Automotive radar technology, market and test requirements

White paper

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ROHDE & SCHWARZ

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This white paper explains the basics of automotive radar, MIMO radar signal processing, applications and market trends. Test and measurement requirements for research and development, mandatory ETSI tests and production verification of automotive radar sensors in the 24 GHz, 77 GHz and 79 GHz domains are described.

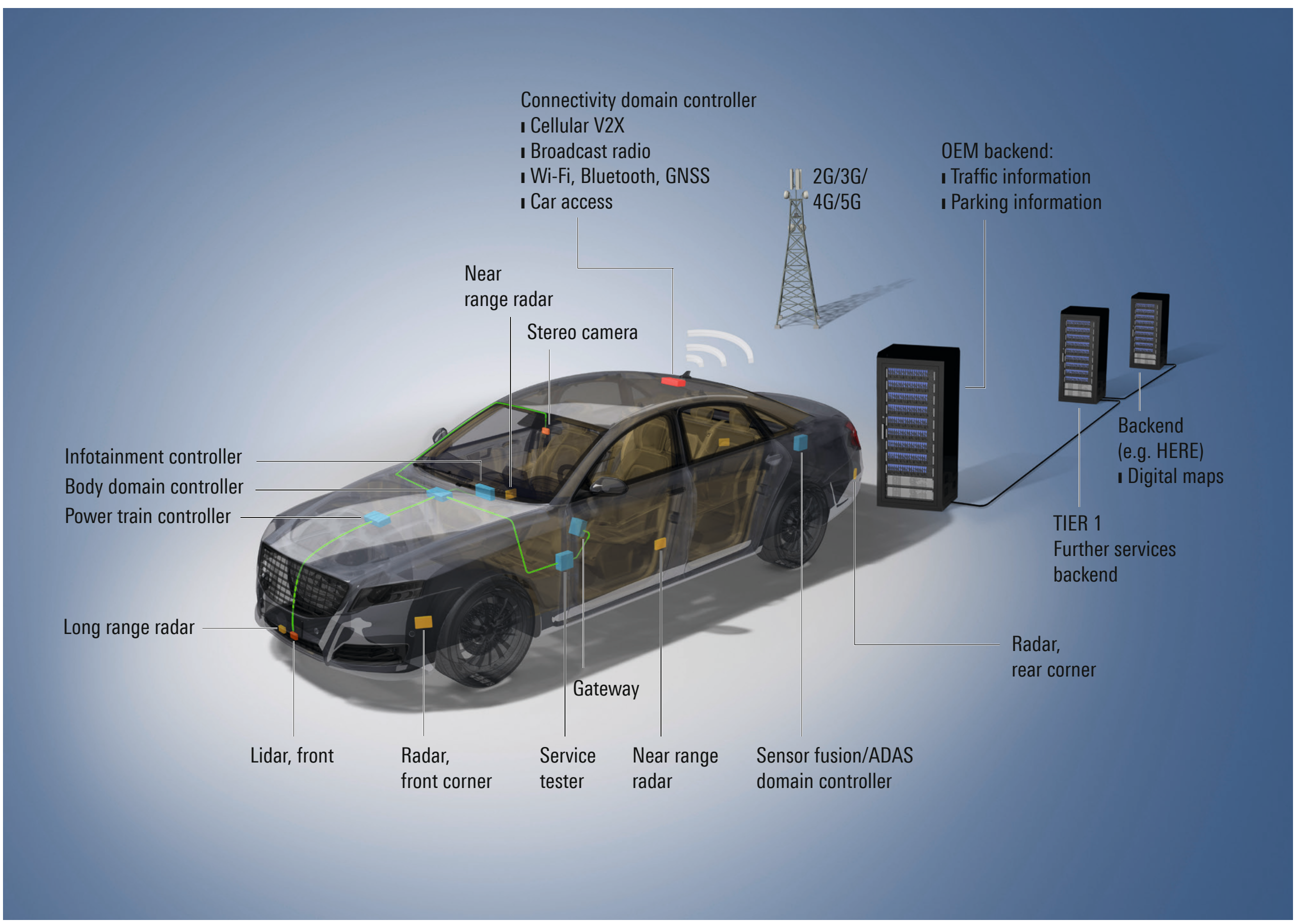
Note:
Please find the most up-to-date document on our homepage
www.rohde-schwarz.com/appnote/Automotive_radar_technology_wp_en_5216-2930-52_v0100.pdf

1 Introduction

Automobiles are increasingly being equipped with radar sensors that support drivers in critical situations, helping to reduce the number of accidents (Fig. 1). Radar makes it possible to quickly and precisely measure the radial velocity, range, azimuth angle and elevation angle of multiple objects. That is why the automobile industry is widely using this technology in advanced driver assistance systems (ADAS).

Fig. 1 shows an upcoming vehicle architecture. Automotive radar is used in many applications (indicated in yellow). Typically, blind spot detection (BSD) radars operate in the 24.05 GHz to 24.25 GHz range (radio resource allocation: ISM, RR 5.150, ITU references: WRC 19, AI1.13, Res. 238, resolves 2), while most automotive radars operate in the 76 GHz to 81 GHz range as part of the radiolocation service.

Fig 1: Automotive radar is rapidly expanding to offer greater vehicle safety



The 76 GHz to 81 GHz frequency band is of major interest since:

- Only automotive radar in the 76 GHz to 81 GHz range can claim protection from interference due to its regulatory status (final acts/outcomes of WRC-2015)
- The sensor package is smaller
- Radar chips are less expensive
- More bandwidth is available (resulting in higher range resolution)
- Measurements at 77 GHz give better Doppler resolution than at 24 GHz for the same signal transmit duration
- It offers more antenna space

For a system designer, all these new techniques play an important role. Next to the selection of the radar waveform, test and measurement accuracy is critical in the development and launch of a new radar system. New radar designs need to ensure that all hardware and software components work in the desired manner under all considered conditions. This creates specific measurement needs and tasks for the measurement equipment. A technical understanding of waveform design is fundamental.

To reduce design uncertainty, test solutions are required that deliver the performance, precision and insight to solve these advanced design challenges.

2 Automotive radar market trends

Since the first automotive radar trials in 1978, automotive radars have been rapidly evolving. While the first versions in 1978 used pulsed radars attached externally in front of the car, today radars are fully integrated and invisible behind design radomes, bumpers or mirrors.

Fig. 2: Automotive radar in 1978, 1999 and today

In addition to all the OEMs that utilize the radar sensors for comfort and safety applications, there are many radar suppliers with a common goal: to reach level 5 automation. This requires many radars with different functionality on a single car.

The number of produced units is heavily increasing since nearly every new car is equipped with at least one radar, making the automotive radar market quite large and a substantial area of growth for our industries.

According to the news, the global automotive radar market is projected to reach approx. USD 10 billion by 2023. Estimating a price of USD 50 to USD 100 per radar sensor, this would lead to an annual production of 100 million to 200 million radars, which sounds quite reasonable considering a production of more than 70 million cars per year and the number of radars necessary for level 4 and level 5 autonomy.

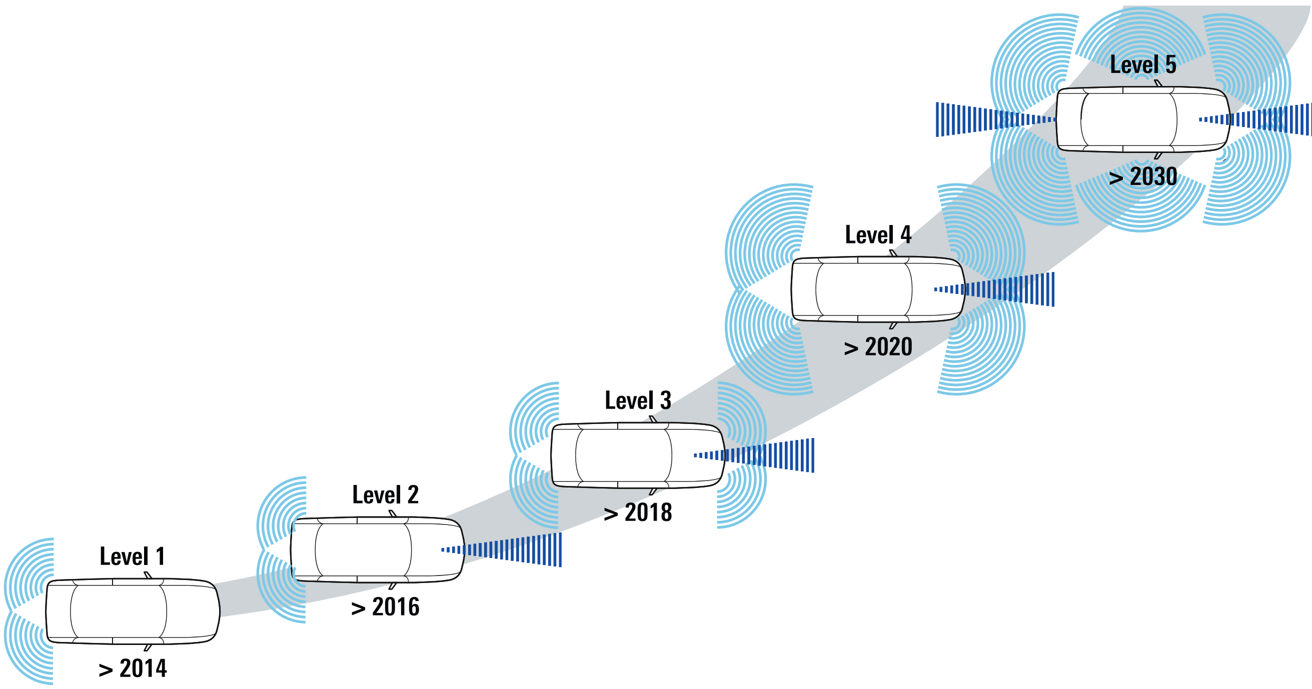
> Global automotive radar market is projected to reach approx. USD 10 billion by 2023.

