By David Marsh, Contributing Technical Editor

AS YOU DRIVE HOME TONIGHT, IT'S ODDS-ON THAT YOUR RADIO WILL CUT TO NEWS OF AN ACCIDENT THAT MAY BLOCK YOUR JOURNEY. BUT RADIO TECHNIQUES CAN DO MORE THAN JUST ALERT YOU TO INCIDENTS. NEW INITIATIVES RESERVE THE HIGH-FREQUENCY SPECTRUM FOR RADAR-BASED IN-CAR SYSTEMS THAT TARGET ACCIDENT AVOIDANCE.

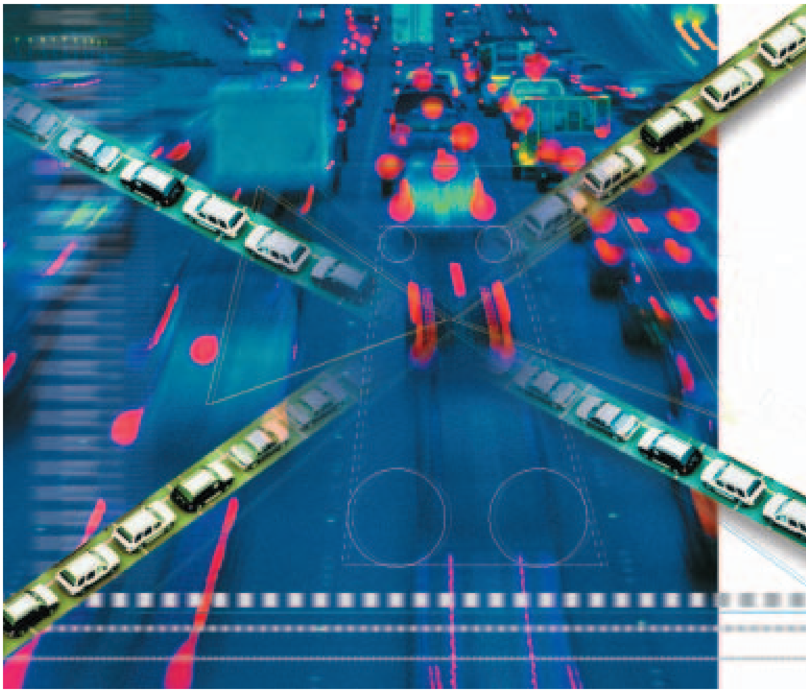


Image by Mike O'Leary

Radar reflects safer highways

As vehicle manufacturers' advertising is keen to affirm, cars are steadily becoming safer. But contemporary accident statistics still make chilling reading: 1998 statistics show some 5.5 million European Union accidents that resulted in 42,200 fatalities.

Elsewhere in the industrialised world, carnage in the United States that same year claimed another 42,000 lives, and 9000 more were lost in Japan. Overall, the cost to these nations totalled some €682 billion—overshadowed only by inestimable human misery. As a result, the respective governments have been spending billions on measures to make roads safer. The obvious starting point is vehicle design, as consumer activist Ralph Nader famously identified in 1960s America. His best-selling book disturbed a largely complacent Detroit auto industry into adopting measures to improve occupant protection (**Reference 1**). In Europe, Volvo popularised safety with features such as impact-absorption zones, safety cells, and occupant-restraint systems. Governments, too, have played a major role, by requiring carmakers to include such features, and the results have been impressive. US Department of Transportation figures show fatality reductions from 5.5 per 100 million vehicle miles travelled in the mid-1960s to 1.7 per 100 million in 1994—that's almost 70% in three decades.

Of course, the smarter way to survive your driving career is not to crash in the first place, and this objective is the subject of intense global research efforts. The emphasis here is active safety—measures that car designers can take to significantly reduce the likelihood of a driver's losing vehicle control. Now, even low-end cars include antilock brakes, and more expensive models add features, such as traction control, electronic brake-force distribution, and stability-control systems, which can help keep drivers out of trouble in compromising situations. But none of these systems tackles driver inattention, which a study by the US NHTSA (National Highway Traffic Safety Administration) identifies as the prime cause of accidents (**Reference 2**). From the study's sample of 723 serious collisions, 99% involved driver behavioural errors that contributed toward or caused the accident. An overview of the study's results classifies crash causes into six main categories that account for more than 90% of the sample's accidents; further interpretation suggests that as many as 68% of accidents involve a major element of driver inattention. However you view the numbers, this and parallel studies in the European Union agree that warning drivers of conditions that compromise safety, such as inappropriate proximity to other road users, can significantly reduce the accident toll.

