Automotive Radar – Status and Trends

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Abstract — **The paper gives a brief overview of automotive radar. The status of the frequency regulation for short and long range radar is summarized because of its importance for car manufacturers and their sensor suppliers. Front end concepts and antenna techniques of 24 GHz and 77 GHz sensors are briefly described. Their impact on the sensor's field of view and on the angular measurement capability is discussed. Esp. digital beamforming concepts are considered and promising results are presented.**

I. INTRODUCTION

First experiments in the field of automotive radar took place already in the late 50's. In the 70's, more or less intensive radar developments started at microwave frequencies. The activities of the last decades were concentrated mainly on developments at 17 GHz, 24 GHz, 35 GHz, 49 GHz, 60 GHz, and 77 GHz. Even from the early beginning in automotive radar the key driver of all these investigations has been the idea of collision avoidance; this idea has spent enormous motivation for many engineers all over the world to develop smart vehicular radar units. During this quite long period a lot of know-how has been gained in the field of microwaves and in radar signal processing. Accompanied by the remarkable progress in semiconductor microwave sources (esp. Gunn sources and GaAs MMICs) and in available computing power of microcontrollers and digital signal processing units, the commercialization of automotive radar became feasible in the 90's.

Competing and complementing technologies in vehicular surround sensing and surveillance are Lidar, ultrasonics, and video cameras (based on CCD or CMOS chips including near-infrared sensitivity). Car manufacturers and suppliers are developing optimized sensor configurations for comfort and safety functions wrt. functionality, robustness, reliability, dependence on adverse weather conditions etc. Last but not least the total system costs have to meet the marketing targets to be attractive for the end customers. First applications with surround sensing technologies were parking aid (based on ultrasonics), collision warning, and Adaptive Cruise Control (ACC). For instance, collision warning systems were successfully introduced in the US in the 90's. Greyhound installed more than 1600 radar systems (24 GHz) in their bus lines yielding a reduction of accidents of 21 percent in 1993 compared to the year before.

ACC was commercialized for the first time in Japan in 1995. Whereas Lidar-ACC has been favored esp. in Japan, European and US companies have been focused mainly on radar based ACC. In 1999, Mercedes introduced the 77 GHz "Distronic" into the S class, followed by other premium models equipped optionally with an ACC, such as BMW 7 series, Jaguar (XKR, XK6), Cadillac (STS, XLR), Audi A8, and VW Phaeton. ACC is also available in Mercedes E, CL, CLK, SL class, BMW 5 and 6 series, Audi A6, Nissan (Cima, Primera), Toyota (Harrier, Celsior), Lexus (LS, GS), and Honda (Accord, Inspire, Odyssey). Furthermore, ACC will become an option in the new BMW 3 series and in the new VW Passat, both with start of production in 2005.

Whereas European car manufacturers offer 77 GHz systems only for ACC systems so far, their Japanese competitors Honda and Toyota already introduced an active brake assist for collision mitigation (additionally to ACC) in 2003 based on 77 GHz long range radar (LRR) technology. In contrast to the only smooth deceleration capability of an ACC system (because ACC is only marketed as a comfort feature), the active brake assist provides much higher braking forces for deceleration, when a threatening situation is identified and the driver starts braking, but maybe not as strong as it would be necessary to avoid a crash.

This shows the trend from "comfort only" functions to active safety systems with radar sensing technologies that serve both the comfort and the safety domain. Within the next few years these active safety systems will be introduced in Europe. Mercedes started with the first generation of their Presafe system in the S class in 2003, which isn't based on surround sensing techniques yet but (only) on the data of the electronic stability program (ESP) and the antilock braking system (ABS). If these control units identify an imminent accident due to the car's dynamics, electronic seat belt tensioners will be activated, seat orientations will be adapted, and the sunroof will be closed.