These days, many commercial automotive radars operate with a signal bandwidth smaller than 1 GHz. Chip manufacturers have for some time been supporting a signal bandwidth from 4 GHz to 5 GHz with a modulation speed of 100 MHz/100 ns in the scalable 28 nm CMOS. Therefore, there is a trend to increase the signal bandwidth and the range resolution.

Many automotive radars will soon enter the market with greater range resolution and signal bandwidth up to 4 GHz or even 5 GHz. With increasing numbers of transmitting and receiving antennas, these radars will allow 3D imaging.

To enable future technology and pave the way towards automated driving, it is essential to have test and measurement equipment that supports high signal frequencies and large bandwidths, and even dedicated test equipment that allows manufacturers to design, test and verify these radar sensors for automotive applications.

Fig. 3: Trend and number of radar units for different levels of automation



Object detection

Features

SRR mode BSD, LCA

Device	#
SRR	2

Object detection

Features

SRR mode BSD, RCW, LCA, LRR mode ACC, AEB

Device	#
SRR	2
LRR	1

High-resolution target separation

Features

SRR mode BSD, FCW, RCW, RCTA
LRR mode ACC, AEB

Device	#
SRR	4
LRR	1

3D detection

Features

SRR mode BSD, RCTA
MRR mode AEB pedestrian
LRR mode ACC, AEB

Device	#
SRR to MRR	4
LRR	1

360° object recognition

Features

USRR mode AVP, PA
SRR mode BSD, RCTA
MRR mode AEB pedestrian
LRR mode ACC, AEB

Device	#
USRR to MRR	6
LRR	2

USRR = ultra short range radar, SRR = short range radar, MRR = mid-range radar, LRR = long range radar

3 Radar measurement

A specific task of radar is to simultaneously measure the range and radial velocity of a single object within a single measurement cycle. The range is measured by transmitting and receiving a signal and measuring the time delay. The radial velocity is measured either with a continuous wave signal or with consecutive pulses (pulse-Doppler radar), where the echo signal holds a Doppler frequency shift in the case of a moving object. Pulse-Doppler radar performs several transmit and receive cycles to measure Doppler frequency by varying the phase of the radar echo signals.

To measure the range and radial velocity within a single measurement cycle, automotive radar uses a variety of continuous wave (CW) signals. Compared to pulsed radar signals, these CW waveforms have some major advantages that are the reason for their application in automotive applications:

- Theoretically no blind range
- Low output power
- Low hardware complexity
- Low manufacturing cost
- Radial velocity resolution depends on transmission time
- Range resolution depends on signal bandwidth
- Low sampling rates and low IF filter bandwidth even at high transmit signal bandwidth

3.1 Range and radial velocity

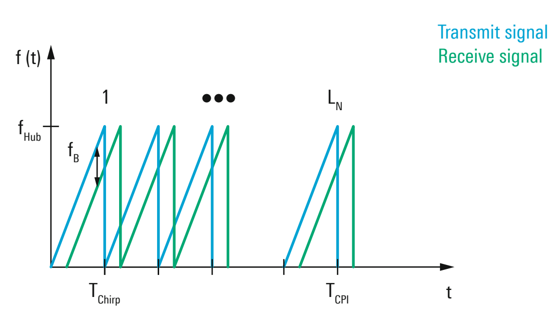
Automotive radar uses waveforms such as linear frequency modulated continuous wave (LFMCW), frequency shift keying (FSK), multiple frequency shift keying (MFSK), chirp sequence (CS) and many others.

Fig. 4 shows an example transmit signal (chirp sequence):

- f_{sweep} describes the signal bandwidth, which can be up to 5 GHz in the 76 GHz to 81 GHz frequency band
- T_{chirp} is the transmit duration of a single FMCW chirp, typically in the domain of 10 us to 40 ms
- T_{CPI} is a block of chirps that is several milliseconds up to 100 ms long

The radar transmits and receives at the same time. By mixing the receive signals with the transmit signals, the so-called beat frequency (f_B) is measured. Each object (each echo) contributes to a beat frequency. After fast Fourier transformation, the estimated beat frequencies can be used to calculate range and radial velocity.

Fig. 4: Chirp sequence



Many radar sensors also use a variety of these signals, which are transmitted in several different modes and selected by the radar scheduler based on the application and, for example, the required unambiguities and resolutions.

For example, in one transmit burst, the signal bandwidth is selected to be low, which offers increased maximum range but lower range resolution. In order to resolve and classify the targets, the next measurement cycle might use a high signal bandwidth, which reduces the maximum unambiguous range.

Another application could be the mitigation of interference from other automotive radar sensors. A radar sensor scheduler can apply frequency hopping or waveform diversity (and select those with less IF bandwidth). An automotive radar sensor therefore has to switch between frequencies after T_{chirp} or T_{CPI} depending on the implementation of the algorithms.

Each waveform has specific features that show the development and importance of radar waveform design within the past years.

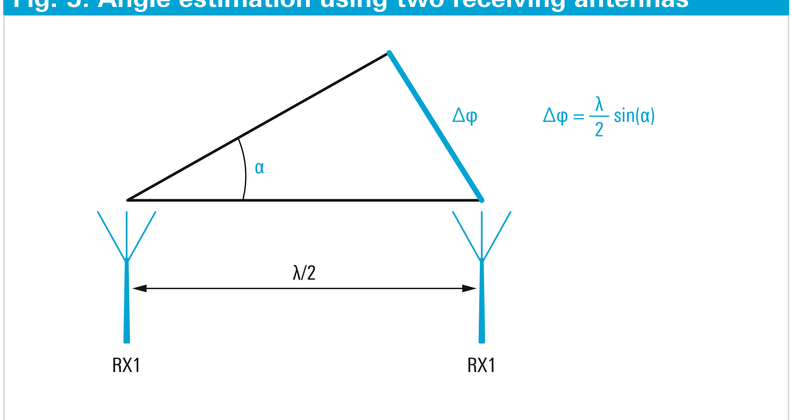
More details on waveforms can be found in the white paper on radar waveforms for A&D and automotive radar [8].

3.2 Azimuth and elevation

Azimuth and elevation angle are measured by using several transmitting and receiving antennas. Depending on the number of antennas, resolution in azimuth and elevation is also possible.

To estimate the angle, a radar generally measures the phase difference of a received signal at multiple antennas. Using a uniform linear array consisting of at least two receiving antennas, the angle α can be estimated by $\Delta r = d \sin(\alpha)$, where d is the distance between the antenna elements spaced by $\lambda/2$.

Fig. 5: Angle estimation using two receiving antennas

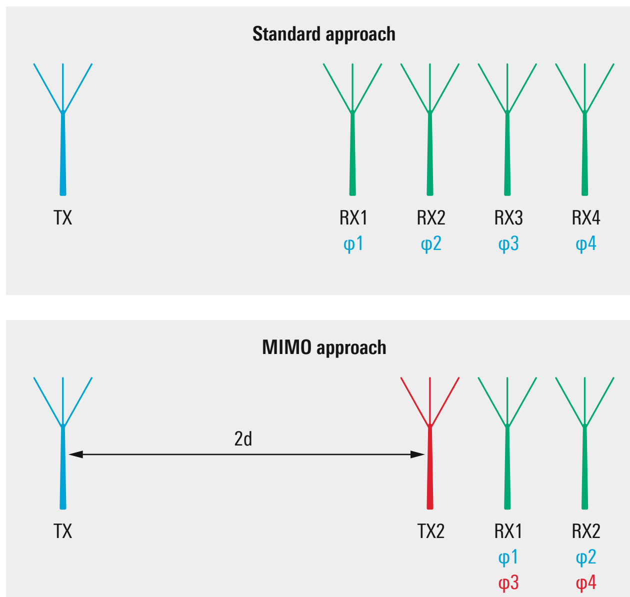


By increasing the number of antenna elements, azimuth resolution becomes possible and the accuracy of the angular measurement improves.

Today many automotive radars apply MIMO radar signal processing to improve angular resolution. Fig. 6 shows a radar frontend with one TX and four RX that are spaced by $\lambda/2$. The total number of antennas, which defines the spatial resolution, is defined by $N\_TX \times M\_RX$ with proper antenna alignment. The upper case shows $1 \times 4 = 4$ elements and the lower case $2 \times 2 = 4$ elements. Hence, the same resolution can be achieved with both arrays. The measured phase differences depend on the TX and RX.

Since TX1 and TX2 are different apart from the receiver array, the phases at the receivers are different. If two transmitters are active, four phases are measured with two receiver antennas [1].

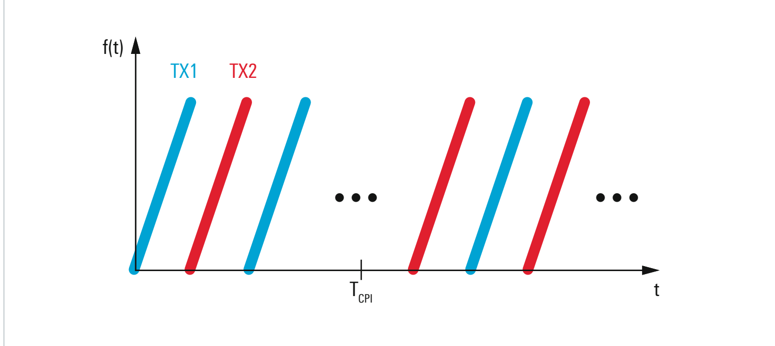
Fig. 6: MIMO Principle



In order for the receivers to distinguish between the various transmitter signals, several different approaches are used:
- Time division multiplex
- Frequency division multiplex
- Code multiplex.