As a result, US and EU authorities have launched major programmes to identify and apply driver-aid technologies. In the United States, the NHTSA commissioned a consortium led by Delphi-Delco Electronic Systems to undertake the ACAS (automotive-collision-avoidance-system) programme (**Reference 3**). The report summarises: "The introduction of automotive collision warning systems potentially represents the next significant leap in vehicle safety technology by attempting to actively warn drivers of an impending collision event, thereby allowing the driver adequate time to take appropriate corrective actions in order to mitigate or completely avoid the event." Elsewhere, the EU Commission's e-Europe programme aims to reduce road fatalities by 50% by 2010. One major programme element is its Response project, which seeks to deploy advanced technology to produce advanced driver-assistance systems. The objectives envision a marriage between telematics and in-vehicle control systems, such as roadside sensors that may warn drivers of approaching dangers. The commission also proposes that researchers develop systems that compare a driver's control inputs with internal models of optimum behaviour in specific situations to provide driver assistance "without taking over the totality of a driver's responsibility for vehicle control" (**Reference 4**).

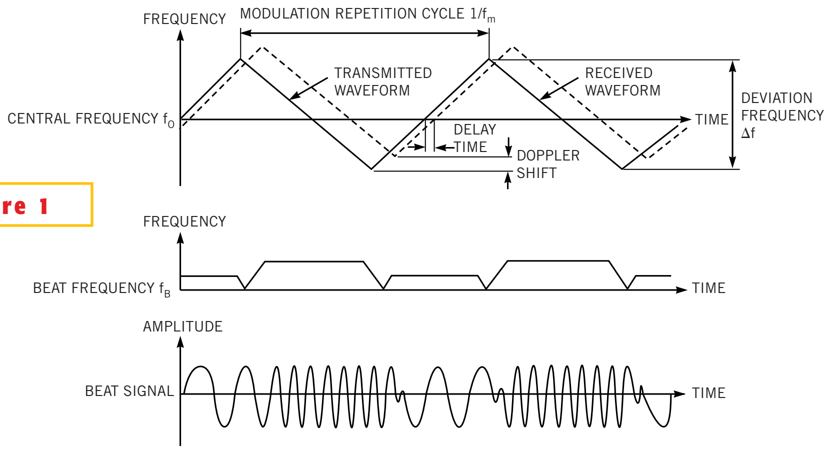
AT A GLANCE

- ▷ EU and US authorities research radar-based accident-reduction technologies.
- ▷ Millimetre-wave ACCs (adaptive cruise controllers) at 77 GHz herald autonomous systems.
- ▷ ACC radars use pulse-modulated continuous-wave techniques, frequency-modulated continuous-wave techniques, or both.
- ▷ Industry proposes lower frequencies, such as 24 GHz, to cut cost.

It is important to differentiate between the capabilities of systems that fall into three broad categories: collision-warning systems, collision-mitigation systems, and collision-avoidance systems. Collision-warning systems simply report an object's presence within the threat zone while leaving the driver in complete control, and system applications need know only the object's position to function properly. Collision-mitigation systems improve road-user security by determining whether an object poses a threat to the vehicle. Responsibility for vehicle control still lies exclusively with the driver, but a threat response may trigger actions, such as pretensioning seatbelts or deploying air bags. For this application, the sensor system must determine object mass and velocity and the likely point of impact. Finally, collision-avoidance systems determine the vehicle's optimum path and take control if the driver fails to respond adequately to the threat. This application requires complete knowledge of the environment around the vehicle, as well as close integration with the vehicle's control systems.

