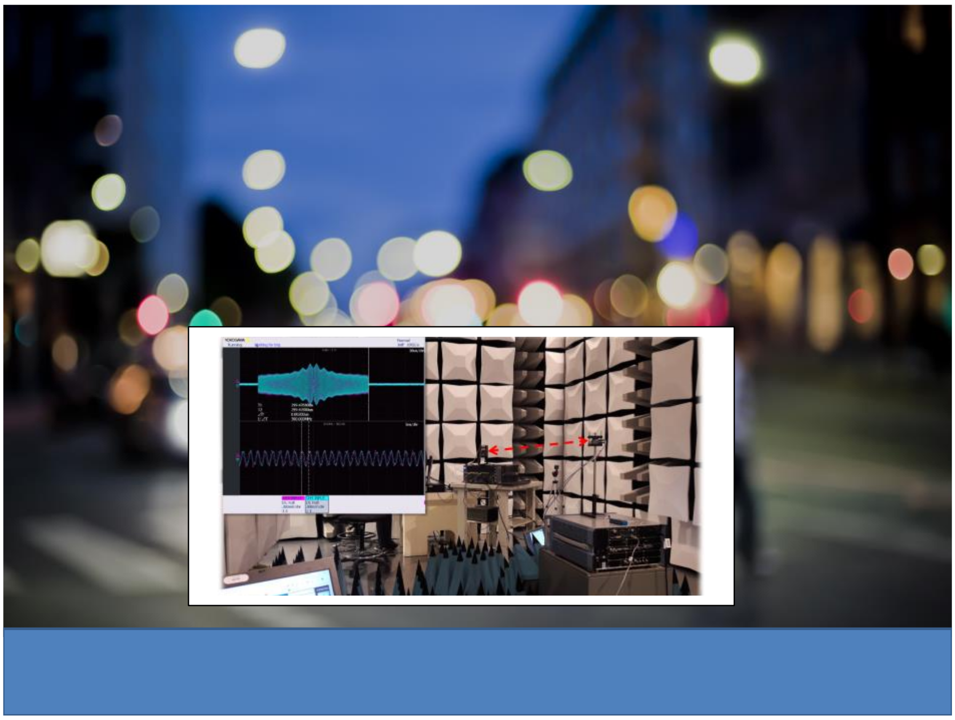
Combined Radar-Based Communication and Interference Mitigation for Automotive Applications

Public report



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Project within Road safety and automated vehicle projects

FFI Fordonsstrategisk Forskning och Innovation

Contents

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1 Summary

Radar is becoming standard equipment in all modern cars, supporting, e.g., cruise control and collision avoidance in most weather conditions while providing high-resolution detections on the order of centimeters in the millimeter-wave (mm-wave) band. The next generation of advanced driver assistance (ADAS) and AD vehicles will have a multitude of radars covering numerous safety and comfort applications such as crash avoidance, self-parking, in-cabin monitoring, cooperative driving, collective situational awareness, and so on. Because automotive radar transmissions are uncoordinated, there is a nonnegligible probability of interference among vehicles, as shown in Figure 1. Although current automotive radars have already been impacted by interference to some extent, today, they are unlikely to raise customer awareness because state-of-the-art automotive radars are continuously updated and improved upon at many system levels.

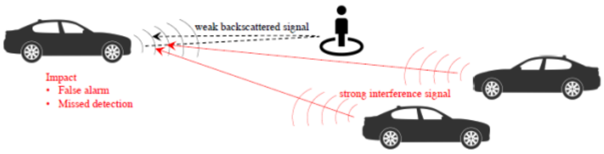

Figure 1.
Interference is generally much stronger than the desired radar signal, due to its one-way propagation. Interference increases with more interfering radars and leads to false alarms and missed detections.

However, the mutual interference problem is expected to become more challenging if not properly handled, as more vehicles are equipped with a greater number of radars providing 360° situational awareness at various distances that enable more advanced future ADAS and AD functionalities. This is evidenced by multiple international studies, such as the MOSARIM project [1] and the more recent IMIKO radar project. All of the major players in the automotive sensor market, such as Volvo and Veoneer, are studying the next generation of “interference-free radars.” This includes, for example, enhancing models to determine the impact of a larger density of radars, simulating new interference scenarios, and investigating different medium access control (MAC) models and methods to coordinate radar transceivers, both decentralized and centralized.

