Microwave Journal E-BOOK

# Automotive Radar Design Considerations for Autonomous Driving and Safety Systems

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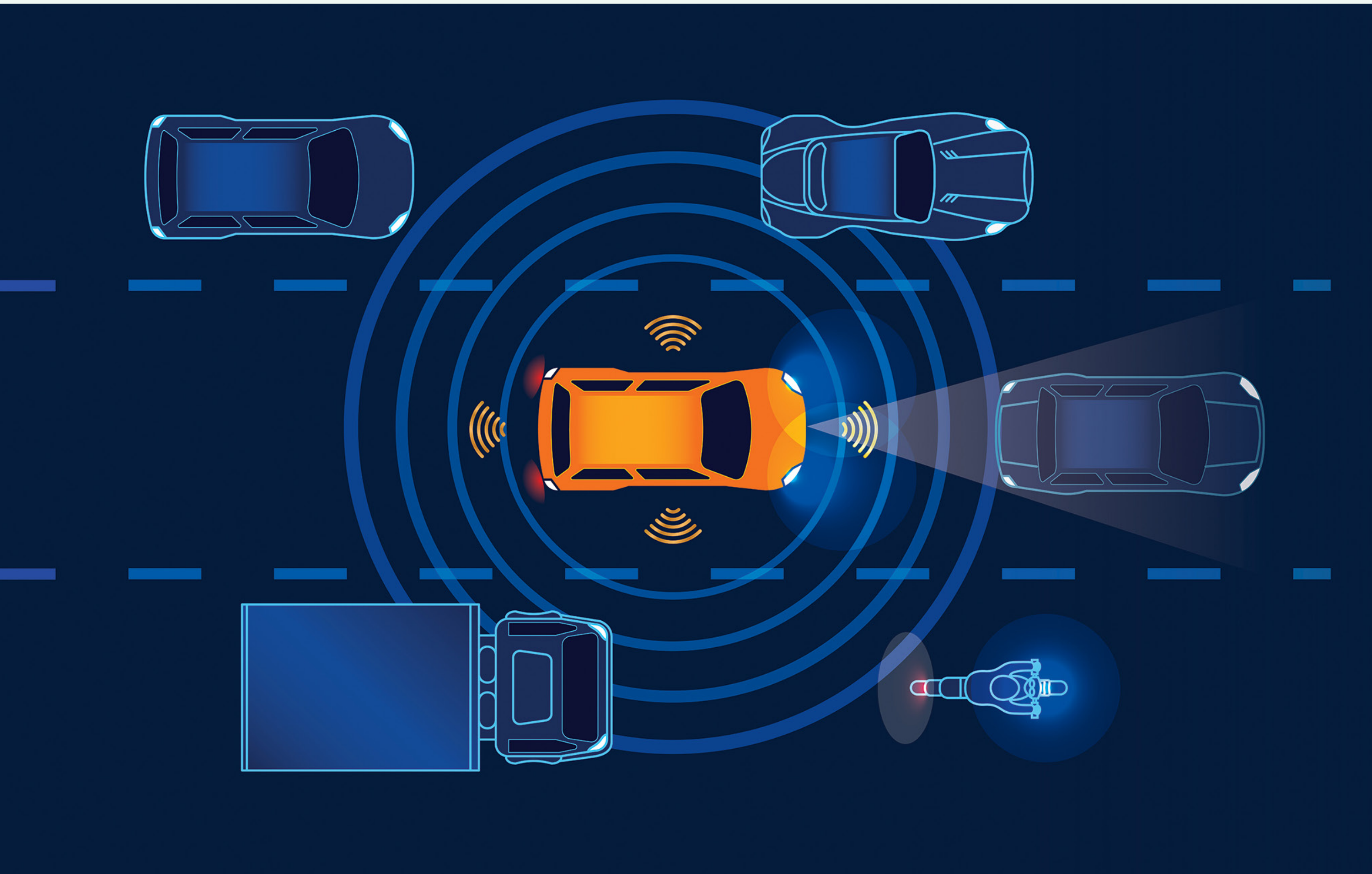

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# Introduction

## Automotive Radar Market is Growing and Evolving

In 2016, twenty major automotive manufacturers (representing more than 99% of the US market) agreed with the NHTSA and IIHS to make automatic emergency braking (AEB) virtually standard on all cars by 2022. By the end of 2017, four of the twenty reported that AEB is standard on more than half of their cars. By 2025, the commitment will prevent 28,000 crashes and 12,000 injuries according to IIHS estimates. AEB and other driver safety and convenience systems are rapidly expanding in all types of vehicles including adaptive cruise control, parking assistance, blind spot detection progressing eventually to partial and fully autonomous driving.

The first automatic cruise control (35 GHz radar) was road tested in 1975 with Mercedes Benz commercializing a 77 GHz system in 1998. By 2014, Delphi had shipped 1 million 77 GHz radar sensors. Today, long range radar sensors (up to 300 m) are targeting the newer 76-81 GHz band using wider bandwidths for improved resolution. Short range radar sensors (<50 m) are typically in the 24 GHz band but are phasing out in some countries so 76-81 GHz might serve both purposes in the future.

Today, vehicles are heading toward full autonomy and radar, along with LIDAR and cameras, will enable that future. Radar is needed in the autonomy sensor group for adverse weather conditions, accurate angular resolution, quick velocity determination, and long range detection (>100 m) where optical based systems perform relatively poorly. Optical systems, however, enable 3D detection, imaging, lane departure and other capabilities where radar is not as good.

As a key sensor in the advanced driver assistance system (ADAS) that is increasingly being demanded on vehicles, the demand for radar sensors is expected to be strong. Technavio's market research analyst predicted that the global automotive radar sensor market will grow at a CAGR of just over 20% between 2017 and 2021 while Yole predicted about 23% CAGR over the similar period (total market value was $2.3 billion in 2016).

According to Technavio, one of the latest developments in the market is the introduction of signal synthesis and receptor isolation techniques, which will drive the implementation of high accuracy and low power radar sensors in the automotive radar sensors market. These techniques include the creation of signal boxes or isolation cubes that can create virtually noise-free environments for radar signal detection by the processing platforms for better radar accuracy. Manufacturers are also developing system-on-chip (SoC) solutions that can incorporate multiple sensors on a single chip to reduce size and cost.

Yole notes that as the radar sensor converges at 76-81 GHz, it will reach new levels of complexity requiring innovation in antennas, modulation techniques and resolution algorithms. New radars will develop 3D detection capabilities for imaging and these efforts are currently underway in several companies. The radar sensor and network will therefore have to process and handle a tremendous amount of data pushing semiconductor and bus technologies. There are also new technologies like using metamaterials being developed by startups that might improve the current radar sensor capabilities. Synthetic aperture radar, micro-Doppler detection and wider bandwidths are technologies that will probably be incorporated into next generation automotive radar sensors.

This eBook is a compilation of recent articles published by *Microwave Journal* on mmWave technology, automotive radar sensor trends and innovation, choosing the right PCB materials and configurations for high frequency automotive radars, the future of automotive radar testing and interference issues that need to be addressed. We hope this will help readers quickly learn about the future possibilities in automotive radar sensors.

*Pat Hindle*, Microwave Journal Editor

# mmWaves Hit the Highway

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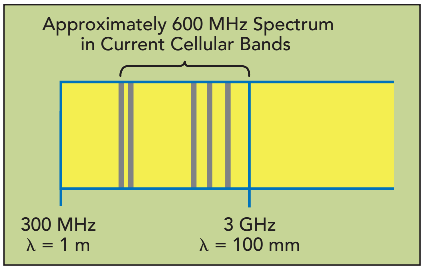
The need for speed and ubiquitous connectivity is a major driver behind today's revolution in MHz to THz technologies. Barely a decade ago, who would have guessed that the world would be trying to connect billions of devices on the Internet and preparing to download a movie in a few seconds to a smartphone? Wireless applications have evolved from point-to-point to broadcast systems to mesh and cellular networks, and now systems with directive networks combining point-to-point and cellular systems are being explored.

mmWave frequencies refer to the electromagnetic spectrum with wavelengths between 1 to 10 mm representing the frequency range between 30 and 300 GHz. There are many innovative applications of mmWave technology being implemented today including telecommunications, wireless communications, automotive, aerospace and defense, imaging, security, medical and other industrial applications. However, in the context of wireless communication and automotive radar sensors, the two fastest growing applications, mmWaves are generally referred to as multiple bands of spectrum in the frequency range of 24 to 86 GHz. This article is focused on the technology and major applications in this frequency range.


The mmWave spectrum has many advantages when compared with lower frequencies, as it is congestion free and has the capacity to move data at speeds of up to 10 Gbps and beyond. Due to its short range, frequency re-use is a big advantage in many use cases. Smaller size components, and particularly antennas, are also an advantage. On the negative side, the transmission distance is typically less than lower frequencies due to higher propagation loss and, presently, is higher in cost.

## GROWTH EXPECTATIONS

The mmWave technology market is expected to grow 10x in the next five years to more than $4 billion.[1] The growth of this market is being propelled by the growth in mobile data traffic and higher usage in small cell backhaul networks. Telecommunications are one of the largest markets for mmWave technology because they have been widely used in small cell backhaul networks. The mmWave backhaul equipment is used as an integral part of the LTE/4G deployments. For 5G, the aggregate data rates are expected to be 1000x more than that of the existing 4G data rates; thus, there will be an even greater need for the mmWave spectrum to provide desired data rates. Over the frequency range from 24 to 86 GHz, the potential bandwidth available is about 20 GHz compared to less than 1 GHz bandwidth available in frequency spectrum below 6



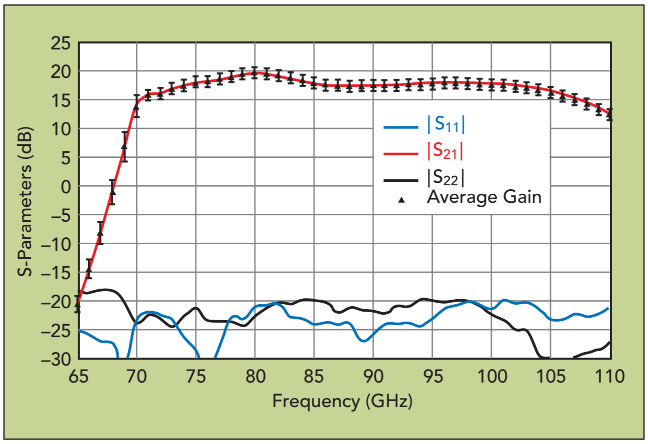

▲ **Fig. 1 Frequency bands available for wireless communications in the U.S.**

GHz. This opens the door to a huge data carrying opportunity (see ***Figure 1***).

mmWave growth in commercial markets started with the need for cellular backhaul in the early 1990s. Long range radio relay links at lower frequencies (1 to 18 GHz) were in use for quite some time, but the need for higher frequency, shorter distance links were necessary with the fast-developing cellular infrastructure. These point-to-point radios used licensed bands of 23, 26 and

▲ **Fig. 2 Microwave Tower, Hamburg, Germany. Photo Credit: Kristof Hamann**

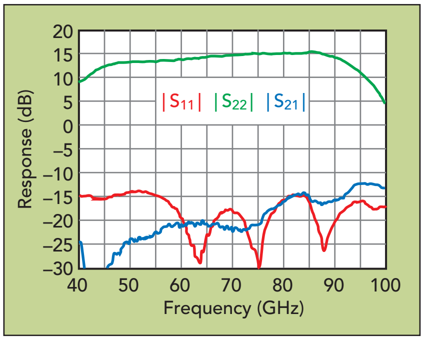
38 GHz (see ***Figure 2***). The range for these radios is less than 10 km and enabled the building of worldwide cell phone infrastructure during rapid deployment phases. These developments happened when RF technology developments were going through an evolution to increased use of MMICs. Higher frequencies were added more recently including unlicensed 57 to 64 GHz band and lightly licensed bands of 71 to 76 and 81 to 86 GHz offering higher bandwidths, increased capacities, smaller size but shorter range. All these bands are presently being used for digital radio links for point-to-point links within and outside the cell phone infrastructure providing multiple Gbps capacities. Fiber optical links are a big player in this application, but mmWave links provide faster implementation and lower cost. Additionally, in many locations fiber is not even an option due to challenging terrain or other issues.




▲ **Fig. 3 HRL GaN power amplifier MMIC 70 to 105 GHz BAL-WPA.**

## SEMICONDUCTOR TECHNOLOGY

Semiconductor technology development over the last two decades is largely responsible for enabling the mmWaves to meet the growing demand for speed, bandwidth and connectivity. The III-V semiconductors have been carrying the load, with GaAs being the first to support mmWave MMIC functions. It continues to be important for providing individual circuit functions but GaN has become a significant player for broadband power applications. InP HEMT/mHEMT are commonly used for low noise niche applications at ultra-high frequencies. InP HBTs also perform well at high frequencies with sufficient breakdown voltages and moderate integration capability. ***Figures 3*** and ***4*** show examples of a high performance mmWave power amplifier and low noise amplifier MMICs op-




▲ **Fig. 4 Analog Devices LNA MMIC GaAs PHEMT 50 to 95 GHz.**

erating in the 50 to 100 GHz band. Recent developments of integrated mmWave transmitters and receivers and new phased array and beamforming techniques are paving the way for the mmWave communications like they did in the military for radar systems.

Operation at mmWave frequencies at reasonable costs is largely the result of the advancements in CMOS and SiGe technologies. Packaging the analog components needed to generate mmWave RF signals, along with the digital hardware necessary to process massive bandwidths, has only been possible in the last decade. Today, transistors made with CMOS and SiGe are fast enough to operate into the range of hundreds of GHz, as shown in ***Table 1***. The SiGe HBT is presently being used in many applications as it is fast and provides high integration, but has low breakdown voltages, which can be overcome by stacking in many cases.

Inexpensive circuit production processes are making system-on-chip (SoC) mmWave radios possible—a complete integration of

**TABLE 1**

**CUTOFF FREQUENCIES FOR VARIOUS SEMICONDUCTOR TECHNOLOGIES**

| Technology | $f_T$ |
|---|---|
| GaAs mHEMT | 1000 GHz |
| GaN HEMT | 300 GHz |
| InP HBT | 500 GHz |
| SiGe HBT | 250 GHz |
| RF CMOS 45 nm | 400 GHz |

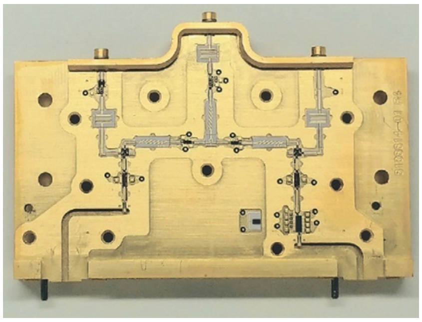


**Fig. 5 E-Band transceiver (courtesy National Instruments).**

all analog and digital radio components onto a single chip. For mmWave communication, the semiconductor industry is ready to produce cost-effective, mass-market products. For demanding applications requiring highly customized performance and low volumes, thin film hybrid technology using ceramic/quartz substrates for filters/power distribution circuits and mmWave MMICs are used in shielded metal housings. These applications include test equipment, satellite communications, back-haul radios and mil-aero applications. ***Figure 5*** shows an E-Band transceiver (without lid) using ceramic substrates and mmWave MMICs.

