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Improve TPMS Design Flow with Circuit Design Software and EM Verification

To meet the latest performance requirements for tire-pressure monitoring systems, designers are turning to high-frequency design software.

Automobile safety concerns are increasing worldwide, which has led many countries to issue legal mandates that encourage a variety of car safety features. One such system, the tire-pressure monitoring system (TPMS), offers as a very effective way of reducing single-car accidents caused by insufficient tire pressure. TPMS systems not only actively measure actual tire pressure, but many also sense temperature and can wirelessly report sensor data to the automobile's computer.

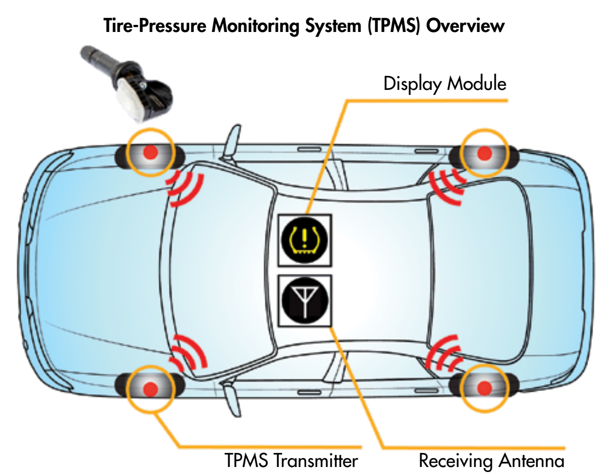
As performance demands on car electronics intensify, integrated design environment tools can enable more efficient and robust designs. Sensata Technologies, a sensing and controls company in Attleboro, Mass., employed RF/microwave circuit design software to meet the performance and optimization challenges for its TPMS system.

This article describes how the design team used Microwave Office circuit design software, as well as the AXIEM 3D planar electromagnetic (EM) and Analyst 3D finite-element method (FEM) simulators, to enhance the design process and optimize the system's performance. Planar EM simulation, Monte Carlo analysis using load-pull techniques, parametric optimization with component swapping, and EM environmental disturbance analysis were all performed within the single integrated environment.

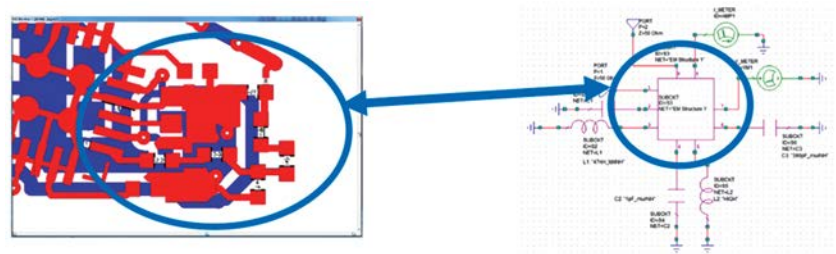
TPMS DESIGN CHALLENGES

Active TPMS technologies must be installed and operate on, or within, the tire. The latest active TPMSs are wireless devices that can monitor several critical tire conditions and provide timely updates to the car's computer *(Fig. 1)*.

Being located on or within the tire, a TPMS will be subjected to adverse weather conditions, corrosion, physical obstructions, and dirt/grime from road and car conditions. Therefore, TPMS systems must be extremely rugged and reliable. They must also continue to operate for several years after installation. Most TPMS must rely on non-replaceable battery power, which requires very low standby current drain and low-power sensing/transmission to extend the battery life. The extremely wide temperature, pressure, and physical forces in which the TPMS must operate often significantly impact circuit behavior and performance. For TPMS to meet rigorous quality standards, the design must perform within specification over –40 to 125°C.



1. This is an overview of a tire-pressure monitoring system.



2. The printed-circuit-board's physical model was imported as a subcircuit in the circuit design software.

From an EM perspective, the constant rotation of the wheel, the metallic wheel structure, electromagnetic interference (EMI), radio-frequency interference (RFI), and a non-ideal antenna structure are all factors that will negatively impact the performance of an active TPMS using RF communication technology. Additionally, to meet worldwide RFI and EMI regulations, the TPMS must be designed to avoid any harmful or disturbing radiation. This requires complying with over 30 RF regulations, which puts a burden on the harmonic filtering and circuit design.