This classification suggests several competing and potentially complementary technologies. Ultrasonic sensors are in widespread use for parking aids, but with a typical range of less than 3m and no facility for accurate object or speed discrimination, this technology can't meet advanced safety objectives. More promising approaches include conventional and infrared imaging as well as laser techniques. But alone, each of these technologies suffers from susceptibility to poor environmental conditions, such as fog or road spray. Low-power radar isn't immune from these conditions but is far more tolerant, especially at lower frequencies at which environmental-absorption characteristics are less significant. As a result, most studies agree that radar is the single most promising technology. Notably, as part of the EU-funded RadarNet project, studies at the University of Birmingham (United Kingdom) resulted in the first 77-GHz radar that's characterised for road-spray conditions. Radar can also complement vi-

Figure 1



FMCW (frequency-modulated continuous-wave) systems modulate the carrier with a triangular waveform to derive range and relative velocity information from sum-and-difference beat frequencies.

sion-system technologies to form one approach for detecting driver aberrations, such as straying out of lanes, which according to a German study, accounts for around one-third of all accidents.

CRUISE IN SAFETY WITH ACC

Systems that fulfill some of the objectives of a collision-avoidance driver-warning system are already in production. First introduced to passenger cars in DaimlerChrysler's 1999 model Mercedes S-class saloon, the company's "Distronic" ACC (adaptive-cruise-control) system employs a millimetre-wave radar to gauge forward distance to another vehicle and its relative speed. Based on original design work from Automotive Distance and Control Systems, M/A-Com supplies the 77-GHz, pulse-mode Doppler radar sensor that mounts behind the vehicle's front bumper. With an effective range of about 150m, M/A-Com's sensor uses a triple-beam switched antenna that transmits 36-nsec pulses, each with 3° beam width. In conjunction with baseband electronics that interface with the vehicle's power-train- control network, this "far-distance" sensor maintains a safe distance from the vehicle ahead at a speed that the driver sets. If this distance becomes too small—for example, when a vehicle unexpectedly cuts into the lane ahead of you—the system automatically throttles back and applies braking to widen the gap, resuming the preset speed only when conditions permit. Carmakers that offer the system now include BMW, Fiat, Jaguar, Renault, and Volkswagen. System suppliers include Robert Bosch, Delphi, Fujitsu-Ten, Valeo Raytheon Systems, and Visteon (see **sidebar** "For more information").

Significantly, ACC represents the first step in mass-market acceptance of autonomous driving, which some researchers see as the logical conclusion to active safety-system applications. But for fear of potential lawsuits following accidents, carmakers currently market the system as a convenience rather than a safety aid. Given that ACC is most effective in motorway/autobahn use, the main challenge to system designers is to detect all objects inside the observation area and to measure the target's range, relative speed, and azimuth angle. The system must simultaneously perform these measurements within a 100-msec period and unambiguously resolve threats in the presence of multiple targets. Other typical specifications require a ±6° horizontal observation area, 0.5° azimuth-angle accuracy, and 2 to 180m working range. Range and velocity resolution are typically better than 1m and 1m/sec, respectively.

Millimetre-wave radars generically divide into pulse- and continuous-wave types, with further classifications that include FMCW (frequency-modulated- continuous-wave) and spread-spectrum derivatives. In general, pulse radars require high-speed broadband-signal processing to unambiguously resolve multiple targets, while an FMCW system has relatively relaxed-measurement time constraints to achieve similar performance. All radars operate by transmitting a signal and listening for reflections, or echoes. In the classic case of a pulse radar, the system transmits pulses for some tens of nanoseconds and then waits slightly longer to acquire reflections. The waiting time between pulses depends on the longest range at which the radar expects to resolve targets. If the waiting time between pulse transmissions is too short, an echo from a long-range target may arrive after the next pulse transmission. If the system can't discriminate between this long-range, "second-time-around" echo and in-range echoes, the distant echo appears as a target at much closer range. Thus, the range beyond which targets appear as second-time-around echoes is the system's maximum unambiguous range, which you determine by dividing signal-propagation speed by twice the pulse-repetition frequency. As the signal propagates at around 3×10^8m/sec, it takes about 1 µsec for a pulse to travel 150m to the target and back to the receiver; thus, 1m accuracy requires 6.5-nsec resolution. One method of obtaining this resolution relies upon a technique that's analogous to a DSO in its equivalent-time-sampling mode and similarly relies upon repeated sampling of a stable periodic signal. Post-processing then constructs an envelope of received-signal strength that's proportional to target range. An FFT can extract from the Doppler information the phase shift between transmitting and receiving signals and, thus, derive target-speed data.