## AUTOMOTIVE RADARS

### History

Research and development of automotive radars started in the 1970s. Different frequency radars were tested, and in 1989, the World Administrative Radio Conference (WARC) settled on 77 GHz band for this application. It was not until 1998 that a commercial product at 77 GHz was implemented by Mercedes.[2] In 2006, 24 GHz radars were introduced for shorter range applications. While 77 GHz radar was used for obstacle detection and automatic cruise control (ACC), 24 GHz was used for blind spot detection and lane departure warning. A timeline showing the evolution of the automotive radar is shown in ***Figure 6***. As per the National Highway Traffic Safety Administration, 20 U.S. automakers made an agreement last year that all new cars produced starting in September 1, 2022 will be outfitted with automatic emergency braking (AEB) systems.[3] Millions of cars on the road today are already outfitted with radar sensors, as the cost has dropped over the years.

Automotive radar is a key sensor of advanced driver assistance systems (ADAS). Other sensors include light detection and ranging (LiDAR), ultrasonic sensors and camera vision systems. Compared to radar, a LiDAR today offers higher resolution and can build a 3D image of the target. However, it is very expensive and offers limited use in bad weather and at night, plus it covers a shorter range. ***Figure 7*** shows a typical ADAS system consisting of various types of sensors.

The rapid evolution of ADAS is paving the path to fully autonomous vehicles. At one time, ADAS systems, or parts thereof, were the domain of high-end luxury cars. But now, thanks to technology evolution and reduced costs, they are finding their way into mid-range and economy vehicles. Consumer demand for ADAS is high, and governments worldwide are considering benefits of passing laws to make such systems standard equipment in all vehicles. The need for radar sensors is supported by studies that have shown a significant reduction in fatal accidents by using ADAS systems. According to the World Health Organization, more than one million people die every year in traffic accidents. Once ADAS systems are implemented, this number is expected to decline more than 50 percent.

In order to reduce costs and size, automakers would like to integrate multiple ADAS functions onto a single platform that handles data from multiple sensor types. This "sensor fusion," representing the combination of data derived from different sensors, results in a higher level of accuracy and is more comprehensive than would be possible if the sensors were used individually. Fusion sensors, particularly ones combining radar chips and image sensors (cameras), are now becoming available.

### Radar Technology

Automotive radars for ACC and collision avoidance operate over 76 to 77 GHz and are used for Long Range Radar (LRR) up to 300 m, with typical bandwidths between 400 MHz and 1 GHz. Using a linear FMCW modulation, these sensors provide resolu-

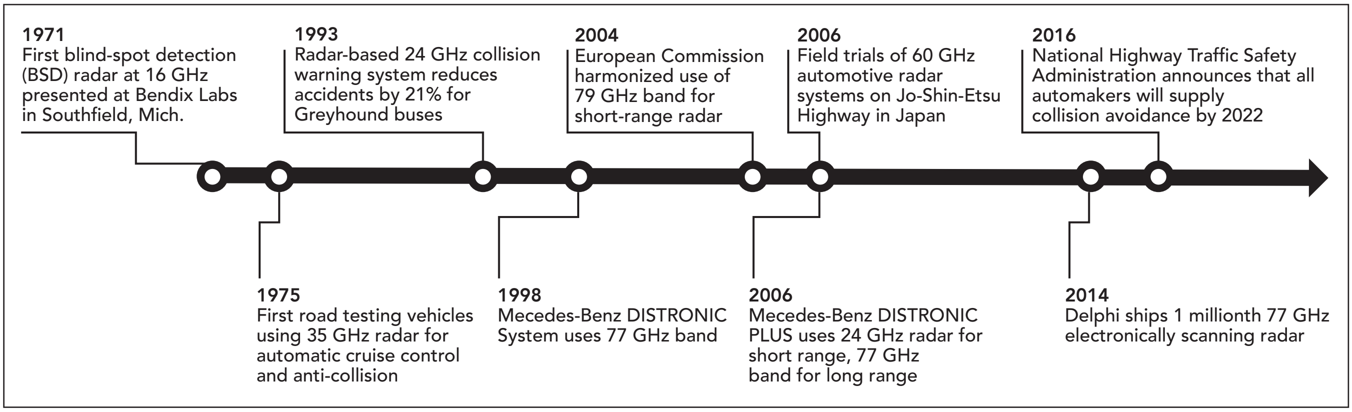
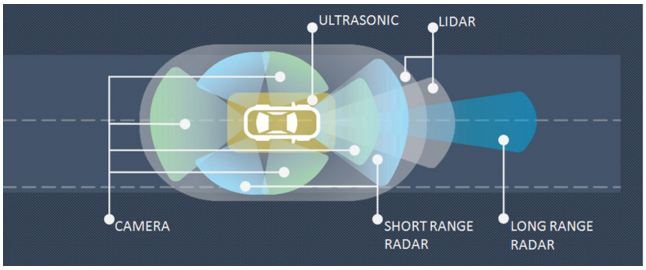


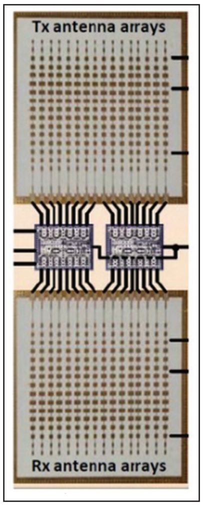

**Fig. 6 Timeline of automotive radar history.**



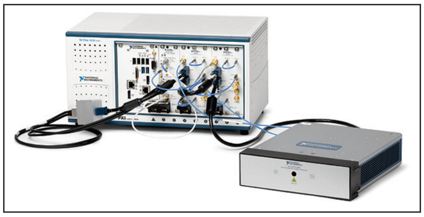

▲ **Fig. 7 Advanced Driver Assistance System sensors.**

tion of about 0.5 m. Until 2010, GaAs PHEMT was the technology typically used for these frequencies. As the technology matured and volumes increased, SiGe MMICs took over as the technology of choice. Presently, RF CMOS using 45 nm or FD SOI 22 nm has advanced to cover this frequency range and is expected to take the lead because of cost advantages and the potential for higher levels of integration.

A new frequency band 76 to 81 GHz has been approved in many countries and is expected to become the long-term solution for automotive radar sensors globally. Using 4 GHz of bandwidth, it has the potential to achieve resolution better than 10 cm. As an example, ***Figure 8*** shows a 75 to 85 GHz, 8Tx/8Rx chip with up/down-converter and built-in self-test (BIST) for automotive radar applications. It was made with the GF8HP 0.12 µm SiGe BiCMOS process (200 GHz $f_T$) and has an area of 26 mm.[2] Receiver gain is 24 dB at 77 GHz and Tx to Rx coupling is an impressive 52 dBc.[4] Over the last few years, several semiconductor companies have released high performance and small size 77 GHz ICs that enable potential use of multiple radar sensors in a car to provide high resolution 360 degrees coverage. Multi-channel ICs providing electronic scanning are also available.




▲ **Fig. 8 SiGe BiCMOS 8Tx/8Rx chip. (Courtesy Gabriel Rebeiz, UCSD)**



▲ **Fig. 9 77 GHz Auto Radar test front-end (courtesy National Instruments).**

The 24 GHz radar sensor covers 24 to 24.25 GHz and is used as Short Range Radar (SRR) for distances to 50 m. It is commonly used for parking aid, blind spot detection and lane change assist. Using linear FMCW modulation, range resolution of 1.5 m can be achieved. Highly integrated transceiver MMICs based on 0.18 µm SiGe technology are commercially available. Millions of 24 GHz sensors are in operation presently and are also used in industrial sensing. It is important to note that in Europe, there is a sunset date in 2018, meaning no new cars will be fitted with these sensors there. This assumes that 76 to 81 GHz sensors will be fully deployed by that time and will cover both SRR and LRR applications.

## Test Challenges

Testing vehicular radar sensors involves target simulation as well as measurement of key RF parameters. Until recently, testing for target distance, speed, angle and size was accomplished in a field using physical obstacles and moving vehicles. With the increasing volumes and technology advancements, it has become possible to simulate the targets and take measurements of EIRP, spectral occupancy, phase noise, antenna beamwidth and chirp analysis. An example is shown in ***Figure 9*** of the National Instruments' Vehicular Radar Test System. A 76 to 77 GHz signal from the radar sensor is received and down-converted to C-Band before feeding a vector signal transceiver (VST) that measures desired parameters. Beamwidth is measured by placing the radar on a calibrated rotor, and signal strength is measured as a function of angle. This will become even more important for autonomous driving as it is difficult to test all the physical scenarios in the field.

Simulation of a target includes simulating distance, speed, angle and size of the target. A down-converted signal uses a hybrid method of passive and active approaches to simulate targets covering the full distance range of 3 to 300 m. Active simulation uses the VST to simulate targets with the help of LabVIEW FPGA-based signal processing. Target distance is simulated by delay, speed (Doppler) by Tx-Rx frequency offset and target size (RCS) by controlling power level. The VST also has capability of adding multiple targets. This system was demonstrated by Konrad at NIWeek 2017.[5]

## Future Directions

There is a high level of activity to develop radar sensor ICs which can provide 4 GHz bandwidth (77 to 81 GHz) to achieve finer resolution. A combination of high resolution based on wide bandwidth and micro-Doppler techniques will provide enhanced performance. 3D imaging radars are gaining interest in the framework of ADAS, and synthetic aperture radar techniques are being investigated for use in automotive radar applications. In terms of modulation schemes, linear FMCW slow single carrier is being replaced by fast chirp single carrier. Advanced modulations like fast chirp FDM and OFDM PCM will be implemented in a phased manner. Frequencies higher than 77 GHz are also being explored for future use.

While ADAS is the enabler for autonomous vehicles, there are other technologies which will need to be integrated to arrive at autonomous vehicles, including vehicle to vehicle (V2V) networking, in-car networking, vehicle to everything (V2X) and satellite navigation. The autonomous vehicle technology has the potential of not only dramatically reducing road fatalities, but also providing a new transportation for the disabled and those who are too old or too young to drive. Governments all over the world are interested in enabling necessary regulations, but there are certainly challenges to overcome. In the

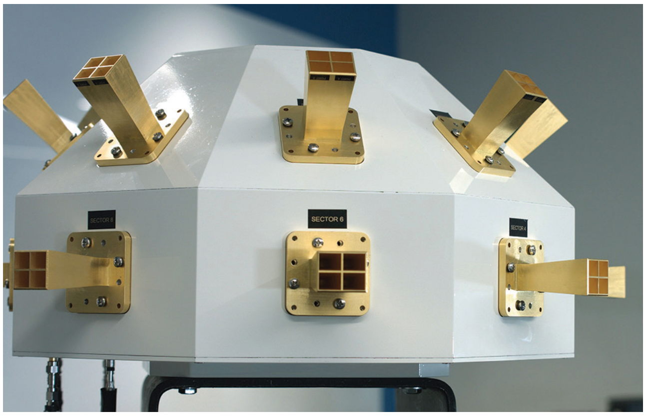


Fig. 10 28 GHz Channel sounder by AT&T and National Instruments (courtesy National Instruments).

U.S., 18 states have passed regulations to allow autonomous vehicles on the roads under certain conditions.

## 5G

The exponential growth of connected "things" and the capacity necessary for intercommunication are fueling the need for speed in wireless communications. From just a few billion "things" connected five years ago, we have already crossed 10 billion devices including hand-held smart devices.[6] This number is expected to double in three years and is expected to continue increasing rapidly due to explosion of the Internet of Things (IoT). Everything from smart homes, cities, cars, pets, sensors, etc. are being connected. Industries including health, energy and transportation are expected to go through an unforeseen revolution due to intercommunication of people and things. The combination of need for high bandwidth data capacity, low latency and an exponential number of connected devices has researchers investigating access networks operating above 6 GHz. Frequencies below 6 GHz have wide area coverage when compared with higher frequencies, and while innovative techniques will be put into action to make more efficient use of this already allocated spectrum, there is a growing need to look for new spectrum bands for 5G that are above 6 GHz.

There are several deployment scenarios for mmWaves as part of 5G access network. These include high capacity backhaul point-to-point radio links, point-to-multipoint Fixed Wireless Access (FWA) and cellular access. Backhaul mmWave applications have provided a commendable service for the 2G, 3G and 4G infrastructure. Commonly used licensed frequency bands include 23, 26, 38 and 60 GHz. 5G deployments are expected to use upgraded links to handle increased data capacities.

While the use of mmWave frequencies is assured in backhaul and FWA, efforts are still on the way to enable its use in cellular access. In order to evaluate the radio environment for mmWaves communication, especially the systems with multiple antennae, channel sounding efforts were started in the last decade. Many research organizations have been studying and experimenting at different frequency bands all over the world. At NIWeek 2015, Nokia and National Instruments demonstrated a 2 x 2 MIMO system at 73 GHz using 2 GHz bandwidth, which provided a 10 Gb/s link over 200 m with better than 1 msec latency.[7] National Instruments also partnered with AT&T to develop a 5G mmWave channel measurement tool. The channel sounder provides real-time channel parameter measurement and monitoring capability. The channel sounder was designed by AT&T and uses an architecture based on National Instruments' 28 GHz Transceiver System shown in ***Figure 10***. This channel sounder captures channel measurements where all the data is acquired and processed in real-time with the capability to take about 6000 measurements in 15 minutes.[8]

The small size of antennas at mmWave frequencies enables the use of multiple antennas in phased arrays and MIMO systems more effectively. MIMO allows a communications system to use spectrum more efficiently by employing spatial multiplexing and beamforming. With spatial multiplexing, a base station uses multiple transmit antennas to beam distinct streams of information to multiple users at the same time using the same spectrum. Now 5G researchers are looking to massively increase the number of spatial streams used in a mobile communications system. Eventually, the 5Ms (**mm**Wave **m**assive **mim**o) are expected to enable the peak performance of these 5G systems. Hybrid beamforming and MIMO systems will provide significantly increased speeds using directive beam configurations compared to previous omni-directional radiations.

Several different frequency bands between 24 and 86 GHz are being considered for this application, with 28 and 39 GHz currently being developed for FWA. The final decision for approved frequency bands for mobility will be taken at the WRC19 meeting of ITU in November 2019. ***Figure 11*** shows various bands available for 5G in different parts of the world.

## FAST Wi-Fi

Wireless Internet implementation started about 20 years ago using the 2.4 GHz frequency band. Wi-Fi standards have so far been limited to 2.4 and 5.8 GHz; however, the performance over time has slowly evolved through 802.11 a/b/g/n/ and more recently, 802.11ac. These standards can effectively cover a large home or estate, using recently released systems with multiple routers as mesh networks. These links have capability to provide data rates of several hundreds of Mbps. The next standard in the series, 802.11ax, is based on multi-user MIMO and is expected to provide more than a Gbps data rates soon.