These factors place a high standard and burden on TPMS circuit design, component choices, impedance matching, and optimization. Size, weight, power, and cost (SWaP-C) must all be very low to avoid impacting the wheel balance and reduce automobile production costs. Because yield contributes to the profitability of a manufacturing process, these devices must also take production variations into account.

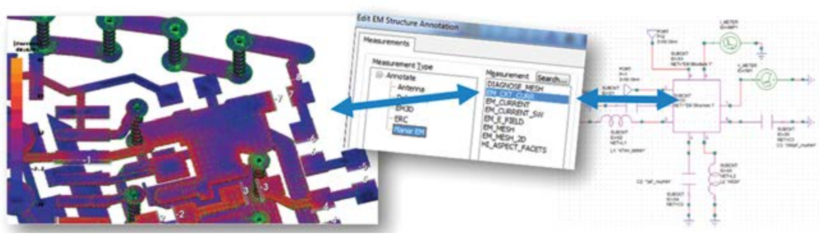
Component parasitics, as well as physical characteristics of the PCB and components, aren't negligible in a TPMS. Thus, the design tools used to select and optimize circuit components must account for the EM behavior and circuit simulation behavior under an expanse of conditions. This requirement demands design tools that are both sophisticated and highly reconfigurable/customizable in order to enable refined adjustments and detailed analysis techniques.

PCB ANALYSIS

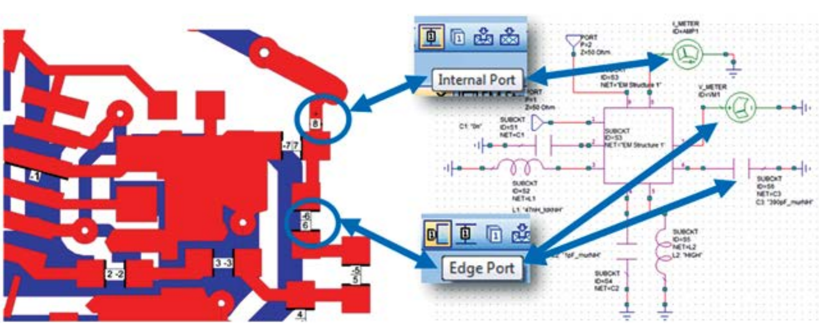
The size and weight constraints of a TPMS require a small printed-circuit-board (PCB) area; however, cost structures limit the use of custom technologies. Furthermore, TPMS systems are completely contained, along with onboard power, in a single sealed device embedded with the pressure valve in a tire. Therefore, careful design of the sensing, control, and RF electronics is often implemented using standard surface-mount-technology (SMT) in highly compact layouts.

However, the parasitics introduced by the close-knit PCB traces will affect the component parameter optimization and RF performance. Hence, the PCB trace leads must be carefully modeled and accounted for before selecting optimal inductor, capacitor, and resistor components.

To overcome these challenges and begin the optimization process, Sensata's engineers imported a DXF file of the PCB traces into the circuit design software. The PCB traces were imported as a subcircuit component *(Fig. 2)*, which was then simulated in a virtual testbench that provided flexibility in probing voltages and currents using AXIEM.



3. Planar electromagnetic simulation allowed current densities to be visualized.



4. Edge ports were created to monitor components and voltages/currents throughout the circuit.

Once inside the tool, planar simulation was used to visually analyze current densities within the EM structure *(Fig. 3)*. Additionally, edge ports were created in the EM simulator that revealed voltages between different circuit sections, currents along specified PCB tracks, and component locations that would later require optimization *(Fig. 4)*. The designers were able to ensure a proper meshing of the geometry using a built-in "snap-to-grid" function *(Fig. 5)*. This solved the predominantly high aspect ratio meshing issues with only negligible modification of the geometries of the PCB traces.

