CASE STUDY

Designing Next-Gen Distributed 5G Vehicular Antennas

Virtual environment for modeling and simulation guides configuration choices before chamber and road tests

KEYSIGHT

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Getting Ahead of 5G Performance on the Road

Organization

- Molex Connected Mobility Solutions (CMS)

Challenges

- Moving from a “shark fin” package to four separate antennas in various locations within the vehicle
- Addressing physical spacing and properties of materials like glass and carbon fiber
- Combining different design domains – electromagnetic, RF, and baseband – in one simulation environment

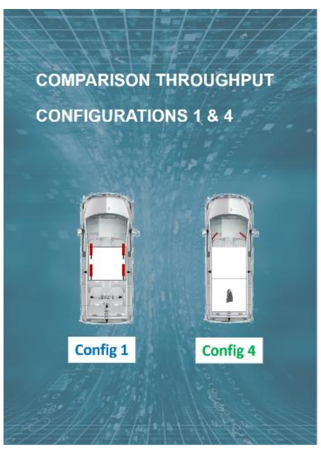
Solutions

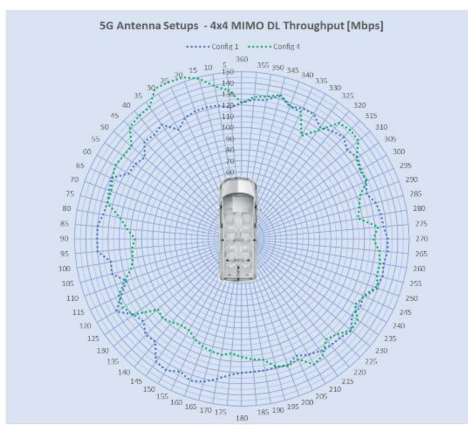
- Integrate a virtual 5G antenna design environment using Keysight SystemVue and Keysight 89600 Vector Signal Analyzer in a model-based system engineering approach
- Leverage technology and services from the Keysight ecosystem including test and measurement equipment, KeysightCare, and third-party component modeling
- Blend 3GPP 5G statistical channel models with baseline anechoic chamber measurements into fast, accurate simulations

Results

- 8 hours to perform a 360° scan in simulation
- 4x4 MIMO configuration performs best
- Compression/decompression improvements

Molex Connected Mobility Solutions (CMS), with headquarters in Rochester Hills, Michigan and engineering teams in sites across Germany, is transforming vehicular antenna technology for 5G communication on the road, with an eye toward vehicle-to-everything (V2X) applications and non-terrestrial networks (NTNs). Molex distributes 5G antennas around the vehicle, offering auto manufacturers more aerodynamic, aesthetic antenna choices while improving beamforming for delivering the 5G network experience.





In a little over two years, a core team of five engineers, plus five others across the organization and several Keysight customer engineering team members, Molex developed a virtual vehicular antenna design environment built around Keysight SystemVue to analyze distributed antenna performance quickly and accurately in a range of configurations and conditions.

Challenge: Hiding antennas, yet increasing performance

Modern vehicular antenna design reflects the tension between two design camps with partially overlapping objectives. Auto manufacturers want streamlined, near-invisible antennas that add minimal aerodynamic drag to a vehicle. They are also concerned with manufacturability; antenna placement choices can impact secure attachment, reliable electrical connection, and ease of repair. Antenna designers prioritize 5G performance while working within auto manufacturer constraints. Physical separation between antennas improves reception diversity, MIMO (multiple input, multiple output) performance, and beamforming potential but makes connectivity more challenging.

Molex specializes in the science of concealing a variety of vehicular antennas (for functions shown in Figure 1) while designing subsystems delivering the performance drivers and automakers expect. “Designing 5G antennas for automotive applications isn’t like designing 5G antennas for smartphones,” says Alexander Herold, Staff Engineer, RF, at Molex. “Our idea for virtual vehicular antenna design stems from the difficulty and inflexibility of real-world vehicle hardware prototypes and anechoic chambers big enough to fit a car, truck, or SUV that are expensive to build and operate.”