On the other hand, 802.11ad is a fast lane Wi-Fi system, operating on an unlicensed 57 to 64 GHz band, that is separate from present Wi-Fi standards in use. Using a maximum of 2.16 GHz of bandwidth, it is designed to support data rates up to 7 Gbps. Using a new mmWave frequency band that has limited range reduces interference. 802.11ad covers about 10 m, effectively making it best suited for in-room activities such as: wireless docking station, streaming from a smart device to a smart TV or Chromecast, transferring heavy media files such as 4K footage or raw images and certain

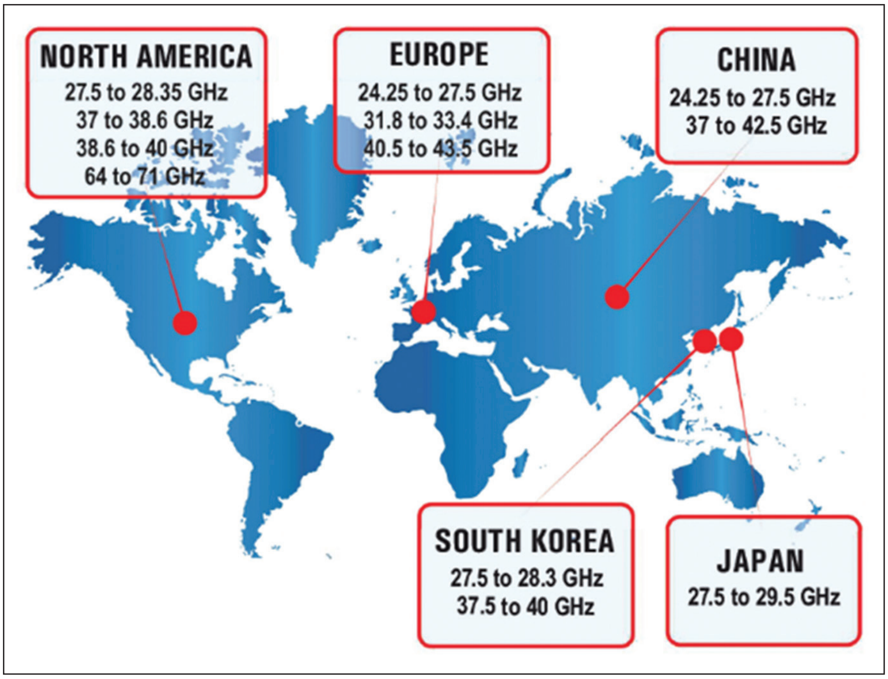



Fig. 11 Frequency bands available for 5G.

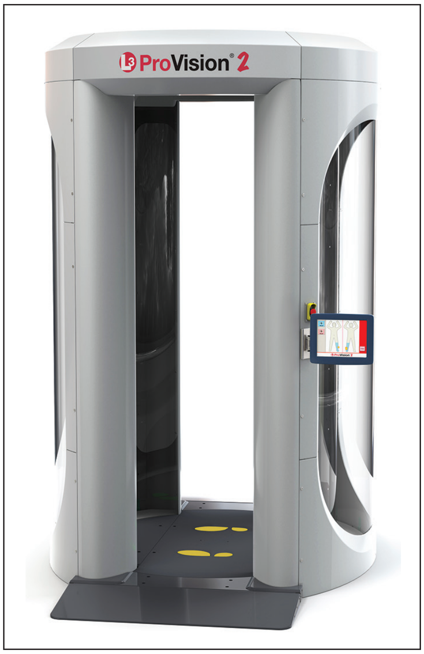



Fig. 13 Millimeter Wave full body scanner by L-3.

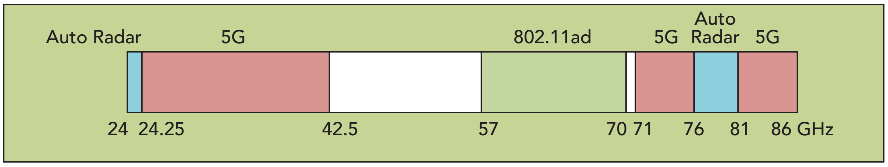



Fig. 12 Frequency bands available in the U.S. for the three major mmWave applications.

gaming applications. This capability is showing up in laptops but has not yet entered the smartphone market.

802.11ay, an extension of the 802.11ad based on channel bonding and MU-MIMO, is in development and is expected to be ready by the end of the year. This standard is expected to ramp up transmission rates from the current 7 Gbps to about 30 to 40 Gbps, and to extend transmission distance from the current 10 m to as far as 300 m. 802.11ay will use 57 to 70 GHz and bond four of 802.11ad channels together for a maximum bandwidth of 8.64 GHz. 802.11ay applications potentially include replacements for Ethernet and other cables within offices or homes, as well as provide backhaul connectivity outside for service providers. The limitation of practical speeds achieved will shift to the infrastructure and ISPs, which will have a harder time keeping up with the new Wi-Fi standards. It is obvious that mmWaves are bound to play a significant role in future Wi-Fi systems requiring moving large amounts of data. ***Figure 12*** shows frequency bands for the three key mmWave applications discussed.

## SECURITY APPLICATIONS

mmWaves are used in various security functions, from wireless fences to intruder sensors to safe full body scanners. Over the last 10 years, mmWave scanners have gradually replaced metal detectors at U.S. airports. These scanners have the capability of detecting metal and non-metal objects on the body, and due to their low power operation, represent a safe scanning method. The mmWave safety standards are power density based and expressed in mW/m$^2$. The power density for a mmWave scan is between 0.00001 and 0.0006 mW/cm$^2$.[9] This type of scanning is thousands of times less than what is permitted for a cell phone. Unlike X-ray scanners, they emit non-ionizing radiation that does not cause cell damage that could result in cancer. Operating between 24 and 30 GHz, mmWave scanners use multiple antenna arrays to transmit and receive high frequency radio waves as they scan the person. The raw data is turned into a hologram that is examined for suspicious objects by algorithms. The holograms are then rendered into 3D figures for inspection. The entire process takes six to eight seconds. For privacy reasons, the algorithms used convert the 3D image to a generic outline of the human body on the computer screen. Presently, mmWave scanners are being used in hundreds of locations in the U.S. and Europe. ***Figure 13*** shows a commonly used mmWave scanner by L-3.

Last year, Rohde & Schwarz introduced a mmWave security scanner operating in the 70 to 80 GHz frequency range that automatically detects potentially dangerous items carried on the body or in clothing. This scanner is being deployed at many airports across Europe for airport security checks. This scanner transmits about 0 dBm power, has an impressive data acquisition time of 32 msec and uses fully electronic scanning.

## MEDICAL APPLICATIONS

mmWaves have shown a great promise for medical applications—continuous wireless monitoring of breathing and heart rate is one of them. Using coherent radar systems, phase shifts associated with small displacements in a human body can be accurately measured. These micro-Doppler features can be used to determine biometric information related to respiration, heartbeats and other subtle motions of the body. This non-contact, remote technique can provide information related to a person's physiological and medical condition. This is useful in maintaining health and timely detection of many health issues. This can enable hospitals to unwire patients who need continuous monitoring.

Many frequencies have been used, including 60, 94 and 228 GHz. In one system by UC Davis using 60 GHz, the mmWave signals were directed to the body and the reflected signal was analyzed for an accurate estimation of breathing and heart rates. Directional beams of mmWave are also used to monitor multiple humans in an indoor space, and can be used to locate individual humans in the room as well. Researchers can measure breathing rates with a mean estimation error of 0.43 bpm and 2 bpm in heart rates. Therefore, the system can locate the human subjects with 98 percent accuracy and is effective in monitoring multiple people in parallel, even behind walls. In another application, a 228 GHz heterodyne radar system has been used to measure respiration and heart rates simultaneously, at distances of up to 10 m. A key advantage to higher frequency systems is the ability to focus the beam and illuminate one subject at these distances, thus reducing clutter and the complexity of the signal.[10]

mmWave imaging can also be used for noninvasive diagnosis, with one of the applications being skin burn injuries. Using 26.5 to 40 GHz, it has been shown that the degree of skin burns can be diagnosed and the healing process monitored without opening the wound. This technique takes advantage of the fact that reflection properties of the healthy tissue are very different from the drier, burned tissue. Similar approaches have been used for diagnosing skin cancer and breast cancer. The dielectric constant of the tumor tissue is approximately 5x greater than that of fat. In one case, a 30 GHz signal with a bandwidth of 20 GHz was used and the reflected signal was analyzed using stepped frequency continuous wave modulation.[11] Wide bandwidth enables high resolution, while the choice of frequency provides adequate penetration in the human tissues for breast imaging applications. The experimental results obtained by employing the prototype in a real scenario show a cross resolution down to 3 mm, with a range resolution of 8 mm and a high dynamic range of about 60 dB by using 35 antennas. The results to date are promising, and they will serve as the baseline for the development of a full breast imaging system.

## CONCLUSION

mmWaves have hit the road—the investments in developing the technology and products are finally paying off, and commercial applications are being released. Once an exotic technology, mmWaves are already used in several applications including short distance links, chip-to-chip connections on board, HDMI video from laptop to screen, fast Wi-Fi, wireless docking stations and automotive radars. Significant efforts are on the way in developing mmWave technology and bringing the cost down to enable continued growth of applications in the mil-aerospace, telecommunications, imaging, security, satellite communications and medical fields. The next decade is expected to see more applications and innovative products in the mmWave frequency ranges to 300 GHz.

Studies and experiments are in place to prove utility of this technology in the cell phone access field. Many propagation studies at 28, 38, 60 and 73 GHz have been carried out with encouraging results. Several challenges remain, and global harmonization of frequency bands needs to be achieved. Acceptance of mmWave bands for cell phone access will potentially provide the final push to get these tiny waves in the hands of billions of people in 5 to 10 years.■

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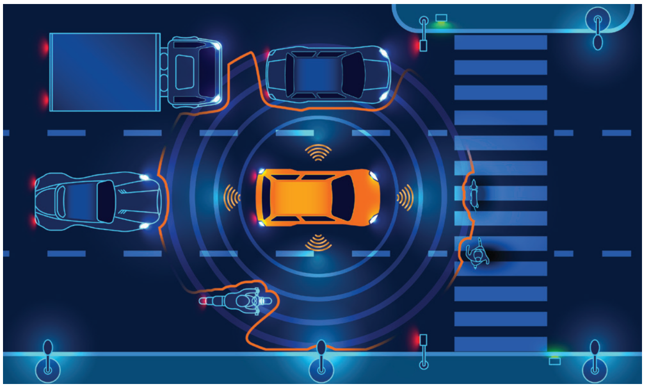
# Automotive Industry: Radar is Part of the ADAS, Autonomous Driving Revolution

Yole Developement

In its latest report, "Radar Technologies for Automotive 2018," Yole Développement (Yole) investigated radar's various evolution trends as well as its ecosystem and supply chain. Yole positions radar as a key technology for automotive sensing, with an increasing penetration rate.

The use of electronic components in automotive is exploding, as OEMs and Tier-1s focus heavily on the ADAS (Advanced Driver Assistance System) to deliver safer cars and reduce road fatalities. Safety bodies like Euro NCAP (Europe New Car Assessment Program) are pushing this way too, encouraging OEMs with high ratings for cars equipped with advanced safety functions such as AEB (automated emergency braking). Applications are still evolving with requirements for highways and cities, road intersection scenarios, and vulnerable road-user detection specific to pedestrians and cyclists. Today's most advanced cars, which currently assist the driver as defined by automation levels 2 and 3, will progressively upgrade to levels 4 and 5, leading to more accurate sensor integration. Numerous sensors have been developed to serve as a car's "eyes", and support automation. The camera sensor is a natural technology of choice for this task, with its object recognition capability. However, it has range limitations (100 m best-case) and struggles to work in adverse weather conditions. Thus, other sensing technologies are required to enable further car automation. Radar technology fills the gap, since it is able to detect objects up to 250 m in front of the car, even in fog and poor visibility. Radar also has an impressive technology roadmap that allows for huge range and angular resolution improvement, as well as device miniaturization and cost reduction. It is also well suited for accurate velocity extraction.



Yole believes radar technology will achieve an outstanding penetration rate in car sensors complementing camera devices. Despite small growth (~3 percent) in global car sales until 2022, Yole Développement expects an average growth rate of 23 percent for radar module sales, and an average growth rate of 22.9 percent for radar chip sales over the next five years--with autonomous driving being the next long-term driver for radar technology growth.

Automotive radar operates at 24 GHz in the unlicensed ISM (industrial-scientificmedical) band for short-range (up to 30 m) applications (blind-spot detection, lane-change assist) and at 77 GHz in the W-Band for long-range (up to 250 m) applications (adaptive cruise control, automated emergency braking). However, this heterogenic approach might generate interference issues with an increasing number of radar-equipped cars, and so a more unified platform called 79 GHz has been proposed, based on the 77 GHz frequency with its 5 GHz of available bandwidth from 76 to 81 GHz. 79 GHz offers other advantages too: it improves radar resolution to enable better target separation, while reducing antenna and high-frequency circuit size.

Based on this new platform, radar architectures will reach a new level of complexity, requiring innovation in antenna design, complex modulation techniques and target-resolution algorithms. Multi-beam, multi-range approaches lead to more complex antenna arrays that multiply transmit-and-receive paths while adding 3D detection capability. Imaging capability, which is the only thing radar lacks, is envisioned too, and radar-based developments for object classification are under way.

To support these stringent requirements, a new chip generation is needed with increasing channel numbers and integration of the analog-to-digital converter, as well as digital signal processing, together with the radar front-end on a single chip. A battle is underway between the well-established SiGe technology and the more recent RFCMOS platform, which is quickly becoming a reality thanks to players like Texas Instruments--which has spent the last decade developing RFCMOS technology.

Innovative startups like Metawave and Uhnder, which propose disruptive technologies for very high-resolution electronic steerable antennas and imaging radar, are competing head-to-head with well-established module makers like Continental and Bosch. Regarding automotive 77 GHz radar chips based on a 130 nm SiGe platform, NXP and Infineon are the top suppliers, with other big semiconductor companies like Texas Instruments and ADI offering products based on advanced CMOS nodes (down to 28 nm).

Foundries are also positioning themselves in this ecosystem. For example, GLOBALFOUNDRIES and its 22FDX platform, TOWERJAZZ and its 180 nm SiGe platform and UMS too. It is exciting to see such a wide diversity of technology offerings, a clear confirmation of the automotive radar market's traction. However, penetrating the automotive market with new technologies is no easy task. On the contrary, entering and maintaining a position in the automotive supply chain is a long, trust-based process.

We are certainly entering a new "radar age," with many developments, disruptive technologies and new entrants positioning this technology as the primary sensor--along with imaging (cameras) for ADAS and autonomous vehicles.■

# Choosing Circuit Materials for the Different Types of Automotive Radars In Advanced Driver Assistance Systems (ADAS)

Ingmar van der Linden
*Advanced Connectivity Solutions, Rogers BVBA, Belgium*

Autonomous, self-driving vehicles may one day create safer roads than present-day highways with motor vehicles and their human drivers. But before drivers start letting go of their steering wheels, a number of electronic functions must become standard equipment in commercial vehicles, including millimeter-wave radar systems, cameras, and/or LIDAR. Radar is probably more closely associated with the battlefield than the highway. But it is steadily becoming a very reliable sensor technology, providing electronic safety functions in modern commercial motor vehicles as part of Advanced Driver Assistance System (ADAS) technology in modern motor vehicles. Millimeter-wave radar systems are a proven technology in the automotive industry, having been used by Mercedes-Benz since 1996 as part of the first active safety functions, such as brake assistance, and commonly used in modern ADAS systems for blind-spot detection and collision-avoidance protection.

Millimeter-wave radars may help make autonomous, self-driving vehicles possible, but they will require the right blend of ingredients, including circuit materials that provide stable foundations for electronic devices and circuits at frequencies to 77 GHz and higher. In an ADAS application, for example, the circuit material must support transmission lines that handle microwave and millimeter-wave signals at 24, 77, and sometime 79 GHz with minimal loss, while delivering consistent, repeatable performance over wide operating temperature ranges. Fortunately, such circuit materials are commercially available, from Rogers Corp., with the consistent performance needed for ADAS applications from microwave frequencies through such high millimeter-wave frequencies.

Vehicular radar systems are used with a number of other technologies as part of a commercial vehicle's ADAS electronic sensing protection (see ***Figure 1***). Radar systems transmit electromagnetic (EM) energy in the form of radio waves and receive reflections of those radio waves from a target, such as another vehicle, and most often multiple targets. Radar systems can extract information about a target that they have illuminated, including its location, range, relative velocity, and its radar cross section (RCS), from those received reflections. The range (R) can be determined based on the speed of light (c) and the round-trip time ($\tau$) required for the radio waves to travel from the radar energy source (a radar transmitter), to the target, and back to the radar energy source which, in a vehicular radar system, is most likely a PCB antenna used for both radar transmission and reception. The value of R can be found by simple math, by dividing the product of the speed of light and the round-trip transit time from the radar signal source to the target and back to the radar source, by two: $R = c\tau/2$.