At this point, the automotive industry is ready to consider novel designs and approaches, which may impact standardization bodies before a new frequency spectrum is made available in the higher radio-frequency (RF) bands. Signal processing can provide ways to reduce or mitigate interference, both at the raw signal level as well as at the postdetection/target-tracking level. The particular properties and requirements of automotive radar impose significant challenges in terms of signal processing. This includes the combination of radar and communication waveforms, which brings up further possibilities regarding ultrareliable low-latency communications in vehicular ad hoc networks (VANETs). It is therefore important and timely to investigate automotive interference, its effects and ways to solve it before it becomes a severe problem for the future AD systems.

This project analyzes automotive radar interference and proposes several new approaches that combine industrial and academic expertise toward the goal of achieving interference-free autonomous driving (AD), whereas realization of a hardware demonstrator is also included. Although the focus of this project is the frequency-modulated continuous wave (FMCW) radar since it is the most common and robust automotive radar; we also provide analysis for the impact of interference under coexistence of PMCW and OFDM radars. We study different proactive ways to mitigate interference, ranging from changing FMCW parameters to new signal structures and the explicit coordination between vehicles. We also study new techniques that are potentially more robust toward interference, including stepped-frequency orthogonal frequency-division multiplexing (OFDM). Finally, we describe what we believe will be the long-term evolution of automotive radar and its relation to mobile communication.

2 Background

Radar has been used in automotive applications for a long time. In 1949, unfortunate car drivers were issued speeding tickets based on speed measurements obtained from the radar speed gun, recently invented by John L. Barker. However, on-board automotive radar was not made commercially available until 1999, when it was introduced for collision warning and automatic cruise control (ACC). See [2] for an early history of automotive radar with some entertaining vintage photography. Over the years, there has been a strong push to increase the integration level of mm-wave electronics used for automotive radar and industrial radar sensors. The early discrete hardware designs have been replaced by a few chips in III–V-materials, and now, CMOS single-chip solutions are available. CMOS technology provides the ability to fully integrate analog and digital electronics, making very advanced protocols and detection schemes possible at low cost and low power. Consequently, radar is becoming more and more common for supporting various automotive applications. ADAS systems based on radar are today standard equipment in most new vehicles. Vehicles capable of some level of AD are also expected to rely, at least to some degree, on radar systems for monitoring vehicle surroundings. The number of radar transceivers operating throughout the traffic environment is foreseen to increase rapidly over the coming years. As the number of radar transceivers in the traffic infrastructure increases, radar interference is also expected to increase.

Today, most radar transmissions are uncoordinated, meaning that there is no a priori agreement on who is allowed to transmit and when. A number of recent studies have identified the interference situations that are likely to arise as the automotive radar transceiver market penetration increases [1], [3]. FMCW waveforms can, up to a point, be relatively easily repaired in the event they are intermittently corrupted by interference [4], which is why they are still operational. Future radar systems are expected to occupy frequency bands that are higher and higher in frequency. Transceivers operating around 77 GHz are available today, and transceivers operating at carrier frequencies beyond 100 GHz are expected. Frequencies as high as 300 GHz and beyond are being considered for some applications, such as synthetic aperture radar mapping. Operation at such high frequencies brings the obvious benefits of improved miniaturization, but also presents challenges in terms of hardware complexity and signal attenuation. Moreover, interference-free operation will require radar transmission standardization. A standardized transmission scheduling system resembling today’s cellular communication system would present a solution to the interference problem, but it is not without challenges, both technical and political.

3 Purpose, research questions and method

The purpose of the project was to analyze automotive radar interference and propose several new approaches that combine industrial and academic expertise toward the goal of achieving interference-free autonomous driving (AD). Additionally, we aimed to realize a hardware demonstrator to show the real-world performance of the proposed approaches.

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

- Q1 What are the expected needs and requirements for future radar and communication systems from a safety perspective?
- Q2 What are the performance trade-offs for different link-level and network-level designs?
- Q3 How should the RadCom physical layer and MAC layer be designed?
- Q4 How to utilize quasi orthogonal radar signals for automotive applications?
- Q5 What is the system-level performance?
- Q6 What is the real performance of a RadCom system?
- Q7 What are the implications for standardization and regulation?

