

# mmWave Automotive Radar and Antenna System Development

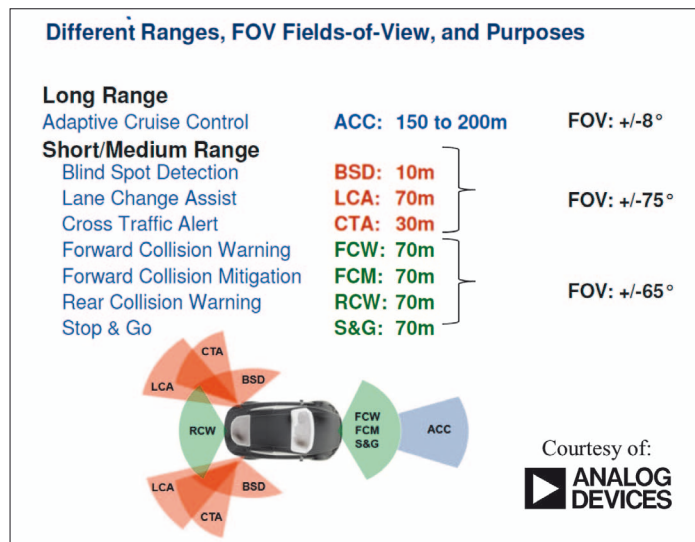


Figure 1: Different ranges, fields of view (FOV), and functions for advanced driver assist systems.

**This application example presents some of the challenges behind developing millimeter-wave (mmWave) radar systems and the antenna array technologies for the next generation of smart cars and trucks.**

Examples will be presented demonstrating how NI AWR Design Environment platform, specifically the radar design capabilities within VSS system design software, can be used successfully in ADAS applications.

## Overview

As modern vehicle development expands to include more and more sophisticated electronics, automobile manufacturers are equipping their new models with advanced driver-assistance systems (ADAS) to obtain high safety ratings by increasing automotive safety. Most road accidents occur due to human error and ADAS are proven to reduce injuries and fatalities by alerting drivers to and assisting them with a variety of issues, including collision avoidance and low tire pressure using radar technology mostly focused over the 76 to 81 GHz spectrum. They perform over a range of applications, operating conditions, and object detection challenges in order to provide reliable coverage over the range (distance) and field of view (angle) as dictated by the particular driver assist function.

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## ADAS Technology

ADAS is made possible through a network of sensors that perform specific safety functions. Manufacturers are currently implementing these systems based on vision sensor technology and radar systems operating at either 24 and/or 77 GHz. Vision systems detect lane markings and process other visual road information, however, they are susceptible to inadequate performance due to precipitation, particularly snow and fog, as well as distance.

On the other hand, long-range radar (LRR) supports multiple functions, comfortably handling distances between 30 and 200 m, and short-range radar (SRR) can detect objects below 30-meter distances. While the 24 GHz frequency band, which addresses SRR detection, is expected to be phased out of new vehicles by 2022, today it is commonly found in hybrid architectures. Meanwhile, the 77-GHz band (from 76-81 GHz) supporting LRR is expected to provide both short and long-range detection for all future automotive radars. Figure 1 provides details on short/medium and long-range radar.

Technical advantages of the 77 GHz band include smaller antennas (a third of the size of the current 24 GHz ones), higher permitted transmit power, and, most importantly, wider available bandwidth, which enables

higher object resolution. As a result, advances in radar modulation techniques, antenna beam steering, system architecture, and semiconductor technology are driving the rapid adoption of mmWave radar in future ADAS enabled cars and trucks.

To manage the adoption of these technologies, radar developers require RF-aware system design software that supports radar simulations with detailed analysis of RF front-end components, including nonlinear RF chains, advanced antenna design, and channel modeling. Co-simulation with circuit and EM analysis provides accurate representation of true system performance prior to building and testing costly radar prototypes. NI AWR software provides these capabilities, all within a platform that manages automotive radar product development – from initial architecture and modulation studies through the physical design of the antenna array and front-end electronics based on either III-V or silicon integrated circuit (IC) technologies.

The NI AWR Design Environment platform integrates these critical radar simulation technologies while providing the necessary automation to assist the engineering team with the very complex task of managing the physical and electrical design data associated with ADAS electronics. ADAS support includes:

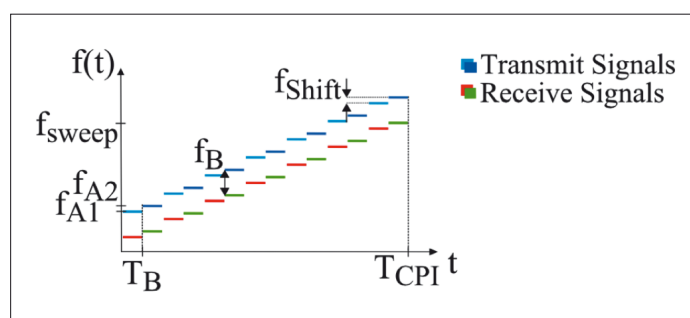


Figure 2: Multiple frequency shift keying.

	Pulse Doppler	FCW	FSK	UWB
Signals/Plots				
Description	<ul style="list-style-type: none"> <li>Single-carrier frequency is transmitted in a short burst</li> </ul>	<ul style="list-style-type: none"> <li>Typically a sawtooth waveform with 100 - 150 MHz bandwidth</li> </ul>	<ul style="list-style-type: none"> <li>FSK with 1 MHz steps</li> <li>Coherent processing interval (CPI) per frequency is 5 ms</li> <li>Range info is derived from phase difference</li> </ul>	<ul style="list-style-type: none"> <li>Dirac pulse</li> <li>Measure time-of-flight auto correlation</li> </ul>
Advantages	<ul style="list-style-type: none"> <li>Simple algorithm for distance</li> </ul>	<ul style="list-style-type: none"> <li>Good range accuracy</li> <li>Easy to calculate relative speed and range</li> </ul>	<ul style="list-style-type: none"> <li>Simple voltage controlled oscillator (VCO) modulation</li> <li>Short measurement cycle</li> </ul>	<ul style="list-style-type: none"> <li>Simple principle</li> <li>Can measure at close range due to large BW</li> </ul>
Disadvantages	<ul style="list-style-type: none"> <li>Difficult-to-determine range rate</li> <li>Cannot transmit and receive simultaneously</li> </ul>	<ul style="list-style-type: none"> <li>Computation to eliminate ghost targets</li> <li>Long measurement time for multiple chirps</li> </ul>	<ul style="list-style-type: none"> <li>Coherent signal required for accuracy</li> <li>Poor range direction information</li> </ul>	<ul style="list-style-type: none"> <li>Medium-to-low range</li> <li>No direct measure of range rate</li> <li>Sensitive to disturbance</li> </ul>

**Table 1: Different radar architectures and their technical advantages/disadvantages in target detection, range, robustness, and resolution.**

Design of waveforms, baseband signal processing, and parameter estimation for radar systems, with specific analyses for radar measurements along with comprehensive behavioral models for RF components and signal processing.