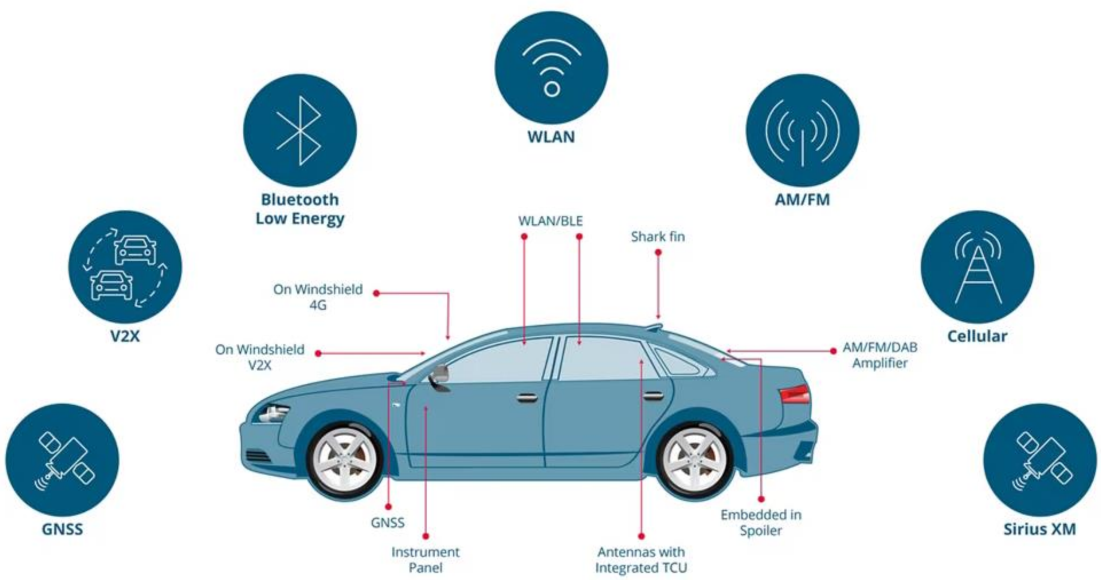


Figure 1. Various antennas support many wireless communication systems in and around a typical vehicle

5G forces designers to revisit the familiar roof-mounted “shark fin” antenna of earlier cellular generations. 3^{rd} Generation Partnership Project (3GPP) 5G specifications define massive MIMO schemes using up to eight antennas to increase effective channel capacity between 5G UE (user equipment) and a 5G gNodeB (formerly known as base station) under good signal conditions.

“At Molex, we’ve made a strategic decision to get deeper into predictive analysis and simulation,” says Ryan Price, Director of Strategic Marketing for Transportation Innovative Solutions at Molex. “For antennas, we don’t have to invest as much capital in testing – we can use software to define and investigate a variety of configurations, work out the details, and then invest in the right solutions.” Price also points out that automakers tend to have their own preferences, so more than one configuration helps in a competitive market.

Near-invisibility of antennas means conformal or concealed designs and potential electromagnetic (EM) interactions with surrounding materials. “We’re seeing more exotic materials, like glass with metallic element reinforcement and carbon fiber composites, not to mention traditional metal structures, which can alter antenna performance,” says Herold. “We have to space distributed antennas several wavelengths apart to keep them from interfering with each other in transmit mode, but too much spacing results in signal loss, increased noise, and phasing problems.”

Matching real-world measurements poses another challenge for complex simulation. Herold’s team could draw on anechoic chamber and road test results to form a baseline. Replicating channel behavior in rural, urban canyon, and other driving scenarios would require innovation around those use cases. Herold’s team took on the challenge of unifying three domains – EM, high-frequency RF, and baseband – in one simulation environment that could provide equivalent results to physical testing.

Solution: Integrated, model-based system design

The idea for the Vehicle Digital Antenna System (VDAS) environment started with existing Molex modeling and simulation done in Simulink, a graphical-based modeling and automatic code generation tool for MATLAB. “Model-based system engineering (MBSE) tools are easier and more productive for people with a hardware background who don’t code as frequently,” observes Herold.

GNU Octave was considered and then discounted due to its limited integration capability. Molex had two other tools in its workflow: Keysight 89600 Vector Signal Analyzer (89600 VSA) and Ansys HFSS. “The 89600 VSA is the crucial link between our simulations and our testing and integration,” says Herold. Flowing antenna patterns from HFSS directly into a system simulation environment would also save time.

Keysight SystemVue, an integrated MBSE design and simulation environment, emerged as the winning choice. (For more information on SystemVue and MBSE, read the solution brief “Creating Digital Twins of RF Systems” cited later.) Figure 2 shows an overview of the VDAS RF co-simulation in SystemVue.

