiver modules. Analog voltage-controlled phase shifters were used before frequency multipliers, thus lower frequency phase shifters can be adopted to reduce cost. A programmable voltage generator was used for phase shifter control and python code was developed for phase adjustment with consideration of frequency multiplier factor and control voltage linearity. The radar front end demonstrator topology design, phase adjustment design, selection of components and related test validation results was given in D2.4 and antenna design was cross-referenced to D3.2.

D3.1 Non-Linear Hardware Model

The RadCom electronic system has been modelled with two different commercially available tool chains. The tool chains include circuit simulators and ray tracing simulators. One of the goals in this project was to verify our simulations, at least in part, with measurements. The D-band frontends are the most critical components in terms of unwanted non-linear signal response, and thus most important to characterize. However, due to manufacturing problems the frontends were not available until very late in the project. Also, to some extent the planned D-band components had to be replaced with commercial substitutes. One specific issue here was the self-induced oscillations caused by electronic feedback loops in the die packages. The project now had to prioritize between characterization of non-linearities and assembling the phase array antenna. It was considered that the assembly of the phase array antenna would be of more general interest. Further, the characterization of non-linearity of a D-band frontend is a very difficult task, with a very high risk of inconclusive results.
The two investigated tool chains partly solved the task of modelling non-linearities. Tool chain number one had a streamlined interface between its simulation components but was very limited in its raytracing tool. Due to this it was impossible to simulate interference between JRC units in any convenient way. On the other hand, this tool had a good support for communication system simulations and for modeling of electronic impairments. Tool chain number two was focused on the raytracing simulation, with inherent support for simulation of interference between JRC units. The modelling of non-linear electronics was not well adapted for typically required engineering tasks though. The conclusion is that it is possible to model non-linear response in RadCom systems, but that the available tools are far from satisfying. Furthermore, it is still not confirmed how well these simulations can predict the actual performance of an implemented system.

D3.2 Multiple Antenna Model Simulation and Measurement Results

The mmWave antennas has been designed and simulated using a full wave solver. These results have been shown in D3.2. The design features a linear antenna array of 4 antenna elements at half a wavelength. This setup was chosen following the requirements which were found based on the planned hardware together with the results from D1.2. Each antenna element used 5 radiating slots to achieve the necessary directivity in the elevation plane, while maintaining a wide field of view in the azimuth plane to facilitate the operation of the JRC unit within the use cases given in D1.1. The design was manufactured using CNC milling and chemical etching to achieve the needed mechanical tolerances. After assembly the antenna array has been characterized in an anechoic chamber and the radiation pattern showed close resemblance to the simulated values. Furthermore, the measured radiation patterns have been simulated for their use in the planned beamforming operation of the JRC unit and this is later verified with active measurements in an anechoic chamber.

D3.3 JRC Channel Model Including Hardware Simulation Results with 5G Waveform

The investigated simulation tool chains described in D3.1 allow for standard multi path and Doppler channel models; they also allow for simulation of individual scenarios. However, the value of a simulation of specific individual scenario is very limited at the investigated radar band. The short wavelength at these bands calls for an immense precision in the setup of real-world scenarios. It must be done down to the level of texture of the surfaces. The added value of this deliverable was instead to add the influence from analogue electronic imperfections into the simulation models. Our interest was in deviations from the ideal linear response, since that have potential to create false targets and to corrupt 5G waveforms such as OFDM. The investigated tool chains allow for this type of models. Non-linear models were implemented and demonstrated but could not be verified by experiments. The lack of parameter data for the D-band frontends made it impossible to build a hardware model of the demonstrator. Further, due to the lack of availability of the D-band frontends until the end of the project, it was impossible to compare simulation results with measurements.

D4.1 Report on Evaluation of 3GPP 5G Waveforms and Technologies

The deliverable presents an evaluation of 5G technologies against the use cases defined in the project. The focus is on assessing both communication-centric and radar-centric JRC waveforms. Communication-centric waveforms, such as OFDM, OTFS, and DFT-s-OFDM, are evaluated for their suitability in sensing applications, while radar-centric waveforms like FMCW and PMCW are analyzed for embedding communication functionalities. The evaluation considers key performance indicators (KPIs) such as range resolution, maximum unambiguous range, velocity resolution, and communication data rates. The study concludes that no single waveform is best for all use cases. Communication-centric waveforms are optimal for scenarios requiring high data rates, whereas radar-centric waveforms are better for low data-rate applications with cost-effective and power-efficient hardware. The deliverable also explores various multiplexing strategies for MIMO operation and discusses future studies focusing on accuracy analysis, side-lobe levels, and distributed MIMO deployments.