## Design of transceiver RF/microwave front-end with circuit-level analyses and modeling

(distributed transmission lines and active and passive devices) to address printed circuit board (PCB) and MMIC/RFIC design.

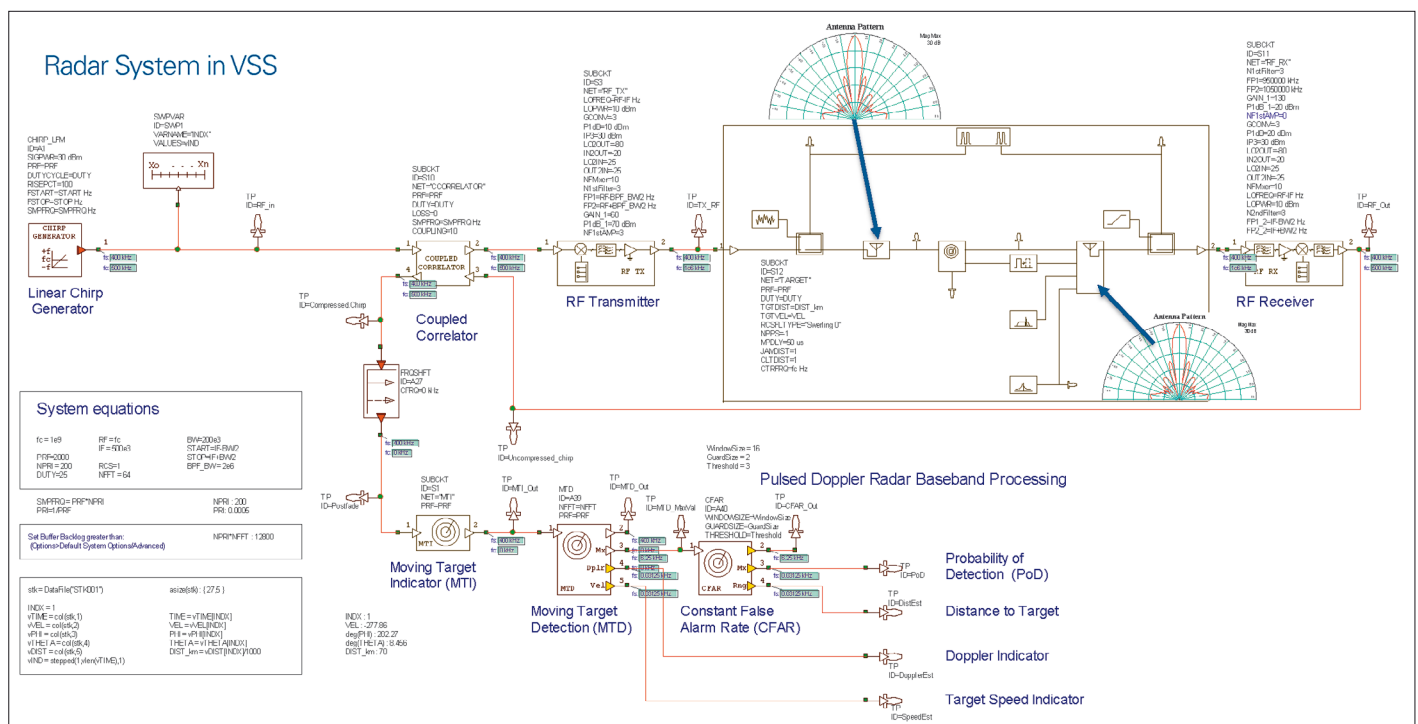
Planar/3D EM analysis for characterizing the electrical behavior of passive structures, complex interconnects, and housings, as well as antennas and antenna arrays.

The connection between simulation software and test and measurement instruments.

## Radar Architectures and Modulation

For adaptive cruise control (ACC), simultaneous target range and velocity measurements require both high resolution and accuracy to manage multi-tar-

get scenarios such as highway traffic. Future developments targeting safety applications like collision avoidance (CA) or autonomous driving (AD) call for even greater reliability (extreme low false alarm rate) and significantly faster reaction times compared to current ACC systems, which utilize relatively well-known waveforms



