Chapter 10
Radar Sensors in Cars

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10.1 Introduction

Advanced Driver Assistance Systems (ADAS) and autonomous driving, also based on mm-wave radar, are in discussion everywhere these days. It is already several years back—about 50 really—since the first attempts of implementing radar sensors into cars have been started. In those days, the car was entirely a mechanical device, even the injection control was done manually; the ignition coil—besides lighting—then was the only electric device in the car.

Already 50 years ago, there were some people envisioning the changes towards the electronic content in a car that have become reality today. However, they were laughed at then. Diagram 10.1 shows the increase of electric/electronic parts in a car as thought of in 1990s.

More electronics needed higher and—most importantly—lower cost integration by the utilization of automated assembly lines and the use of integrated circuits RFICs and MMICs. It was only in the early 1990s that in a MELECON Conference in Ancona, Prof. Alberto Sangiovanni-Vincentelli (today at the University of LA, Cal., USA) postulated to have Si wafers as large as 15 in. at the end of the century (being said in a time with production wafers having a diameter of 4–6 in. only)—half of the audience left the auditorium laughing.

Recently, Infineon has sold more than ten million radar chips for cars (Microwave Journal—Microwave flash—July 2015).
In the early 1970s, we had the oil crisis with *car free sundays* all over Europe (Fig. 10.1),—the development of more comfortable and safer cars was not at all in focus—the objective was to lower the fuel consumption.

Was that really the right time to develop microwave radar systems for cars, or the Automotive Collision Avoidance System (ACAS)—as it was dubbed then?!

Still it was done and beginning in 1972, the German government sponsored a research program investigating radar-based Automotive Anti Collision Systems—named NTÖ 49—which was launched at AEG-Telefunken in Ulm, Germany, employing 35 GHz technology. Earlier attempts implementing car radar systems were carried out at X-Band and Ku-Band, around 10 GHz and 16 GHz, shown in Figs. 10.2 and 10.3, respectively. However, the radar units were quite too large to fit into a standard sedan.
10.2 Forward Looking Radar (FLR)

Within the research project, NTÖ AEG-Telefunken thoroughly investigated automotive radar design strategies and developed the first radar system operating at 35 GHz in the millimeter wave frequencies range. Many innovative design ideas were implemented, such as narrow beam width antennas with 2.5 by 3.5° pencil beams. The 2.5° in azimuth was illuminating just one lane 100 m in front, while 3.5° in elevation was good enough to look over hills and under the bridges. The utilization of miniaturized semiconductor two terminal devices, namely
IMPATT-, GUNN-, and Schottky diodes and hybrid assembly technology, made it possible to significantly reduce the size of such a radar unit and fit it into the front of a standard sedan. IMPATT diodes were used for the radar pulse generation in the transmitter, while GUNN diodes served as a local oscillator (LO) in the receiver unit, and discrete beam-lead-type Schottky diodes were used as the mixing element in the receiver.

Figure 10.4 shows the block diagram of this first 35 GHz collision avoidance radar designed by AEG-Telefunken. The transmit (TX) and the receive (RX) units
were realized as separate modules with their own transmit and receive antenna, as no adequate and technically sufficient circulators at 35 GHz were available then. The achievable pulse output power was about 100 mW with 20 ns of pulse width.

Already then, at the very beginning, the idea of using an automotive radar as a means to reduce the accident rates on our streets was one of the major driving forces. Therefore various cars, buses, and trucks were equipped with radar sensors (Figs. 10.2, 10.3, 10.5, and 10.6) and tested worldwide.

In other countries, mainly in the USA and Japan, research on automotive radar systems was initiated as well, however, at very different frequencies such as 35, 47, 60, and 94 GHz, the later being a “leftover” from military applications and
thus components were readily available, e.g., from the DARPA sponsored MMIC program in the USA.

Nevertheless, these first mm-wave units operating at 35 GHz showed promising performance. Several ten units had been built and were tested on several millions of highway test kilometers in Germany, jointly together with Bosch, one of the AEG-Telefunken partners within the NTÖ 49 research program.