When multiple radar targets are closely spaced, such as two vehicles in traffic, fine radar range resolution is needed to distinguish between the illuminated objects. This can be accomplished by means of shorter radar pulses to illuminate a target, although

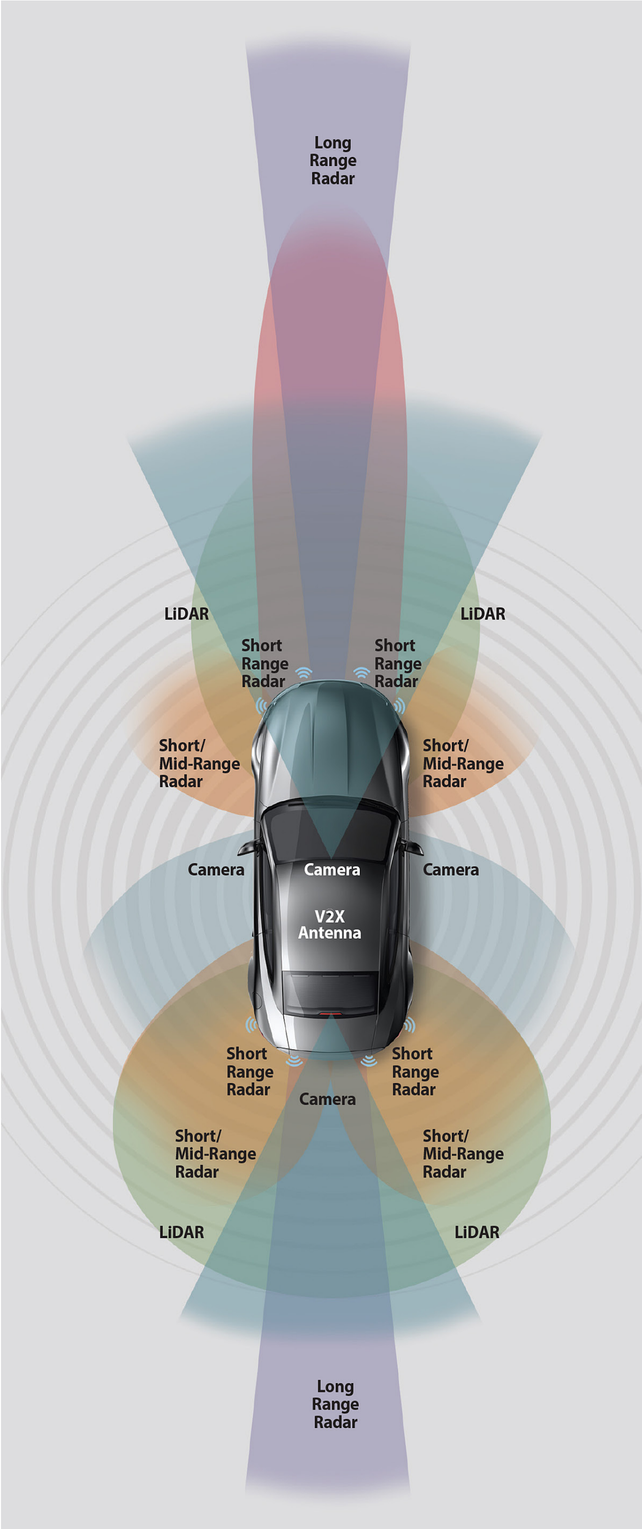



**Fig. 1 Modern vehicles can be equipped with a variety of sensors, including cameras, LiDAR, and radar systems as part of ADAS protection.**

shorter pulses or signals of any kind will have less energy to reflect from a target and back to a radar receiver. More energy can be added to shorter pulses through the use of pulse compression, in which phase or frequency modulation is added to the transmitted radar signals to boost their power levels. For this reason, radars based on frequency-modulated continuous-wave (FMCW) signals (also known as "chirp" signals) are commonly used for vehicular radar systems.

Estimation of a target's velocity can be performed by means of the Doppler Effect, a shift in the frequency of the signal reflected from a radar target based on the motion of the target relative to the motion of the radar transmitter/receiver. The Doppler frequency shift is inversely proportional to wavelength: positive or negative depending on whether the radar target is approaching or moving away, respectively, from the radar source.

An FMCW or chirp radar system can measure the speed, distance, and angles of multiple targets. Both narrowband (NB) and ultrawideband (UWB) FMCW radars have been used at 24 GHz, although the use of that portion of the frequency spectrum for vehicular radar is decreasing. Growing use of NB 77 GHz radar systems with a 1 GHz bandwidth is being made in vehicular safety systems. In addition, the automotive industry is looking at UWB 79-GHz radar for future use. A CW radar is relatively simple and can detect the speed of a target but not its range. A pulsed CW radar can also estimate range using multiple Doppler frequencies. Pulse duration and the pulse repetition frequency (PRF) are two key parameters in designing a dependable pulsed CW radar system.

Due to pulse compression, the range resolution of a FMCW radar is inversely proportional to the bandwidth of the FMCW signal and independent of pulse width. A short-range FMCW radar uses UWB waveforms to measure small distances with high resolution. The Doppler resolution is a function of pulse width and the number of pulses used for the estimation. Clutter in any radar system is noise that results from radar signals reflected by objects other than the target of interest. In any radar system, valid targets must be identified compared to other objects around them that may have been illuminated by the same transmitted radar signals.

Vehicular electronic safety systems employ other physical parameters, such as vision and light, to provide usable data to a vehicle's ADAS domain controller, which performs sensor fusion to help safely guide a vehicle. Front cameras use imaging for lane-departure warnings and object detection, while rear-mounted cameras can provide additional imaging in reverse and as needed. Light detection and ranging (LiDAR) systems transmit pulses of infrared (IR) light to a target, such as another vehicle or the wall in a parking garage, and detect IR pulses returning to the source to calculate the distance between the source and the target based on the speed of light. By using details about the lengths and wavelengths of the IR pulses, and the times required to reflect from an object and return to an IR detector/receiver in the vehicle, calculations can be made about the position and relative motion of IR-illuminated objects. Unfortunately, the performance and effectiveness of vehicular LiDAR systems can be severely degraded by environmental conditions, such as snow, rain, and fog, much more than vehicular radar systems.

Vehicular radar systems operate in the manner of LiDAR systems, but with EM energy at millimeter-wave frequencies and their corresponding small wavelengths.

EM energy is used within specific segments of the frequency spectrum, in particular at 24, 77, and 79 GHz. These are bands of frequencies that have been approved for use by various standards organizations, such as the Federal Communications Commission (FCC, www.fcc.org) in the United States and the European Telecommunications Standards Institute (ETSI, www.etsi.org) in Europe.

At present, a variety of radar configurations are used as parts of ADAS applications, with widespread use of FMCW signals due to their effectiveness in measuring the speeds, distances, and angles of multiple targets. Vehicular radar systems have been designed for some time at 24 GHz, in both NB and UWB configurations. The 24 GHz NB vehicular radar format occupies a 200 MHz span from 24.05 to 24.25 GHz while the 24 GHz UWB format can operate within a total bandwidth of 5 GHz from 21.65 to 26.65 GHz. NB vehicular radar systems at 24 GHz provide effective short-range detection of traffic targets and are used for simple functions like blind spot detection. UWB vehicular radar systems have been used for higher range resolution functions like adaptive-cruise-control (ACC), forward-collision-warning (FCW), and automatic-emergency-braking systems (AEB)

However, as worldwide mobile communications applications continue to consume frequency spectra at "lower" frequencies, including around 24 GHz, vehicular radar systems are moving higher in frequency, to available millimeter-wave frequency spectra with their shorter wavelengths at 77 and 79 GHz. In fact, 24 GHz UWB vehicular radar technology is no longer used in Japan. It is being phased out in Europe and the U.S. according to timetables set by each region's standards organizations, ETSI and the FCC, respectively, and being replaced by higher-frequency, NB 77- and UWB 79-GHz vehicular radar systems as the automotive industry moves to millimeter-wave radar systems in some form as function blocks for autonomous, self-driving vehicles.

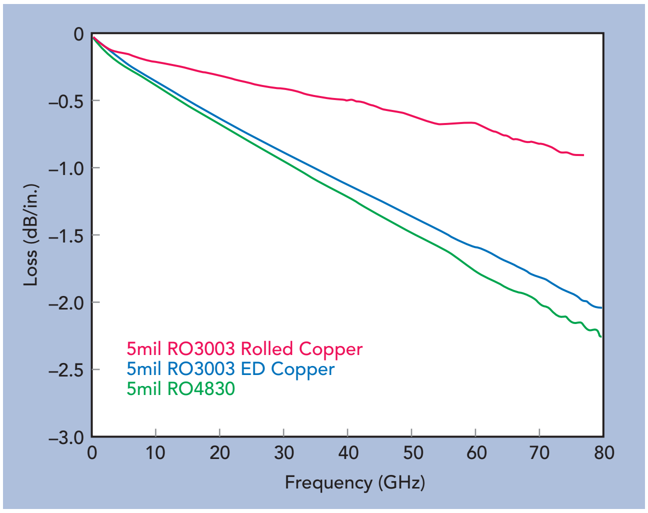
## MATERIAL REQUIREMENTS

Autonomous, self-driving vehicles will employ a number of different electronic technologies for guidance, control, and safety, including sensors using light and EM energy. EM radar signals at millimeter-wave frequencies will make widespread use of a signal-frequency range and circuit technologies once considered exotic, experimental, and perhaps even reserved for military use. The growing use of millimeter-wave vehicular radar technology tracks an overall trend of increasing integration of electronic technology and circuits into motor vehicles, for driver convenience and support, to help make vehicles safer, and to free owners and operators from the "chores" of driving a vehicle. This use of high-frequency electronics in commercial motor vehicles may even trigger a whole new way in which a driver interacts with a vehicle. At the very least, the use of technologies such as millimeter-wave radar will change the definition of "driving" a motor vehicle.

The design of these vehicular, millimeter-wave radar systems usually starts with an antenna, and that antenna is typically a high-performance printed-circuit-board (PCB) antenna, or a number of them mounted in different locations, to transmit and receive low-power milliwatt-level, millimeter-wave signals to detect or "illuminate" a target in the vehicle's operating environment. The vehicular radar and the vehicle's other electronic systems use different electronic methods to provide information about the world around the motor vehicle for use by that vehicle's object detection and classification algorithm.

**Insertion Loss Comparison for 77-79 GHz Laminate Options**

Microstrip insertion loss, differential length method using 5mil and 9.4mil RO4830™ laminate and 5mil RO3003™ laminate.

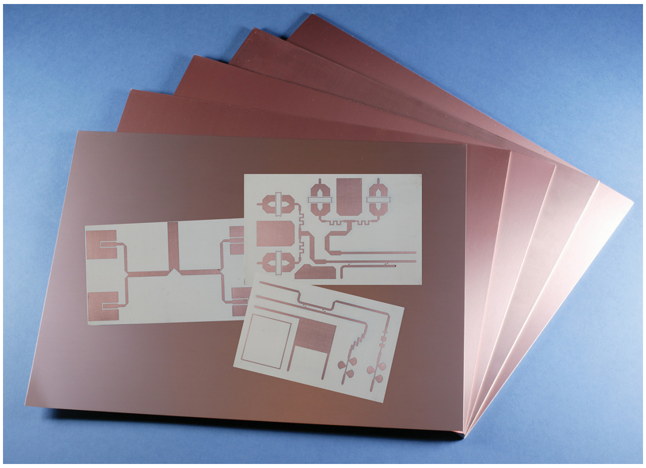



▲ **Fig. 2 Low loss from a circuit material is vital when seeking high gain and directivity from a PCB antenna, especially at millimeter-wave frequencies.**

Vehicular radar's signals may be in pulsed or modulated CW forms. Vehicular radar systems have been produced for some time at 24 GHz for blind-spot detection. However, with time, and with increased competition for frequency spectra for other functions, such as wireless communications, vehicular radar systems are moving higher in frequency, to more narrowband, approximately 1-GHz-wide bands centered at 77 GHz and, eventually, at 79 GHz.

Whether at 24, 77, or 79 GHz, the performance of PCB antennas is vital to these vehicular radar systems, to transmit towards and almost instantaneously receive signals reflected by a target, which most often will be another vehicle. Key PCB antenna performance parameters include gain, directivity, and electrical efficiency, and low circuit material loss is essential for achieving good PCB antenna performance (see ***Figure 2***). These compact antennas and their high-frequency transmitter and receiver circuits must operate continuously (while the vehicle is running) and reliably in one of the more challenging operating environments in electronics: a commercial motor vehicle.

In addition to guidance/warning systems such as radar, LiDAR, and sonar, motor vehicles will use wireless communications with other vehicles to create an electronic sense of the surroundings, such as traffic and obstacles. Such wireless communications will involve



▲ **Fig. 3 RO3003™ circuit laminates feature the characteristics essential for high-performance millimeter-wave PCB antennas for vehicular radars.**


▲ **Fig. 4 RO3003™ circuit laminates exhibit almost negligible changes in Dk with temperature, as evidenced by a TCDk of only -3 ppm/°C.**

PCB antennas and high-frequency circuitry as part of "vehicle-to-everything" or "V2X" communications systems to maintain awareness of other vehicles and traffic around them. This combination of multiple electronic technologies, including communications, LiDAR, and radar, will help form a safety shield around each vehicle and provide its central control computer with the input data needed for a safe, self-driving autonomous vehicle.

Radar technology has an edge over other vehicular electronic safety technologies: It functions effectively in all weather conditions, even in weather in which sound- and light-based ADAS technologies, including video cameras, can be severely degraded. But radar systems, intended for use in autonomous vehicles, require stable, high-performance PCB antennas for transmit and receive functions. Achieving angular and high lateral resolution along with repeatable performance with a PCB antenna, calls for circuit materials with the characteristics that support operation at such high frequencies and in such operating environments.

At millimeter-wave frequencies, candidate circuit materials for high-performance PCB antennas must exhibit low losses with tightly controlled dielectric constant (Dk) across the material and across the changing conditions of a motor vehicle's operating environment, such as temperature and humidity. In addition, circuit materials for vehicular millimeter-wave radar PCB antennas should have smooth copper surface, low dissipation factor (Df), and low moisture absorption.

One of the more popular choices of circuit material for such high-frequency PCB antennas is 5-mil RO3003™ laminate from Rogers Corp. (see ***Figure 3***). It features the tightly controlled dielectric constant (Dk) needed for consistent millimeter-wave circuits, within ±0.04 of 3.00 at 10 GHz.

It also exhibits minimal change in Dk with temperature, as indicated by a quite low temperature coefficient of dielectric constant (TCDk) of only -3 ppm/°C (see ***Figure 4***). RO3003 laminate has the smooth copper surface needed for millimeter-wave circuits, along with low Df of 0.0010 at 10 GHz and moisture absorption of less than 0.04%. In addition, it is fabricated without woven glass, to avoid adverse and inconsistent woven-glass effects at millimeter-wave frequencies.