**Figure 3: PD radar example.**

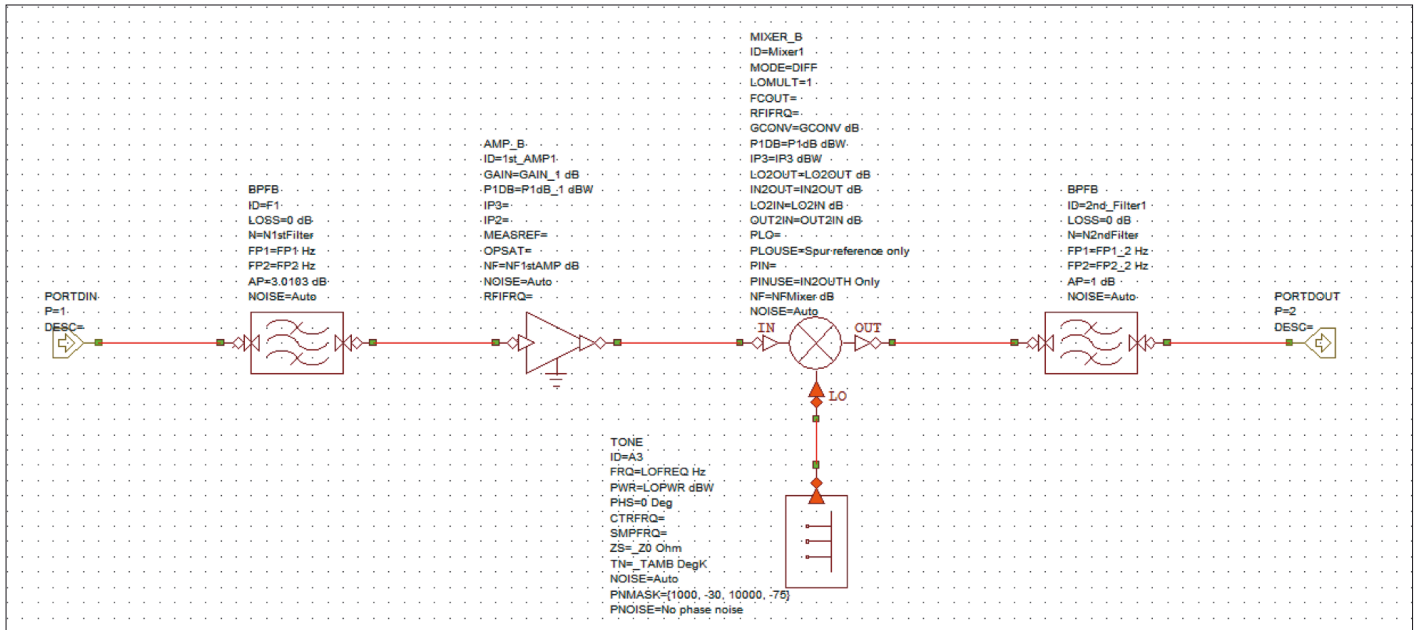


Figure 4: RF transmitter block.

with long measurement times (50...100 ms).

Important requirements for automotive radar systems include the maximum range of approximately 200 m for ACC, a range resolution of about 1 m and a velocity resolution of 2.5 km/h. To meet all these system requirements, various waveform modulation techniques and architectures have been implemented,

including a CW transmit signal or a classical pulsed waveform with ultra-short pulse length.

The main advantages of CW radar systems in comparison with pulsed waveforms are the relatively low measurement time and computation complexity for a fixed high-range resolution system requirement. The two classes of CW waveforms widely reported in literature include

linear-frequency modulation (LFMCW) and frequency-shift keying (FSK), which use at least two different discrete transmit frequencies. Table 1 compares the different radar architectures and their advantages and disadvantages.

For ACC applications, simultaneous range and relative velocity are of the utmost importance. While LFMCW and FSK fulfill

these requirements, LFMCW needs multiple measurement cycles and mathematical solution algorithms to solve ambiguities, while FSK lacks in range resolution. As a result, a technique combining LFMCW and FSK into a single waveform called multiple frequency shift keying (MFSK) is of considerable interest. MFSK was specifically developed to serve

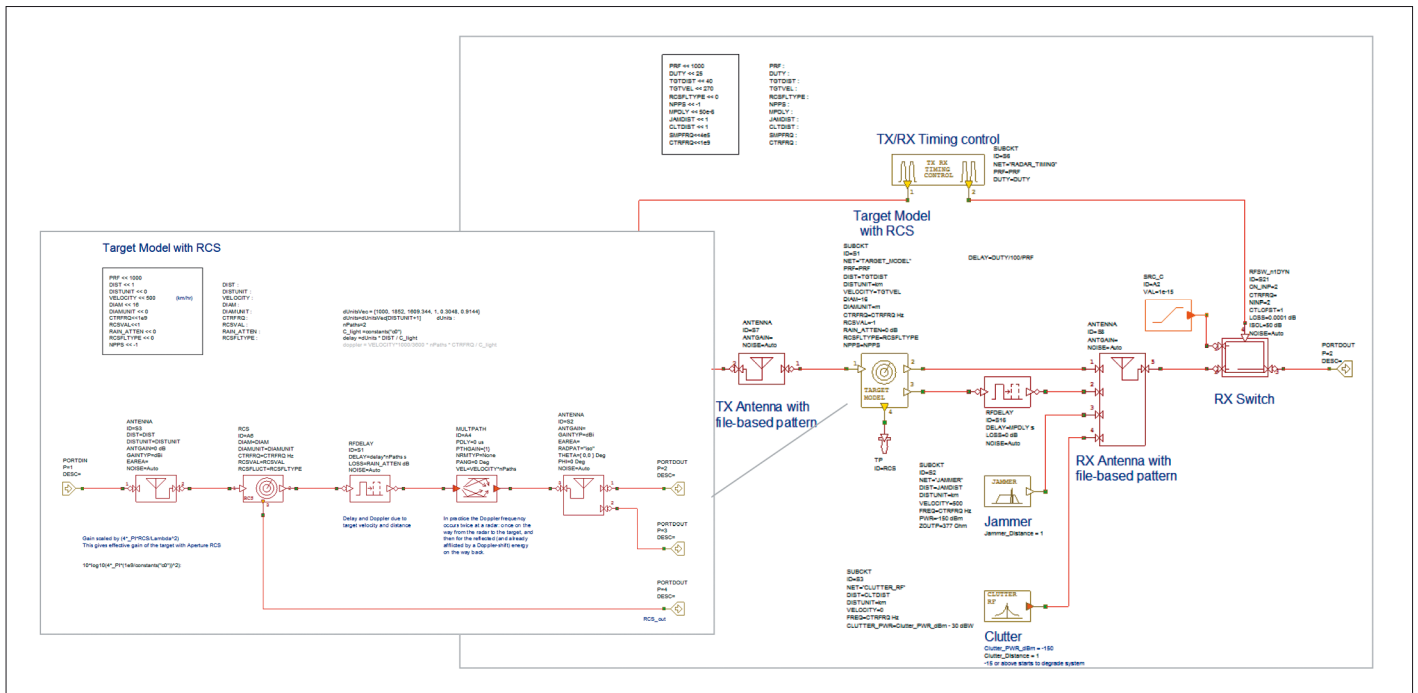


Figure 5: Subcircuit defining transmit and receive antennas, channel, and target with swept distance to radar.



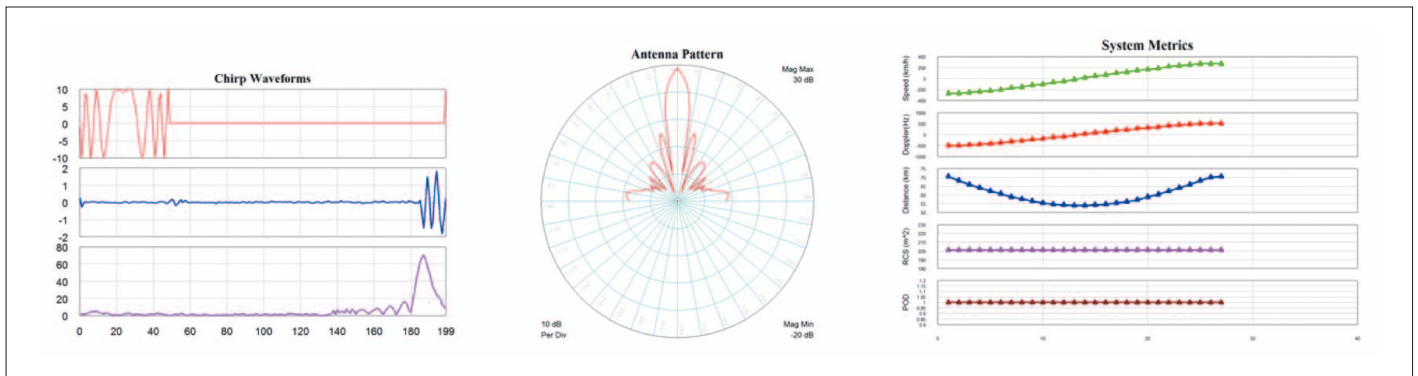


Figure 6: Results of the simulation are shown in the system metrics graph.