To answer these questions, we decomposed the problem into sub-problems, which were tackled in different work packages (WPs). Chalmers University of Technology coordinated this project through WP1 (WP 1: Project management, exploitation, dissemination). VCC coordinated WP2 (WP2: Scenarios, Requirements, and Models) to set scenarios and requirements, as well as to develop channel models and simulation software. Chalmers coordinated WP3 (WP3: Fundamental trade-off analysis), which studied the trade-offs between communication in a single link and a complete network, using methods from optimization theory. QamCom coordinated WP4 (WP4: Physical layer design), where a physical layer simulator was developed for different radar waveforms. Veoneer coordinated WP5 (WP5: MAC layer design), which specified medium access control protocols and designs. SAAB coordinated WP6 (WP 6: System-level Evaluation), considering novel waveforms designed for interference robustness, as well as a functional safety analysis of joint radar communication. Finally, Halmstad University coordinated the WP7 (WP 7: Experimentation and Validation) in order to develop the demonstrator. Halmstad University presented a draft design and compiled a requirement specification; analyzed and re-designed; purchased components and assembled; and finally brought up and tested the system in controlled environments. Together with Veoneer, Halmstad University made a test plan and performed field tests; analyzed collected data.

4 Goal

The project goals were to develop expertise in the area of joint radar and communication as well as the realization of a demonstrator. Moreover, the project aimed to provide inputs to regulation bodies for future radar standards in the 60 GHz band. The specific goals of the project can be stated as follows:

- SG1: Research and understand radar interference.
- SG2: Develop expertise in joint radar and communication technology for robust sensing and communication for automotive safety.
- SG3: Include a functional safety perspective.
- SG4: Develop key technologies to make radar more robust to interference.
- SG5: Identify needs for a joint RadCom system, analyze the involved trade-offs, design physical and medium access control, conduct a system evaluation (radar, communication, functional safety performance).
- SG6: Reuse radar hardware to create a low-latency communication link.
- SG7: Build a demonstrator and validate the key ideas of the project.
- SG8: Provide input for standardization bodies.

In terms of the fulfilled goals, they can be summarized as follows: we have developed an internationally recognized expertise in the area of joint radar and communication (RadCom), made significant progress towards novel key technologies to make radar more robust to interference, identification of needs for a joint RadCom system. We have analyzed the involved trade-offs, designed physical and medium access control methods and performed a system evaluation (radar, communication, functional safety performance). Finally, we have successfully built a demonstrator and validated the key ideas of the project. In terms of deviations, we did not provide direct inputs to regulation bodies for future radar standards in the 60 GHz band. We do participate in the SRD (Short Range Devices) workgroups within both ETSI and CEPT and provide comments to the proposed change for a better harmonization between all applications within this band. The applications include ITS/Automotive, 5G backhaul and wireless access.

5 Results and fulfillment of the goals

1. ***<u>Track 1: SG1-SG3</u>***

In order to achieve **SG1-SG3**, VCC coordinated Workpackage-2 (WP2: Scenarios, Requirements, and Models). Several presentations given by the automotive industry partners (VCC, Veoneer) were useful for the project group to discuss and identify the needs and requirements of the automotive industry. We defined reference use case scenarios of relevance to the automotive industry, including vehicle density, mobility, radar placement, radar environment (clutter) and communication environment (multipath). All these studies can be found in the deliverables D2.2, D2.4, D5.1 and the EuMC workshop [14]. For these scenarios, we specified performance metrics and performance requirements for radar and communications, for different radar waveforms (FMCW, PMCW, OFDM). VCC focused on performance evaluations for FMCW and PMCW radar waves, whereas Chalmers and QamCom focused on performance of FMCW and OFDM. We developed suitable models that capture the salient scenario parameters in terms of the physical layer and MAC layer and specified reasonable parameters for practical hardware configurations (e.g., transmit power, ADC sampling rates). Radar theory, radar signal processing, statistical signal processing are used as tools. QamCom developed an object-oriented simulator that can describe the detection performance and integration between radars on different positions on the same or other moving objects and has studied detection performance on different scenarios. A system simulator software (D4.1) and a conference paper evaluating the influence of interference on the signal detection for FMCW and OFDM waveforms are delivered (D4.2) [10]. Moreover, determined critical scenarios are implemented with this simulator to study radar interference. The system simulator allows to observe the increase in the noise floor after interference with FMCW radars and the detection suppression with interference between OFDM radars. It is shown that a waveform adjustment with a RadCom system can reduce/suppress the interference effect, which is addressed in the conference paper [10]. Moreover, FMCW interference analysis for various values of chirp slope ratios between ego and victim radars, FMCW interference analysis in the presence of oscillator phase noise in ego and victim radars (range decorrelation analysis, spectral smearing effect), identification of cases where the interferer appears as ghost target or noise floor increase (coherent, partially coherent and incoherent interference), radar-to-radar, radar-to-comm and comm-to-radar interference analysis, which shows the need for coordinated radar and comm transmissions are done [5-8,10].