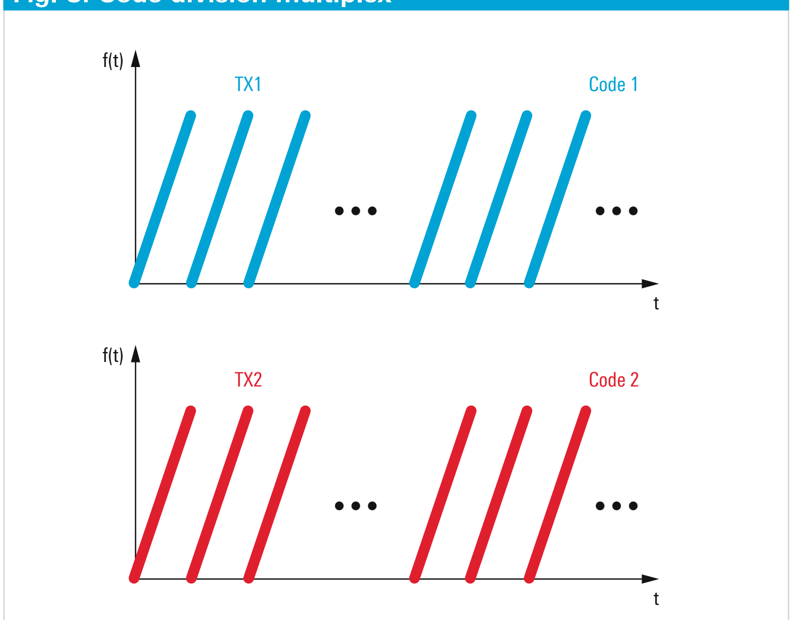
In time division multiplex, each transmitter is active sequentially (Fig. 7). This way, the receivers know the origin of the signal based on its timing.

Fig. 7: Time division multiplex



Alternatively, both transmitters can be active at the same time. In this case, the receivers have to distinguish between the origins of the signal based on orthogonal codes. Such a code can be, for example, a Hadamard sequence as a binary phase code. Due to simultaneous transmission, there is theoretically a signal-to-noise ratio benefit of 10log10(N_TX) in the case of perfect separation.

Fig. 8: Code division multiplex



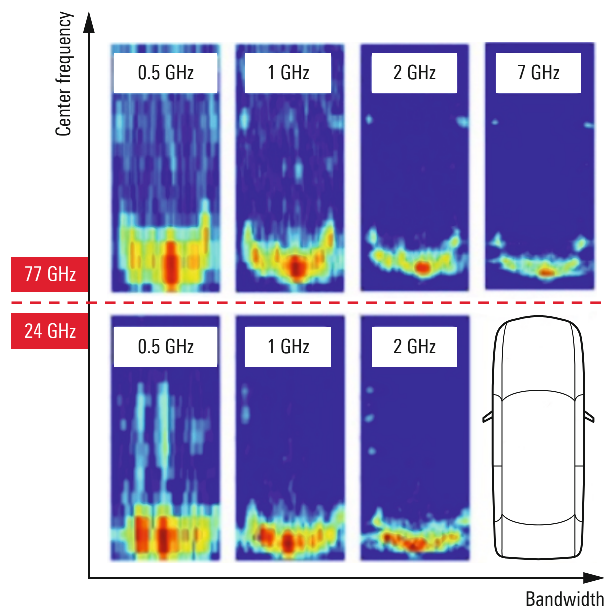
3.3 Radar resolution and why signal bandwidth is required

Depending on the applications that the radar is used in, a low or high range resolution is desired and required.
The range resolution $\Delta R = \frac{c}{2B}$ (B = signal bandwidth and c = speed of light) depends on the signal bandwidth.

The larger the signal bandwidth, the finer the range resolution and the more scatter points of an object of the same size are visible compared to measurements with coarse range resolution (the object gets more defined and can be classified more easily).

Fig. 9 shows the scatter points of a vehicle when measured with different resolutions. While the side mirrors are not visible at 500 MHz range resolution, they become visible at 2 GHz and distinguishable when using 7 GHz resolution.

Fig. 9: Bandwidth requirements for future safety and comfort applications, as demonstrated by Markus Andres, Ulm University



Rohde & Schwarz has been made another high-resolution mmWave measurement with a signal bandwidth of 10 GHz using several thousand transmitting and receiving antennas.

These many transmitting and receiving antennas result in a super high azimuth and elevation resolution, where radar images start to look like pictures (Fig. 10).

Fig. 10: mmWave picture taken by Rohde & Schwarz, frequency 70 GHz to 80 GHz, several thousand transmitting and receiving antennas

Resolution is a key factor and of major interest. Automotive radars operating in urban environments have to distinguish between other cars, vulnerable road users such as pedestrians or cyclists, static poles, houses, edges, cobblestone, etc. Resolution in any domain improves this capability.

The finer the range resolution, the more scatter points of an object can be detected. Increasing the range resolution reduces the maximum unambiguous range.

For example, if the range resolution is very fine, a high signal bandwidth would be required:
- 5 GHz signal bandwidth ▷ ΔR = 3 cm range resolution

If the signal bandwidth is rather low, the range resolution is coarser:
- 150 MHz signal bandwidth ▷ ΔR = 1 m range resolution

3.4 Radial velocity resolution and why high frequencies are favorable

Some applications, such as pedestrian detection, require fine radial velocity resolution. The radial velocity resolution defines the minimum distance in speed that two reflections must have in order to be separated as two. High (fine) radial velocity resolution allows detection of micro-Doppler and separation of slow-moving echoes from ground clutter and own ego-motion (that causes all static targets to appear with their own negative radial velocity).

The radial velocity is measured based on the Doppler frequency shift and therefore depends on the carrier frequency. Higher frequencies have a higher Doppler frequency shift for the same radial velocity. The radial velocity also depends on the time-on-target of a signal, i.e. the duration of the coherent processing interval T_{CPI} according to

$$\Delta v_r = \frac{\lambda}{2} \frac{1}{T_{CPI}} .$$

This formula shows that either a longer T_{CPI} or higher carrier frequency helps improve the radial velocity resolution.

Current regulations allow the use of 24 GHz and the 77 GHz/79 GHz bands for automotive radar applications. According to the formula above, it can be seen that the Doppler frequency shift is about three times higher at 77 GHz than at 24 GHz. That causes the radial velocity resolution to improve by a factor of three for the same coherent processing interval duration.

4 Test and measurement of automotive radar sensors

Automotive radar sensors are to be tested according to the harmonized standard ETSI EN 303 396 [2] as a common base of test procedures, with a focus on:

- **ETSI EN 302 858** [3] for the 24.05 GHz to 24.25 GHz radars
- **ETSI EN 301 091-1** [4] for 76 GHz to 77 GHz radars
- **ETSI EN 302 264** [5] for 77 GHz to 81 GHz radars

In line with EN 303 396 V1.1.0 (2016-04), the tests include measurements of:

- Operating frequency range
- Total power spectral density
- EIRP peak power
- EIRP mean/average power
- EIRP mean spectral density
- Power access duty cycle
- Spectrum access duty cycle
- Dwell time and repetition time
- Frequency modulation range
- Unwanted emissions in the OBB domain
- Receiver spurious emissions
- Receiver in-band, out-of-band and remote band signals handling

The tests above are according to the standard, but during R&D typically many more tests are required:

- Spectrum and signal analysis
- Power measurements
- Radar echo simulation for accuracy, ambiguity, detection performance
- Interference tests to test mitigation algorithms
- Radome tests for integration of the radar sensor behind bumpers
- Antenna pattern verification
- Tracking/software/classification tests
- Receiver sensitivity, saturation, dynamic range

Mass production of these sensors involves additional tests to ensure sensor performance, functionality and accuracy, such as:

- Power consumption
- Antenna pattern calibration
- Accuracy measurements
- End-of-line tests

4.1 ETSI tests

In line with the EN 303 396 standard, several tests are required. For each radar frequency band, another standard applies. For 76 GHz to 77 GHz radars, for example, EN 301 091 is applicable. While the tests are the same for all bands, the limits may be different.

The following table summarizes which test is mandatory for which frequency band and how it can be done. Red indicates that this test is not applicable.

Note:
Although this table is updated regularly, please see the latest version of the ETSI standards to ensure correct testing.

ETSI EN 303 396 Test methods	ETSI EN 302 858 24.05 GHz to 24.25 GHz/24.5 GHz	ETSI EN 302 264 77 GHz to 81 GHz	ETSI EN 301 091-2 76 GHz to 77 GHz
Operating frequency range	specified		
Peak EIRP			
Mean EIRP	not specified		
Mean EIRP spectral density			
Unwanted emissions in the OOB domain			
Unwanted emissions in the spurious domain			
Receiver spurious emissions			
Receiver in-band, out-of-band and remote-band signal handling			
Receiver sensitivity		mentioned but not specified	mentioned but not specified
Power duty cycle			
Spectrum access duty cycle	WLAM only		
Dwell time and repetition time	cat. C/D only		
Frequency modulation range	cat. C/D only		
Unwanted vertical plane transmitter emissions	WLAM only		

Some tests are required for wideband low activity mode (WLAM) radars only.