radar development for automotive applications and consists of two or more transmit frequencies with an intertwined frequency shift and with a certain bandwidth and duration, as shown in Figure 2.<sup>1</sup>

As previously mentioned, pulsed radars are also widely used in automotive radar systems. Relative velocity can be determined from consecutive pulses using a

coherent transmitter and receiver to measure pulse-to-pulse phase variations containing the Doppler frequency that conveys relative velocity. For a pulsed-Doppler (PD) radar, range is still measured by signal propagation time. To measure both range and relative velocity, the pulse-repetition frequency is an important parameter. There are many tradeoffs to be considered when deciding which architec-

ture and waveform modulation technology delivers the necessary performance while maintaining development and production cost goals. These requirements can be met with VSS system design software, which is dedicated to RF system design and implementation, offering a toolbox of commonly called-for simulation technologies and radio block/signal processing

models, along with support for user-developed coding.

VSS software is an RF and wireless communications and radar systems design solution that provides the simulation and detailed modeling of RF and digital signal processing (DSP) components necessary to accurately represent the signal generation, transmission, antenna, T/R switching, clutter, noise, jamming, receiving, signal processing, and channel model design challenges and analysis requirements for today's advanced radar systems.

The VSS workspace example in Figure 3 demonstrates a possible ACC radar architecture, modulation scheme, channel modeling and measurement configuration. This workspace includes a pulse-Doppler (PD) radar system design with signal generator, RF transmitter, antenna, clutter, RF receiver, moving target detection (MTD), constant false alarm rate (CFAR) processor, and signal detector for simulation purposes. The chirp signal level is set to 0 dBm, PRF = 2 kHz and Duty = 25%. The target model is defined by the Doppler frequency offset and target distance, and angles of arrival (THETA/PHI) are specified in a data file and vary over time. The Doppler frequency and channel delay were generated to describe the target return signal with different velocities and distance, while the radar clutter model can be included, and the power spectrum can be shaped. In this example, the clutter magnitude distribution was set to Rayleigh

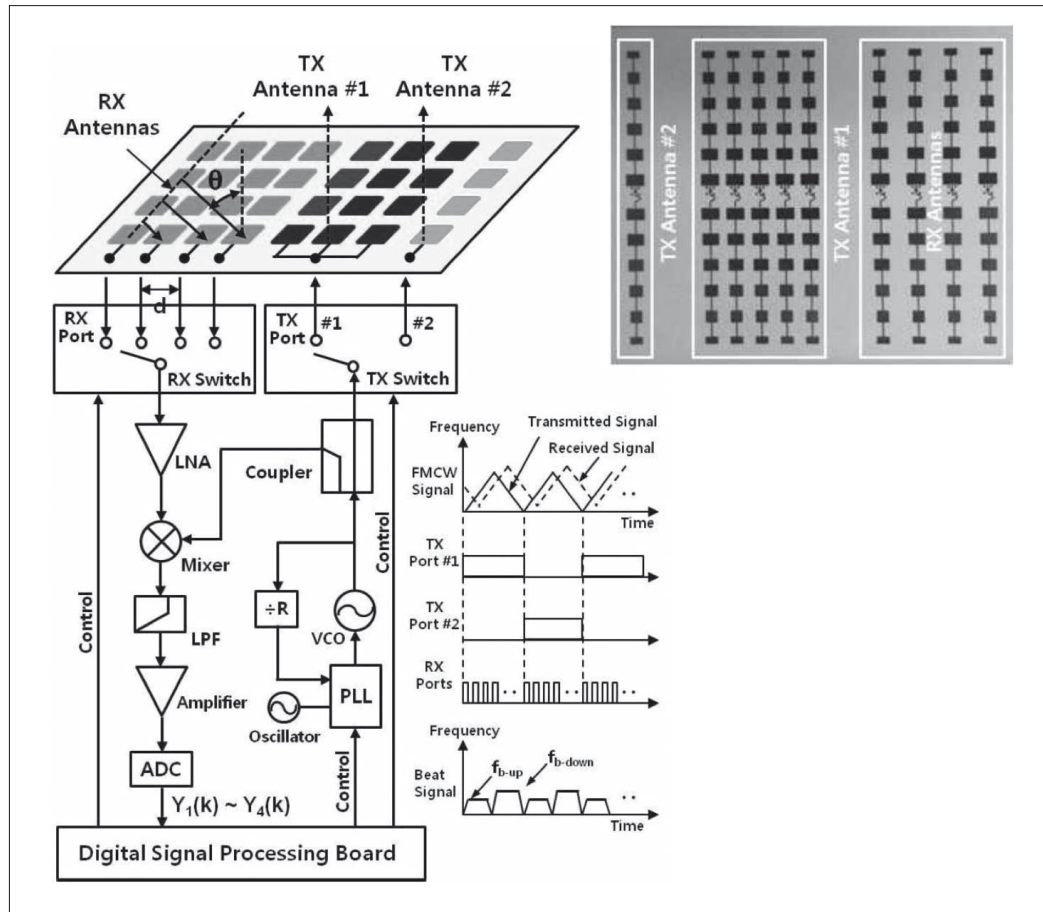
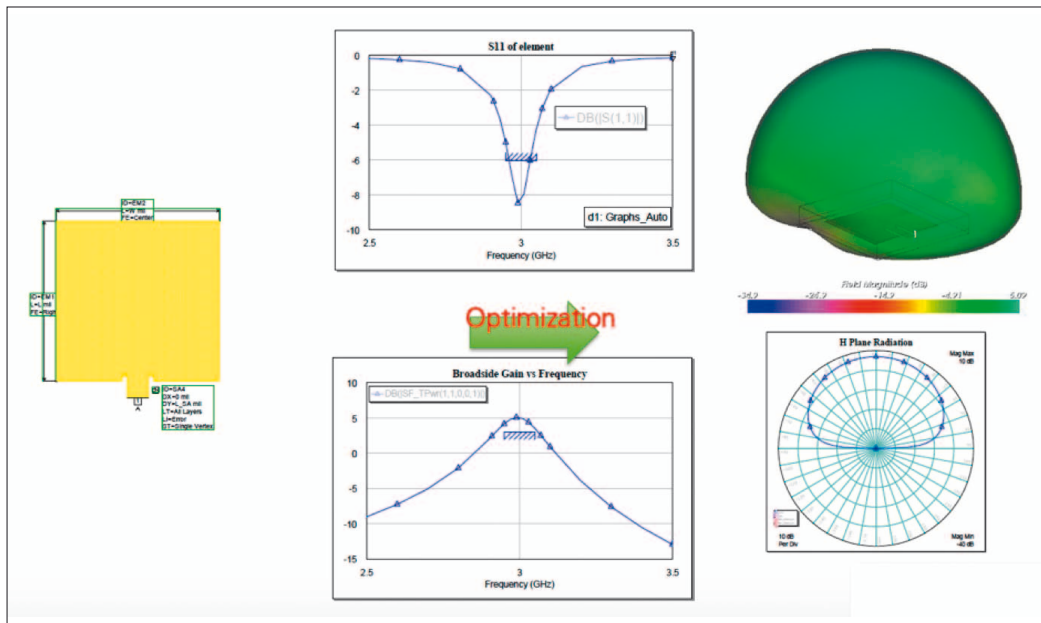