Figure 2

ACC radars, such as this 77-GHz example, mount a single module in the vehicle's front bumper (courtesy Robert Bosch).

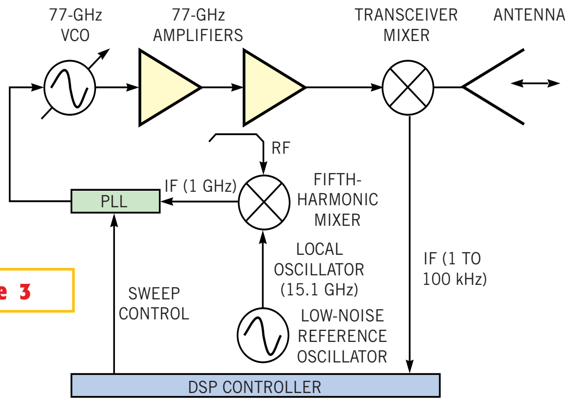
By contrast, continuous-wave radars continuously transmit a single frequency and listen for echoes. Thus, echoes arrive all the time and intrinsically yield no range information, because they all integrate into a single result. But the technique can measure target velocity from Doppler-shift information, and it simplifies the radar front end, because it employs no high-speed pulse-generation, synchronisation, or routing circuits. But applying frequency modulation to the continuous wave restores the ability to simultaneously resolve both range and velocity information. An FMCW radar transmits a frequency-modulated signal for a sampling period of approximately 1 msec and mixes a portion of the transmission signal with reception signals over this period to obtain a beat signal. Relative to the instantaneous source frequency, this beat signal contains sum-and-difference components that represent a time delay proportional to the target distance, as well as a Doppler shift that represents the target's relative velocity (**Figure 1**).

The modulation waveform is conventionally a triangle, and each ramp is a "chirp." Altering triangle amplitude or chirp gradient sweeps a VCO (voltage-controlled oscillator) through varying frequency ranges. The system transmits each sweep in a CPI (coherent processing interval), during which it samples and Fourier-transforms the downconverted echo signals. A single sweep potentially returns ambiguous range and velocity measurements, and, if computation detects a spectral peak in the Fourier spectrum at normalised integer frequency, you can calculate these ambiguities. Therefore, the radar must make multiple measurements over a series of CPIs—a process that slows measurement time and is this technique's principal disadvantage. Factors that affect CPI duration include velocity resolution, which you determine by dividing signal wavelength by twice the chirp period. At 77 GHz, or

4 mm, a chirp period of 2.5 msec provides 0.8m/sec resolution. Similarly, dividing signal propagation speed by twice the sweep frequency determines range resolution. Therefore, a bandwidth of 150 MHz provides 1m resolution.

Sequential lobing techniques determine target azimuth angle by measuring how far and in which direction the target lies from the antenna axis. Derived from aviation-tracking radars, sequential lobing traditionally employs multiple antenna feeds to sequentially point the radar beam away from the antenna axis in four directions: above, below, and from side to side. Comparing the relative amplitudes of up-down and right-left echoes then determines the target's off-axis position in azimuth and elevation. But sequential lobing can suffer errors due to echo-amplitude fluctuations during scanning that a single pulse, or monopulse, technique avoids. In the equivalent monopulse technique, four off-axis beams are simultaneously in use. Combining these beams into three channels provides sum-and-difference azimuth and elevation deltas and overall sum data. Referencing the delta channels' phase and amplitude to the sum channel derives the target's angular information; the sum channel conventionally provides range information. The situation is simpler in an ACC application because the radar has to observe only the azimuth angle; objects that pose potential threats are in the same plane as your vehicle.

Figure 3



Infineon's first-generation MMIC chip set shows the key building blocks necessary to construct a 77-GHz ACC radar.