WLAM radars operate in short and mid-range applications using frequency modulation techniques such as FMCW. WLAM radars have two modes:
- Narrowband regular mode (standard mode) applies up to 200 MHz bandwidth in the 24.05 GHz to 24.25 GHz frequency range
- WLAM mode with up to 450 MHz bandwidth operates in the 24.05 GHz to 24.50 GHz frequency range and is activated only a limited percentage of the operation time

Other tests are specified for 24 GHz radars that fall into categories C and D.

Category C or D radars use the 24.075 GHz to 24.150 GHz frequency range. They apply:
- Fast modulation (≤ 4 µs/40 kHz over 3 ms accumulated dwell time) or
- Slow modulation (≤ 1 ms/40 kHz over 40 ms repeating dwell time) with 20 dBm output power

4.1.1 Test site requirements

Besides the test conditions mentioned in EN 303 396, such as temperature, humidity, voltage control and reference receiver bandwidth, test site requirements are also specified.

For radiated measurements, the norm describes the required distances to ensure far field for the devices under test. If these range lengths cannot be met, far-field uncertainties have to be taken into account as specified in Table 3 chapter 5.3.2 in EN 303 396 V1.1.0.

Far-field distance	Approximate power level error due to near-field effect
d_{FF}	0.25 dB
$d_{FF}/2$	0.9 dB
$d_{FF}/3$	2.0 dB
$d_{FF}/4$	3.5 dB

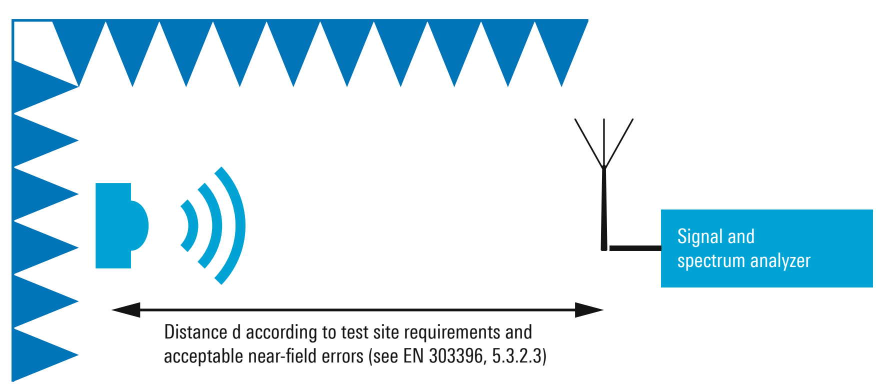
The far field is estimated by $d_{FF} = \dfrac{2(d_1 + d_2)^2}{\lambda}$,

where λ is the wavelength and d_1 and d_2 the transmitting and receiving antenna apertures.

Assuming a radar sensor with an antenna size of 5 cm and a test antenna diameter of 2 cm, this would lead to a far-field distance of 2.5 m. If an anechoic chamber is chosen that is smaller in size and, for example, 2 m high, a near-field effect level error of 0.9 dB would have to be considered.

The maximum allowed measurement uncertainty is 6 dB according to the specification.

Fig. 11: Typical test setup in an anechoic chamber



4.2 Transmitter tests

4.2.1 Operating frequency range

The lowest f_L and highest f_H frequencies occupied by the radar under test (RUT) define the operating frequency range.

The operating frequency range is defined as 99% of the occupied bandwidth. In line with 3GPP TS 34.121 section 5.8, the occupied bandwidth (OBW) is the bandwidth that contains 99% of the total integrated power of the transmitted spectrum centered on the center frequency.

The operating frequency range is measured with a spectrum analyzer configured as follows:

- Frequency range: $< f_L$ to $> f_H$ (e.g. for a 77 GHz radar this could be, for example, 76.5 GHz center frequency and 1.5 GHz SPAN)
- Resolution: 1 MHz
- Video bandwidth: 3 MHz
- Detector mode: RMS
- Display mode: max. hold
- Averaging time: ≥ 1 ms per sweep point

This test can be done with a signal and spectrum analyzer in spectrum mode with the OBW measurement.

Select OBW from the MEAS menu and configure the analyzer to the settings according to your radar specification. After configuring the OBW constraints, set the MARKER to MAX. HOLD trace. The instrument will automatically estimate the occupied bandwidth, the center frequency and the offset.

Example

The figure below shows a measurement example. The absolute power level of this sensor should not be considered at this moment because the test has been done on a benchtop. It is just to demonstrate the OBW measurement. The relative power levels are correct.

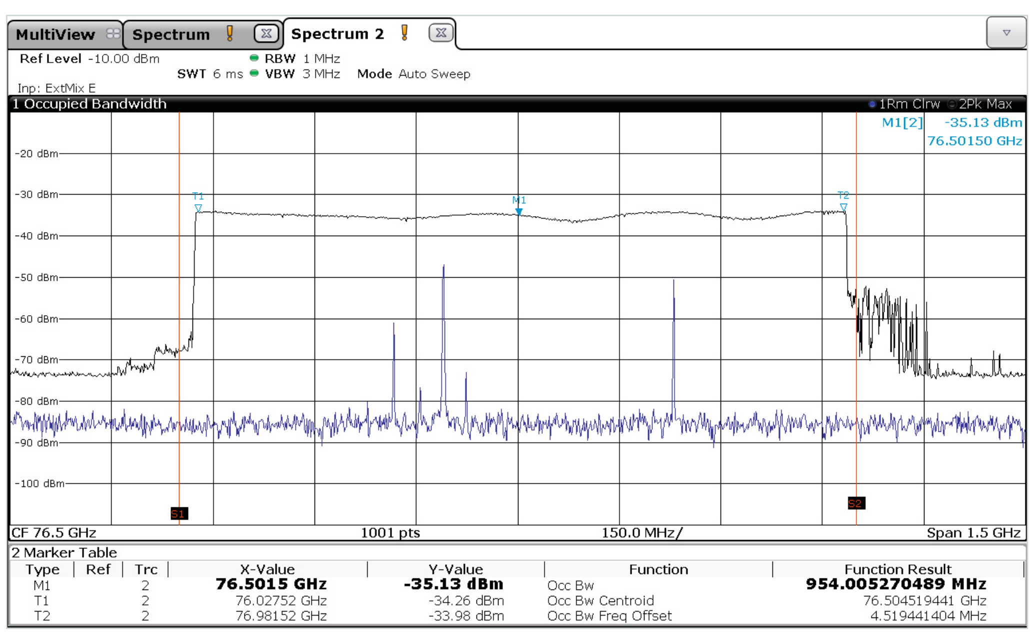


Fig. 12: Example of an OBW measurement on a 77 GHz radar

4.2.2 Total power, peak EIRP and mean (average) EIRP

All power measurements can be done with a signal and spectrum analyzer in spectrum mode and the time domain power measurement or a power meter. In the spectrum analyzer, the time domain power measurement is selected and configured according to the specification that is close to the settings mentioned in the operating frequency range measurement.

One important thing to consider is increasing the RBW depending on the chirp rate of the radar under test. For radars that operate at <1 GHz/ms, an RBW = 1 MHz is recommended.

The sweep time needs to be larger than the cycle time of the radar under test. For this test, the cycle time of the radar must be known.

With the transient analysis application, the transmit signal of the radar under test can be automatically analyzed. The option automatically detects, demodulates and analyzes the duration and chirp rate of chirp and hop signals as well as other parameters.

Example

It should be noted that most radars have several modes and use several different chirps, bandwidths, duty cycles, etc. In this measurement, we consider a single chirp as one cycle.

The following figure shows that the chirp is detected with a spectrum analyzer measurement bandwidth of 490 MHz. We know from the OBW measurement that nearly 1 GHz is used. From the measured chirp rate, the duration of the entire signal can now be calculated (–156.268 kHz/μs) for a 1 GHz signal bandwidth (1 GHz/156.268 kHz/μs = 6.4 ms).

The sweep time of the power measurements should therefore be > 6.4 ms.

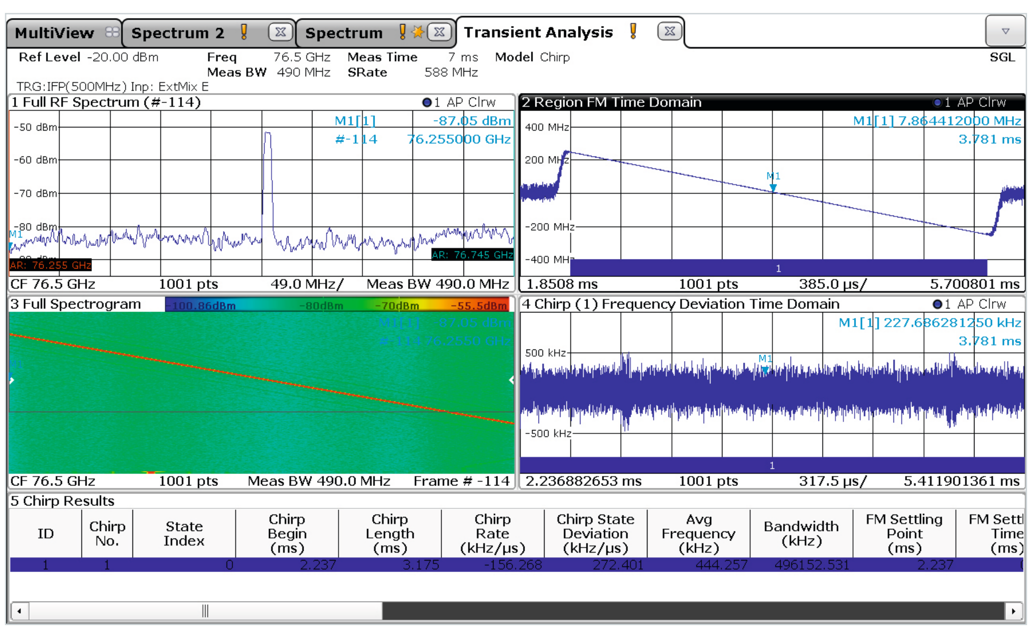


Fig. 13: Example of a chirp sweep time measurement with the R&S®FSW-K60 transient measurement application

4.2.3 Spectrum access duty cycle

The spectrum access duty cycle measurement applies only to WLAM radars in the 24 GHz domain with the limits specified in ETSI EN 302 858 V2.1.1, chapter 4.5.1.3, table 10 and is therefore not further evaluated in this white paper.