Even trucks have been equipped and tested with the first 35GHz radar sensors. Based on these results, similar and slightly improved 35 GHz radar units were forwarded to SEL company working together with Mercedes-Benz within the regime of the sponsored NTÖ 49 program.

The Japanese 60 GHz approach was a political and very pragmatic one; mm-wave radar and future communication systems could be set up and investigated, employing the entirely same semiconductor devices and mm-wave components being developed at 60 GHz then, Fig. 10.13.

Only the introduction of 77 GHz radar sensing, being started in Germany in the early 1980s, as a worldwide standard for long range automotive radar (LRR) (see also Fig. 10.7) within WARC 89 cleared this turmoil of different frequencies.

### 10.3 Blind Spot Detection Radar

A first Blind Spot Detection (BSD) sensor, i.e., a Short Range Radar sensor (SSR) for the recognition of vehicles, being in the optical blind spot of the standard rear mirror, was presented in the early 1970s by Dunlop & Assoc. and Bendix (Fig. 10.8) in the USA, employing slotted array-type antennas at 16 GHz. "The antenna patterns intersect adjacent (street) lines to illuminate the blind spot areas"
and to warn of the presence of approaching automobiles with a light or audible signal.”

More than 20 years later, in 1995, HE Microwave Corp. (Hughes Electronics) in Tucson, AZ, USA, already proposed 24 GHz for their SDS (side detection sensor) system for trucks (Fig. 10.9). “The SDS was conceived to assist the driver in accessing the viability of a planned lane change,” as well a BSD sensor.

Today, the 24 GHz range is the general frequency approach being taken for BSD sensing (Fig. 10.10).

Narrow-Band (NB) systems, operating in the ISM-Band (24.05–24.25 GHz)—standing for Industrial, Scientific and Medical—and Ultra-Wide-Band (UWB)
systems operating between 21.65 and 26.65 GHz with various advantages and disadvantages, are on the market today. Companies such as Valeo or Hella, just to mention two companies in Germany, are already producing more than two million of these NB sensors per year (2014) each. Autoliv is manufacturing UWB Blind Spot Detection systems for Mercedes-Benz, e.g., the so-called CPA (Collison Prevention System).

Nowadays, basically all long range automotive radar (LRR) sensors with “pencil” beams are operating in the 77 GHz frequency range that has been allocated by the ETSI standardization organization, whereas the SRRs for urban traffic applications with wider azimuth antenna values are operating in the 24 GHz range—these days (more on this subject in the Sect. 10.5).

The development of new markets and the worldwide deployment of a technically innovative product like automotive radar is typically a reaction to social developments and the upcoming of specific needs. The worldwide trend towards huge megacities accompanied by the democratization of mobility in highly populated countries like the BRIC States (Brasil, Russia, India, and China—together amounting to more than 40% of all car sales in 2012) has led to a dramatic increase in traffic density and thus accident rates on the streets, prompting the need for enhanced vehicle safety and more driver assistance.

Due to their unique physical performance, automotive radar sensors are the backbone of modern vehicle safety and driver assistance systems, though not being the only means; laser scanner and video camera systems are mostly complementary and sometimes competing technologies. However, based on the described trends, it is quite simple to forecast that the density of radar systems will explode over the next decades, along with the worldwide hugely increasing number of cars (Diagram 10.2).
Diagram 10.2 Total car stocks by region. Source: IEA—International Energy Agency

The higher the automotive radar density operated on the road will grow the more important it will be to guarantee the interoperability of such sensors, especially as we are on the move from simple comfort systems to highly sophisticated safety applications, e.g., for autonomous driving utilizing automotive radar systems. TÜV certification based on further developed ASIL definitions (i.e., setup of sensor structures) within DIN 26262 will become necessary.

10.4 Early Systems and Their Results

1992 As early as 1992, the EATON VORAD CWS (collision warning system) operating at 24 GHz was installed in more than 4000 buses and trucks in the USA, from Greyhound buses (Fig. 10.11) to rental trucks providing an acoustic warning for the driver only.

Being driven on more than 900 million road km, the study confirmed that the amount of accidents per km travelled was reduced by more than 50%; more than that, the resulting severity of accidents still occurring was significantly reduced (Fig 10.12).