Several methods are available for automotive azimuth-measurement applications. TriQuint Semiconductor's automotive-radar expert Heinz-Juergen Siweris first explains that ACC radars require an antenna-beam width of the order of 1.5°: "According to laws of antenna physics, this requirement means that the size of the radiating aperture must exceed a multiple of wavelengths at the operating frequency. Higher frequencies therefore reduce antenna dimensions and those of the complete radar module, which is an important parameter for the carmakers." To accommodate the antenna behind a radome, typical modules are variations on a 10-cm cube (**Figure 2**). The narrow beam is a trade-off between range and output power, which is on the order of 10 mW. The system also requires a 12 to 16° field of view with an angular resolution of less than 3° to reliably discriminate targets on adjacent motorway lanes. As a result, designers employ either a single mechanical scanning antenna with small beam width or a relatively expensive fixed antenna with three to eight narrow beams that are electrically switched using devices such as PIN diodes. Siweris notes that another popular antenna concept combines a single broad-beam transmission antenna with two or more narrow receiving-antenna beams. Computational methods include extracting and normalising the sum-and-difference components of the relative field intensities to yield an equivalent angular-error signal; comparing this value with a predetermined discrimination curve translates this information into the target's azimuth angle.

You can see the main elements of a 77-GHz radar in Infineon's ACC chip set, which TriQuint Semiconductor took over late last year (**Figure 3**). The diagram shows an FMCW radar, which Siweris says is the most frequently used system concept for car radars. He notes that an important characteristic of FMCW radars is their need for a signal source with low phase noise and high tuning linearity. Normal free-running millimetre-wave oscillators do not meet these requirements, so the design includes an automatic frequency-stabilisation and -linearisation loop that comprises a lower frequency PLL and a downconversion unit with a harmonic mixer and reference oscillator. The downconversion unit is necessary because currently available PLL circuits, such as frequency dividers, can't directly handle millimetre-wave frequencies. According to Siweris, "The reference oscillator's 15-GHz operating frequency is a compromise. An oscillator with lower frequency would be more convenient to fabricate and thus would cost less. However, the mixer would need to operate at a higher harmonic of the oscillator signal," which, he notes, "would result in a higher conversion loss."

Siweris observes that, thanks to a proprietary mixer design, the technology uses the antenna for both transmission and reception: "In this so-called transfer mixer, a well-defined fraction of the local oscillator power is transferred to the RF input port of the mixer and is utilised as the radar's transmission signal. Any signal received by the antenna is downconverted by mixing with the local oscillator signal." Because the transmission signal, signal reflections, and the local oscillator signal originate from the same source, their frequencies are almost equal, resulting in typical IFs of 1 to 100 kHz. "In fact," Siweris notes, "according to the operating principle of an FMCW radar, the frequency difference—[that is], the IF—is related to the distance and the relative speed of the target. Processing the IF signal using a fast-Fourier transform obtains the relevant target information."

Like many such radars, the design relies upon GaAs (gallium-arsenide) semiconductors to fabricate the MMICs (monolithic-microwave ICs) that form the key VCO, medium-power-amplifier, and mixer building blocks. These expensive construction techniques provide optimum performance at this high frequency but contribute significantly to the additional €1600 per car that today's ACC systems typically incur. In common with his peers elsewhere, TriQuint's Siweris considers that the only semiconductor-device technology with sufficient performance and volume-production maturity is the GaAs-based pHEMT (pseudomorphic high-electron-mobility-transistor) process: "Today, car radars are not a mass-market item, and future prices will depend on high-volume production." Siweris estimates that "a complete chip set that covers all millimetre-wave functions of the radar front end will finally sell for €50 to €100 in volume"—a price that he says "should be compatible with an attractive end-user price for the complete ACC system." The GaAs process is also essential to minimising timing jitter in the reference oscillator to maximise the system's resolution. Frederic Petit, business-unit manager of microwave-ceramic materials at Temex, notes that early systems using Gunn-diode reference oscillators increasingly give way to dielectric resonators that have a Q figure as high as 20,000 at 12.5 GHz. Temex uses this material to construct low-jitter digital clock sources to minimise noise that PLL frequency multiplication amplifies.