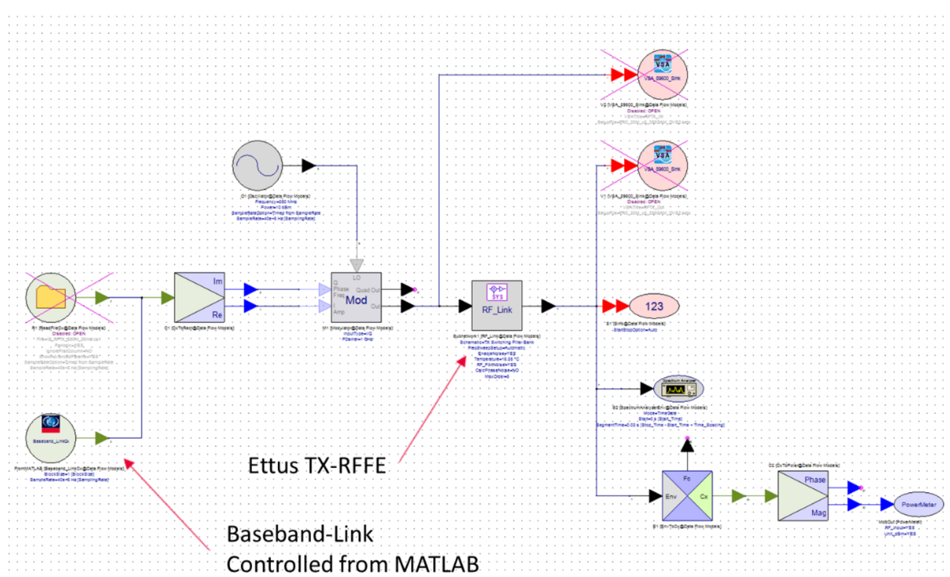


Figure 2. VDAS system model with imported blocks for digital baseband and transmitter RF front-end functions

An Ettus N300/N310 Software Defined Radio provides the transmitter RF front-end and power amplifier in the physical VDAS system. Its detailed SystemVue block in the virtual system includes behavioral models for Skyworks, Qorvo, and other third-party RF components inside.

Figure 3 shows a model for a 5G-NR PUSCH (Physical Uplink Shared Channel) input signal in SystemVue. CCDF (Complementary Cumulative Distribution Function) and noise density blocks add real-world effects to the modulated signal. Figure 4 shows the 89600 VSA plots for the PUSCH signal.