For CW radars in the 24 GHz domain or automotive radars in the 77 GHz/79 GHz domain, the spectrum access duty cycle does not need to be measured.

4.2.4 Dwell time and repetition time

In line with the specification, dwell time and repetition time must be within certain limits and apply only for 24 GHz radars in category C or D (see ETSI EN 302 858 V2.1.1, chapter 4.2.1) using fast or slow modulation with 20 dBm output power.

The dwell time describes the time interval for which a certain frequency range is used. There is no applicability for this measurement for radars in the 77 GHz/79 GHz domain.

4.2.5 Frequency modulation range

In line with the specification, this test applies only for 24 GHz radars in category C or D (see ETSI EN 302 858 V2.1.1, chapter 4.2.1).

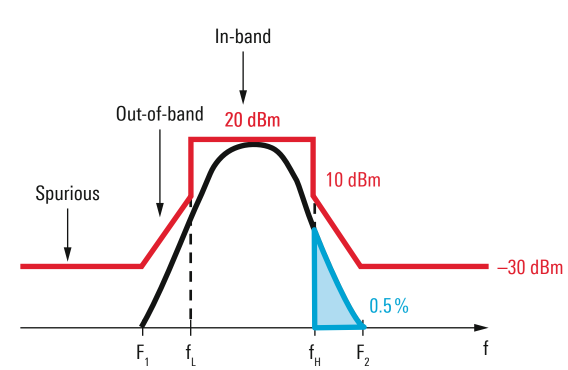
4.2.6 Unwanted emissions in the out-of-band and spurious domain

For 24 GHz radars and WLAM radars, the spectrum has to be within the limits given in Fig. 14.

In line with EN 303 396 V1.1.0, the frequencies F_1 and F_2 are related to the bandwidth:

- Center frequency $f_c = \frac{f_L + f_H}{2}$
- Out-of-band (OOB) lower frequency $F_1 = f_c - (2.5 \times (f_H - f_L))$
- OOB upper frequency $F_2 = f_c + (2.5 \times (f_H - f_L))$

Fig. 14: Spectrum emission mask for 24 GHz and WLAM radars

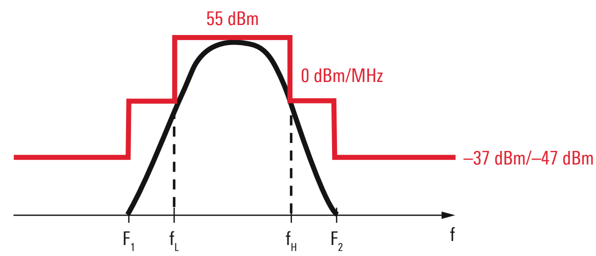


For the f_L = 24.05 GHz to f_H = 24.25 GHz band, this results in:

- Center frequency f_c = 24.125 GHz
- Lower limit F_1 = 23.65 GHz
- Upper limit F_2 = 24.65 GHz

In line with ETSI EN 302 858 V2.1.1, unwanted spurious emission measurements are performed up to 50 GHz for 24 GHz radars. From 1 GHz to 50 GHz, the limit is –30 dBm EIRP RMS.

Fig. 15: Spectrum emission mask for 77 GHz radars



For the f_L = 76 GHz to f_H = 77 GHz band, this results in:

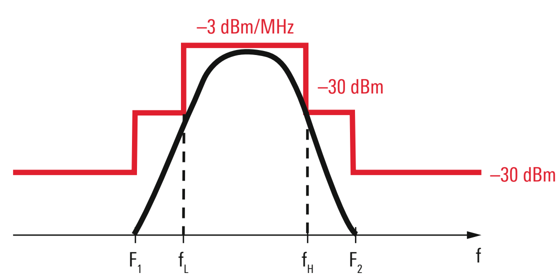
- Center frequency f_c = 76.5 GHz
- Lower limit F_1 = 74 GHz
- Upper limit F_2 = 79 GHz

In line with ETSI EN 301 091 V2.1.1, unwanted spurious emission measurements are performed up to 154 GHz for 77 GHz radars. From 1 GHz to 300 GHz, the limit is –37 dBm EIRP RMS for wideband spurious emissions and –47 dBm EIRP RMS for narrowband spurious emissions.

For the f_L = 77 GHz to f_H = 81 GHz band, this results in:

- Center frequency f_c = 79 GHz
- Lower limit F_1 = 76.5 GHz
- Upper limit F_2 = 81.5 GHz

Fig. 16: Spectrum emission mask for 79 GHz



In line with ETSI EN 302 264 V2.1.1, unwanted spurious emission measurements are performed up to 162 GHz for 79 GHz radars. From 1 GHz to 300 GHz, the limit is –30 dBm EIRP RMS.

A spectrum analyzer is required for the tests. The measurement starts at 30 MHz up to 1 GHz with a resolution bandwidth of 100 kHz (QPK detector) and continues from 1 GHz to 50 GHz with 1 MHz RBW (RMS detector).

The averaging time must be longer than the radar under test cycle time. For details, see ETSI EN 303 396 V1.1.0 chapter 6.3.10.

4.3 Receiver tests

4.3.1 Receiver spurious emissions

Receiver spurious emissions must be tested in a mode other than the transmit mode. This is important because receiver stages, such as low noise amplifiers, can become unstable (tend to oscillate) and cause radiated emissions.

For 76 GHz to 77 GHz radars and 77 GHz to 81 GHz radars, the standards refer to the basic standard EN 303 396, clause 6.2.12. This states that the test applies if the device can be operated in receive-only mode or as a receive-only device.

If your radar also operates in receive-only mode, the test applies and the limits are the same for 77 GHz and 79 GHz radars.

Frequency range	Limit	Detector
30 MHz to 1 GHz	–57 dBm (ERP.)	quasi-peak (QPK)
> 1 GHz to 300 GHz [1)]	–47 dBm (EIRP)	RMS

1) According to CEPT/ETC/REC 74-01, the measurement is required up to the second harmonic, which is 162 GHz for 79 GHz radars and 154 GHz for 77 GHz radars.

A spectrum analyzer or EMI such as the R&S®ESR or R&S®ESW receiver is used. To cover frequency ranges up to 162 GHz, harmonic mixers are required. The harmonic mixer is connected to the spectrum analyzer that drives the local oscillator (LO) and displays and analyzes the received intermediate frequencies (IF).

Rohde & Schwarz harmonic mixers extend the frequency ranges of the spectrum analyzers up to 500 GHz. These tests use harmonic mixers such as the R&S®FS-Z140, which downconverts frequencies from 90 GHz to 140 GHz to IF, and the R&S®FS-Z170 that covers frequency ranges from 110 GHz to 170 GHz.

4.3.2 Receiver in-band, out-of-band and remote-band signal handling

Automotive radar performance is affected by mutual interference. Any interference signal falling into the band of the sensor could be mixed into the baseband domain and pass through the IF filter.

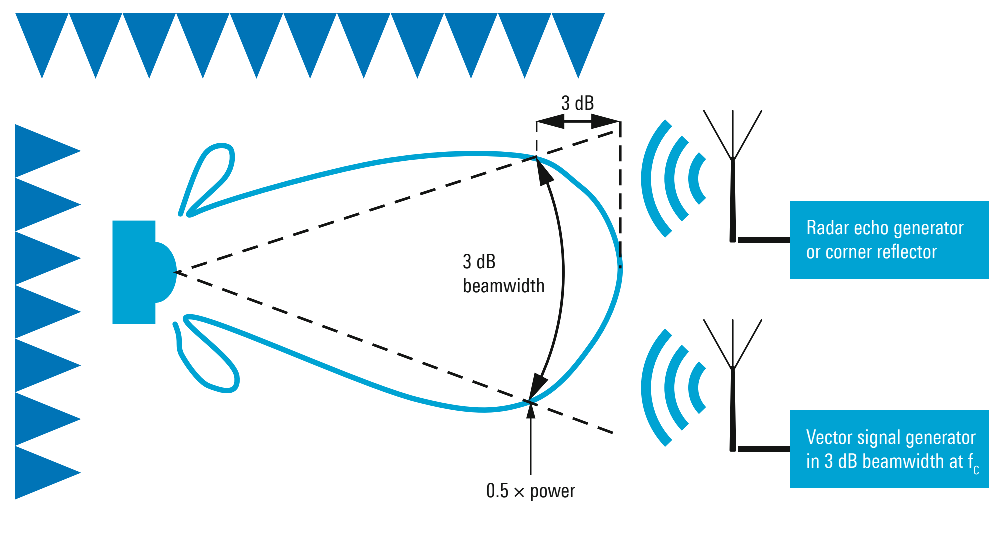
In this case, the radar sensitivity level decreases as the noise power increases, and the targets appear with a lower signal-to-noise ratio than in a non-interferer scenario.

To address this issue, ETSI specifies in-band and out-of-band signals to be applied to the radar under test. This test applies to all automotive radars and verifies that the radar receivers can operate as intended if there are unwanted in-band, out-of-band or remote-band signals.