In terms of **SG3**, additionally, functional safety perspective is investigated. A functional safety analysis is done according to ISO 26262 on a fictive CACC function. The fictive function has perception of surrounding based on radar sensing and collaboration capability through wireless communication. We described an analysis of a fictive CACC function and used the main points of the procedure outlined in ISO 26262, delivering D6.3 as a presentation at internal meetings.

In summary, we identified that the automotive industry expects a future joint radar communication system to accomplish two tasks: 1) solve the mutual radar interference problem among vehicles, which is foreseen to become a safety threat in the future due to the increased noise floor and ghost targets in radar sensing, and 2) provide a low-latency communication among vehicles. It is required that the interference is solved, and warning messages are communicated with less than 500 ms latency for avoiding crashes with high probability (D5.1). Moreover, it is figured out that the high processing gain and highly directive nature of -especially LoS- radar transmissions may result with interference coming from kilometers away, and this can only be avoided if communication range of a joint radar communication system is adjusted to be comparable. This suggests that communication should also be directed and have a high gain. Another conclusion is that adjacent radar interference (interference among radars mounted on the same vehicle) is also a problem, which needs to be solved. The mentioned studies above, showed us that it is possible to mitigate interference by radar communications, which allows us to coordinate radar transmissions so that they do not overlap in time, frequency and space.

2. ***<u>Track 2: SG4, SG5, SG6</u>***

Motivated by this result, we investigated methods for interference-free radar sensing. We focused on three methods for **SG4**, which were then analyzed in SG5-SG8.

- slow-chirp modulation (led by SAAB and Halmstad University);
- RadChat (led by Chalmers);

- stepped-carrier OFDM radar (led by Chalmers and Veoneer) [7].

For achieving **SG5**, Chalmers coordinated Workpackage-3 (WP3: Fundamental trade-off analysis), QamCom coordinated Workpackage-4 (WP4: Physical layer design), Veoneer coordinated Workpackage-5 (WP5: MAC layer design) and SAAB coordinated Workpackage-6 (WP 6: System-level Evaluation). We used input from WP2 and used tools like optimization theory analysis of communication and radar trade-off, as well as waveform optimization. A method (RadChat) for interference coordination, which is brought in as a background knowledge to the project, is investigated for various use cases and parameters. Characterization of rate-radar performance trade-off for OFDM radar is conducted. Design of radar-optimal and radar-communications trade-off waveforms for OFDM, characterization of achievable rate vs. radar accuracy performance trade-offs for OFDM joint radar-communications, development of inter-carrier interference (ICI) aware sensing algorithms for OFDM, development of range-angle mapping algorithms for 5G NR uplink sensing with OFDM waveform, detection/estimation schemes for OTFS radar sensing, exploitation of ISI and ICI effects to improve radar performance are included in these studies. Moreover, radar-aided communication is investigated, and it is shown that using radar sensing data for beamforming in vehicular networks increases the SNR and results with narrower beams [11]. Deliverables D3.1, D3.2, D3.3, D5.3, software code on GitHub and several published papers (see https://research.chalmers.se/project/8692) summarize the outcomes of these studies. For the three investigated three methods there are various trade-offs. For RadChat, allocation of a communication bandwidth and coordination of radar sensing over this channel, is shown to have negligible effect on radar sensing performance. The synchronization among radar communication units is seen to be important, however it is also shown that a synchronization-free RadChat protocol is possible with negligible performance degradation. Radar and communication bands should be designed to cover disjoint bandwidths for FMCW radars (RadChat). A carrier sense multiple access based random access MAC technique is investigated and it is shown to perform well [5]. For stepped-carrier OFDM radar, the waveform design has been shown to come up with a trade-off between the radar sensing and communication performance. For slow-chirp modulation, a range-Doppler ambiguity was shown to be a challenge, requiring novel signal processing tools.