D4.2 Report on Evaluation of Beyond 5G Waveforms and Technologies

Deliverable D4.2 evaluates waveforms and technologies beyond 5G, focusing on their application in JRC systems. The evaluation includes a holistic investigation of Orthogonal Frequency Division Multiplexing (OFDM) towards 6G and the analysis of MIMO-OTFS (Orthogonal Time Frequency Space) for Integrated Sensing and Communication (ISAC). The study explores the impact of modulation order, beamforming strategies, and the trade-offs in time-frequency and spatial domains. OFDM's prevalence in wireless systems and its adaptability for ISAC are highlighted, along with its trade-offs in sensing accuracy and communication efficiency. MIMO-OTFS is evaluated for its potential to enhance ISAC by exploiting inter-symbol interference (ISI) and delay-Doppler multiplexing, showing superior performance in detection and localization tasks. The deliverable concludes that while no single waveform is optimal for all use cases, both OFDM and MIMO-OTFS present promising solutions for future JRC systems, contributing to the development of 6G technologies.

D5.1 Simulator System Level Block Description

This deliverable details the design and implementation of a simulator for joint radar and communication (JRC) systems in automotive applications, aiming to expedite testing and functional verification of various traffic scenarios. The simulator leverages the open-source CARLA simulator, known for its scalable client-server architecture and realistic traffic simulations. Key components of the JRC system include separate transmit and receive channels, transmit and receive antennas, RF hardware, coder and decoder modules, a backbone communicator, a controller, and a radio channel model. Each sub-block is defined with specific parameters and interface signals, ensuring comprehensive simulation capabilities. Responsibilities for developing these sub-blocks are distributed among different work packages. The simulator's performance will be evaluated using key performance indicators (KPIs) such as communication coverage, radar coverage, range and angular resolution, interference rejection, communication capacity, and latency. The document emphasizes the importance of correlating simulator outputs with real-life hardware and algorithm measurements to ensure accuracy and reliability.

D5.2 Full Use-Case Simulator

In D5.2, the full use case simulator, which is based on the CARLA framework, the components of the simulator are described. The data relating to the position and movements of the vehicles according to the use cases was generated using CARLA, post-processed, and then distributed to the project members for further use. As the JCS system is capable of beam-steering, consequently being able maintain their best performance for all geometries in the use cases, the antenna gain could be considered constant. Concerning the vehicles' radar signature, simulations relating to extended targets were carried out using the Ansys AVxelerate tool to explore the scattering properties of the vehicles. The sensing and communication models are based on OFDM and also incorporate the wave propagation environment which consisted of one direct and one ground reflected path between two vehicles, providing a basic level of modeling. Finally, results regarding the sensing and communication are compiled and re-inserted into CARLA for visualization purposes.

D5.3 Test and Validation Report

In D5.3, the assembly and testing of the JRC system is described. The four-element slotted waveguide antenna array was tested in an anechoic chamber and parameters for beamforming and beamsteering, which takes place at the base band, were set. The performance was clearly sufficient for the JRC application, providing a welcome addition to the link budget. The transmitter and receiver chains consist of signals generated at the base band which are then multiplied to the operating frequency bands. This is an important feature from a cost perspective as commercially available components can be used together with frequency-multiplying up- and downconverters to create possibilities to provide advanced sensors at without the need for extremely advanced manufacturing processes. A structure for mechanical assembly of the transmitters, receivers and antennas was designed and manufactured. The system was tested in a laboratory environment, and it was determined that it was possible to transmit information signals and perform sensing of objects.

Relation to FFI (sub-) programs

These deliverables were designed to ensure comprehensive development, testing, and validation of the JRC technology, contributing to the project's overall goals of enhancing vehicular safety and communication efficiency. This project also aligned with the sub-program “Trafiksäkerhet och automatiserade fordon” by addressing several critical areas within the program:

1. **Grundläggande säkerhetsegenskaper hos fordon**: The JRC technology developed in this project enhances fundamental vehicle safety by improving sensing and communication. This improvement is crucial for safety-critical scenarios.
2. **Intelligenta och krockundvikande system och fordon**: The project aims to develop technical solutions for cooperative sensing between vehicles via a low latency, secure communication link between JRC units. This link synchronizes different radars to avoid mutual interference and shares sensor data between vehicles, leading to fewer traffic accidents, enhanced situational awareness, better traffic flow, and lower energy consumption.
3. **Automatiserade fordon i transportsystemet**: Enhancements in environmental perception enabled by vehicles equipped with JRC units will improve vehicle safety and advance autonomous vehicles. Detailed information about surroundings allows for better path planning and smoother journeys, contributing to more environmentally friendly transportation of people and goods.