The test requires a known radar echo signal (target) that can be generated by a corner reflector or an echo generator such as the R&S®AREG100A radar echo generator and an interference signal added to the echo, generated by a vector signal generator such as the R&S®SMW200A.

Although EN 303 396 V1.1.0 states that the position, RCS and distance of the target to the radar is defined in the related harmonized standard, there are no pass/fail values or further description in EN 301 091-1 V2.1.1 or EN 302 264 V2.1.1 or EN 302 858 V2.1.1.

Fig. 17: In-band and remote-band signal handling setup



From a test and measurement perspective, the user should select a target RCS representing a truck (high RCS), a vehicle (medium RCS), and a pedestrian (low RCS) at reasonable distances. In an anechoic chamber, these distances might be below 5 m due to the physical dimensions of the chamber. By using a radar echo generator, these distances can be greater than the physical size of the chamber. The radar echo generator receives the transmit signal of the radar, adds a delay, changes the frequency (Doppler) and attenuates the signal (RCS). In this way, nearly arbitrary ranges and targets can be simulated even in small anechoic chambers.

The unwanted signal source is positioned in the 3 dB beamwidth and configured to operate at the center frequency f_c of the radar under test. Currently, only continuous wave signals (CW) are mentioned in the standard for testing the RUT. The interference signal varies in power level and frequency.

According to many tests, as in the MOSARIM project [6] or described in "Automotive radar sensors must address interference" [7], it might be useful to verify automotive radar sensors against common waveforms and not only CW carriers.

To date, there is no pass/fail criteria for this test. However, it should be appreciated that this test is of high interest for all OEMs and users, and radar designers should implement mitigation and healing algorithms if there is echo signal interference. The test is described in detail in EN 303 396 V1.1.0 chapter 6.3.12.

4.4 Antenna tests

4.4.1 Unwanted vertical plane transmitter emissions

The unwanted vertical plane transmitter emissions describes the radiated power in the elevation direction, where 20 dB attenuation at an elevation of 30° is to be met.

The measurement applies only to WLAM radars in the 24 GHz domain with specific limits in ETSI EN 302 858 V2.1.1, chapter 4.5.1.3, table 10.

4.5 Tests during research and development

4.5.1 Signal quality

The radar transmit signal quality, such as the linearity of the FM slope, affects the accuracy and resolution of the radar sensor. Any unintentional non-linearity in the receive signal that is mixed with the non-linear transmit signal may cause the frequency bin to become broader than expected (compare Fig. 18 and Fig. 19).

Fig. 18: Optimal situation with a linear FMCW

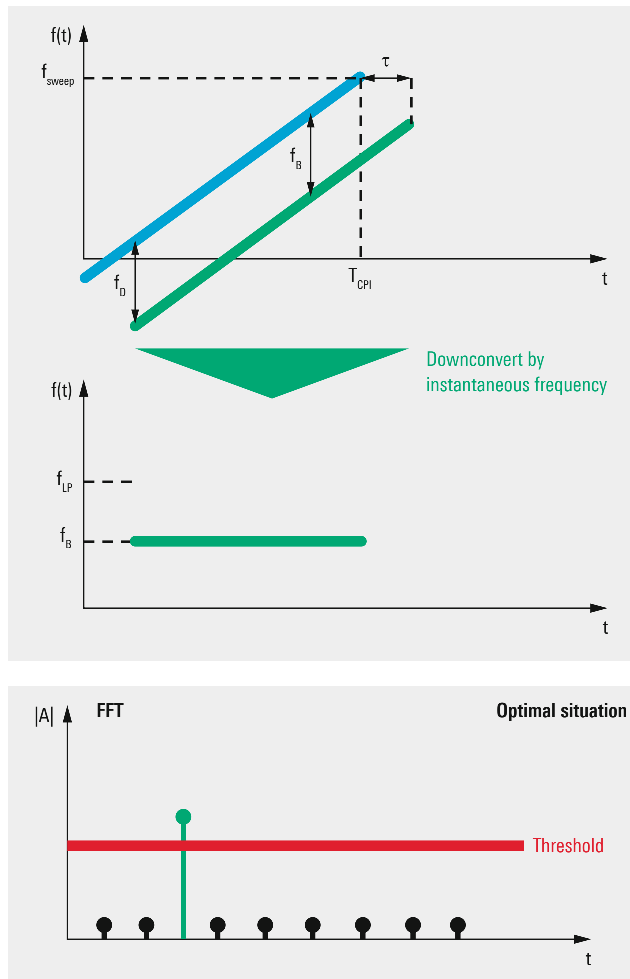


Fig. 18 shows an ideal case in which the transmit signal is linear and therefore the down-converted echo signal appears as a narrow peak in the FFT spectrum.

Fig. 19: Non-linear situation

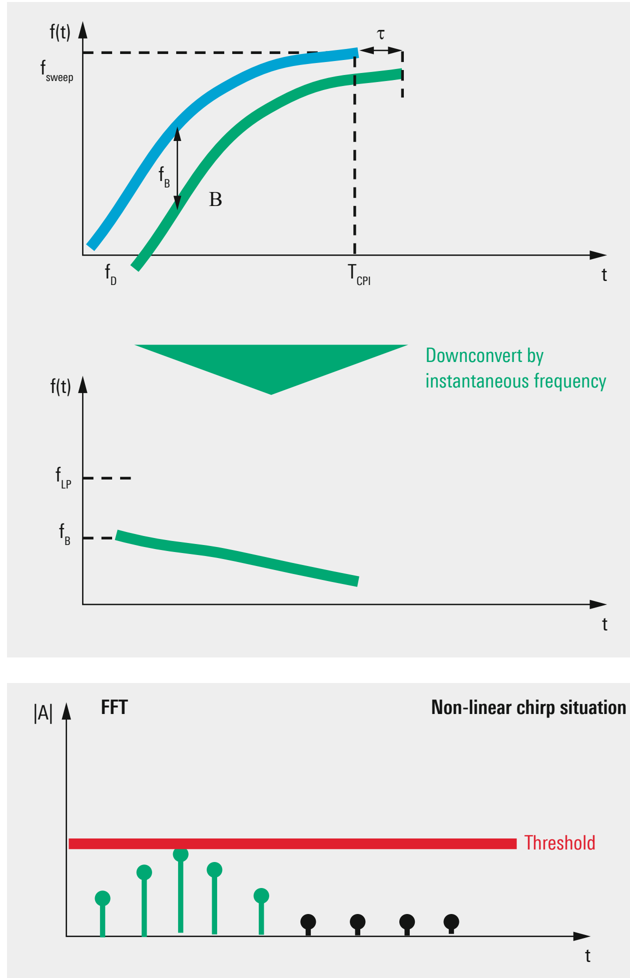


Fig. 19 shows the case where the transmit signal is non-linear. The kind of non-linearity (e.g. saturation and sinusoidal non-linearity), the range of the target echo, the Doppler of the target echo and the slope of the transmit signal define how wide the frequency bin in the FFT spectrum gets.

For example, when saturating at a higher frequency, long range targets are more affected than short range targets because the radar mixes more linear parts with non-linear parts of the signals. This is not the case for close range targets.

Linearity is of great importance for chirp sequence radars, where chirp signals are extremely short. This can be measured with the transient analysis software option of a suitable signal and spectrum analyzer (Fig. 20).

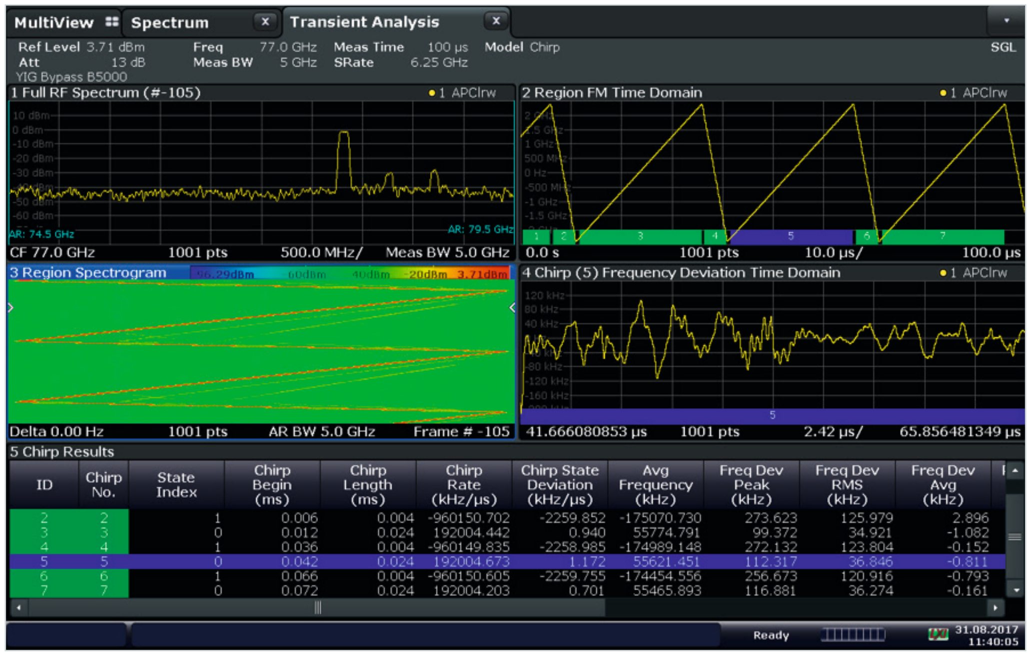


Fig. 20: Transient analysis detecting chirp signals and measuring chirp linearity; measured with the R&S®FSW85 signal and spectrum analyzer and the R&S®FSW-K60 transient analysis option

4.5.2 Antenna pattern measurements

The antenna pattern of the radar under test is important to verify the field of view (FoV) and improve the angular accuracy through calibration.