In terms of **SG6**, Link-level performance trade-offs for OFDM dual-functional radar-communications (DFRC) systems have been analyzed by comparing radar estimation accuracy and communications data rate. It is shown that time-frequency power allocation for OFDM subcarriers has a huge impact on radar accuracy and data rate. We observe that radar-optimal waveforms exhibit a sparse/peaky nature, meaning that only a small percentage of subcarriers are allocated non-negligible power, while communication-optimal waveforms have water-filling structure where most subcarriers get non-negligible power. Using a radar similarity constraint to adjust the trade-off behavior, the proposed DFRC waveforms are demonstrated to offer a flexible trade-off between radar and communications, outperforming the conventional uniform and water-filling solutions in terms of accuracy and/or data rate. In addition, different from such conventional approaches, the proposed waveforms can be dynamically adapted to varying practical system requirements (i.e., whether it is a radar-critical scenario or a communications-critical scenario). Moreover, it is seen that the range and velocity accuracies can be improved substantially with only a negligible loss in communications performance. Similarly, the proposed DFRC waveforms can increase capacity up to a certain level of radar similarity without degrading the range-velocity accuracy of radar. Finally, the time-varying waveform design is shown to be superior to its traditional time-invariant counterpart in terms of radar-communications trade-off performance.

3. ***Track 3: SG7 and SG8***

Halmstad University coordinated the Workpackage-7 (WP 7: Experimentation and Validation) in order to develop the demonstrator. Halmstad University presented a draft design and compiled a requirement specification; analyzed and re-designed; purchased components and assembled; and finally brought up and tested the system in controlled environments. Together with Veoneer, made a test plan and performed field tests; analyzed collected data. The outcome of these studies is a demonstrator for the testing of arbitrary waveforms and interference; and knowledge of critical scenarios in automotive sensor application; measurement data from field tests and controlled environment. A demonstrator system (D7.1) and a report on the demonstrator system together with measurement data (D7.2) are delivered. Much more data than imagined was created. More time should have been reserved for data analysis.

4. *How the results and deliverables serve the FFI objectives:*

Mutual radar interference among vehicles increases the noise floor and hinders especially the detection of low radar-cross-section-targets such as pedestrians/cyclists and creates ghost targets which end up with false braking/maneuver decisions. By introducing and proving the effectiveness of three methods in preventing interference, this project contributes to one main goal of FFI: it will reduce the number of people injured and killed in traffic accidents in the future.

Another main goal of FFI, which is to strengthen international competitiveness, is also achieved. Through a vast number of journal publications and attendance to international conferences/workshops, the RadCom project group achieved an international visibility. The RadCom project also serves another FFI objective indirectly, to reduce the environmental impact of road transports, by bringing up and proving effective operation of radar communication, which is an environmental-friendly method. Radar communication combines functionalities of two separate technologies (automotive radar and vehicular communication) into one hardware, that makes it more energy-efficient, more hardware-efficient (considering the forthcoming deficiency of rare earth metals) and more spectrum-efficient, which all serve to a greener transportation.

Due to the same reasoning, with its results and deliverables, the RadCom project has also served to the three sub-programmes within FFI subprogrammes: ‘Road Safety and Automated Vehicles’, ‘Efficient and Connected Transport Systems’, ‘Electronics, Software and Communication’.

6 Dissemination and publication

6.1 Dissemination of knowledge and results

How does the project result have/are planned to be used and disseminated?	Select with X	comment
Increase knowledge in the field	X	The project partners developed expertise in the respective research fields.
Passed on to other advanced technological development projects	X	A spin-off company is under commercialization stage by support of Chalmers Innovation Office. Inventors of the RadChat protocol plan to provide software solutions on top of RadChat for RadCom localization, security and adaptive techniques. Veoneer has initiated internal evaluation of the proposed solutions in cooperation with the Veoneer radar product line. The project partners plan to apply for Vinnova/FFI call in 2021 for a second extension project RadCom-II, in order to further develop expertise, for incorporating antenna design and developing a prototype.