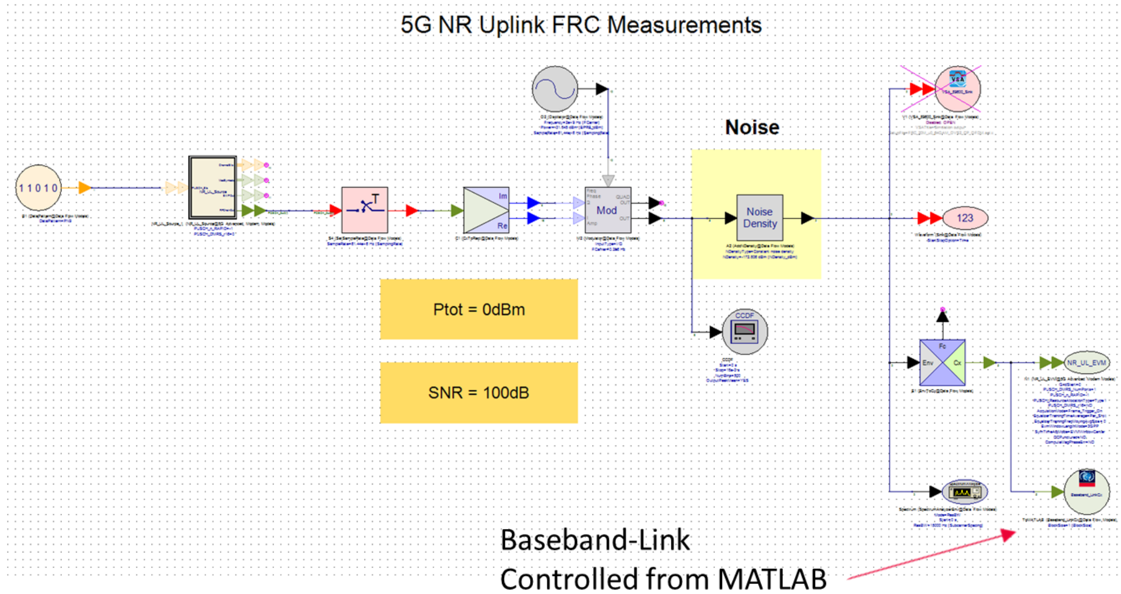


Figure 3. SystemVue model for generating a 5G-NR PUSCH signal

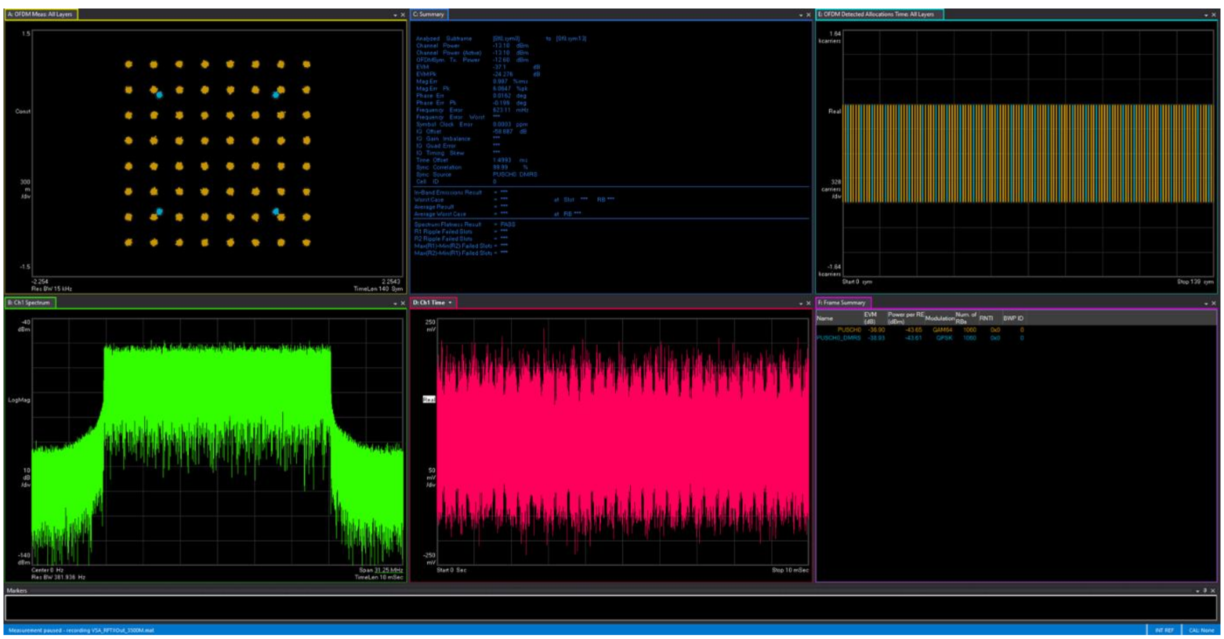


Figure 4. 89600 VSA time and frequency domain plots for 5G-NR PUSCH signal with 64-QAM modulation

Figure 5 shows the digital baseband link imported as a Simulink block into SystemVue models, with an Analog Devices AD9371 transmitter block as a library component. Another block contains Molex-designed VHDL for the digital link compression and decompression, reducing data rates to and from each 5G antenna.