Typical automotive radar sensors have a FoV of ±5° to ±70° depending on their application. While long range adaptive cruise control radars have a small FoV, blind spot detection radars and cross traffic alert radars need to have a very wide FoV.

Fig. 21: Typical measurement setup

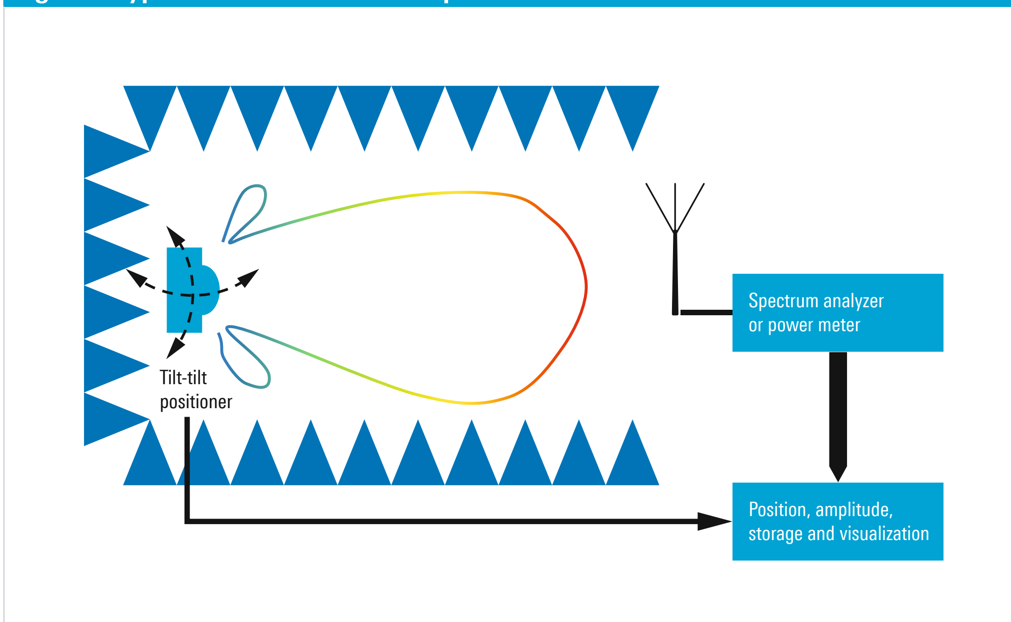


Fig. 21 shows a typical measurement setup in which a radar sensor is mounted on a tilt-tilt positioner inside an anechoic chamber. A spectrum analyzer or a power meter such as the R&S®NRP110T thermal power sensor can be used to measure the emitted power level at each azimuth/elevation position of the RUT.

Automation software can be used to control the instruments, store the measured data, and connect azimuth and elevation position to the measured power level to draw the azimuth pattern.

An example result of a 77 GHz radar sensor measured using an R&S®QuickStep test executive software and an R&S®FSW signal and spectrum analyzer is shown in Fig. 22.

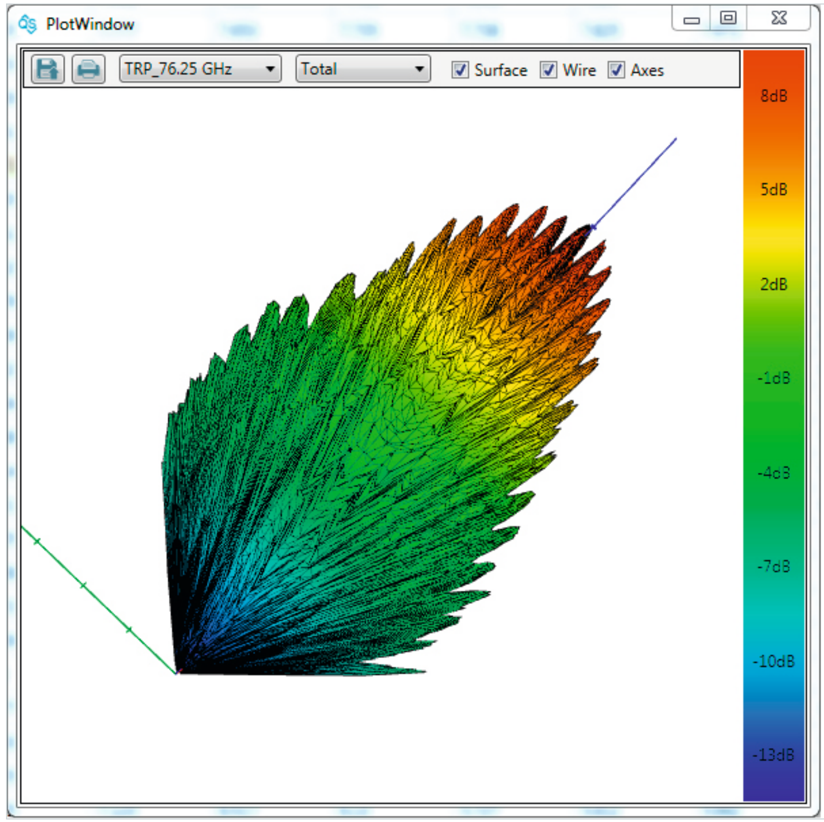


Fig. 22: Example of antenna pattern measurement

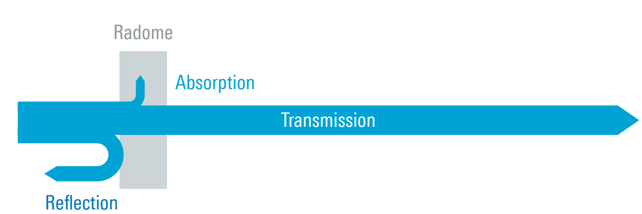
4.6 Integration tests

For reasons related to appearance than functionality, automotive radars are covered by a radar dome (radome) constructed of a material transparent to RF signals. The emblem on the grille is often used for this purpose, but plastic bumpers are also good hiding places for radars. In the past, emblems mainly promoted the brand and had no other significant role. However, their use as radomes now makes them more like RF components. If that is not taken into account in their design, it can have a very adverse impact on the performance and accuracy of the radars behind the emblems.

Therefore, it is of great interest to measure the radome and its impact on radar performance. In the past, differential measurements were conducted in which corner reflectors were mounted in front of the radar at predefined distances and azimuth angles were compared with and without the radome. The radome passed the test if the ranges and azimuth angles determined by the radar and the echo signal levels were within specified limits. However, this method only checks specific azimuth angles, making it easy to miss problem areas in the radome.

For complete testing, it is necessary to measure the reflectivity and the transmission loss of a radome placed in front of a radar sensor (Fig. 23).

Fig. 23: Radome measurements



4.6.1 Reflectivity measurement

The reflectivity measurement quantifies the energy that does not pass through the radome. Reflectivity degrades performance or even impairs correct operation. Certain areas can have higher reflectivity for various reasons, e.g. material defects, air inclusions, unwanted interactions between different material layers or an excessive amount of certain material components.

Reflectivity of a radar signal at a "bad" radome is comparable to a camera that uses a flash behind a window. Due to the high reflectivity of the window, parts of the flash get reflected and injected into the camera sensor, which gets saturated and causes blind spots (compare Fig. 24 and Fig. 25).

Fig. 24: Camera "transmitting" a flash with no window/no reflectivity

Fig. 25: Camera "transmitting" a flash with reflectivity at a "radome" (window)

The same principle holds for radar. A non-optimized radome causes reflection of RF signals and degrades the performance of the radar.

4.6.2 Transmission loss

The transmission loss describes the power level that is absorbed by the radome material. The higher the transmission loss, the lower the maximum range of the radar.

In a measurement, a transmitter unit located behind the RUT sweeps over a selected frequency span. This allows precise assessment of the transmission frequency response of the radome. The frequency response delivers detailed information about the RF matching of the DUT at the exact frequency band intended for radar operation. By using a frequency sweep, the measured information is independent of the actual signal waveform used by the radar unit and is therefore valid for all types of radars that can be installed behind the radome.

For demonstration purposes, a test radome was produced that contains the Rohde & Schwarz logo milled with different thicknesses (Fig. 26). The results of the measurements made with R&S®QAR quality automotive radome tester are shown in Fig. 27.

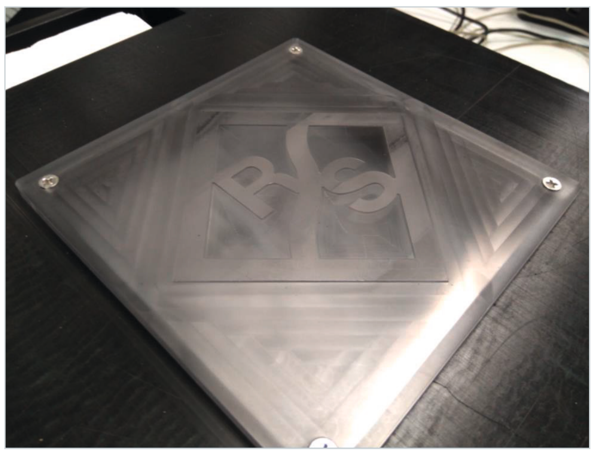


Fig. 26: Photo of the Rohde & Schwarz radome

The high-resolution radar image shows what a radar sensor covered by this radome would see. The brightness levels represent the reflectivity. The brighter an area, the more it reflects the radar signal. Metal objects show up as white (the screws in the four corners). The clearly visible contours of the logo indicate localized high reflectivity and a very non-uniform overall image. The greater thickness of 0.6 mm in the logo area would be sufficient to considerably degrade radar performance on the road.