RO4000® laminates from Rogers Corp. have been well established as reliable circuit materials for 24-GHz vehicular radar sensors and antennas for short-range, blind-spot detection in ADAS applications. The evolution of autonomous, self-driving motor vehicles will involve the use of many different sensor systems within each vehicle, as a form of "system of systems" that coordinates multiple radar systems, sonar, LiDAR, and cameras providing many different electronic "vantage points" about the driving environment for an autonomous vehicle. Lower-frequency, 24 GHz radars have been used for parking-assist functions and shorter-range, pre-crash warnings. Higher-frequency vehicular radar systems, at 77 GHz and, eventually, 79 GHz, will be used for medium-range functions, such as lane-change assistance (LCA), and long-range functions, such as adaptive-cruise-control (ACC), forward collision warning, and automatic-emergency-braking systems. The amount of data generated by autonomous vehicle electronic detection and warning systems will be enormous while the vehicle is moving, requiring significant in-vehicle signal-processing and microprocessor computing power.

Of course, generating and maintaining usable signal levels at such high frequencies has never been trivial. For these higher-frequency millimeter-wave antennas and circuits, RO3000® and RO4000 laminates from Rogers Corp. provide the material characteristics needed to achieve stable and reliable electrical performance at such high frequencies even in vehicular operating environments. Truly autonomous, self-driving vehicles will require some form of electronic detection on all sides, to create a 360-deg. field-of-view electronic detection barrier around the vehicle, in effect, replacing how a human driver would have sensed variables external to the motor vehicle and guide the vehicle according to the detected variables.

Radar is just one of the electronic technologies that will contribute to autonomous, self-driving vehicles of the future. Self-driving vehicles must of necessity be surrounded by sensors of different kinds that contribute to a continuous gathering of environmental data to maintain the safety of the vehicle and its passengers (one of which may be considered the driver). Self-driving vehicles will also rely on a process that has been described as "sensor fusion," to combine the data gathered by the many different sensors into usable intelligence that can be translated into a safe and comfortable ride.

Many miniature multilayer PCB antennas and other sensor circuits will be needed to gather the data required for autonomous, self-driving vehicles, built on stable, low-loss circuit materials such as RO3000, RO4000, and Kappa™ 438 laminates from Rogers Corp. with the performance and stability needed at RF through millimeter-wave frequencies.

The sizes of circuit features shrink with increasing frequencies, becoming quite fine at operating frequencies of 77 and 79 GHz as those signal wavelengths become quite small. Various circuit transmission-line formats are used at those frequencies, including microstrip, stripline, and coplanar-waveguide (CPW) circuits, but the fine circuit features require extremely consistent and predictable circuit materials, such as RO3003™ and RO4830™ laminates. High-frequency circuit materials, such as Rogers RO3003 laminates provide the tightly controlled Dk performance across a circuit board and across changing environments, along with the low dissipation factor (Df) or loss essential for maintaining scarce signal levels at millimeter-wave frequencies. RO4830 thermoset laminates are well suited for price-sensitive millimeter wave applications, such as 76-81 GHz automotive radar sensors, and are a reliable, lower cost alternative to conventional PTFE-based laminates. RO4830 laminates have a dielectric constant of 3.2 at 77 GHz. LoPro® reverse treated copper foil cladding contributes to RO4830 laminates' excellent insertion loss at 77GHz of 2.2 db per inch.

The excellent mechanical and electrical performance levels of the RO3000 and RO4000 circuit materials are backed by RO4400™ bonding materials needed to create consistent, low-loss circuit assemblies through 79 GHz. These unseen but critical circuit materials will provide the repeatable and reliable electrical performance and sensor data that an autonomous vehicle's onboard computer can use to safely return that vehicle to its port of call.

# Hybrid Multilayer PCBs Help Keep Vehicles Safe

John Coonrod
*Rogers Corp., Chandler, Ariz.*

Advanced automotive electronics systems have relied on the reflections from on-board vehicular radar systems for some time. Those radar systems are becoming more common in new car and truck models, helping drivers to avoid collisions with their millimeter-wave reflections at frequencies as high as 77 GHz. The vehicular radars are often fabricated on what are known as hybrid multilayer printed-circuit boards (PCBs). These are PCBs formed of different kinds of circuit-board materials, matching the characteristics of the different materials to the needs of the different circuit functions, from DC through 77 GHz.

Many new drivers will be putting their safety in the hands of a technology—millimeter-wave signals—that they might have considered a bit mysterious a few years ago but that is rapidly becoming an essential electronic function in new-vehicle models. By bouncing short-wavelength signals at 77 GHz off potential "targets" front and rear, a vehicular radar system can provide a warning to a car and its driver for a possible obstruction in the path of the vehicle. To transmit and receive such high-frequency radar pulses, this type of commercial radar system requires PCB material with low loss and high stability, among other outstanding characteristics, such as the RO3003™ circuit laminates from Rogers Corp. with dielectric constant (Dk) of 3.0.

But a vehicular radar system also depends upon many other power and control circuits for proper operation, not just those millimeter-wave radar circuits at 77 GHz. It can perform repeatably and reliably in terms of power and control circuits with materials customarily used for those functions, such as good-quality FR-4 circuit material with high glass transition (Tg) temperature. Combining the various circuits required for an advanced electronic function such as a vehicular radar system leads to hybrid multilayer PCBs that employ circuit materials with the characteristics (and costs) best suited for many of the different functions needed under the modern vehicle hood.

Vehicular collision-avoidance radars are just one application for hybrid multilayer PCBs, of course, using something of a "systems-level" approach to the design and structure of electronic circuits. In many cases, multiple-function circuit designs can be realized as hybrid multilayer PCBs, using the different characteristics of several circuit materials to their greatest advantages. As an example, RO4835™ circuit material from Rogers Corp. provides stable, repeatable RF/microwave performance when used for high-frequency amplifier circuits in wireless base-station applications. It is a high-performance circuit material that is priced accordingly. The material's laboratory-like RF performance is not required for amplifier supporting circuits, such as control and power-supply circuitry. It can make more sense to fabricate those supporting circuits using good FR-4 circuit material. Many wireless base-station amplifiers, such as in 4G LTE wireless infrastructure systems, take advantage of hybrid multilayer circuits to extract the best features from each type of circuit material. They may use a circuit material capable of good high-frequency performance, such as RO4835 laminate, for the RF/microwave circuitry and additional circuit material, such as high-Tg FR-4, for control circuits, power/bias circuits, and ground planes for the amplifier. The different circuit materials combine for a hybrid multilayer circuit that provides the RF electrical performance as needed but at reduced costs because of the substitution of lower-costing circuit materials for non-RF functions.

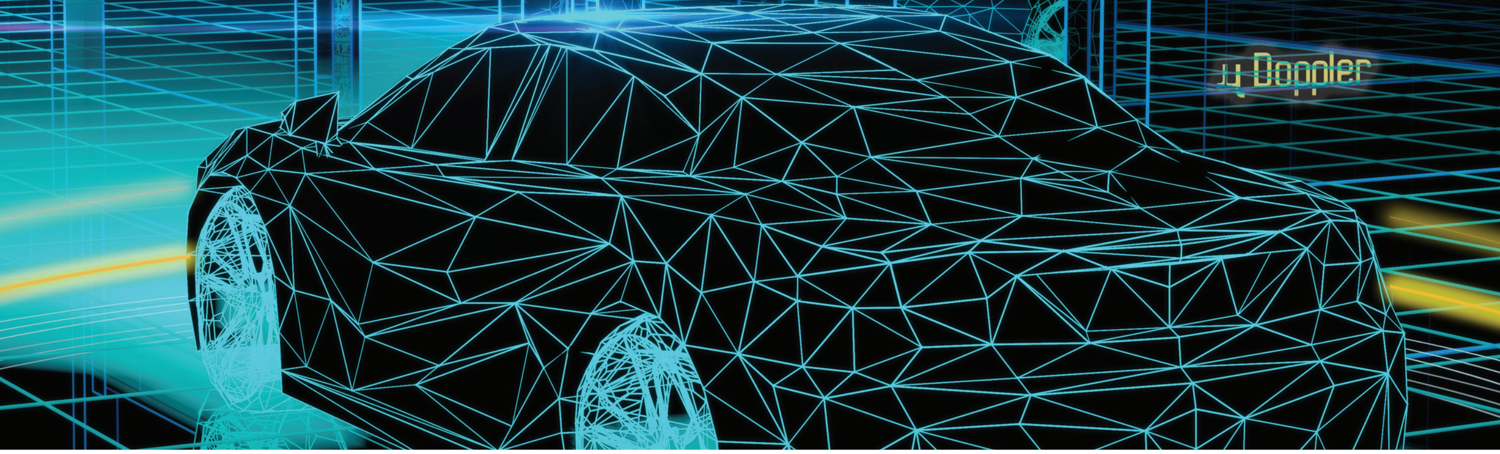
As more and more RF, microwave, and millimeter-wave circuits enter a vehicular operating environment, they face an increasingly hostile thermal operating environment. A material property known as thermal conductivity can make a significant difference in the behavior of circuit materials within that operating environment, especially where it is important to properly dissipate heat while handling significant amounts of electrical power.

A circuit material such as RT/duroid® 5880 laminate from Rogers Corp. features low circuit loss at RF/microwave frequencies for a wide range of applications, with a dissipation factor (Df) of only 0.0009 at 10 GHz. But this may not be the primary material of choice for an electronic circuit application which has thermal management concerns, since its thermal conductivity is only 0.22 W/m-K. However, by using RT/duroid 5880 in a hybrid multilayer PCB with a different circuit material that brings enhanced thermal conductivity to the combination, such as 92ML™ circuit material from Rogers Corp., the "systems-level" approach to circuit design makes it possible to combine the excellent 2.0-W/m-K thermal conductivity of the 92ML circuit material with the extremely low loss of the RT/duroid 5880 at microwave frequencies. The lower losses of the RT/duroid 5880 causes less heat to be generated by an applied RF power source and the overall circuit thermal conductivity is greatly improved by the 92ML materials, which combine to yield a multilayer circuit with significantly improved thermal properties.

This combining of the traits of multiple circuit materials can be advantageous in hybrid multilayer PCBs when balancing good electrical performance, such as low RF loss, with characteristics that may not be so good, such as that material's high coefficient of thermal expansion (CTE). A high CTE will result in a large amount of material expansion with increasing temperature. Such expansion can be a concern for PCB reliability. In a base-station or vehicular operating environment in which a material's excessive CTE may ordinarily limit its use, it is often possible to improve the reliability of that material by combining it in a hybrid multilayer circuit construction with additional circuit materials having better (lower) CTEs.

Similarly, hybrid multilayer circuits can be constructed from different circuit materials, such as RF/microwave materials and FR-4. Differences in CTE values between circuit layers can lead to warping in a hybrid multilayer circuit. But by balancing layers in a multilayer assembly, such as top and bottom, with similar CTE characteristics, warping from CTE disparities can be minimized and manufacturing yields improved, even if the RF/microwave performance of the selected circuit material layers is not required for the functional purposes of those circuit layers.

Hybrid multilayer PCBs offer circuit designers an opportunity for creativity, by using circuit materials, for example with different values of dielectric constant (Dk) to realize a particular electrical function, such as a coupler. By using low-loss, low-Dk materials for some parts of the coupler, and higher-Dk material for other parts of the coupler, its performance and response can be tailored as needed with realistic fabrication tolerances, depending upon frequency and coupling value. In general, the use of hybrid multilayer PCBs allows for a certain amount of re-thinking of many designs, by using circuit material characteristics that best suit a particular design goal.■



*Editor's Note:* Microwave Journal *reached out to three leading test & measurement companies for contributions on the future challenges and solutions for radar sensor testing for automotive safety and autonomous driving applications.*

*Contributions From:*
*National Instruments*
*Rohde & Schwarz*
*Keysight Technologies*

# The Future of Automotive Radar Testing

## The Future of Automotive Radar Testing with Modular Solutions

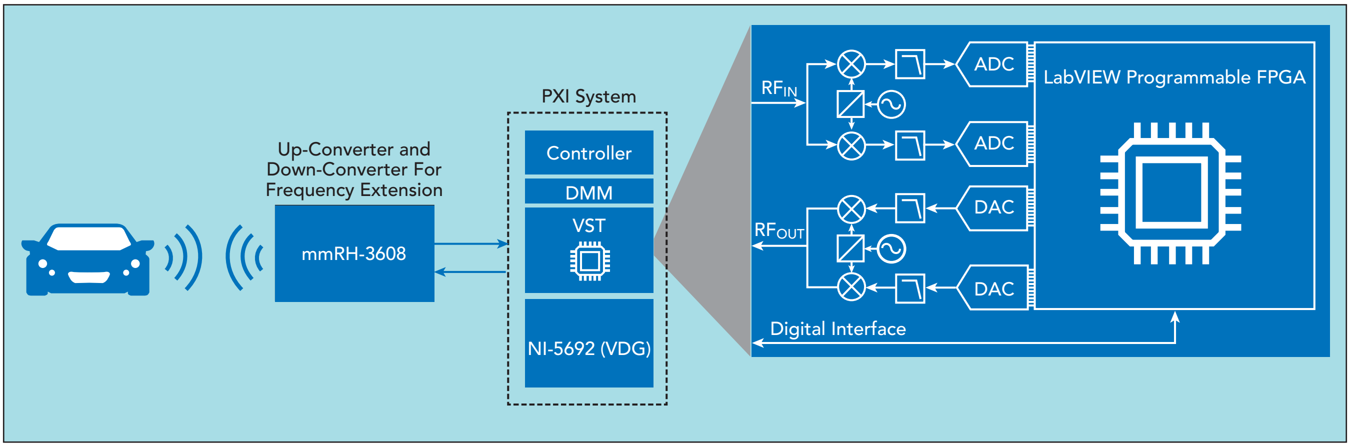
*Matt Spexarth*
*National Instruments*
*Austin, Texas*

Radar has multiple advantages over alternative sensing technologies, securing its role in automotive active safety and autonomous driving well into the future. Radar has the unique abilities to instantaneously detect the velocity of detected objects via the Doppler shift of their radar signatures, and to penetrate inclement weather conditions such as rain, fog and snow. These benefits are driving automakers to adopt radar in increasing numbers. In the U.S., the National Highway Traffic Safety Administration (NHTSA) reached an agreement with 20 automakers, representing more than 99 percent of the U.S. market, to voluntarily equip all production vehicles with Automatic Emergency Braking (AEB) by 2022, a safety feature often enabled by radar.

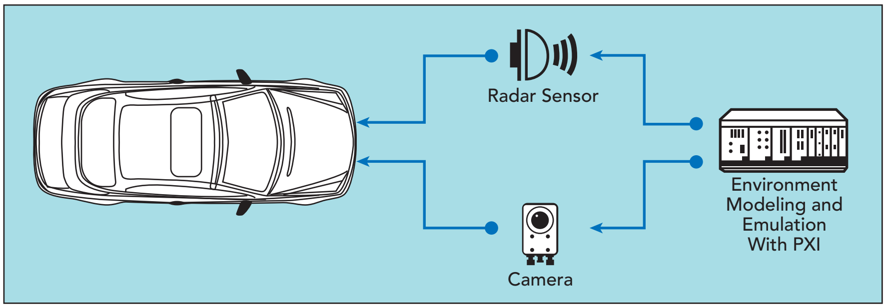
As vehicles evolve from Advanced Driver Assistance Systems (ADAS) to full autonomous driving, sensors such as radar, LIDAR and cameras are the critical input devices that enable the vehicle to accurately sense the environment around it, providing the context needed for the vehicle to make decisions. Future vehicles may include up to eight radar sensors to provide a full 360° surround view of the car.

### Automotive Radar Test Evolution

The growth and advancement in automotive radar has led to several challenges for the test and validation of radar sensors. The first set of challenges center on meeting the increasing technical requirements for testing modern automotive radar while maintaining or lowering the cost of production test. It is typical for a modern radar sensor to require 1 GHz of bandwidth at 76 to 77 GHz and few companies have the expertise to build test systems in this frequency range. Higher bandwidth sensors provide finer resolution, and radar manufacturers have already demonstrated sensors with higher bandwidths approaching 4 GHz with a 79 GHz center frequency making the testing even more challenging.