Passed on to product development projects	X	Veoneer is planning for a hardware implementation proof-of-concept project to be started during 2021.
Introduced to the market	-	
Used in investigations/regulations/ permit cases/ political decisions	-	

6.2 Publications

Within this project, 9 reports were delivered, 7 journal and 10 conference articles were published. The list of publications is listed below:

Delivered reports:

1. Preliminary report on interference modelling and impact on radar performance (D2.2)
2. Final report on interference modelling and impact on radar performance (D2.4)
3. Report of vehicle safety level impact on required communication robustness (D5.1)
4. MAC software simulation model (D5.2)
5. Specification proposal for communication data structure (D5.3)
6. System Analysis Report (D6.1)
7. Waveform Generation Report (D6.2)
8. Report on Functional Safety aspects on RadCom (D6.3)
9. Report on the outcome of the demonstrator tests (D7.2)

Journal and conference publications:

1. Canan Aydogdu, Nil Garcia, L. Hammarstrand and Henk Wymeersch, “Radar Communication for Combating Mutual Interference of FMCW Radars”, IEEE Revolutions in Radar, Boston, USA, 22-26 April 2019. (D3.1)
2. Canan Aydogdu, Musa Furkan Keskin, Nil Garcia, Henk Wymeersch and Daniel W. Bliss, “RadChat: Spectrum Sharing for Automotive Radar Interference Mitigation”, IEEE Transactions on Intelligent Transportation Systems, Dec. 2019.
3. Canan Aydogdu, Gisela K. Carvajal, Olof Eriksson, Hans Hellsten, Hans Herbertsson, Musa Furkan Keskin, Emil Nilsson, Mats Rydström, Karl Vanäs, Henk Wymeersch, “Radar Interference Mitigation for Automated Driving: Exploring Proactive Strategies”, IEEE Signal Processing Magazine, vol. 37, no. 4, pp. 72-84, doi: 10.1109/MSP.2020.2969319, July 2020. (D3.3)
4. M. F. Keskin, C. Aydogdu, and H. Wymeersch, “Stepped-carrier OFDMV2V resource allocation for sensing and communication convergence,” 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, March 2020.
5. C. Aydogdu, H. Wymeersch, and Mats Rydström, “Can Automotive Radars Form Vehicular Networks?”, IEEE Radar Conference, Florance, Italy, 21-24 Sept. 2020 (D3.2)
6. G. Carvajal, M. F. Keskin, C. Aydogdu, Olof Eriksson, Hans Herbertsson, Hans Hellsten, Emil Nilsson, Mats Rydström, Karl Vanäs, Henk Wymeersch, “Comparison of Automotive FMCW and OFDM Radar Under Interference”, IEEE Radar Conference, online, 21-24 Sep. 2020. (D4.2)
7. C. Aydogdu, F. Liu, C. Masouros, H. Wymeersch, “Distributed Radar-aided Vehicle-to-Vehicle Communication”, IEEE Radar Conference, online conference, 21-24 Sept. 2020.
8. H. Hellsten and E. Nilsson, "Multiple Access Radar Using Slow Chirp Modulation," 2020 IEEE Radar Conference (RadarConf20), online conference, 21-24 Sept. 2020.
9. C. Aydogdu, M. F. Keskin, H. Wymeersch, “Automotive Radar Interference Mitigation via Multi-Hop Cooperative Radar Communications”, EuRad, Jan. 2021.
10. M. F. Keskin, R. Firat Tigrek, C. Aydogdu, F. Lampel, H. Wymeersch, A. Alvarado, F.M.J. Willems, “Peak Sidelobe Level Based Waveform Optimization for OFDM Joint Radar-Communications” EuRad, Jan. 2021.