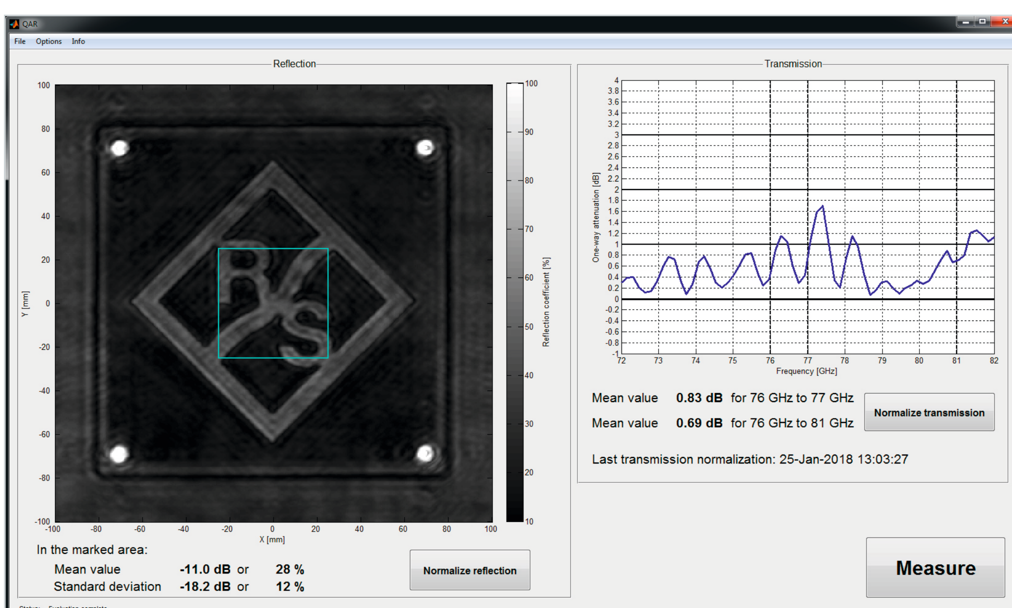


Fig. 27: Reflectivity and transmission loss measurement

In this example, the middle of the radome where the sensor is usually mounted has an average reflectivity of −11.0 dB with a standard deviation of −18.2 dB. In many use scenarios, this is too high to ensure reliable radar operation. In practice, the expected reflectivity depends on the sensitivity of the radar unit and the maximum required detection distance.

The graph in Fig. 27 shows the transmission measurement result for the demo radome. Due to the high waviness between 76 GHz and 79 GHz, this radome would not be suitable for radars in that frequency band. The one-way attenuation of 0.69 dB in the 79 GHz band is reasonable.

4.7 Production tests

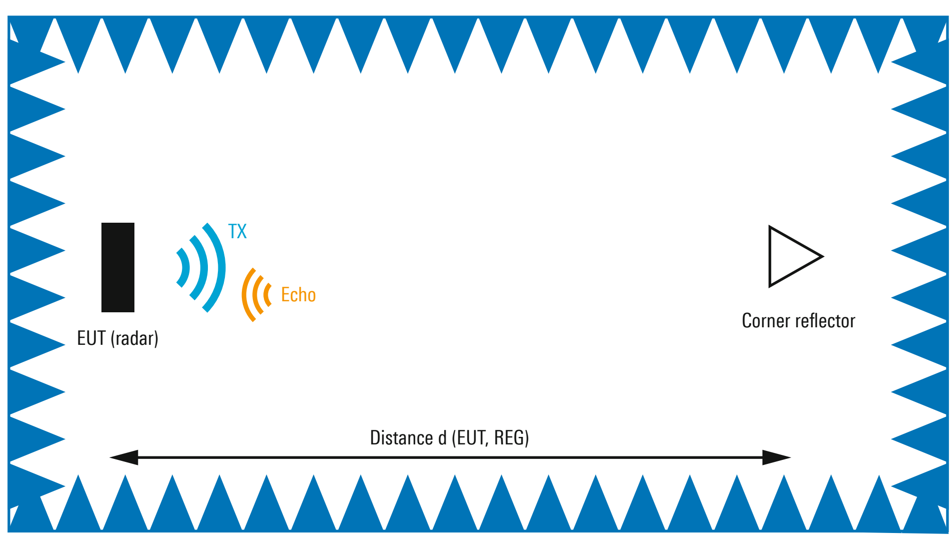
The production process for 77 GHz frontends is not perfectly stable due to high frequencies and varying material parameters. This causes the antenna pattern to vary a little from sensor to sensor.

To ensure a very precise angular measurement, each radar sensor has to be calibrated according to a known reference reflector. Typically, a corner reflector or a radar echo simulator is applied for this purpose. The radar is in normal operation and measures the range and azimuth/elevation of the echo signal and stores the calibration data in the EPROM. This calibration data will be used for later measurements.

To measure the performance of a radar sensor in a reproducible environment with reduced noise, anechoic chambers are used. The radar sensor is mounted within the chamber, which causes radar echo signals to be absorbed by specific absorption material in form of pyramids.

Placing a corner reflector with high RCS at a certain distance, the radar measures the corresponding echo signal at a certain range. Due to the physical size limits of anechoic chambers, the radar can only measure the maximum distance at which the corner reflector can be placed.

Fig. 28: Radar corner reflector inside an anechoic chamber



To measure accuracy at longer ranges, radar echo simulators are applied. This device receives the radar transmit signal, adds delay, Doppler, and changes the RCS before retransmission. Radar echo simulators are dedicated for operation in the automotive radar bands and allow fast functional tests for different ranges and radar signals. Interference mitigation tests, receiver saturation tests and many other tests are also possible.

A major advantage of radar echo generators, such as the R&S®AREG100A, is the reduction of the anechoic chamber footprint.

4.7.1 Near field and far field

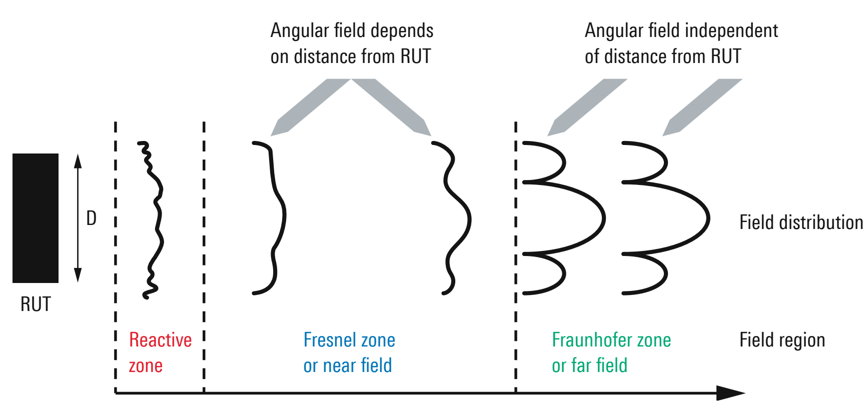
For size reduction, near-field and far-field considerations have to be taken into account (Fig. 29). The Fresnel region is the region up to the far field in which a quadratic phase approximation can be used in the vector potential integral.

In the far field, the radial dependence of electric and magnetic fields varies approximately as: $e^{-iwr/r}$ (dependent only on distance r).

The zones depend on the wavelength and antenna size of the radar under test. Close to the radar and up to $\lambda/2\pi$, the reactive zone is present, which leads to the near-field zone and then the far field starting at approximately $\frac{2D^2}{\lambda}$.

This shows that a radar operating at 77 GHz with 5 cm antenna aperture D would require a distance of approximately 1.3 m to be in the far field according to theory.

Fig. 29: Near-field and far-field considerations



RUT = radar under test

For an automotive radar with 5 cm antenna aperture, the far field starts at a distance of approximately 1.3 m.

5 Automotive radar trends

There are several trends in the automotive radar market. This technology is highly driven by autonomous driving. OEMs push suppliers to increase resolution, accuracy, reliability and performance at lower cost and with a smaller footprint.

Higher frequencies, signal bandwidth and an imaging radar
An imaging radar requires a higher signal bandwidth and many more antennas. Current research is investigating 120 GHz (ISM) and 134 GHz to 141 GHz frequencies. To increase the aperture, many more transceiver units are required and are stacked as a virtual array to increase the number of antennas.

Even higher frequencies are possible because a radiolocation service is available in frequency regulations.

Interference mitigation
To address interference mitigation, frequency hopping, waveform diversity, communication, polarization, transmit beamforming and many more topics are being discussed. In the European Union, several projects between OEMs, Tier1s and chip manufacturers are addressing this topic.

Simulated environments
Test drives are expensive and time-consuming, but soon simulated environments, such as software in the loop (SIL), hardware in the loop (HIL), vehicle in the loop (VIL), will be available to test cars on dynos and on virtual test drives (Fig. 30).

Fig. 30: Research project on virtual test drives

Integration
Integration of sensors becomes difficult as more and more electrical components are implemented in a car. Since space is limited, car manufacturers integrate radar sensors behind bumpers, in mirrors and behind design emblems. These materials cause the radar to behave differently compared to free space radiation.

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7 Abbreviations

PA - parking assist

AVP - automated valet parking

BSD - blind sport detection

RCTA - rear cross traffic alert

AEB - automatic emergency breaking

ACC - adaptive cruise control

RCW - rear collision warning

LCA - lane change assist

FCW - forward collision warning

RUT - radar under test

DUT - device under test

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