Future trends and directions in radar concerning the application for autonomous driving

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***Abstract*—The top down approach to derive requirements for future radar sensors for autonomous driving is due to its complexity hardly possible. Thus this paper presents the bottom up approach and shows future trends and directions of automotive radar development. This overview paper focusses on functional and non-functional aspects, whereas technological trends are only treated very shortly.**

Keywords—automotive radar, autonomous driving

I. Introduction

Autonomous driving is one of the technical key challenges of the next 20 years. There are many different stages and definitions of what autonomous or semi/fully automated driving is. Among many others, see e.g. [1] for some definitions on these terms. All of them have in common, that they require an extremely complex system with a long signal processing path from the sensor to the actor with many layers in between. The sensing layer itself has many sublayers like modulation and demodulation, raw data signal processing, like detection and matching and finally clustering and tracking of the targets. So do the other layers like perception, localization, situation interpretation, situation prediction, trajectory planning, and decision making. Therefore it is not possible to derive straight forward from functions in the area of autonomous driving the requirements for future radar sensors. What we know is very general: radar sensors need to measure with a much higher resolution than today's sensors contours, i.e. outer dimensions or L-shapes of targets, they need to detect free space areas and need to deliver more attributes on the targets to allow for a better target classification. This paper summarizes bottom up latest research results giving an impression, what future automotive radar sensors might master.

II. Non-Functional ASPECTS

Future functions towards autonomous driving come with tough requirements on functional safety, i.e. ISO 26262 [2], robustness, and reliability of radar sensors, as can already be seen when looking at today's safety functions in the area of emergency breaking. A functional safety concept for radar sensors has to be defined. As up to now, [2] gives explicit requirements to avoid or mitigate E/E failures only. In recent years a number of publications have shown concepts to monitor the active components of the RF-frontend, namely the MMIC, of the sensors, see e.g. [3]. But even for the passive components monitoring capabilities are required as shown in [4]. The paper proposes monitoring concepts for the whole receiver chain, including antennas and bonding structures. Failures regarding the detection performance of environmental sensors due to external physical influences, e.g. systematic failures due to rain, are not in scope of the ISO 26262. But nevertheless such failures have a high influence on the functionality of the safety function on vehicle level. Within the EU-Project MOSARIM [5] furthermore the investigation of influences on radar sensors due to interferences from other automotive radar devices or incumbent frequency users was carried out and led to a detailed failure description and the definition of FIT rates to describe the functional safety. Guidelines and recommendations for future radar devices were derived accordingly [6]. The hints and opinions stated here in respect to mutual radar interference mitigation are on an advisory level only and yet lack any right for mandatory or regulatory implementation. The MOSARIM consortium saw such guidelines more in the sense of a self-commitment to contribute to a minimum or even interference-free radar operation. Thus, in the regulatory direction more work has to be initiated.

III. Functional Trends and Directions

Future automotive radar sensors require better resolution in basically all measurement dimensions. Many researches work on different aspects of that, as will be shown later. The question that arises is, is there a fundamental limit what we can expect to see with radar? Of course each type of radar has its limits in terms of resolution as can be seen from standard radar literature, but with increasing bandwidth, observation time, aperture, processing effort and so on these limits are pushed further. But target properties, such as the radar cross section [7] or the materials the targets are composed of cannot be influenced by the radar. This might help to answer the question of the fundamental limits. The outer face of cars is composed mainly of metallic and plastics material. It has many curvatures with different radii, slots and corners. This is the reason why a vehicle has many scattering centers [8], that all superpose, and some parts of a vehicle like the bumpers rather reflect very low signals. Resolving bumpers and measuring precisely the outer shape of a vehicle is therefore challenging. On the other hand, radar sensors are continuously improved to get better performance and to resolve details of the targets, that could not be seen so far. There is a huge variety of completely different approaches to improve the perception of the environment as we will be show in the following sections.

A. Imaging and MIMO radar

In the field of imaging for automotive radar we see the most advances in recent years. On the one hand, multi-channel integrated phased arrays have been proposed and evaluated [9]. Such systems use classical phased array concepts, but are now integrated in a single MMIC. On the other hand, a lot progress has been done in the field of MIMO and digital beamforming approaches for automotive radar. MIMO for lens based systems, so radars with high antenna gain or long range systems in other words are suggested in [10]. The potential of automotive MIMO systems to reduce ambiguousness and to increase angular resolution is demonstrated. [11] suggest an extremely flexible radar architecture for FMCW MIMO radars with the option of frequency division multiplexing for different channels. Different super resolution algorithms for imaging have been evaluated for the application of automotive radar in [12, 13]. It is first shown that the angular resolution can be distinctly increases by ROOT-MUSIC, ESPRIT, or similar approaches in automotive scenarios, but at the cost of high computational complexity. A new approach is suggested to first identify targets by standard imaging algorithms at low computational effort and then, in a second stage, to run the super-resolution algorithms.