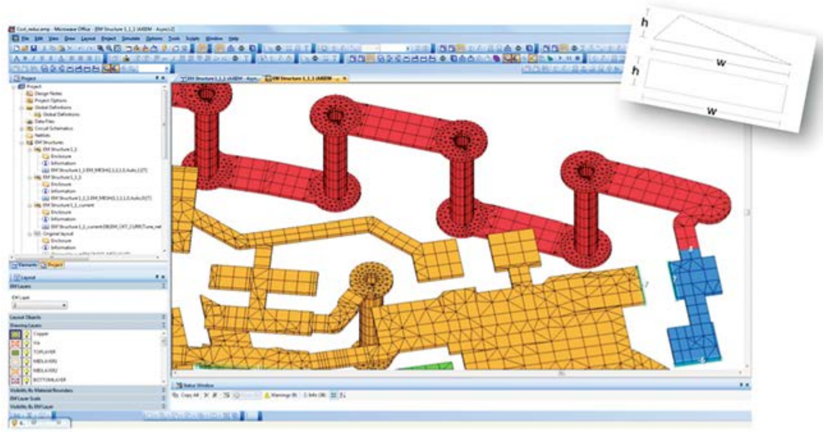
Along with the TPMS PCB optimization, the EM simulator was used to optimize the design of the TPMS antenna. The antenna size, weight, and efficiency were an extremely delicate balance in this design. The engineers used shape modifiers and optimization routines in the simulator, allowing the optimum structure for the antenna to be designed while still meeting impedance, radiation pattern, and efficiency goals.

RF CIRCUIT SIMULATION

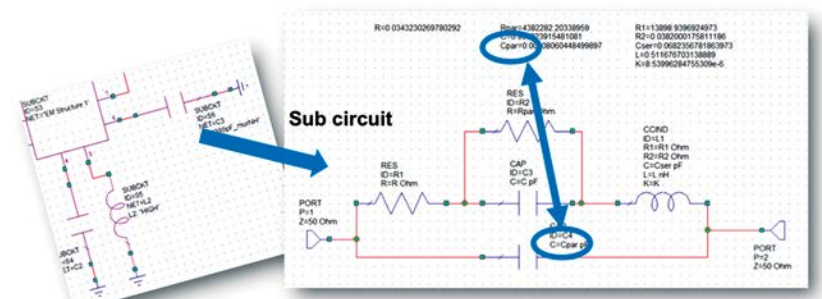
Once the simulator contained a complete PCB trace structure with port assignments, the external components were modeled and values were optimized to meet design specifications. Intent on leveraging a detailed Monte Carlo analysis, the engineers modified each component internally to enable the statistical analysis.

While many applications may not require the level of optimization depth that was employed in this design, the reliability and robust operating requirements of a TPMS sensor in an automotive environment demand a design that can perform in a wide range of environmental factors and up to 10 years on a single battery. Therefore, the multilevel component selection, optimization, and analysis phases were necessary to meet quality and reliability standards.

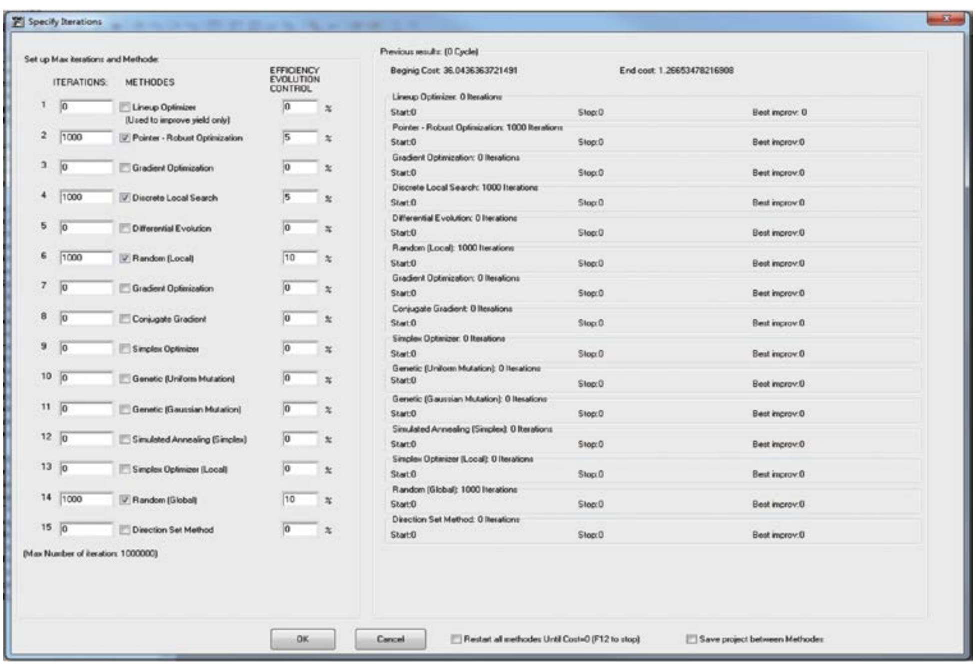
The designers used optimization features in the Microwave Office software to avoid the painstaking task of running a batch of simulations with a wide range of component values from different manufacturers. These features enabled the designers to swap components among a full library containing detailed performance data for each component *(Fig. 6)*. In applications that need very precise impedance matching, power transfer, or filtering, this feature has the potential



5. The "snap-to-grid" feature can help solve traditionally time-consuming, complex meshing issues.



6. The circuit design software is able to import component models, which can be modified to enhance the performance of the circuit.