▲ **Fig. 1 Block diagram of the NI Vehicle Radar Test System.**




▲ **Fig. 2 Validating the software for ADAS and autonomous driving requires synchronized emulation of multiple vehicle sensors so the vehicle "thinks" it is driving in the real world.**

While the technology in future radar sensors continues to improve, the time and cost of testing those sensors must be optimized to meet the price and volume requirements to enable the broad adoption of radar. Early radar sensor manufacturers used large anechoic RF chambers and corner reflectors to functionally test and calibrate modules. These chambers were commonly three or five meters long and consumed large amounts of manufacturing floor space. To reduce floor space, radar functional testing evolved to use analog delay lines to emulate long-distance radar obstacles followed by a second test station to perform parametric measurements of the radar.

Radar functional testing has evolved even further with dedicated systems such as the NI Vehicle Radar Test System (VRTS). The VRTS is a hybrid simulator built with a Vector Signal Transceiver (VST) which integrates an instrument-quality Vector Signal Analyzer with a Vector Signal Generator via a high-performance, low-latency FPGA (see ***Figure 1***). This approach can consolidate a radar module production test cell by combining the functional test (object simulation) and the parametric tests into a single tester. The combination reduces manufacturing floor footprint and eliminates the overhead of transferring radar modules between test stations, improving throughput and freeing up space for additional testers.

Beyond the higher frequency and bandwidth requirements of automotive radar testing, the next challenge of testing future radar sensors is the validation of increasingly complex software built into sensors. A radar sensor with 1 GHz or more of bandwidth produces massive amounts of raw data. To avoid overwhelming the communication buses and ECU of the vehicle, radar sensors include a processor to reduce this data into a summarized snapshot. Periodically, the radar transmits a parameterized object table with a summary of all the objects currently tracked by the sensor. Each object includes a range, velocity, radar cross section (RCS), object ID and confidence (a measure of the radar's confidence that an object exists). The radar's software detects these objects and tracks their real-time movements. Algorithms look for inconsistencies such as an obstacle that is moving away from the sensor but has a Doppler signature that indicates the obstacle is approaching.

In the lab, engineers must validate these algorithms and the software that implements them. In-vehicle field testing of these algorithms is critical, but lab testing with a compact radar test system allows software developers to quickly validate software changes immediately. Combined with mechatronics to move the radar simulator antennas, systems like VRTS can generate standardized radar environments to characterize and validate radar sensor software, including simulating corner case scenarios that would be difficult or dangerous to emulate with drive testing. Lab testing with simulators is critical to maintaining the pace of innovation of automotive radar sensor design.

Within the context of the entire ADAS or autonomous driving system, engineers must also consider radar emulation for system validation test. Increasingly, these systems rely on a combination of sensors, including cameras, LIDAR and radar. Validating the overall performance of an ADAS function, like AEB, increasingly utilizes sensor fusion, the combination of two or more sensors to improve the quality or increase the confidence of obstacle detection. For example, if the ADAS radar sensors "sees" an obstacle but the cameras indicate the path is clear, then the ECU may disregard the radar obstacle as a ghost or interference.

When testing these functions at the system level, engineers need a test platform that can support a wide set of synchronized sensor simulations to emulate the entire sensed environment around the vehicle. Because systems like VRTS are built on PXI-Express, the standard in modular, automated test equipment, engineers can support additional sensors by adding additional PXI modules, such as the NI FlexRIO, to emulate digital camera inputs in sync with the radar emulation (see ***Figure 2***).

Finally, advanced radar modulation techniques will have an impact on the future of automotive radar testing. Frequency Modulated Continuous Wave (FMCW) radar has been the standard bearer for automotive radar. Radar designers are now looking to use MIMO antennas to augment automotive radar capability to accurately detect obstacle elevation or even provide a raster image similar to a camera. Radar sensor researchers are demonstrating higher performance based on modulation schemes that are similar to those that were commonly used in cellular communication. These schemes can channelize the frequency spectrum allocated to automotive radar, enabling MIMO radars to characterize individual radar reflections between parallel Tx and Rx paths.

This approach promises to improve radar resolution and field of view while enhancing the radar's immunity to interference from other vehicles. In response, radar test systems must also grow in sophistication. Accurately emulating an obstacle at the resolution of these imaging radars may require demodulating individual radar channels, applying the obstacle effects of distance, Doppler and RCS for each Tx channel, modulating each channel per the original scheme and reflecting that obstacle back to the sensor—all at the roundtrip speed of light. These requirements will challenge radar test vendors and suppliers, requiring a high bandwidth, low-latency system architecture with extreme signal processing capabilities.

# The Future of Automotive Radar Testing with Radar Echo Generators

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Automotive radar sensors are safety-relevant and have to be comprehensively tested to ensure reliable functioning. As radar performance, functionality and usage increases, test procedures have to become smarter to eliminate millions of kilometers of drive tests. This article addresses today's radar measurement procedures for functional testing and outlines ideas and essential requirements for future test approaches.

As driving automation moves towards autonomy levels 4 and 5, radars are playing a significant role in complementing other sensor platforms to assure practically all-weather 360° vision capability. In many advanced vehicle designs, several radar units are located around the vehicle to complete the field of view and to allow low-range to high-range coverage up to a few hundred meters. At the same time, the semiconductor industry is progressing rapidly towards multi-static radar operation with antenna arrays consisting of tens of transmit and receive antennas. Some manufacturers are migrating to an all-CMOS design or mixed signal SiGe architecture in order to integrate the digital chain into the radar chip. As a result, radar solutions for ADAS functions and later for autonomous driving have become a cost-effective, irreplaceable solution. Additionally, machine-learning techniques are typically used to facilitate the sensor fusion decision-making process for maneuvering the vehicle in real-time on the street. Several worldwide leaders in the digital processing business are working to achieve highly efficient processors adapted to machine learning requirements, for deep learning algorithms for instance. Some processors are based on a GPU architecture, parallelized CPUs or even on dedicated controller units with direct sensor interfaces.

## Automotive Radar Test Challenges

Radar sensors are unique in their ability to measure range, radial velocity, azimuth angle and size of objects by evaluating the echo signals in the observation area in terms of time delay, Doppler shift, angle of arrival and amplitude, respectively. Some modern radar sensors can also estimate the elevation angle and the next generation should provide true measurement of the elevation angle. Determining these parameters simultaneously and in complex multiple object environments, such as intersection scenarios, poses technical challenges for the radar design. To accomplish this, radars need to deliver high-resolution data, a fact that has encouraged many contributors to report on imaging radars or to seek synthetic aperture methods to enhance the radar data. All these requirements place stringent demands on the validation and verification of each radar unit or sensor system to ensure the expected performance.

Due to the increasing complexity and intelligence of radars, it is not sufficient to use direct evaluation of the radar signal quality to judge its performance on the street. Beyond conventional testing of its signal phase noise, Doppler resolution, phase reproducibility, temperature stability, output power, receiver noise figure, chirp slope and linearity, it is becoming necessary to test the function of the complete unit. The influences caused by integrating the radar inside the vehicle itself, e.g. internal reflections of the housing and radome (emblem or bumper) add to this complexity and degrade performance. Consequently, functional testing is becoming a mandatory step for approval by many premium car manufacturers.

## Automotive Radar Solutions

Today, the simplest functional test relies on a corner reflector mounted in front of the radar at a specific reference distance. For a stable and reproducible test environment, a large anechoic chamber, such as the R&S ATS1000, is usually needed to suppress any unknown environmental conditions. While this sounds simple, this setup is actually only capable of testing the detection threshold at a given SNR level for a stationary idealistic target. It is not possible to test Doppler resolution and the dynamic behavior of a target, for example to verify tracking and classification processes. It is therefore essential to have a more realistic setup to mimic real-life situations. It is also necessary to include simulated foreign signals from radars of other moving cars to ensure interference mitigation.

Newer on the market are dedicated radar echo generators, such as the R&S AREG100A, that can manipulate the radar-transmitted signal in real-time in order to impose time delay, Doppler shift and attenuation before retransmitting the captured signal back towards the radar under test. A typical implementation would be receiving the radar RF signal and down-converting it to an intermediate frequency, where a time delay (range), radial velocity (Doppler shift) and attenuation (RCS) are introduced. The manipulated signal is then phase coherently up-converted to the RF and retransmitted to the radar under test. The radar under test receives and processes this modified version of the signal it originally transmitted and reports the detected range, Doppler shift and RCS.

Analog and digital radar echo generators both follow the same concept, but they may manipulate the radar echo signal differently. While analog echo generators use delay lines, e.g., waveguides, coaxial or over fiber optics, in order to delay the signal to a fixed distance, digital solutions have more flexibility in also dynamically changing the range through programmable time delays. A critical parameter in the digital solution is, however, the latency caused by the associated signal processing. Converting the radar waveform from the analog into the digital domain requires at least several digital clock cycles. Since the radar signal propagates at speed of light, each nanosecond of latency would correspond to a distance of approximately 15 cm, which cannot compensated for. While analog radar echo generators are used in verification tests and production lines, digital generators are more often used in research and development and have the potential to test more complex radar scenarios. Single radar echo generators can be used to validate the tracking algorithms for simple radial movements of targets. This would be the case in many Automatic Cruise Control (ACC) scenarios, for instance. To test functions such as lane change assist, the target azimuth angle must be varied and hence the angle of arrival needs to be simulated through the simulator frontend.

## Future Testing Methods

Automotive radar development cycles are decreasing due to the tremendous demand resulting from highly automated driving. Radar performance, functionality and applications are all increasing. As the number of applications grows, the scenarios in which the application and ultimately the radar sensor have to be tested increase accordingly.

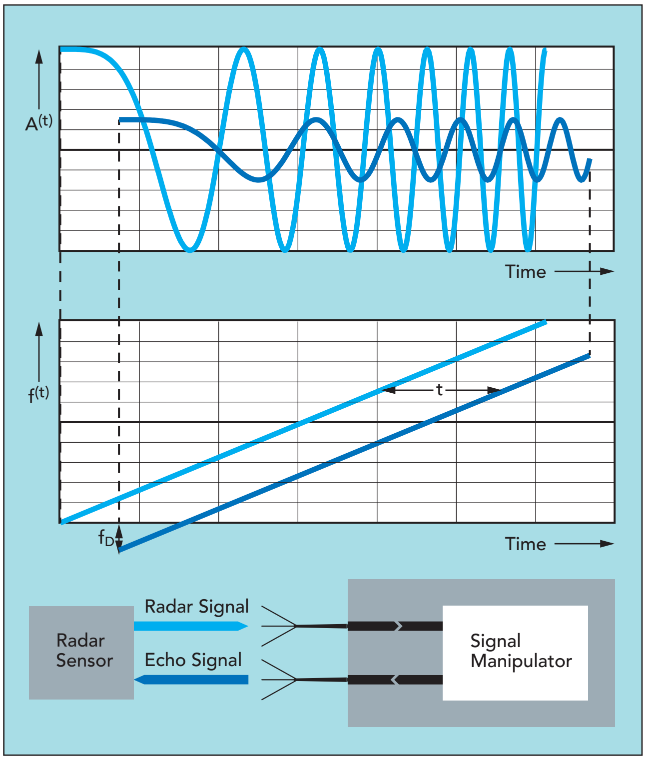


Fig. 3 State-of-the-art radar echo generator principle.

Today, a million test kilometers have to be driven before a function can claim to be validated. Considering all the new sensors and new cars every year, it is impossible to keep up with drive tests. In addition, decision networks that have been trained with data from “older sensors” may not be valid anymore because the training data and classification algorithms depend on the sensor itself. This means, a new sensor requires a new training and test data set, which means another million test kilometers. Since future production cars will be highly automated and fully autonomous, we need to find ways to reduce the required kilometers of drive tests. For legacy cars, vehicle in the loop (VeHIL) test rigs are available. But for newer production cars that rely on radar sensor information, these test rigs have to be updated with additional test equipment.

In many cases, a car on a test rig will not even accelerate before the radar is manipulated. Radar echo generators and simulation of radar sensor echoes via electronic control unit (ECU) interfaces are a good starting point. While software simulation of radar sensors can be comprehensive and fulfill many demands, it does not really replicate the radar’s real-life behavior. Radar echo generators, on the other hand, test the radar and simulate range, Doppler and azimuth. At the present time, however, radar echo generators are not able to generate realistic scenarios for many azimuth and elevation angles that a sensor detects in a normal environment. This is because radar echo generators have a limited number of transmit and receive antennas and therefore cannot simulate a varying angular direction for the radar sensor under test (see ***Figure 3***). As already indicated, this is sufficient for simple functional tests or performance tests such as accuracy, detection threshold

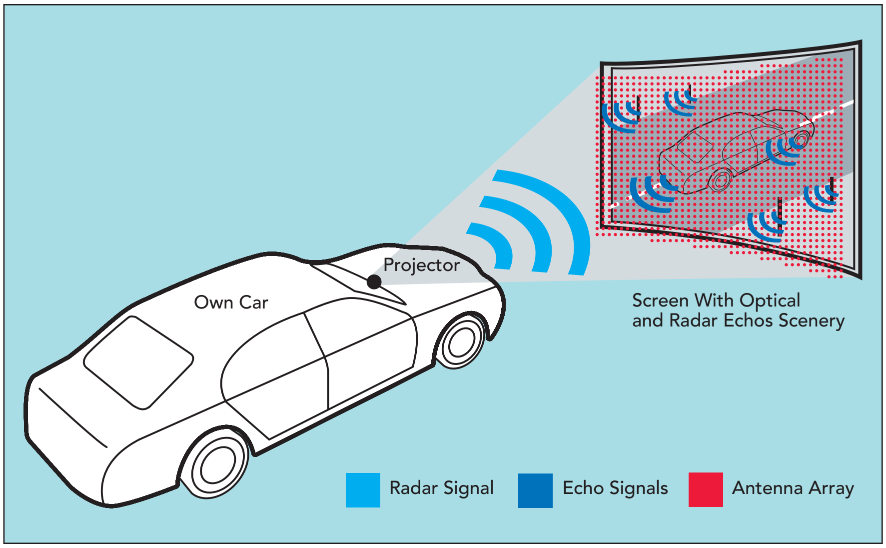


**Fig. 4** Future radar echo generator principle.

or resolution, but definitely not for functional testing of advanced driver assist systems and autonomous vehicles.

A radar echo generator may require hundreds of receivers and emitters to capture, manipulate and retransmit echo signals that are as realistic as typical radar echo signatures. Besides the angular limitation, today's radar echo generators also cannot simulate distributed targets (known as cloud targets). Pedestrians do not appear as a single reflection. They have multiple reflection points and the torso, legs and arms have different velocities. Vehicles do not appear as a single scatter point, but have distributed scatter points in range and azimuth with mainly a single Doppler component. All these requirements have to be taken into account when generating the realistic radar echo signals needed to test tracking, classification and decision processes from a scenario and functional point of view.

***Figure 4*** shows a concept where a radar echo generator consisting of an antenna array is mounted behind a screen. The screen shows a driving scenario, for example a highway scenario, for the camera sensor that supports the driver assist system.

A completely electronically controllable antenna array with thousands of emitters with a digital processing backend could be used to stimulate a radar sensor with complex targets and their maneuvers. The sensor is positioned in front of the measurement system, which receives the radar transmit signal, manipulates the range, Doppler, RCS in real-time and routes the echo signals to a specific antenna inside the antenna array, resulting in an azimuth and elevation angle for the radar under test. The beauty of this modular approach is that the reflection of the echo signal would be just like in real life. Large antenna arrays in this frequency range exist and can be used for radar testing, but there is presently no commercial radar echo generation solution available that can generate complex point cloud targets from such an antenna array.