Figure 7: Multi-band, multi-range FMCW digital beam-forming ACC radar.



**Figure 8: Edge-coupled single patch antenna optimized for center return loss and broadside gain.**

and the clutter power spectrum was formed by a Weibull probability distribution.

The RF transmitter in Figure 4 includes oscillators, mixers, amplifiers, and filters, whereas the gain, bandwidth, and carrier frequency were specified based on the requirements of the system or actual hardware performance as provided by the RF design team. Likewise, the

RF receiver includes oscillators, mixers, amplifiers and filters with gain, bandwidth and carrier frequency specified according to the system requirements. Co-simulation with the Microwave Office circuit simulator is possible as the transceiver front-end design details become available. As will be discussed later, the interaction between the transceiver electronics and a beamforming antenna array can

be analyzed via circuit, system, and EM co-simulation.

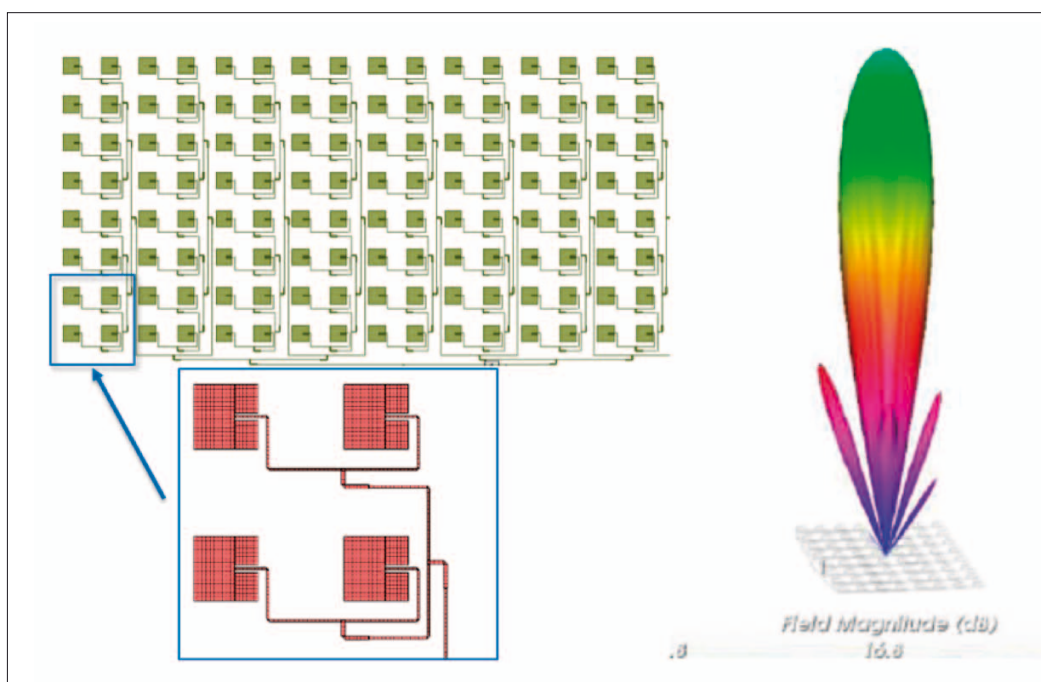
To detect the moving object more effectively, MTD is used. The MTD is based on a high-performance signal processing algorithm for PD radar. A bank of Doppler filters or FFT operators cover all possible expected target Doppler shifts and the output of the MTD is used for the CFAR processing. In this parti-

cular example, measurements for detection rate and CFAR are provided.

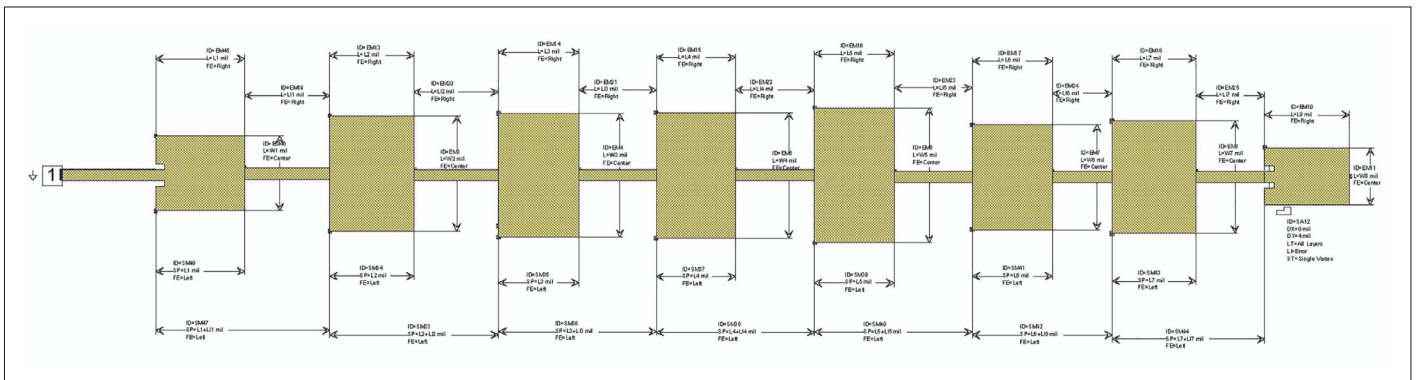
The radar signal waveform must be measured in the time domain at the receiver input. Since the target return signal is often blocked by clutter, jamming, and noise, detection in the time domain is not possible and an MTD is used to perform the Doppler and range detection in the frequency domain. In the MTD model, the data is grouped for corresponding target range and Doppler frequency. Afterwards, a CFAR processor is used to set the decision threshold based on the required probabilities of detection and false alarm, as shown in Figure 5.