However, these radar system units had to be de-installed on the long run due to heavy protests of the US-driver unions. The CWS radar system tracked the driving hours on the road as well and hence produced “transparent” drivers to their employers. Obviously, the drivers did not like that at all. The time was not yet ready for such a system.
1996 Four years later in 1996, the “Automated Highway System” was installed and tested in Japan on about 100 km of the newly built Jo-Shin-Etsu highway. The interoperability of several systems was tested. A “leakage coaxial cable” (LCX) was used for vehicle-to-roadside (v2x) communication. Magnetic nails in the road surface and corresponding sensors in the cars provided lane control during driving, and a mm-wave radar at 60 GHz was utilized for distance control. In addition, optical lane markers were detected by a CCD camera installed on the car (Fig. 10.13). The overall system was called ACAS (Automotive Collision Avoidance System) and demonstrated the first driverless cars. The “Electronic Information Systems Research Laboratory” of Nissan Motor Co. LTD. was one of the protagonists of this system.

The achieved and demonstrated results were very promising; however, the required road-side installations—LCX, magnetic nails, etc.—and the sensor systems in the car were thought to be too expensive at the time.

However, these days NISSAN is one of the technology leaders towards autonomous driving.
1998 Two more years later, when the DISTRONIC system was introduced by Mercedes-Benz in 1998, the acceptance rate was not at all favorable and the timely spread from the premium S-Class cars to other classes was quite slow—however, since the introduction of DISTRONIC PLUS (1x LRR plus 4x SRR), another 8 years later (2006), this has changed significantly. With “Brake Assist Plus” and “PRE-SAFE Brake” having become part of the system package (Fig. 10.14), such a system became directly driver recognizable and was well perceived by the public.

2011 The paradigm change from comfort systems to safety systems started to take place, as well as the “democratization” process with the introduction of the new Mercedes-Benz B-class and A-class in 2011 and 2012, respectively. “DISTRONIC PLUS” became available as a special equipment (Sonderausstattung) product fitted also in smaller cars. CPA—Collision Prevention Assist was already a series product although in the beginning only as an acoustical warning signal.

2014 With the introduction of the new Mercedes-Benz C-class in spring 2014, the further developed CPAplus (Collision Prevention Assist plus) and thus automatic brake assist became a standard series equipment in Mercedes-Benz cars.

The “PRE-SAFE BRAKE” system of Mercedes-Benz or the “Intelligent Brake Assist” from NISSAN are the prerequisite for advanced braking systems, that significantly reduce the number and the severity of road accidents.
Figure 10.14 Pre-safe brake—developed and confirmed for sedans—now also in trucks. Source: Daimler AG, Stuttgart, Germany

Figure 10.15 shows the reduction of accidents (in number as well as in severity) due to the introduction of “Distronic PLUS,” a radar-based electronic braking system.

A study from KPMG—August 2015—came to the result that ADAS could reduce accidents by 80%.

Today, we have roughly one accident per 280,000 miles driven; in 2040 this could be only one accident per 1,600,000 miles driven.

10.5 Trends

In the future, as described above, many more sensors will be operated on the road simultaneously. Therefore, it is quite obvious for any OEM investigating and planning the next generation of radar; it will not be sufficient to take a sensor that has demonstrated to be insensitive against others. The sensor itself has also to be proven not to interfere or to blind other systems. Testing the interoperability of radar sensors for OEMs, as well as for the corresponding supplier, it would be very convenient to utilize a standard interferer [10] as a qualification device. Such a test device should be able to generate a large variety of modulation schemes and bandwidths that could be tested against the sensor under question. Another objective has to be keeping the opportunities open to meet future demands in
the process towards interoperability. One prominent issue of this concern is the corresponding frequency band as well as the bandwidth taken per sensor to allow, for example, frequency hopping. Future frequency regulation strategies should aim to get worldwide access to higher frequency bands, as well as using larger bandwidths per sensor. A minimum bandwidth of 1–2 GHz is very likely to be the requirement for future traffic scenarios, like pedestrian recognition (micro-Doppler) or side-impact-alert.