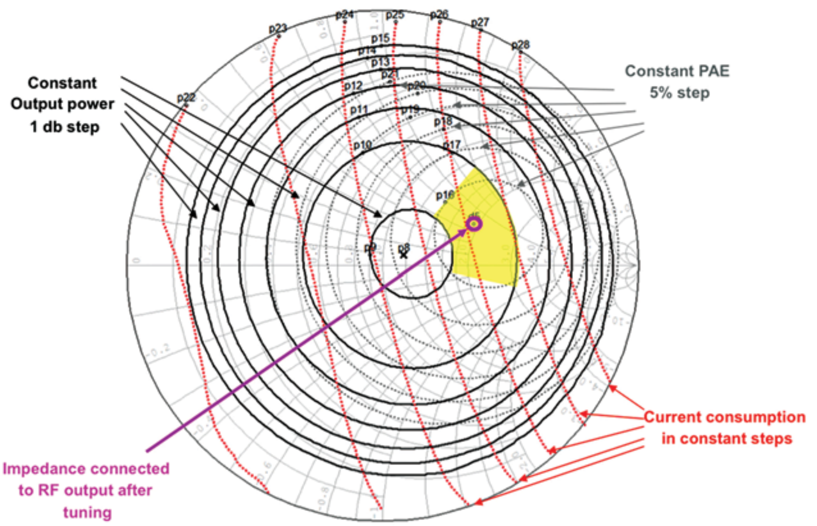


7. A custom Visual Basic script was created that automatically cycled through different methods and controlled the optimization iterations.

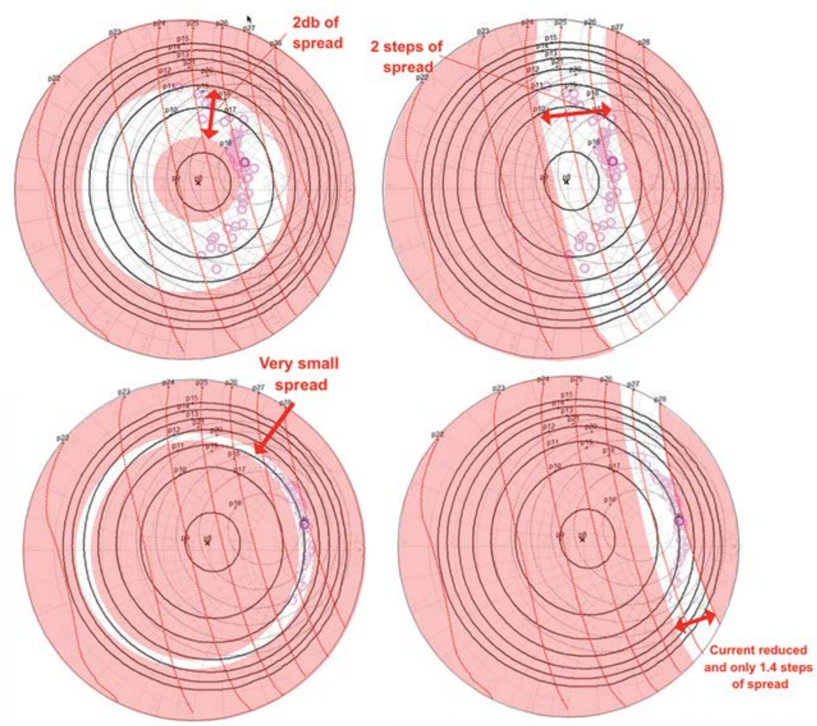
to dramatically reduce design times and parts sourcing challenges during prototyping.

However, out of the box, the Microwave Office optimizer was only able to tune the RF network with discrete optimization methods. Because the designers were interested in a rigorous statistical approach, the team built models that could sweep component values continuously, while maintaining the parasitic elements.