This relatively simple design can be used as a template for different PD applications. The radar signal is a function of pulse repetition frequency (PRF), power, and pulse width (duty cycle). These parameters can be modified for different cases. In the simulation, the radar signal also can be replaced by any defined signal through the data file reader in which the recorded or other custom data can be easily used. VSS provides the simulation and model capabilities to refine the radar architecture, implement increasingly accurate channel models (including multi-path fading and ground clutter), and develop performance specifications for the transceiver link budget and detailed antenna radiation pattern requirements.

The plots in Figure 6 show several simulation results, including the transmitted and received chirp waveform, the antenna radiation pattern, and several system measurements, including the relative velocity and distance. In this simulation, the distance to the target is swept to reflect a vehicle that approaches and passes by a stationary radar, resulting in Doppler frequency that reverses the sign from negative to positive (red curve) and produces a null in relative distance as the target passes by the radar. In an automotive radar for ACC, the velocity and



**Figure 9: 8 x 16 patch antenna array (128-element) with corporate feed (single-feed port).**



**Figure 10: Series feed 1 x 8 patch array with parameterized modifiers.**

distance information would be used to alert the driver or take corrective action (such as applying braking).

## Multi-Beam/ Multi-Range Design

A typical ACC stop-and-go system requires multiple short

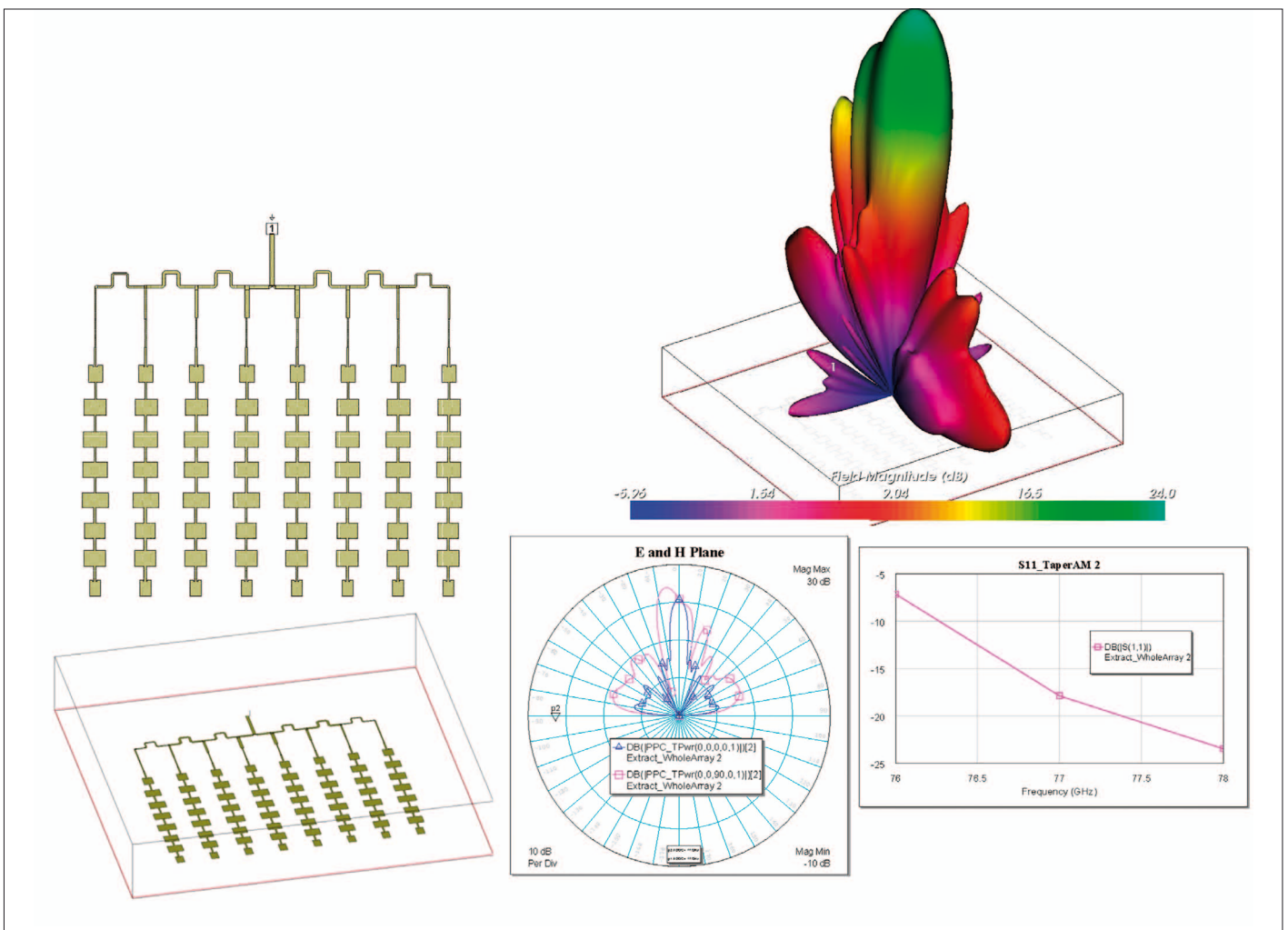
and long-range radar sensors to detect nearby vehicles.

The shorter-range radar typically covers up to 60 m with an angle coverage up to  $\pm 45^\circ$ , allowing the detection of the vehicle's adjacent lanes that may cut into the current travel lane. The longer-range radar

provides coverage up to 250 m and an angle of  $\pm 5^\circ$  to  $\pm 10^\circ$  to detect vehicles in the same lane, further ahead.