B. Automotive SAR

In recent years a number of research groups worked in the area of automotive SAR. [14,15], and [16] have shown the application of parking lot detection based on different SAR algorithms like Range-Doppler and Range Migration Algorithm. With increasing computational power in automotive radar sensors, SAR might be a future solution to increase the lateral resolution of front or rear sensors. In [14] measurements are given, which show the detection of a person standing between parking cars.

C. Doppler Signatures

It has been known for years that Doppler signatures deliver a good attribute to classify radar targets, see figure 1. With the topic chirp sequence modulation for automotive sensors and the necessity of pedestrian recognition this topic has gained new attention, see e.g. [17]. In [18] signal processing approaches for high Doppler resolutions, suitable for automotive radar sensors, are presented. The discrimination of vehicles, walking pedestrians, and inline-skaters by auto-regressive linear prediction is demonstrated. For classifying purposes a detailed analysis of the origin of the Doppler signatures from pedestrians, as discussed in [19, 20], might be beneficial.

When addressing larger bandwidths and larger apertures the question quickly arises, if higher frequencies than today's 76-81 GHz are useful? There has been dome some research work to evaluate the frequency range beyond 100 GHz for automotive radar [21]. Of course aperture would scale with frequency, thus doubling the frequency would rather deliver half the aperture size or about double angular resolution. Antenna concepts at these frequencies have been proposed in [22]. Smaller aperture sizes might even allow for very new options to integrate the sensors in cars at positions where todays bulky sensors do not fit in. One may not oversee the challenges when integrating such radars behind bumpers. The frequency range above 100 GHz might also allow for larger bandwidths to further increase the resolution, as this spectrum is not already fully occupied and regulated.

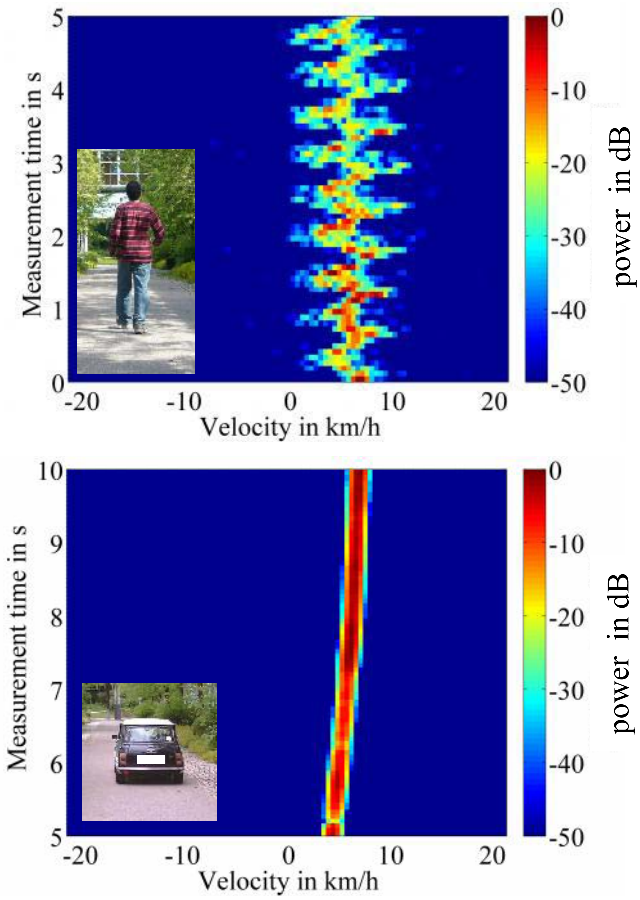

Fig. 1. Doppler signature of walking pedestrian and vehicles by courtesy of Dr. Markus Andres.

This paper does only give a short statement on the future technological development, as a detailed discussion of future technological trends and a huge number of references can be found in [23]. Industrial research strongly focused on bringing the costs of the technology down in recent years, see e.g. rf-packages in [24] and SiGe-technology for automotive MMICs [25, 26]. Concerning the MMIC CMOS and SiGe (BiCMOS) are candidates for future automotive radars, even in the frequency range at 158 GHz, see e.g. [27]. SiGe is today's standard technology for automotive MMIC and is continuously improved [28]. CMOS at 90, 65, and 55 nm nodes has gained at lot in recent years and automotive radar MMIC implementations have been shown in research [29, 30]. On the other hand there are some hints that there might be limits on

CMOS for automotive MMIC as shown in [31]. Concerning packaging, many different approaches are under investigation or are already in use [25, 26], again even up to 170 GHz, see [32].