The next step in this evolutionary process will be to gain some more milliseconds in advance for reaction and for automatic activation of suitable protection measures. Bosch names this system "Predictive Safety System (PSS)", which will have mainly three stages. The first one (PSS1, to be introduced in 2005) is a preset of the brake system. As soon as a threat will be identified by the 77 GHz LRR, the brake system will be pre-filled, but this won't be noticed by the driver. But when the driver pushes the brake pedal in such a situation, maximum braking forces will be available without any latency. In the second stage (PSS2, 2006) the driver will be notified in a hazardous situation with an automatic, very short but intensive brake activation, accompanied by optical or acoustic signals. In the third stage (PSS3) an automatic emergency brake will be initiated if otherwise a crash couldn't be avoided. Bosch was recently awarded for its PSS with the "Gelber Engel (Yellow Angel)" from the

German auto club ADAC (similar to AAA in the US) in the category "Innovation".

Short range radar (SRR) sensors for passenger cars will be mounted first in premium class models for pre-crash sensing, ACC support, parking assistance, and blind spot surveillance. Preferred microwave technology is 24 GHz in ultra wideband (UWB) operation with high range resolution in the range of cm.

II. FREQUENCY REGULATION

A lot of progress has been made during the last years in the frequency regulation for automotive radar. The 76 – 77 GHz band was regulated already in the 90's followed by a standardization in Europe (ETSI EN 301 091). Now, this band is allocated for Intelligent Transport Services (ITS) in Europe, North America, and Japan.

For short range applications UWB sensors are widely preferred because of their low cost perspectives and their high resolution in the range cm. The Federal Communications Commission (FCC) regulated UWB for the North American market (NAFTA) already in 2002. For automotive UWB short range radar systems the FCC allocated the band 22 – 29 GHz with a maximum mean power density of -41.3 dBm/MHz.

In 2002, more than 30 mainly European car manufacturers and suppliers founded the Short range Automotive Radar frequency Allocation consortium (SARA). SARA's main objective is to support UWB regulation for automotive radar in the 24 GHz range in Europe. Because of strong objections of the telecom industry and earth observation institutions, a lot of effort was dedicated to find a compromise and to enable automotive UWB radar systems. On 17 January 2005 the commission of the European Community finally decided to allocate the range of 21.65 – 26.65 GHz for UWB short range radar. The marketing of these systems is allowed from 07/2005 till 06/2013. The penetration rate is restricted to 7 percent of all cars in each country of the European Community. It is expected that this time frame of eight years will be sufficient to develop inexpensive short range radar sensors operating at a new frequency without impairing other commercial, scientific or military systems and services. Hence, in March 2004 the European commission allocated the frequency range 77 – 81 GHz for UWB SRR with permitted usage from 2005 onwards. Anticipating the allocation of this band also in Japan and North America, the SRR suppliers will probably shift their UWB developments from 24 GHz to 79 GHz in the medium term.

III. FRONT END TECHNIQUES AND ANTENNA CONCEPTS

Functional requirements, limited space for the sensors' mounting, regulatory issues, components' and fabrication costs, and marketing schedules mainly determine the choice of sensor concepts. One main requirement for long range radar is a range capability up to 150 .. 200m. With regard to the radar equation of a monostatic radar

$$R_{max} = \sqrt[4]{\frac{P_{Tx} \cdot A^2 \cdot \sigma}{P_{min} \cdot 4\pi \cdot \lambda^2}}, \quad (1)$$

we have in mind that the maximum range R_{max} is proportional to the square root of the effective antenna aperture size A and to the square root of the frequency. σ denotes the reflectivity of the target, P_{Tx} the transmitted power and P_{min} the minimum power necessary for detection. Therefore, highest frequencies should be preferred to get small box volumes. But this demand is contrary to the availability of cost saving microwave technologies. The antenna size of 77 GHz LRR sensors may decrease to approx. 50 x 50 mm². But even when the sensitivity would be sufficient, high antenna directivity and low sidelobes would still be necessary to cope with the effects of guard rails and irrelevant surroundings besides the road lanes.