To further enhance the optimization, the designers leveraged the script automation capability of the optimizer and built a visual basic (VB) script that automatically cycled through different optimization methods and control iterations *(Fig. 7)*. This approach circumvented time-consuming and error-prone guess-and-check, as well as increasing the number of optimization configurations that could be explored.



8. Monte Carlo analysis of the load-pull measurements of a matching network can demonstrate performance over a wide range of parameters.



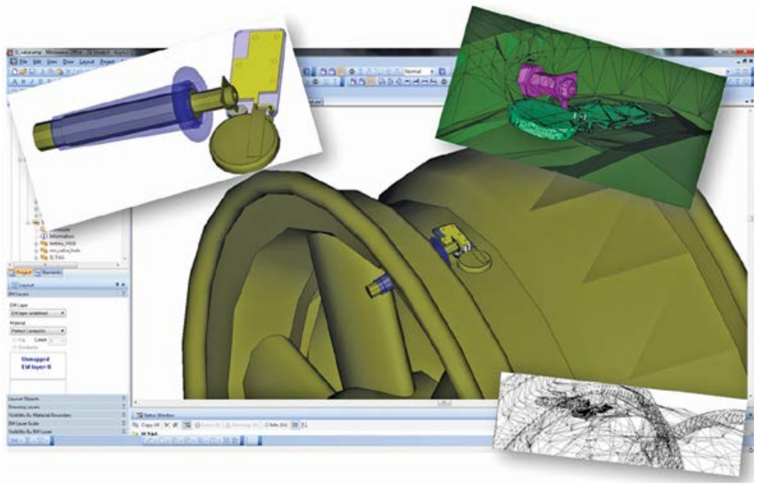
9. The custom method approach leveraging optimization substantially improved the current and impedance spreads over the range of analysis parameters.

MONTE CARLO ANALYSIS

Understanding the full spread of the circuit's operational dynamics helps lead to a maximally efficient end design. Most TPMS have non-serviceable batteries and rely on highly efficient designs to prevent the constant need of replacing the component, making power consumption and transmitter efficiency among the utmost concerns in this design. Accurate simulations of power-added efficiency (PAE) and current consumption at various output power levels of the optimized impedance-matching circuit cut the number of prototypes and tests needed to verify the design.

A Monte Carlo analysis was performed for spread and stability assessment and improvement using a load-pull measurement technique *(Fig. 8)*. The statistical variation of the SMT component values could have led to non-optimal performance if the circuit design wasn't robust. Thus, the Monte Carlo analysis might have revealed the need to redesign or identify component combinations that should be avoided in manufacturing. Ultimately, this approach increased the yield and overall reliability of the end product.

The analysis was performed both with and without optimized network matching as a control experiment to justify the investment in enhancing the design processes with such a sophisticated optimization process *(Fig. 9)*. The end results of the optimized impedance matching were a decrease of roughly 1.5 dB in the ideal transmitted power and almost two steps of current-consumption reduction as compared to the ideal component values. The Monte Carlo analysis also revealed a decrease of 0.6 steps of current consumption spread and a decrease of over 1 dB of output power spread over the full range of statistical variation. These results indicate greatly improved overall power efficiency over statistical component variations, which directly impacts the lifetime of the TPMS.