Testing autonomous vehicles with their increasing amount of radar sensors, different operational modes, and sensor functionalities, will be more complex in future. To address these challenges, radar echo generators with single transmit and receive antennas are a good approach, but do not completely fulfill the requirements of future radar sensors and scenario testing. An antenna array in combination with a digital radar echo generator would have the capabilities to address the needs of testing radar sensors more realistically. Since research and development on autonomous cars, the scenarios to be tested, radar sensors and their fusion with other sensors such as laser scanners and cameras continues, OEMs, Tier 1's and test and measurement manufacturers have to work hand-in-hand to provide solutions for the growing demands.

# The Future of Automotive Radar Testing with Integrated Simulation Software

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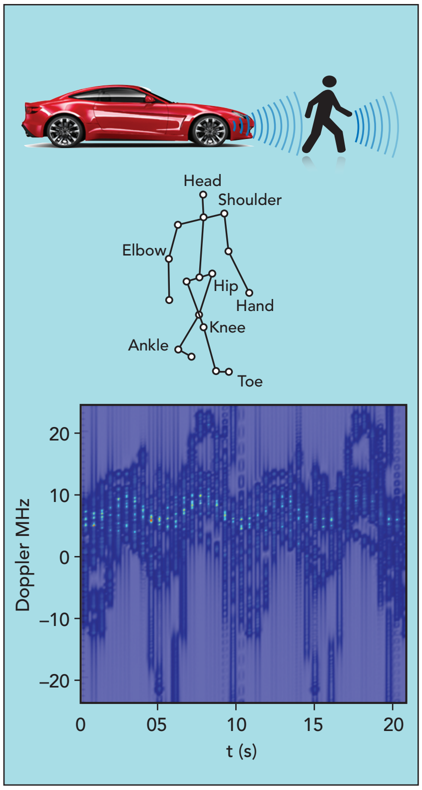
Radar has played important roles in the automotive industry for many years, specifically for safety (emergency automatic braking system, blind spot detection and rear collision protection) and convenience (adaptive cruise control, stop-and-go and parking assistance). Radar's role has since expanded to a higher level of contribution in the industry for autonomous driving systems.

To achieve flawless operation in critical missions, pressure on automotive radar tests has become higher. More complicated design and test solutions are required to characterize higher frequencies (77 and 79 GHz), wider bandwidths (2, 4 GHz and beyond), multi-antennas and other automotive radar technologies like micro-Doppler. Higher performance measurement equipment such as better Displayed Average Noise Level (DANL), higher dynamic range, frequencies up over 100 GHz, 4 GHz and wider bandwidth signal analysis, are helping automotive radar developers achieve their test goals. However, advanced and future automotive radar tests require integrated simulation and measurement solutions with powerful simulation software and high performance test equipment to solve more complicated test challenges.

## Integrated Simulation and Measurement Solutions

Demand for high frequencies and wider bandwidths for automotive radar has continuously grown with the need for better target range resolutions and smaller, lighter sensors. To validate these high frequency and wide bandwidth automotive radar signals, test and measurement companies have introduced high performance signal analysis and generation solutions, such as the Keysight N9041B UXA signal analyzer.




▲ **Fig. 5 Walking passenger trajectory example with visualized micro-Doppler effect in SystemVue Automotive Radar Library.**

In addition to the need for high performance measurement equipment with wide bandwidth mmWave signal characterization capabilities, advanced automotive radar tests require more integrated solutions based on simulation and measurement for faster and more accurate development cycles. For example, multi-scatter target parameterized simulation models are available with the advanced automotive radar simulation software, such as Keysight W1908 SystemVue Automotive Radar Library, to realize and visualize the micro-Doppler effects on the target.

Automotive radar is a critical element of the autonomous driving system—by detecting traffic components around the vehicle, it should also be capable of distinguishing components of urban environments under a complicated scenario with a density of busy traffic from multiple components, including many pedestrians around the environment. Automotive radar with micro-Doppler can separate pedestrians from moving vehicles because when pedestrians are walking or running, they naturally move arms, elbows, hands, knees, toes and other parts of their bodies, which generate different micro-Doppler shifts from their torso. Advanced automotive radar developers will need to simulate and test micro-Doppler to validate their radar to detect slow-moving pedestrians. Considering the large number of complicated test scenarios with automotive radar, micro-Doppler target model simulation and test are quite critical regarding the impact to human lives.

In ***Figure 5***, a walking pedestrian scenario is shown. New software solutions can visualize reflections such as the micro-Doppler signature in the spectrum with different scenarios, such as walking pedestrian, running pedestrian, moving car or even customized trajectory for special scenarios. It also provides >10 scatters for a walking passenger scenario to thoroughly model the micro-Doppler effect with the automotive radar.

After the simulation is complete, developers can generate waveforms and scenarios using test equipment, such as Arbitrary Waveform Generators (AWG), to directly create the signals from simulations as well as post-processed signals captured from test equipment, which accelerate the product development cycle from simulation to prototyping. As technologies used for automotive radar are becoming more complicated, this collaborative simulation software and measurement equipment solution will solve advanced and future radar tests like micro-Doppler.

## Why Arbitrary Waveform Generators?

As wider bandwidth testing is critical for advanced and future automotive radar, AWGs now play multiple roles in the testing process. AWGs can generate extremely wide modulation bandwidth, for example, from DC to 32 GHz, which enables engineers to discern targets even if they are close together. Since waveform generation in AWGs is digital, they can generate multiple signals—at different frequencies and at the same time (see ***Figure 6***). This allows a realistic simulation of radar scenarios with multiple emitters transmitting simultaneously. Also, AWGs typically offer multiple, synchronous channels, allowing engineers to test multi-channel radar receivers and simulate, for example, a certain angle-of-arrival (AOA). With the RF signal coming straight from the DAC, the phase from pulse to pulse and channel to channel is 100 percent repeatable, which is important for consistent test results. Another benefit is the flexibility in terms of modulation formats—this is ideal to develop new modulation schemes that are more tolerant to interference. In addition, AWGs can generate the simulated signals directly downloaded from simulation software tools like SystemVue.

Future automotive radar tests require both software-based simulation and high-performance measurement equipment to improve radar performance and accuracy and reduce development time and cost. Advanced software is now available to help engineers create their own simulations with various example workspaces based on essential automotive radar scenarios: micro-Doppler, multiple target detection, antenna 3D scan, radar scene simulations with ground clutter (asphalt, cement or mud), pedestrian and multi-scatter target, direction of angle (DOA) degree calculation along with phase comparison, propagation loss under rain and MIMO radar.■


# Automotive Radar Sensors Must Address Interference Issues

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Autonomous driving is a current global trend that will continue to accelerate in the future. A key enabling technology in this area is automotive radar sensors, which are a significant step toward more driving comfort, crash prevention and even automated driving. Driver assistance systems are already common and many are supported by radar.

Today's 24 GHz, 77 GHz and 79 GHz automotive radar sensors clearly need to be able to measure and resolve different objects while offering high range, radial velocity and azimuth resolution in any urban or rural environment. A very important feature is immunity to interference from other automotive radar sensors. This topic has not been greatly focused on since the market adoption of radar sensors is low at the present time. However, the proliferation and expected growth is continually increasing and the Advanced Driver Assistance Systems (ADAS) market is expected to grow by up to 10 percent per year.

Considering that 72 million new cars are registered each year with a potential average of three (or more) automotive radar sensors per car, about 200 million more automotive radar sensors could be on the streets in the not too distant future. Consequently, the 24 GHz and 76 to 81 GHz spectrum will be heavily occupied. Automotive radar sensors will need to cope with mutual interference and offer signal diversity and interference mitigation techniques.

The occasional accidents involving automated cars that are under research and development have been reported in the press. In May 2016, questions about the security of self-driving cars and the safety of the technologies rose again after the first fatal accident involving a partially automated car. It is therefore essential to ensure the functionality of the sensing equipment in any environment in the presence of mutual interference.

This article presents the theoretical background of state-of-the-art and next generation automotive radar signals and sensors. It explains the impact of mutual interference and presents measurement possibilities to test and verify mitigation techniques in arbitrary RF environments with norm interferers. This approach helps researchers and developers engineer automotive radar sensors

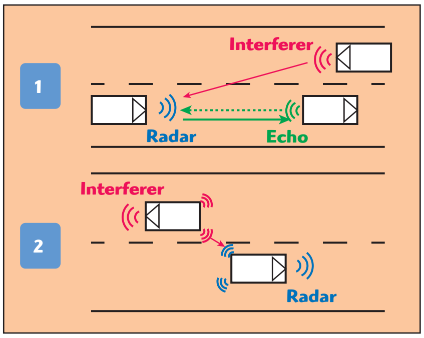



Fig. 1 Interference scenarios.

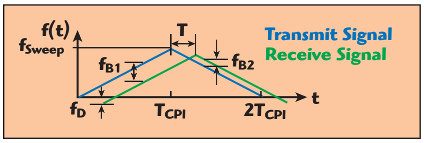



Fig. 2 LFMCW radar signal with upchirp and downchirp.

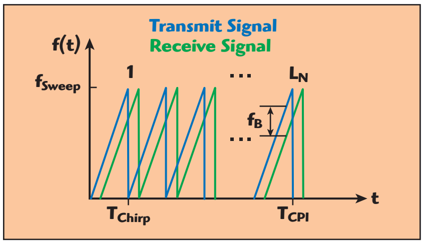



Fig. 3 Chirp sequence.

that function according to specification, even in harsh RF environments.

## AUTOMOTIVE RADAR AND REGULATIONS

Several automotive radar sensors may interfere with each other when operating in the same portion of the frequency band[1] and in close proximity to each other (see ***Figure 1***). Possible scenarios are the creation of artificial ghost targets or decreased probability of detection. Ghost targets do not exist in reality, but appear as real targets to the radar sensor. This may be caused by a copy of the transmitted signal. The copy is not from the original radar transmitter, but falls into the receiver bandwidth and is processed as a real echo signal. For this scenario to occur, timing, waveform and frequency between two or more radars have to match and the echo power has to exceed a certain limit.

Also, arbitrary RF signals with a certain power level that fall into the receiver bandwidth may increase the noise floor of the radar and reduce the Signal-to-Noise Ratio (SNR) of a target. This may cause targets with a small Radar Cross Section (RCS) to disappear since the SNR of these echoes is reduced. For this scenario to happen, a signal that spreads over all frequencies after FFT signal processing has to fall within the receiver bandwidth.

The output power of automotive radar sensors is specified by the Electronic Communications Committee (ECC). Based on the ECC Decision (04) 03 entitled, "The Frequency Band 77 to 81 GHz to be Designated for the Use of Automotive Short Range Radars," the European Conference of Postal and Telecommunications Administrations (CEPT) designated the 79 GHz frequency range for Short Range Radar (SRR) equipment on a non-interference and non-protected basis. Moreover, a maximum mean power density of -3 dBm/MHz e.i.r.p. associated with a peak limit of 55 dBm e.i.r.p was defined, and the maximum mean power density outside a vehicle resulting from the operation of one SRR equipment shall not exceed –9 dBm/MHz e.i.r.p.

All standard automotive radar sensors operating in these bands have to fulfill this criteria. ETSI standards EN 301 091-1 and EN 301 091-2[2] already standardize several aspects related to test conditions, power emission and spurious emissions for 77 GHz radars, but do not mention anything about interference rejection. The same is true for the ETSI standards EN 302 264-1 and EN 302 264-2[3], which regulate the 79 GHz band.

In the maritime domain, for example, navigational radars have to adhere to the International Electrotechnical Commission standard IEC 62388,[4] which specifies the minimum operational and performance requirements, methods of testing and required test results conforming to performance standards of radiocommunications equipment and systems. One very important aspect in the IEC standard is the specification of interference rejection. However, for automotive radar specifications, there is no standard defining interference rejection or performance and test methods that navigational radars have been subject to for decades.

## WAVEFORMS AND IMPACT OF INTERFERENCE

If an interfering signal falls into the radar receiver bandwidth, it should be detected as such and rejected in the signal processing. It is common for manufacturers to each have slightly different waveforms, timings, bandwidths, antenna patterns and signal processing. This is an advantage in terms of interference rejection, but also results in the radar responding differently to interference.

There are mainly two different types of waveforms used in today's automotive radar sensors. Blind Spot Detection (BSD) radars often use the Multi-Frequency Shift Keying (MFSK) radar signal and operate mainly in the 24 GHz band. Radars operating in the 77 GHz or 79 GHz band often make use of Linear Frequency Modulated Continuous Wave (LFMCW) signals or Chirp Sequence (CS) signals, which are a special form of LFMCW signals. Using LFMCW, the radar transmits a frequency modulated signal (chirp) with a specific bandwidth $f_{sweep}$ within a certain time, called the coherent processing interval $T_{CPI}$, as shown in ***Figure 2***.

The radar down-converts the received signal with the instantaneous transmit frequency and measures the beat frequency $f_B$, which describes the offset from the original transmitted waveform. Both radar parameters, range, R and radial velocity, $v_r$, contribute to the measured beat frequency. In order to resolve the target unambiguously for $v_r$ and R, two beat frequency measurements are necessary (see Figure 2, where the beat frequencies are denoted as $f_{B1}$, $f_{B2}$). In multitarget situations, range and radial velocity cannot be resolved unambiguously by two consecutive chirps measuring different beat frequencies. This can be resolved by an additional chirp with a different slope.

To enable a certain radial velocity resolution, $T_{CPI}$ is typically in the region of 20 ms and the number of chirps for a single processing interval is greater than two. $f_{sweep}$ defines the range resolution and varies between 100 MHz and above, and will be more than 1 GHz in the near

**TABLE 1**

**AUTOMOTIVE RADAR WAVEFORM COMPARISON**

| | LFMCW | CS (Fast LFMCW) |
|---|---|---|
| $f_0$ (GHz) | 77 | 77 |
| $f_{Sweep}$ (GHz) | 1 | 1 |
| $T_{CPI}$ (ms) | 20 | 0.025 |
| $f_{B,Upchirp}$ (MHz) | 0.039027 | 10.6997 |
| $f_{B,Downchirp}$ (MHz) | 0.012342 | –10.6484 |

future and probably 4 GHz or even 5 GHz in the distant future.

The chirp sequence waveform consists of several very short LFMCW chirps, each with a duration of $T_{Chirp}$, transmitted in a block of length $T_{CPI}$ (see ***Figure 3***). Since a single chirp is very short, the beat frequency is mainly influenced by the signal propagation time and the Doppler frequency shift, $f_D$ can be neglected.

Signal processing takes place following an initial down-conversion by the instantaneous carrier frequency and a Fourier transformation of each single chirp. Due to the high carrier frequency and the high chirp rate the beat frequency is mainly determined by range. The target range is calculated assuming a radial velocity, $v_r=0\frac{m}{s}$. The radial velocity is not measured during a single chirp, but instead over the block on consecutive chirps with duration $T_{CPI}$. A second Fourier transformation is performed along the time axis, which results in the Doppler frequency shift. After obtaining the Doppler frequency shift, the target range is corrected.

While a single $T_{Chirp}$ is typically in the region of 10 µs to 100 µs, the number of signals $L_N$ should be so high that the entire coherent processing interval, $T_{CPI}=L_N \; T_{Chirp}$ is again in the region of several dozen ms to achieve the desired radial velocity resolution.

The signal bandwidth is high, and the receiver bandwidth is very small in comparison. This can be achieved due to the fact that only the maximum beat frequencies for which the radar is designed are measured. To give two examples, ***Table 1*** shows the resulting beat frequencies of two automotive radar waveforms when measuring a target in 40 m range with a radial velocity of 50 m/s.