You might ask, why choose 77 GHz if this frequency requires exotic materials and construction techniques? Also, there are relatively few vendors with millimetre-wave-semiconductor and MMIC production facilities. (Examples include Agilent, Fujitsu, M/A-Com, Mitsubishi, NEC, TriQuint, and UMS.) Apart from the measurement-resolution and form-factor issues that millimetre waves satisfy, power output and available spectrum are key factors—10 mW at 77 GHz creates little contention, and the 76- to 77-GHz area is now the subject of international agreement for ACC applications. Unsurprisingly, automotive OEMs have been looking to drive down radar costs to position the technology for widespread consumer acceptance. This objective is crucial in the context of collision-avoidance and -mitigation systems that employ as many as 10 near-distance sensors to provide a "virtual safety belt" around the vehicle (**Figure 4**).

These near-distance sensors have markedly different requirements than their ACC relatives. Because these sensors monitor nearby targets that are potentially travelling at widely dissimilar speeds, the application requires range and velocity resolution of around 0.2m and 1m/sec. Target acquisition times must be less than 100 msec and, preferably, as low as 20 msec. Rapid response is critical to providing sufficient driver-reaction time or—in the future—for autonomous systems to react to an emergency. For example, studies reveal that given just 500-msec earlier braking at moderate speeds, vendors can reduce crash energy by as much as 50%. Assuming four sensors mounting in both front and rear bumpers to provide 360° coverage, each sensor requires 45° azimuth angle but no intrinsic angular-resolution capability. Angular measurements derive from applying triangulation techniques across the sensor network and, to reliably discriminate objects in adjacent lanes, include elevation. To effectively monitor the environment from parking distances out across lanes and intersections, the radar must have a range of about 0.3 to 30m with 0.2m resolution. Crucially, these sensors must be available at costs that are commensurate with widespread deployment in midrange vehicles—a factor that bars the use of today's 77-GHz technology.

But designers' experience with 77-GHz systems provides a solid foundation for developing an alternative, low-cost technology. Lower frequencies offer the promise of reducing cost by using non-compound semiconductor materials, low-cost microstrip pc boards, and conventional pick-and-place-assembly techniques. Accordingly, researchers have proposed several potential bandwidths

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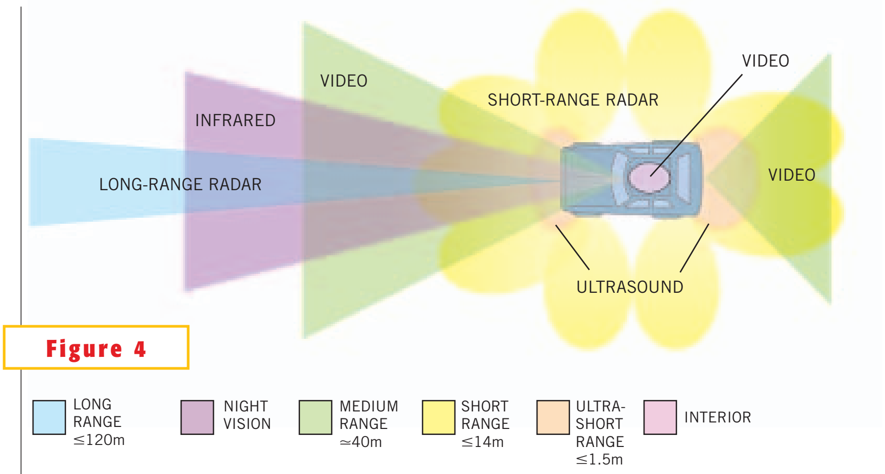
Figure 4



Several technologies may eventually complement short-range radars that provide a virtual safety belt around the vehicle (courtesy Bosch).

for this short-range-radar application. As with 77 GHz, the choice of frequency is a trade-off between many factors; from the technical viewpoint, antenna size for a given range and resolution is key. Also, these bandwidths must occupy spectra either that are available or that offer little contention with other users, and it's worth mentioning that many industry insiders privately acknowledge that the frequency-choice issue is as political as it is technical. The main contenders are the frequencies around 5.8, 10.5, and 24 GHz, and, of these, 24 GHz has the majority vote today. The 24-GHz proposal benefits from the impetus of the SARA (Short-range Automotive Radar frequency Allocation) group, whose members comprise the major European carmakers and their system suppliers (see **sidebar** "SARA pushes for 24 GHz" on the Web version of this article at www.edn.com).