As a consequence, all this demands a common effort between radar manufacturers, backed by their corresponding OEMs, in order to identify and to agree upon a common design rule book. This guideline has to quote commonly agreed countermeasures against interference, while keeping opportunities open for each manufacturer to develop his individual radar. The EU-funded project MOSARIM (MOre Safety for All by Radar Interference Mitigation) was a first step in this right direction. MOSARIM was openly described and broadly discussed within the microwave community during the EuMW 2012 in Amsterdam; the EuMC/EuRAD WS23 being the official and final event of that program.

Today 24/26 GHz is the general frequency approach, being taken for BSD sensing, as stated above. However, the time for changing the operating frequency of future radar sensors from 24/26 GHz to 76–81 GHz is very likely to come soon. There are four main reasons:
1. Technical requirements of future (and more complex) driver assistance and vehicle safety systems, demanding higher resolution and accuracy in space and time.

2. Vehicle integration and sensor packaging demands minimization, while enhancing sensor performances.

3. Cost reduction based on “economies of scale.” Shifting to the 76–81 GHz range allows to develop radar modules being able to be used for all automotive radar types from LRR via MRR to SRR.

4. Interoperability, since the market penetration of automotive radars will explode, interference mitigation has to become the key for further market growth. A large bandwidth enabling frequency hopping or other efficient frequency separation procedures has to be mandatory and is worldwide available only between 76 and 81 GHz.

However, more and ongoing efforts concerning automotive radar performance are already under development, as they will be necessary for the future.

10.6 Future Directions

Taking off from today’s already available and market introduced radar sensors, injury free driving and a better and more efficient vehicle management, resulting in lower consumption, will be a near future issue (Fig 10.16).

Applications like RCTA (Rear Cross Traffic Alert), supporting a driver while backing-up out of a parking lot or RPC (Rear-Pre-Crash) and detecting and calculating critical objects approaching from the rear, are already being implemented, e.g., in the Mercedes-Benz S-Class, having been launched in July 2013 (Fig. 10.17).

Fig. 10.16  Visions for vehicle motion and safety. Source: Bosch GmbH, Stuttgart, Germany, from a EuRAD 2012, Amsterdam, paper
In 2013, Valeo had introduced a combined BSD/RTCA sensor, employing DBF (Digital Beam Forming) antenna technology.

The “All-around collision free” car from NISSAN utilizes the “safety shield,” a concept being already introduced in 2005. The “Safety Shield” is an effort to proactively achieve active safety. The car is able to help to provide assistance to the driver for safer driving depending on the actual situation. By combining aspects of active and passive safety, NISSAN was able to help reduce the number of fatalities and serious injuries.

“Distance Control Assist,” based on ACC, or “Lane Departure Warning” and even more “Lane Departure Prevention” are parts of NISSAN’s “safety shield.”

TOYOTA announced details of its entry into the autonomous vehicle race at the annual “Consumer Electronics Show” (CES) 2013 in Las Vegas, USA, in January. The “Advanced Safety Research Vehicle,” a Lexus RS (Fig. 10.18), utilized a variety of technologies, like GPS, mm-wave radar, laser tracking, and stereo cameras, to achieve its autonomy.

In December 2013, the Volvo Car Corporation (VCC) in Gothenburg, Sweden, has announced the “Drive Me—Self-driving cars for sustainable mobility” project. “Drive Me” is a world unique pilot project with up to 100 self-driving cars on public roads before 2017. If everything is running as planned and smoothly, series production is envisioned to start in 2020 (Fig. 10.19).

Recently, in September 2015, the Dutch government has announced an ambitious program to have automotive vehicles on the roads before 2025. Necessary changes are going to be implemented in existing laws to open the door for such vehicles on public roads. In parallel, the national consortium DAVI (Dutch...
Advanced signal processing of today—incorporating “big data” at very high data rates—has made new solutions and applications possible for car radar employment. Micro-Doppler detection for pedestrian recognition or the distinguished wheel Doppler detection of a car are such recent examples. Super computing with Deep learning capabilities thus will be the backbone for future and advanced signal processing—bringing Automated Driving nearer to reality.
Accident free driving and subsequently autonomous driving have come into reach technically.

The following chapters will describe this situation in detail.

Further Reading

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