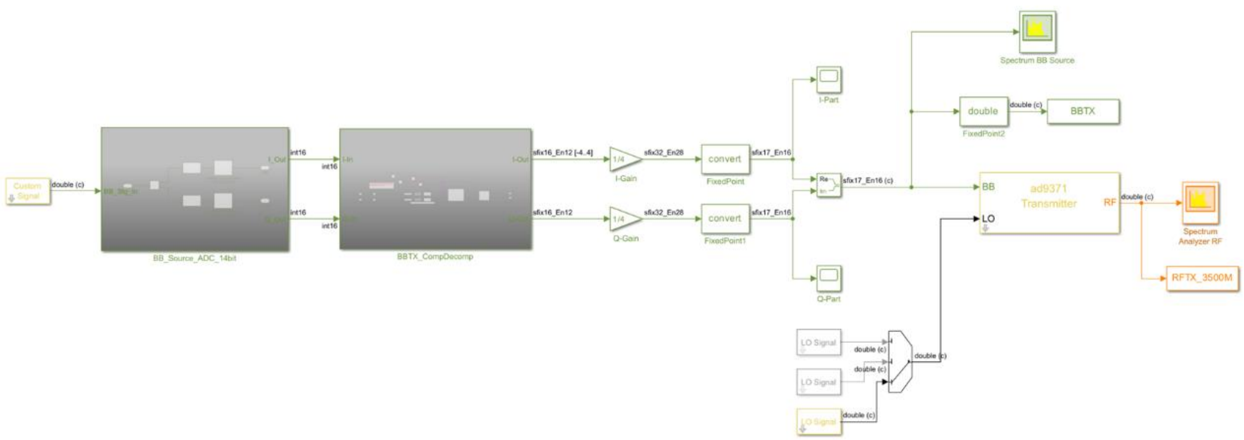


Figure 5. Model for the digital baseband link with custom compression/decompression, imported into SystemVue

With the digital baseband and RF transmit signal chains modeled, Herold's team turned to the final modeling detail: simulating channel variations in different road environments. "For channel simulation, we use statistical models specified by 3GPP tuned with our anechoic chamber measurements," says Herold. "We implemented the 5G NR clustered delay line (CDL) model, which has configurations for rural / long-range and urban / dense urban scenarios."

Results: 4x4 MIMO outperforms, especially in rural

VDAS simulations in SystemVue run a 360° view around the vehicle, with 180 samples at incremental 2° scan angles, and can vary signal-to-noise ratio. A six-core server runs a complete analysis in about 8 hours, using parallel processing options for parameter sweeps in SystemVue.

Three metrics dominate the analysis: throughput, bit error rate (BER), and EVM. "We could see when antennas were set closer together, such as two antennas in a shark fin, performance degrades," shares Herold. "A 4x4 MIMO configuration with antennas spaced several wavelengths apart performed better." Simulations also lead to adjustments in the digital link compression/decompression algorithms. "We could also see how hard we could compress antenna data before performance drops – and it varies as antenna placements change." Since Molex uses Keysight Advanced Design System (ADS) and RFPro for electronic hardware layout and EM / circuit simulation, tool integration with SystemVue simulations may inform more hardware design improvements.

"Our virtual environment is exponentially saving cost and time because we can now do a complete analysis of distributed vehicle antenna configurations without building any hardware," says Herold.

Figures 6 and 7 compare throughput in rural and urban scenarios, and Figure 8 shows throughput versus weighted antenna gain – all highlighting the advantage of the distributed 4x4 MIMO configuration.

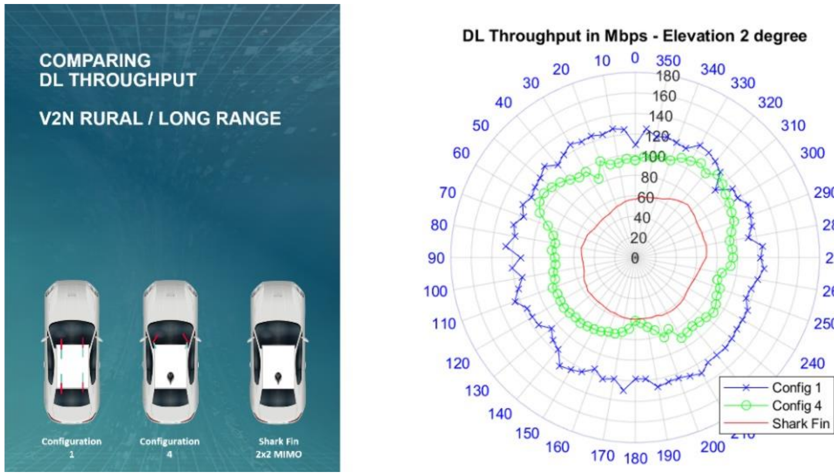


Figure 6. 5G throughput in rural scenario for 4 distributed antennas versus a 2-antenna shark fin and a hybrid