IV. FUTURE FRAMEWORKS FOR AUTOMOTIVE RADARS

When looking at future automotive radars for automated driving, it is essential to consider the framework, these radars will work in. The requirements of the sensors will be very heterogeneous, depending on the function or rather situation, the vehicle is in. Highway cruises require completely different radar parameters than intra-urban or e.g. parking scenarios. A solution to this problem might be to use adaptive or cognitive radars. The technological basis for cognitive radar is an adaptive sensor that can change its perception properties depending on the needs of the higher signal processing layers. Cognitive radars were first suggested by Haykin [33]. Haykin defines cognitive radar by the following three points:

1. Intelligent signal processing, which builds on learning through interaction of the radar with its environment
2. Feedback from the receiver to the transmitter
3. Preservation of the information content of radar returns for the intelligent signal processing.

The last point is not new for the signal processing of automotive radar sensors, but the first one and mainly the second one are new. The second one requires adaptive transmitters in terms of adaptive antennas and modulation schemes. Consequently, the receiver also has to be adaptive. Fig. 2 gives a block diagram, based on [33] or similar in [34], to suggest the structure of automotive cognitive radar. An important question for automotive applications will be what signal processing layer is the feedback information derived from. It could be in a first step the analysis of the targets and environment, as suggested by [33] and later higher layers like situation interpretation and prediction. Some of today's sensors already have some features, fulfilling the above definition of cognitive radars to prevent interference from other radars. Switching the frequency sub-band within the maximum allowed total bandwidth in order not to be disturbed or in some cases even changing the field of view by switching between two antenna modes for the same reason have already been realized. But the way to a fully adaptive radar system reacting on complex situations or functions is still long.

Another important aspect in the framework of future advanced driver assistance systems is car to car and infrastructure communications. Radar, as an RF system, allows for communications at very large bandwidths [35, 36]. Of course, the high frequency range does allow communication based on a short range line of sight path only, but it might be an additional resource to guarantee a reliable connection, if functions are in need for that. Both communications and many options of software defined radars, respectively adaptive radars, at least those with arbitrary modulation schemes require huge bandwidths for the baseband signals.

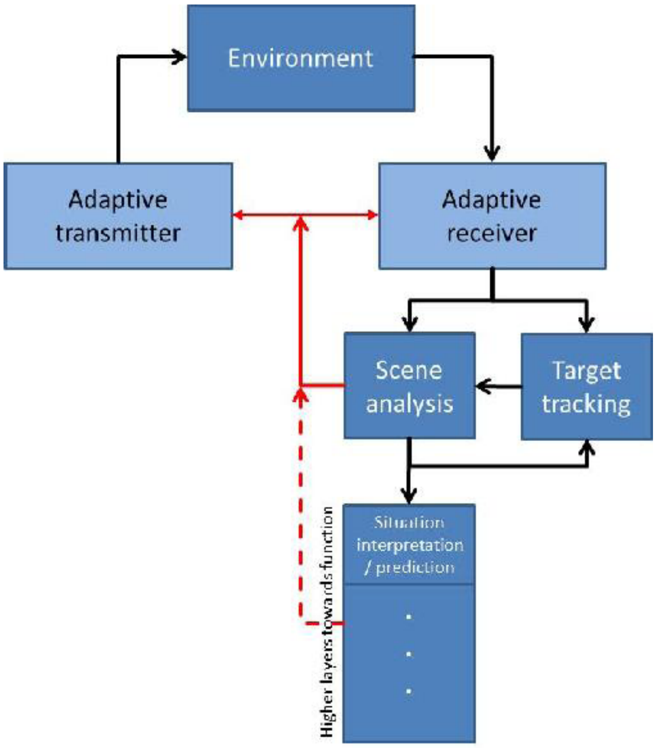

Fig. 2. Cognitive automotive radar sensor with feedback from different layers in the signal processing chain.

V. CONCLUSION

The paper has summarized many different new approaches to increase the functional performance of automotive radar sensors. Actual research work allows concluding, that in particular in the area of imaging and angular performance, as well as by Doppler analysis huge advances may be expected allowing for a better perception performance than with today's sensors. We also expect that the sensors will in future work in a new framework, i.e. the cognitive radar.

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