These calculations are according to the LFMCW equations and show that the occurring beat frequencies are in the range of 100 kHz for LFMCW, but are much higher for CS radars (several MHz). This causes the receiver bandwidth to be higher and may require different mitigation techniques compared to techniques applied when using LFMCW.

The advantage of CS compared to LFMCW is the unambiguity and the increased update rate, because a single coherent processing interval is sufficient to measure and resolve all targets in the observation range. In LFMCW, at least three different chirp signals are necessary. On the other hand, in the CS waveform the processing complexity increases due to multiple FFTs and the receiver bandwidth scales according to the expected beat frequencies, which is why there is a need for interference rejection and mitigation techniques.

***Figure 4*** depicts the down-conversion and Fourier transformation process when an interference signal (red chirp) is present. The interfering chirp is down-converted together with the radar return of the object. In green is the constant beat frequency for a certain range as it would occur in an interference-free environment while measuring a single target. With the introduction of an interference signal, a time-dependent beat frequency is generated (red curve), which appears in addition to the wanted echo. Hence in the Fourier domain, the spectrum shows not only a single beat frequency but several frequencies.

In the optimal solution, the signal-to-noise ratio of the echo signal (green bar) is maximum. When the interference signal is present, the noise floor rises and the signal-to-noise ratio decreases depending on the receiver bandwidth, $f_{LP}$ as indicated in the sketch. Aside from a decreased probability of detection, the lower signal-to-noise of an echo signal results in a less accurate range and a less accurate Doppler measurement.

The receiver noise floor and the signal-to-noise ratio of the object depend on the hardware, software and the object's RCS. Typical noise floor levels are about –90 dBm for an automotive radar operating at 77 GHz. One trend is to combine chirp sequence waveforms with other methods such as frequency shift keying in order to reduce the computational effort. However, at present, there are no common definitions on normative interferers and interference rejection written in standards for automotive radar sensors.

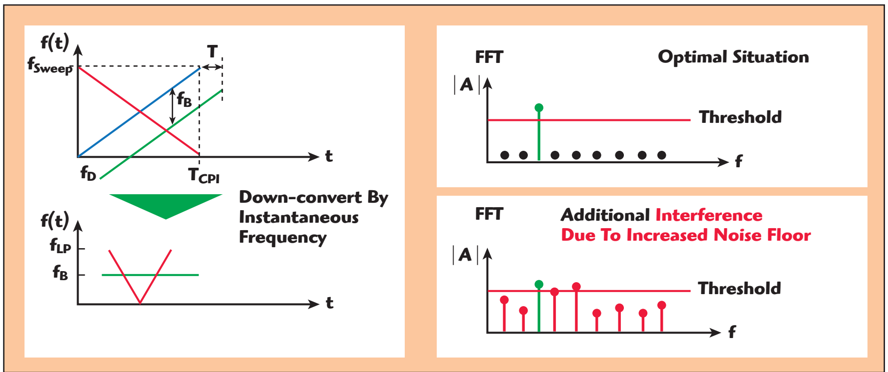



Fig. 4 Effect of interference signals.

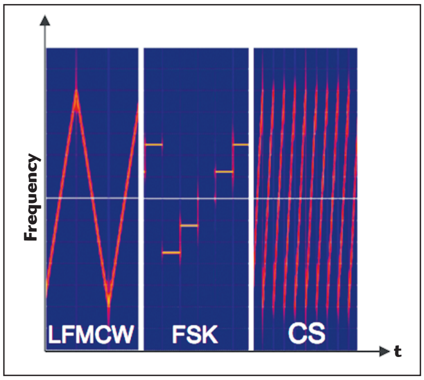
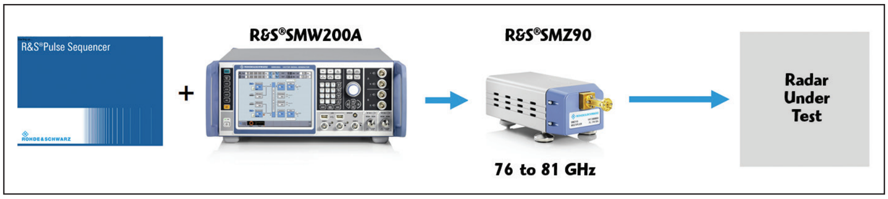
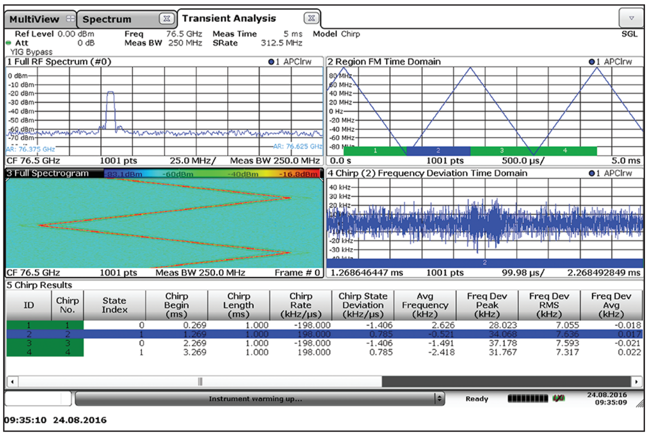



Fig. 5 Typical CW radar signals.




▲ **Fig. 6** Interference test setup using a vector signal generator and multiplier.




▲ **Fig. 7** Radar interference signal.

## T&M INTERFERENCE REJECTION

In order to verify the performance of interference rejection methods and to test the interference robustness of a radar sensor, a measurement was set up in the laboratory that allowed the generation of arbitrary RF signals. These signals can even include, for example, transmitter position, antenna motion and pattern.

***Figure 5*** shows typical radar interference signals generated by Pulse Sequencer software, such as LFMCW, frequency shift keying and chirp sequence. It should be mentioned that the software is not limited to these signals or sequences, but can also create complex RF environments to the laboratory.[5]

Although these signals can be generated in the baseband, bringing these signals up to E-Band frequencies is a challenge. As most automotive radars use only frequency-modulated signals, one way is to use a state-of-the-art vector signal generator together with a multiplier. The advantages of this setup are less complex test setups and high signal bandwidth that can be reached more easily since the multiplier also scales the signal bandwidth.[6] The scaling factor can easily be considered when designing the waveforms in the baseband.

***Figure 6*** shows a typical test setup for automotive radar sensors, using a vector signal generator in combination with a multiplier. The Pulse Sequencer software is used to generate the arbitrary RF environment in which signals are transferred to the vector signal generator over the local network or via a USB stick. The RF signals produced by the vector signal generator at 12.6 to 13.5 GHz are multiplied by a factor of six. An E-Band horn antenna can be connected to the output of the multiplier so that the E-Band signal can then be transmitted over the air towards the Device Under Test (DUT).

In this setup, the bandwidth applied at the vector signal generator also scales by a factor of six. To generate radar chirps with a signal bandwidth of 5 GHz, a baseband bandwidth of 833.3 MHz is required (833.3 MHz × 6 = 5 GHz). With the setup shown in Figure 6, a baseband bandwidth of 2 GHz is possible, which results in an RF signal bandwidth of up to 12 GHz (2 GHz × 6 = 12 GHz).

The spectrum of the interference signal is in ***Figure 7***. It is possible to observe the spectrum and the LFMCW signals with upchirps and downchirps. All chirp signal parameters have been analyzed directly with a signal analyzer equipped with transient analysis software. The chirp length is 1 ms and the signal frequency linearity is in the domain of several kHz, which is comparable to automotive radar sensor signals.

Researchers have already investigated using communications signals like OFDM in automotive radar[7] and designed interference rejection algorithms.[8] However, it may be complicated to process these extremely wideband OFDM signals in a price-sensitive sensor in real time. This will make it complicated to apply OFDM signals in the near future. This is also one of the reasons why it is so important to verify interference rejection algorithms, waveforms and the entire processing chain, starting with the mmWave region.

Not only is the cost-effective, real-time processing of very wideband OFDM signals challenging, generating amplitude-modulated interference signals in mmWave also requires a more complex setup. One approach is depicted in ***Figure 8***, which shows the IF and LO signals generated by a two RF channel vector signal generator. The LO signal is multiplied by a factor of six and shifts the IF signal to 76 to 81 GHz. A vector signal generator with an internal wideband baseband then allows the generation of arbitrarily modulated RF signals in the E-Band with a signal bandwidth of up to 2 GHz. Using vector signal generators incorporating calibrated internal wideband baseband hardware has benefits over solutions using multiple instruments since there is no need for calibration nor compensation of the I/Q frequency modulator response.

## MEASUREMENT RESULTS

To verify the impact of additional radar signals that are present, a state-of-the-art 77 GHz sensor was used. The advantage of this sensor is the availability of IF and FFT raw data. This makes it possible to immediately verify the impact of interference signals on the FFT spectrum. As explained, one should see an increase in the noise floor depending on how much interference signal power is downconverted and falls into the receiver bandwidth. In these measurements, the sensor was configured to transmit an LFMCW signal with 200 MHz signal bandwidth as depicted in ***Figure 9***, where the transient analysis option shows the duration, signal bandwidth, the linearity (frequency deviation time domain) of the transmitted chirps and spurious emissions in the RF spectrum.

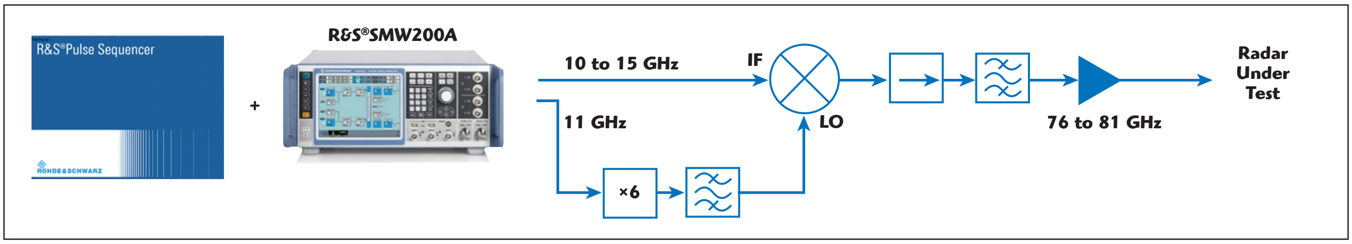



Fig. 8 Interference test setup using a mixer.

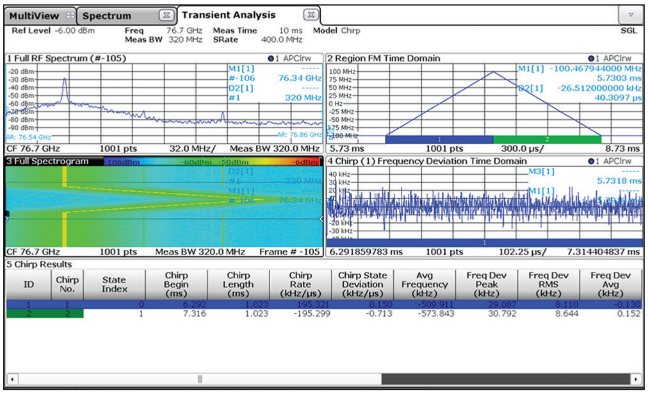



Fig. 9 Radar sensor analyzed with the transient analysis option.

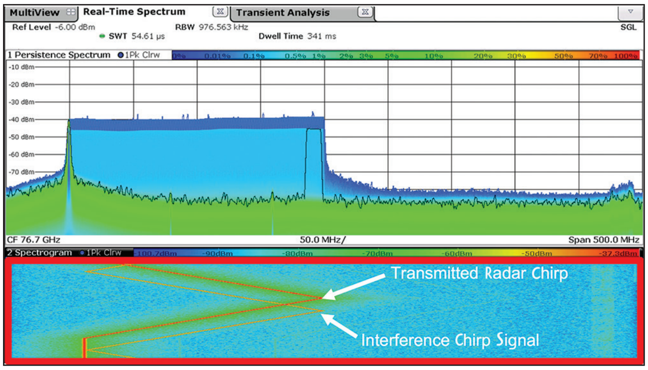



Fig. 10 Real-time spectrum showing wanted signal (on left with single chirp) and continuously chirping interferer.

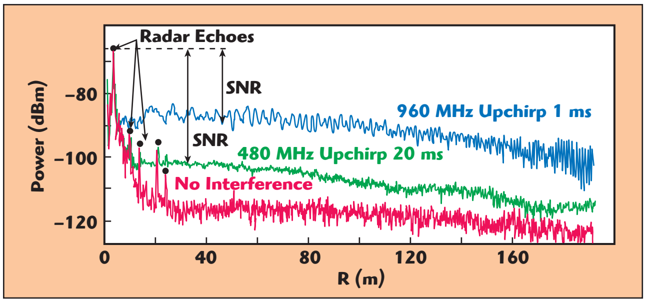



Fig. 11 Radar sensor spectrum.

The Pulse Sequencer software was used to emulate the waveform and test the radar with an additional interference waveform. The real-time spectrum in persistence mode can be used to verify the two signals. ***Figure 10*** shows two RF signals, the chirp which is transmitted by the radar sensor and the interference signal generated by the vector signal generator. While the radar sensor transmitted an upchirp and downchirp followed by an unmodulated CW signal, the interference signals just transmit upchirps and downchirps. The power level of the interfering chirp is about 5 dB less than the transmitted radar signal as shown in the persistence spectrum.

***Figure 11*** depicts a sample of spectrum measurements where the amplitude level over the range is plotted with and without interfering signals present. While measuring into free space without interference, this radar sensor measures a spectrum at a power level in the range of -115 dBm and some radar echo signals in close range.

When an interfering signal is present, the noise floor increases to about -102 and -90 dBm depending on the interfering signal itself. It should be mentioned that this radar sensor does not apply any interference cancellation. Also, the noise floor increase strongly depends on the interference signal level and the interfering waveform itself as can be seen in the measurements. A decrease of 10 to 25 dB SNR has been proved, which can cause objects to be very easily lost during tracking or objects with low RCS, like pedestrians, going undetected.

## CONCLUSION

Automotive radar supports the trend towards additional driving comfort, safety and even automated driving. The number of automotive radar sensors on the streets is increasing rapidly and will grow further in coming years. As a consequence, the allocated spectrum in the 24 GHz, 77 GHz and 79 GHz bands needs to be shared among different types of sensors and signals. As a safety critical element, the radar sensor needs to cope with mutual interference, offer signal diversity and interference mitigation techniques to measure, detect, resolve and classify radar echo signals even in the highly occupied frequency spectrum. Regulations and standards on interference test and mitigation are available for navigational radars, for example, but are not yet required for automotive radars.

To address these needs, this article explained the theoretical background and impact of interference on state-of-the-art and next generation automotive radar. Test and measurement possibilities to verify interference mitigation techniques in arbitrary RF environments have been presented. The impact of interference has been verified using a state-of-the-art commercial 77 GHz radar sensor. These test setups should help researchers and developers ensure the functionality of their radar according to specification even in harsh RF environments.■

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# Microwave Impedance Calculator

This software is intended to assist with microwave circuit design in predicting the impedance of a circuit made with Rogers High Frequency circuit materials. The software also has some capabilities for predicting transmission line losses as well. The user will select the circuit materials and the circuit construction, after which the software will determine the predicted impedance and other electrical information.

The calculator uses well known closed form equations to determine impedance and loss of a given circuit model. The loss calculation is divided into conductor loss and dielectric loss. With specific circuit designs, the calculator also predicts other properties such as wavelength in the circuit, skin depth and thermal rise above ambient.

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