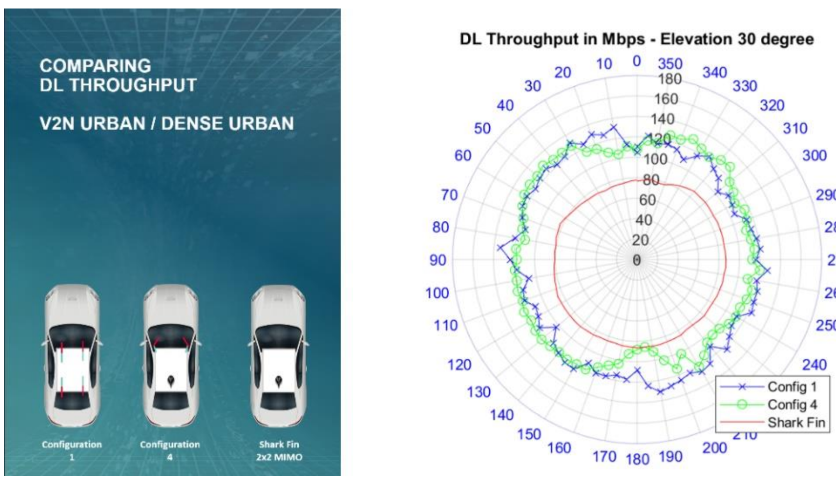


Figure 7. 5G throughput in urban scenario for 4 distributed antennas versus a 2-antenna shark fin and a hybrid

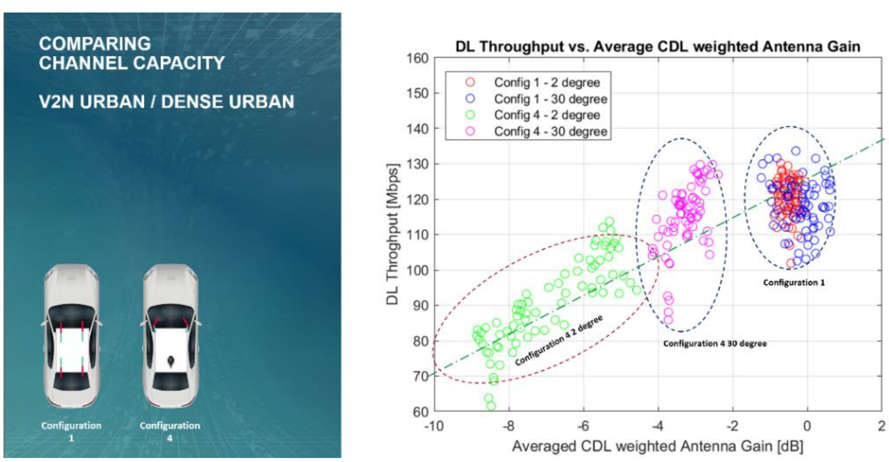


Figure 8. Throughput versus weighted antenna gain illustrates the advantage of 4 distributed antennas

Applying MBSE and virtual system simulation to the challenges of distributed 5G vehicular antennas puts Molex in a position to have productive, data-based conversations with auto manufacturers well before they create advanced vehicle prototypes when they can still optimize configurations.

> “Our virtual environment is exponentially saving cost and time because we can now do a complete analysis of distributed vehicle antenna configurations without building any hardware.”
>
> **Alexander Herold, Staff Engineer, RF, Molex**

During the design and setup of the virtual 5G antenna design environment using Keysight SystemVue and the Keysight 89600 Vector Signal Analyzer, Keysight Services such as in-depth technical training classes and KeysightCare Technical Support backed the Molex engineering team through all phases of the project.

> “We rely on various digital tools, modeling, and simulations, including solutions and services from Keysight Technologies, an innovator in software-centric design, emulation, and test solutions, to develop virtual vehicular antenna design environments in different configurations and conditions—before moving forward with prototypes. The KeysightCare technical support and training was a key reason why we were tying PathWave SystemVue into our simulation project to accelerate our innovation.”
>
> **Scott Whicker, SVP & President, Molex Transportation Innovative Solutions**

Looking ahead: More connections, better channel detail

The VDAS project gives Molex a platform for incremental design. Teams can add capability for V2X and 5G NTN – and 6G networks in the future – by studying distributed antenna behavior in virtual space.

Molex CMS teams identified more possibilities after investing in an initial SystemVue learning curve, including stints in several Keysight online and in-person 5G NR and SystemVue training courses. They indicate that SystemVue and 89600 VSA need future support for V2X features, especially as autonomous vehicles gain momentum. Ray tracing support for channel modeling and AI-based channel modeling (where Keysight research is already underway) would also be helpful.

Related information

Keysight RF EDA solutions

PathWave System Design (SystemVue)

Creating Digital Twins of RF Systems

PathWave Advanced Design System (ADS)

PathWave RFPro

KeysightCare Service and Support

Molex connected vehicles antenna solutions

https://www.molex.com/en-us/products/automotive-connectivity/vehicle-antenna-solutions

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All figures courtesy of Molex Connected Mobility Solutions