11. Canan Aydogdu, M. Furkan Keskin, Gisela K. Carvajal, Olof Eriksson, Hans Herbertsson, Emil Nilsson, Mats Rydström, Karl Vanäs, Mustafa Mete, Per Sandrup, Henk Wymeersch, "Radar Interference Mitigation through Active Coordination," 2021 IEEE Radar Conference (RadarConf21), online conference, May 2021. (D7.2)
12. C. Aydogdu, H. Wymeersch, Olof Eriksson, Hans Herbertsson, Mats Rydström, "Synchronization-free RadChat for Automotive Radar Interference Mitigation?", under review.
13. M. F. Keskin, V. Koivunen, and H. Wymeersch, "Limited Feedforward Waveform Design for OFDM Dual-Functional Radar-Communications," IEEE Transactions on Signal Processing, accepted for publication.
14. M. F. Keskin, H. Wymeersch, and V. Koivunen, "MIMO-OFDM Joint Radar-Communications: Is ICI Friend or Foe?," IEEE Journal of Selected Topics in Signal Processing, under review.
15. C. B. Barneto, E. Rastorgueva-Foi, M. F. Keskin, T. Riihonen, M. Turunen, J. Talvitie, H. Wymeersch, and M. Valkama, "Radio-based Sensing and Environment Mapping in Millimeter-Wave 5G and Beyond Networks," IEEE Journal of Selected Topics in Signal Processing, under review.
16. M. F. Keskin, H. Wymeersch, and V. Koivunen, "ICI-aware Parameter Estimation for MIMO-OFDM Radar via APES Spatial Filtering," accepted to ICASSP 2021.
17. M. F. Keskin, H. Wymeersch, and A. Alvarado, " Radar Sensing with OTFS: Embracing ISI and ICI to Surpass the Ambiguity Barrier," accepted to ICC 2021, Workshop on OTFS for 6G and Future High-Mobility Communications.

Patents

There are two patents filed during this project period, the idea of which were brought in as background knowledge from the partners and the IP is owned by the inventors:

1. Canan Aydogdu and Henk Wymeersch, 'Method for reducing mutual radar interference in radars', filed: 3 July 2019, Patent application no: 16502414, Applicant: Chalmers Ventures, Inventor: Canan Aydogdu and Henk Wymeersch.
2. Hans Hellsten, 'A method, computer program product, system and radar arrangement for resolving range and velocity information', Patent application No. 200007 4-1, Applicant: SAAB AB, Inventor: Hans Hellsten.

7 Conclusions and Further research

The project goals are fulfilled. We developed an expertise in the area of joint radar and communication, developed key technologies to make radar more robust to interference, identified the needs for a joint RadCom system, analyzed the involved trade-offs, designed physical and medium access control, completed a system evaluation (radar, communication, functional safety performance), reused radar hardware to create a low -latency communication link and finally built a demonstrator and validated the key ideas of the project. This project reveals that a mutual radar interference solution is necessary. A standardized solution must be discussed within the regulation bodies for future radar standards in the mmWave frequency bands.

8 Participating parties and contact persons

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[6] Canan Aydogdu, Musa Furkan Keskin, Nil Garcia, Henk Wymeersch and Daniel W. Bliss, "RadChat: Spectrum Sharing for Automotive Radar Interference Mitigation", IEEE Transactions on Intelligent Transportation Systems, Dec. 2019.

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[8] M. F. Keskin, C. Aydogdu, and H. Wymeersch, "Stepped-carrier OFDM V2V resource allocation for sensing and communication convergence," 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, March 2020.

[9] C. Aydogdu, H. Wymeersch, and Mats Rydström, "Can Automotive Radars Form Vehicular Networks?", IEEE Radar Conference, Florance, Italy, 21-24 Sept. 2020 (D3.2)

[10] G. Carvajal, M. F. Keskin, C. Aydogdu, Olof Eriksson, Hans Herbertsson, Hans Hellsten, Emil Nilsson, Mats Rydström, Karl Vanäs, Henk Wymeersch, “Comparison of Automotive FMCW and OFDM Radar Under Interference”, IEEE Radar Conference, online, 21-24 Sep. 2020. (D4.2)

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[12] H. Hellsten and E. Nilsson, "Multiple Access Radar Using Slow Chirp Modulation," 2020 IEEE Radar Conference (RadarConf20), online conference, 21-24 Sept. 2020.

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