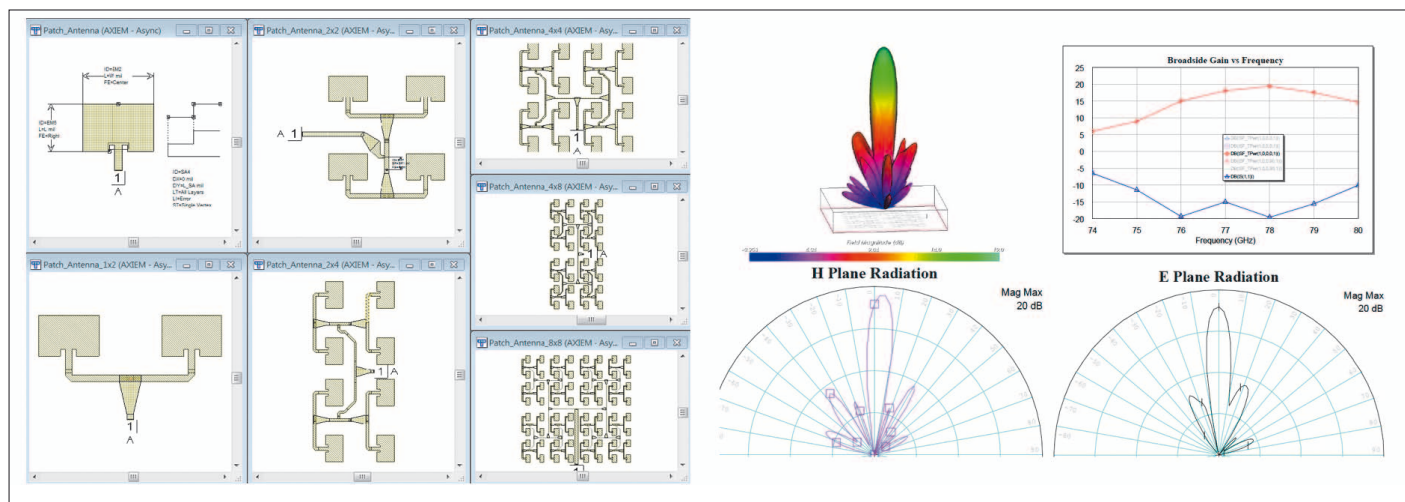
To support multiple ranges and scan angles, module manufacturers such as Bosch, DENSO, and Delphi have developed and integrated multi-range, multi-detect-

tion functionality into increasingly capable and cost sensitive sensors using multi-channel transmitter (TX)/receiver (RX) architectures, as shown in Figure 7. These different ranges can be addressed with multi-beam/multi-range radar by employing radar technology such as FMCW



**Figure 11: 77 GHz 8 x 8 array with  $N*\lambda/2$  feeding with  $\lambda/2 < \text{spacing} < \lambda$ .**





**Figure 12: Simulation of published [2] 8 x 8 patch array on R04003C PCB, approximately 2.3 x 2.5 cm.**

and digital beamforming with antenna array design.

## Antenna Design

A multi-modal radar for an ACC system<sup>2</sup> based on an FMCW radar driving multiple antenna arrays is shown in Figure 8. This multi-beam, multi-range radar with digital beam forming operates at both 24 and 77 GHz, utilizing two switching-array antennas to enable long range and narrow-angle coverage (150 m,  $\pm 10^\circ$ ) and short range and wide-angle coverage (60 m,  $\pm 30^\circ$ ). This example illustrates the use of multiple antenna-array systems, including multiple (5 x 12 element) series-fed patch arrays (SFPA) for long range, narrow-angle detection (77 GHz), a single SFPA (1 x 12 elements designed for 24 GHz) for short, wide-angle detection, and four (1 x 12) SFPA for the receiver that were required for this type of system.

Radar performance is greatly influenced by the antenna technology, which must consider electrical performance such as gain, beam width, range, and physical size for the particular application. The multiple, fixed TR/RX antenna arrays in the example radar were optimized for range, angle, and side-lobe suppression. A patch antenna is relatively easy to design and manufacture and will perform quite well when configured into an array, which results in

an increase of overall gain and directivity.

The performance of a rectangular patch antenna design is controlled by the length, width, dielectric height, and permittivity of the antenna. The length of the single patch controls the resonant frequency, whereas the width controls the input impedance and the radiation pattern. By increasing the width, the impedance can be reduced. However, to decrease the input impedance to 50 ohms often requires a very wide patch antenna, which takes up a lot of valuable space. Larger widths can also increase the bandwidth, as does the height of the substrate. The permittivity of the substrate controls the fringing fields with lower values, resulting in wider fringes and therefore better radiation. Decreasing the permittivity also increases the antenna's bandwidth. The efficiency is also increased with a lower value for the permittivity.

Designing a single patch antenna or array is made possible through the use of design software that utilizes EM analysis to accurately simulate and optimize performance. The NI AWR Design Environment platform includes AXIEM 3D planar and Analyst 3D FEM EM simulators. These simulators not only simulate antenna performance such as near and far-field radiation patterns, input impedance, and surface currents, they also co-simu-

late directly with VSS software, automatically incorporating the antenna simulation results into the overall radar system analysis without the need to manually export/import data between EM simulator and system design tools.

Both AXIEM and Analyst simulators take the user-defined physical attributes of the antenna such as patch width and length, as well as the dielectric properties such as material and substrate height, to produce the electrical response. AXIEM simulator is ideal for patch antenna analysis (Figure 8), whereas Analyst simulator is best suited for 3D structures such as modeling of a coaxial feed structure or finite dielectric (when proximity to the edge of a PCB would impact antenna performance). Figure 9 shows a patch antenna array with corporate feed and 167K unknowns solved in less than 6.5 minutes with a quad core.

To determine the physical attributes that will yield the desired electrical response, antenna designers can use the AntSyn antenna synthesis and optimization module. AntSyn software enables users to specify the electrical requirements and physical size constraints of the antenna and the software explores a set of design configurations and determines the optimum structure based on proprietary genetic optimization and EM

analysis. The resulting antenna geometry can then be imported in a dedicated planar or 3D EM solver such as AXIEM or Analyst simulators for verification or further analysis/optimization.

Planar elements can easily form array structures by combining very simple elements such as microstrip patches. Patches can be configured in a series such as the 1 x 8 patch array in Figure 10, where each element is connected serially by a “tunable” section of transmission line. In this AXIEM project, the lengths and widths of each array element and the connecting transmission lines were defined with variables to allow optimization of the overall array performance.