A. 24 GHz Sensors

SRR sensors do not require long range capability. Hence, lower frequencies are preferred, enabling the use of available microwave components also used in the telecom industry. The 24 GHz technology seems to be the best compromise between today's component costs and sensor size. Typically, SRR sensors do not measure the angle of detected objects and they have a very broad lateral coverage. Therefore, single antenna elements are sufficient. Only vertically the beams are directed to increase antenna gain and to minimize clutter effects from the road surface [1]. SRR sensors are typically operated in pulsed mode (pulse, pulse Doppler) or in continuous wave mode (CW, FMCW, FSK, FMCW & FSK). Also coded radar with spread spectrum techniques (pulsed, CW, pseudo-noise) is a common technique. For instance, Delphi's 17 GHz radar is a phase coded CW radar with a pseudo-noise (PN) BPSK modulation. The M/A-Com sensor is a pulsed radar. Hella is developing a 24 GHz UWB radar for short range applications and a narrowband FMCW radar operating in the license free 24 GHz ISM band with a maximum range of 70m [2].

To measure not only targets' distances but also their angular positions, several adjacent sensors can be used. Their measurements of the targets' distances are fused in a trilateration algorithm yielding also the angular positions. Valeo-Raytheon is developing a multibeam phased array SRR that provides angular information itself.

B. 77 GHz Sensors

Main manufacturers of 77 GHz LRR sensors are ADC (subsidiary of Continental Temic in cooperation with M/A-Com), Bosch, Delphi, Denso, TRW (Autocruise), Fujitsu Ten, and Hitachi. Fig. 1 shows Bosch's LRR in its 2nd generation, production has been started in 2004. The system has a box size of only 74 x 70 x 58 mm³ (H x W x D) and contains all sensing and ACC functionality. The 77 GHz circuitry contains 4 feeding elements (polyrods) directly attached to 4 patch elements on the RF board, illuminating a dielectric lens. The monostatic analog beamforming approach results in a broad illuminating transmit beam and four single receiving beams which partially overlap in azimuth yielding a total azimuthal coverage of ±8 degrees, see Fig. 2. The modulation is FMCW with a triangular shape [3].
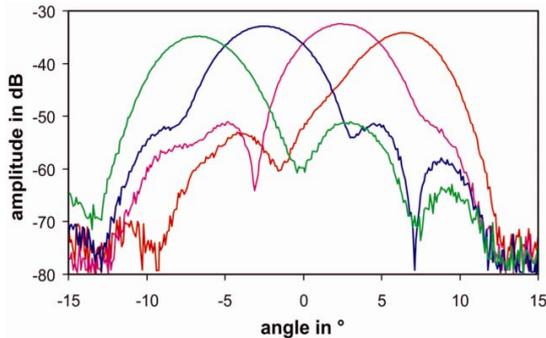
Fig. 1.   Bosch ACC, 2nd generation

Fig 2.   Receive beam pattern of Bosch ACC, 2nd generation

TRW also uses the dielectric lens concept whereas ADC (resp. M/A-Com) takes advantage of a folded structure with a very low profile resulting in a sensor depth of 5cm. Other companies (Delphi, Fujitsu Ten, Mitsubishi electric, Celsius Tech) use mechanical mechanisms to steer the beam in azimuth. Although mechanical radar scanners yield quite good detection performance, they might be sensitive in their mechanical reliability over lifetime. Moreover, they are limited concerning further miniaturization. Delphi's and Fujitsu Ten's mechanical radar are in series production.

IV. DIGITAL BEAMFORMIMG CONCEPTS

77 GHz radar sensors with digital beamforming (DBF) front ends were introduced into the market by Japanese companies in 2003. Denso built a bistatic LRR with planar patch antennas with a range capability up to 150m and a field of view of approx. ±10 degrees [4]. The nine receiving antennas are multiplexed with four 77 GHz SP3T switches to only one base band channel, see Fig. 3.
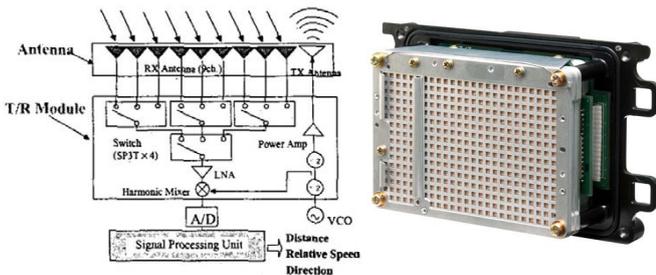

Fig. 3.   Denso's 77 GHz DBF sensor [4]