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	Results have been disseminated via publications and a YouTube video.
Be passed on to other advanced technological development projects	X	Chalmers is currently coordinating the WITECH competence center, which involves several partners of the RADCOM2 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. Lai, Y., Keskin, M.F., Wymeersch, H., Venturino, L., Yi, W. and Kong, L., 2024, April. Subspace-Based Detection in OFDM ISAC Systems Under Different Constellations. In *ICASSP 2024-2024 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* (pp. 9126-9130). IEEE.
2. Keskin, M.F., Mojahedian, M.M., Marcus, C., Eriksson, O., Giorgetti, A., Widmer, J. and Wymeersch, H., 2024. Fundamental Trade-Offs in Monostatic ISAC: A Holistic Investigation Towards 6G. *arXiv preprint arXiv:2401.18011*.
3. Keskin, M.F., Marcus, C., Eriksson, O., Alvarado, A., Widmer, J. and Wymeersch, H., 2024. Integrated Sensing and Communications with MIMO-OTFS: ISI/ICI Exploitation and Delay-Doppler Multiplexing. *IEEE Transactions on Wireless Communications*.
4. Koivunen, V., Keskin, M.F., Wymeersch, H., Valkama, M. and González-Prelcic, N., 2024. Multicarrier ISAC: Advances in Waveform Design, Signal Processing and Learning under Non-Idealities. *IEEE Signal Processing Magazine.*
5. Keskin, M.F., Marcus, C., Eriksson, O., Wymeersch, H. and Koivunen, V., 2023, May. On the impact of phase noise on monostatic sensing in OFDM ISAC systems. In *2023 IEEE Radar Conference (RadarConf23)* (pp. 1-6). IEEE.

All publication will be made publicly available under green open access at https://research.chalmers.se.

Conclusions and future research

Conclusions

The RADCOM2 project has made significant strides in advancing joint radar and communication (JRC) technologies for automotive applications, contributing to vehicular safety, enhanced communication reliability, and improved situational awareness. A major achievement was the development of JRC chipsets that integrated radar and communication functionalities into a single platform, enabling interference-free operation and low-latency communication. This development promises to reduce radar interference while providing higher data rates and more reliable communication links in future automotive systems.

Through extensive evaluation and testing, the project explored various waveforms suitable for JRC, balancing the needs of both radar and communication systems. For example, communication-centric waveforms, such as OFDM, were optimized for high data rate scenarios, while radar-centric waveforms proved more efficient for lower data rate applications that prioritize cost-effectiveness and power efficiency. These insights are crucial for tailoring JRC systems to diverse vehicular environments and traffic conditions.

In addition to the chipset development, the project also focused on building advanced simulation tools that modeled JRC performance in real-world automotive scenarios. These simulations, which included both sensing and communication aspects, allowed for rapid prototyping and validation, providing critical insights into system behavior under realistic conditions. Furthermore, hardware demonstrations validated the JRC chipset's capabilities in areas like beamforming and object detection, showcasing its potential to significantly enhance automotive safety.

The testing and validation of the hardware revealed several design challenges, such as local oscillator distribution inefficiencies and power management, which were addressed through innovative solutions. The project emphasized cost-effective designs, ensuring that the developed JRC systems are not only high-performing but also scalable for mass-market adoption.

Moreover, the project created a simulation environment to evaluate system performance at the system and use-case levels. These tools enabled detailed testing of various traffic scenarios, allowing the team to refine the JRC technology for optimal performance in complex environments. The hardware validation in laboratory settings further reinforced the system's effectiveness in radar sensing and communication tasks.

Despite challenges posed by global supply chain disruptions, which delayed the availability of some components, the project succeeded in achieving most of its objectives. The development of core JRC components, along with simulation tools and hardware demonstrations, has provided a strong foundation for future research and commercial implementation of JRC technologies.

Future Research

Future work should focus on the full integration of JRC chipsets into commercial automotive systems, further optimizing these systems for emerging communication technologies like 6G. Standardization and interoperability of JRC systems will be key to their broader adoption across the industry. Continued advancements in waveform design and system simulations will also be critical for improving both radar and communication capabilities, driving innovation in autonomous driving, traffic safety, and vehicle-to-vehicle communication.

Participating parties and contact persons

Chalmers University of Technology: Henk Wymeersch, henkw@chalmers.se
Comnisens: Hans Hellsten hans.hellsten@comnisens.se
Gapwaves AB: Coen van de Ven, coen@gapwaves.com
VCC: Karl Vanäs, karl.vanas@volvocars.com
Magna: Carina Marcus, Carina.Marcus@magna.com
CIT: Zhongxia Simon He, Simon.he@chalmersindustriteknik.se
Halmstad Högskola: Emil Nilsson, Emil.nilsson@hh.se