Wolfgang Weidmann, managing director of radar-sensor-maker InnoSenT, considers 24 GHz a good compromise between millimetre-wave and the lower frequency proposals. He says that antenna choice is key to application success, and his company maintains an IP (intellectual-property) library of designs to suit customer requirements. He explains that planar patch antennas based on multiple resonating microstrip "patches" can provide varying fields of view, depending on the number and arrangement of the patches (**Figure 5**). For example, a typical 24-GHz design requires one patch for a 120° view and as many as 26 patches for a 5° view. You can feed the antenna with frequencies at different amplitudes and phases to form a phased array. At just 10 to 12 mm deep, the compact sensor can furnish 360° vision with three sensors per bumper. Each sensor in the network independently transmits and receives to generate its own object list that it passes to a central CPU for analysis, typically using CAN (controller-area-network) communications. The CPU graphs 2- or 3-D object-location information for decision-making, using software that carmakers typically produce. Weidmann notes that the key to very low sensor cost—€10 to €20—lies with using conventional microstrip and surface-mount mixed technologies. The receiver section is mostly silicon-based, but the transmitter section currently uses GaAs. However, SiGe (silicon-germanium) work at companies such as Atmel promises to further reduce cost; SiGe is also easier to use than dual-rail GaAs, because it requires only one supply.

It's not yet a foregone conclusion that 24 GHz is the way forward. Many trucks and every Greyhound bus in the United States carry a 10-GHz module for parking assistance, adjacent-lane monitoring, or both. The radar detector is the product of work at the United Kingdom's Microwave Solutions, and Sense Technologies markets it in the United States; Sense provides the signal-processing components. John Hallett, general manager at Microwave Solutions, says the parking sensor is the more sophisticated product, because the lane monitor simply looks for a range of Doppler signals to identify the presence of moving targets. The parking-aid sensor can discriminate between approaching and receding objects by switching between two frequencies at 5-MHz spacing to obtain two Doppler signals. With an end-user-installed cost of less than €300, the patented tunable oscillator uses Schottky diodes rather than the normal varactor. Other cost savings result from the device's ability to sample the Doppler frequencies of around 20 Hz/kph at 1 to 2 kHz. The sensor employs a proprietary antenna design to constrain module dimensions to around 50 mm square by 10 mm deep.

For wider use as collision-avoidance systems, Gordon Oswald, deputy manager of the automotive, transport, and defence business unit at Cambridge Consultants, surmises that 24 GHz may not be the optimum choice. He cites four objections: regulatory problems in the United Kingdom and elsewhere; cost, because the technology is more expensive than carmakers would like; sensitivity to bumper materials, geometry, and contamination; and "the misconception that collision-avoidance systems require 24 GHz to provide the required resolution with an acceptable antenna size." Work at the company proves that designers can construct a 5.8-GHz system that has a field of view of as much as ±75° and angular resolution of 2°. One such sensor can measure azimuth and elevation, and the company's technology can reduce the number of sensors required for monitoring the area around the car to as few as four. Oswald reports that the antennas that these sensors use require a form factor of approximately 80×120 mm, which compares well with 24-GHz devices. A proof-of-concept demonstration shows targets and their relative positions in real time on a head-up display.□

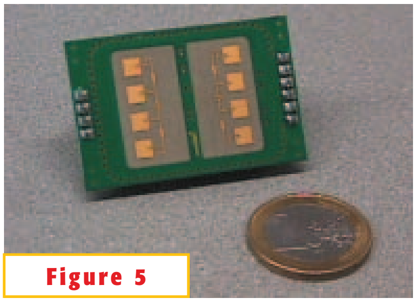


Figure 5

InnoSenT's 24-GHz antennas use microstrip pc boards with planar arrays of self-resonating patches that minimise a module's cost and dimensions.

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