The Toyota CRDL 77GHz LRR radar (Fig. 4, [5]) switches 3 equal transmitting antennas and 3 receiving antennas resulting also in one base band channel, and, after demultiplexing in the digital domain, nine digital receiver channels for DBF.
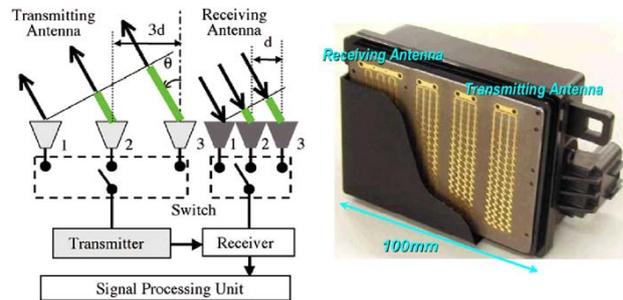

Fig. 4.   Toyota CRDL Radar with DBF, 77 GHz, [5]

A. Direction of Arrival Estimation

All conventional direction of arrival (DOA) estimation methods as monopulse techniques (comparison of the received signals in partially overlapping beams) or spatial power spectrum measurement techniques (mechanical scanning, phased array) do have an angular resolution in the range of the half-power beamwidth. Hence, the angular resolution directly depends on the aperture size, because the 3 dB beamwidth of an antenna with diameter D and constant illumination is approx.

$$\theta_{3dB} \approx 59° \frac{\lambda}{D}. \qquad (2)$$

Therefore, the angular resolution of long range 77 GHz sensors is typically in the range of 2 .. 5 degrees. To overcome this limitation, parameter estimation methods based on subspace techniques can be applied. These methods rely on a subspace decomposition of the noisy received signals of an array of multiple antenna elements. With an eigenvalue decomposition of the autocorrelation matrix of the received signals of a uniform linear array (ULA) the noise and the signal subspace can be determined. Knowing these subspaces, the DOA's of the targets can be estimated. Well known in array signal processing theory are the Music and Esprit algorithms [6, 7]. We applied these techniques to a 24 GHz SRR with digital beamforming and published very promising results in 2002 [8].

In our further work we started to transfer this approach to the 77 GHz domain. The main objectives of our current research activities are to gain know-how about 77 GHz DBF concepts and their benefits in combination with parameter estimation techniques and to investigate their impact on development efforts. Fig. 5 shows one of our 77 GHz DBF front ends with a ULA consisting of eight parallel receiving columns. The transmit antenna consists out of 4 columns with a tapered power distribution yielding a low sidelobe level of approx. -27 dB. The 3 dB beamwidth of the transmit antenna is approx. 26 degrees and the antenna gain is 20.5 dB.
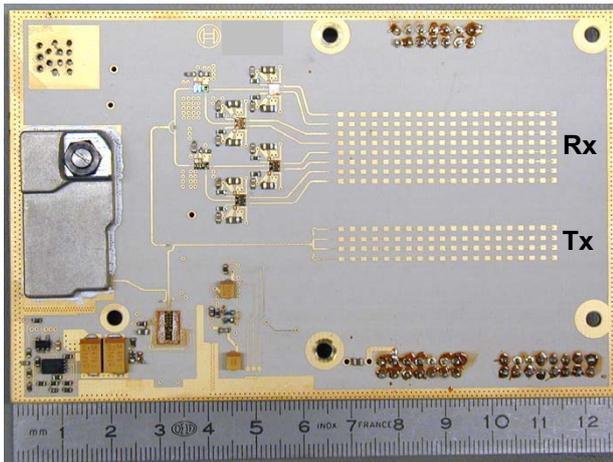
Fig. 5. Bistatic 77 GHz DBF front end with 8 patch antenna columns for receive and 4 columns (fed by a power splitter) for transmit

Another front end with extended arrays for long range operation was put into a water-resistant housing and was mounted on our test vehicle, see Fig 6. First results of our implementation of parameter estimation techniques on a 77 GHz DBF demonstrator are shown in Fig. 7. The markings no. 1 and 2 indicate the estimation of the Esprit algorithm. Although the half power beamwidth of the virtual beams of the DBF sensor is approx. 8.5 degrees, both cars with their angular separation of less than 4 degrees are detected and no ghost target between both objects does appear.