The 1 x 8 array can be further expanded into an 8 x 8 array for a high-gain fixed-beam design, as shown in Figure 11, replicating the 8 x 8 element array reported.<sup>3</sup>

Within NI AWR Design Environment platform, arrays can be represented in VSS software as a system behavioral block using the proprietary phased-array model that enables designers to specify the array configuration (number of elements, element spacing, antenna radiation pattern, impaired elements, gain tapering, and more) for a high-level understanding of array requirements for desired performance such as gain and side lobes. This approach is best for large-scale arrays (thousands of

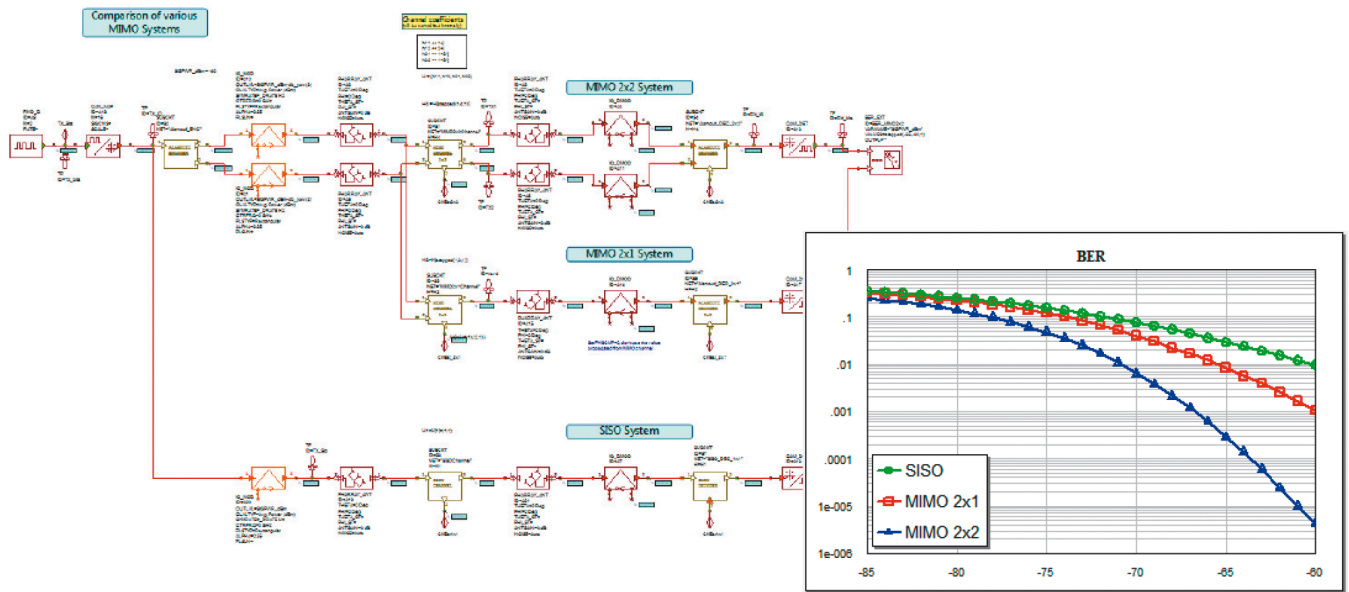


Figure 13: VSS software can implement user-specified MIMO/SIMO algorithms

elements) and system designers developing basic requirements for the antenna array team.

The array can also be modeled with the detailed physical array in AXIEM or Analyst simulators. Individual port feeds can be specified or, if the feed network is also implemented in the AXIEM or Analyst simulator, a single feed network can be specified (Figure 12).

This approach enables the design team to investigate the interaction between the beam angle and the input impedance of each individual element, allowing RF front-end component designers to account for impedance loading effects on transceiver performance. This capability highlights the importance of having RF circuit, system, and EM co-simulation to accurately investigate circuit/antenna behavior before fabricating these complex systems.

## MIMO and Beam-Steering Antenna Technologies

For vehicles, a radar will receive unwanted backscatter off the ground and any large stationary objects in the environment, such

as the sides of buildings and guardrails. In addition to direct-path reflections, there are also multipath reflections between scatterers, which can be used to mitigate the impact of clutter through the use of multiple-input-multiple output (MIMO) antennas.

A MIMO radar system uses a system of multiple antennas with each transmit antenna radiating an arbitrary waveform independently of the other transmitting antennas. Each receiving antenna can receive these signals. Due to the different wave forms, the echo signals can be re-assigned to the single transmitter. An antenna field of  $N$  transmitters and a field of  $K$  receivers mathematically results in a virtual field of  $K \times N$  elements, resulting in an enlarged virtual aperture that allows the designer to reduce the number of necessary array elements. MIMO radar systems thereby improve spatial resolution and provide a substantially improved immunity to interference. By improving the signal-to-noise ratio, the probability of detection of the targets is also increased.

VSS software is able to implement user-specified MIMO algorithms and evaluate the overall

performance as it relates to the channel model, which simulates a highly-customizable multipath fading channel that includes channel path loss, the relative velocity between the transmitter and receiver, and the maximum Doppler spread. Supporting independent or continuous block-to-block operation, the channel can contain multiple paths (LOS, Rayleigh, Rician, frequency shift) that can be individually configured in terms of their fading types, delays, relative gains, and other applicable features.

This module can also simulate a receiver antenna array with user-defined geometry, enabling simulation of single-input-multiple-output (SIMO) systems, as shown in Figure 13.

## Conclusion

This application example has discussed ADAS design challenges and examples have been presented demonstrating how the radar design capabilities within VSS software help designers with overcome these roadblocks. ADAS are becoming more and more prevalent in most vehicles and continued research and development is driving more sophistication and reliability. Advan-

ces in simulation technology like the NI AWR Design Environment platform, particularly in RF-aware circuit design, array modeling, and system-level co-simulation, will enable antenna designers and system integrators to optimize these systems for challenging size, cost, and reliability targets.

- 1 Rohling, Hermann; Meinecke, Marc-Michael, "Waveform Design Principles for Automotive Radar Systems," Technical University of Hamburg-Harburg, Harburg, Germany, Proceedings, 2001 CIE International Conference on Radar.
- 2 H. Jeong, H. Y. Yu, J. E. Lee, et. al., "A Multi-Beam and Multi-Range Radar with FMCW and Digital Beam-Forming for Automotive Applications," Progress in Electromagnetics Research, Vol. 124, 285-299, January 2012
- 3 Jri Lee, Yi-An Li, Meng-Hsiung Hung, and Shih-Jou Huang, "A Fully-Integrated 77-GHz FMCW Radar Transceiver in 65-nm CMOS Technology," IEEE Journal of Solid-State Circuits, Vol. 45, No. 12, December 2010. ◀