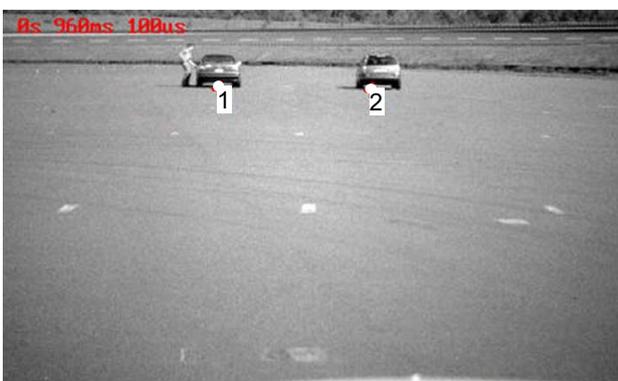Fig. 6. Test vehicle with 77 GHz DBF demonstrator (also insert in right bottom corner)

Fig. 7. Angular measurement of two cars at the same distance (60 m radial distance and 4 m lateral separation)

V. CONCLUSION

Short range radar in ultra wideband operation at 24 GHz and at 79 GHz from 2013 at the latest will be used first in premium and later on in upper class models. Main applications will be ACC support, pre-crash detection, parking assistance, and blind spot surveillance. Market introduction of 24 GHz SRR will start in 2005. SRR sensors won't have angular measurement capabilities in the first generation (except the Valeo-Raytheon sensor), but future generations will also be able to provide angular information. Although these sensors will be more expensive, they will contribute to the minimization of the total number of sensors and therefore they will reduce overall system costs.

77 GHz ACC systems will be extended to be operational at low speeds including full stop capability. This will provide increased customer benefits and it will contribute significantly to the market success of ACC systems. In the same manner the 77 GHz sensor will be used not only for comfortable driving (ACC stop & go) but also for predictive and active safety systems. Active safety systems up to an automatic emergency braking in unavoidable crash situations will be the key for a considerable reduction of the total number of crashes and fatalities.

The detection performance of 77 GHz sensors will be further improved, for instance wrt. false alarm rate and reaction time. Also sensor costs will be lowered. Planar antennas in combination with digital beamforming provide interesting front end concepts for 77 GHz radar. These techniques might become feasible for high volume production as far as costs of 77 GHz components and powerful digital signal processing units will further decrease.

REFERENCES

[1] I. Gresham, A. Jenkins, "Ultra-wideband radar: Regulations, Applications, and Challenges," *Int. Microwave Symposium 2003*, Philadelphia, Penn., June 2003

[2] Th. Wixforth, W. Ritschel, "Multimode-Radar-Technologie für 24 GHz," *auto & elektronik*, vol. 3/2004, pp. 56-58

[3] G. Kühnle, H. Mayer, H. Olbrich et al, "Low-Cost Long-Range Radar for Future Driver Assistance Systems," *Auto Technology*, vol. 4/2003, pp. 2-5, 2003

[4] A. Kawakubo, S. Tokoro et al., "Electronically-Scanning Millimeter-Wave RADAR for Forward Objects detection," *SAE Congress 2004*, pp. 127-134, Detroit, 2004

[5] Y. Asano, S. Ohshima et al, "Proposal of Millimeter-Wave Holographic Radar with Antenna Switching," *Int. Microwave Symposium 2001*, Phoenix, Az, May 2001

[6] R. O. Schmidt, "Multiple emitter location and signal parameter estimation,", *Proc. RADC Spectrum Estimation Workshop*, RADC-TR-79-63, Rome Air Development Center, Rome, NY, Oct. 1979, p. 243 (reprinted in IEEE Trans. Antennas Propag., vol. AP-34, pp. 276-280, 1986)

[7] R. Roy and T. Kailath, "ESPRIT – Estimation of signal parameters via rotation invariance techniques," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 37, pp. 984-995, July 1989

[8] M. Schneider, V. Groß et al, " Automotive 24 GHz Short Range Radar Sensors with Smart Antennas," *German Radar Symposium 2002*, Bonn, September 2002