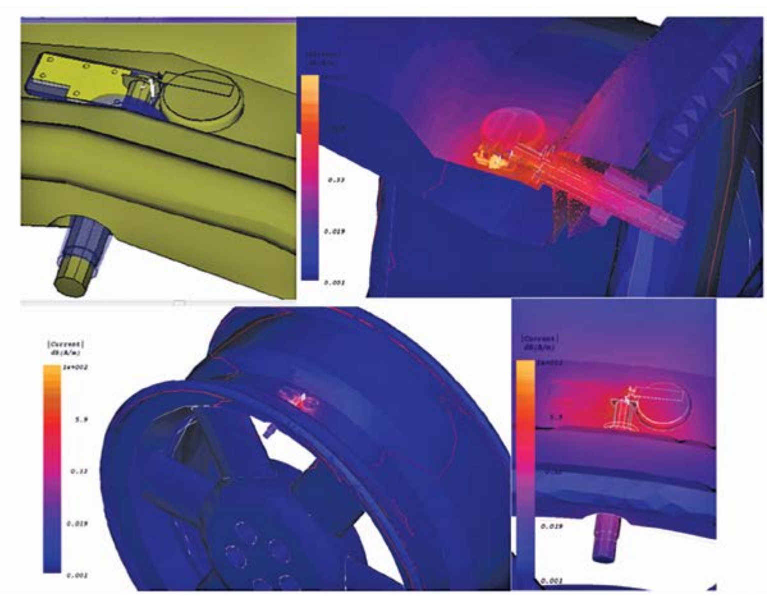


10. Finite-element method simulation was utilized to demonstrate the effects of several environmental factors.

ENVIRONMENTAL DISTURBANCES ANALYSIS

The external environmental parasitics introduced in a final assembly also can significantly affect TPMS efficiency and performance. Though the impedance-matching circuitry optimization revealed substantial internal enhancements, the designers went a step further and simulated a car wheel and TPMS model in the Analyst simulator to explore environmental effects *(Fig. 10)*. The simulation results revealed current patterns, antenna radiation patterns, and even component physical-body effects on PCB trace performance.

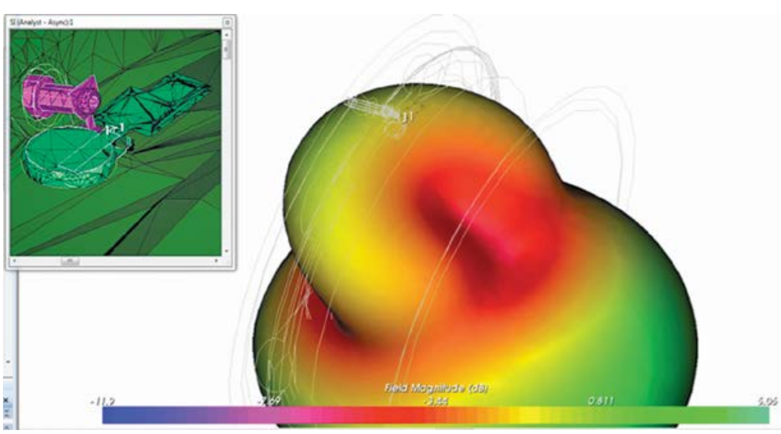
A physical model of the complete TPMS assembly installed within a wheel was used to analyze the current distribution during TPMS transmitter operation. The simulation showed significant current on the inside of the wheel rim that would most likely affect the transmitter performance and radiation pattern of the valve antenna *(Fig. 11)*.



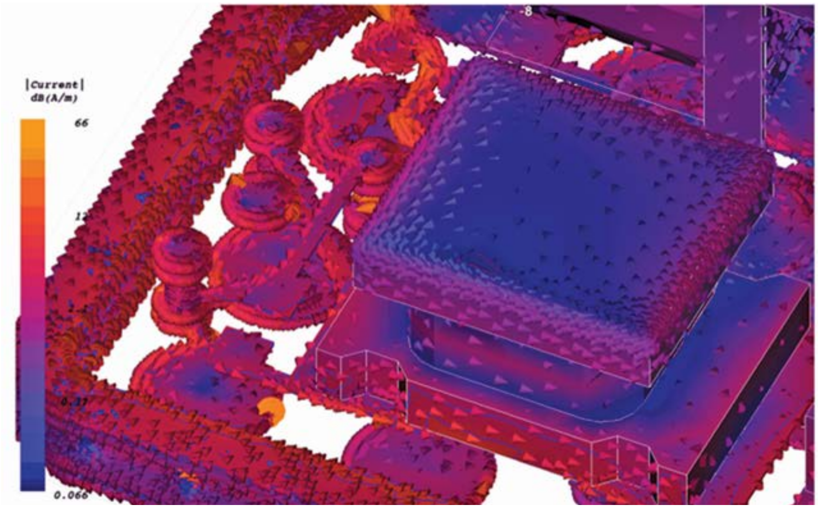
11. The close proximity and metallic nature of the wheel rim introduce reflections and disturbances that must be gauged to ensure design requirements.

The impact of the wheel body and rim on the antenna radiation pattern is observed as a 3D intensity map in the simulator *(Fig. 12)*. A tandem window display shows the physical model's orientation and interaction alongside the antenna radiation pattern to help understand the implications of the wheel's EM influence.

The analysis reveals that only a small portion of the wheel body and rim impact the TPMS sensor behavior. A smaller parametric shape subsection of the wheel and TPMS assembly were used for more detailed simulations. Otherwise, the computational resources for the rather large wheel assembly would limit the resolution of the simulation.



12. 3D mapping of the antenna radiation pattern offers insight into how well the car receivers pick up the tire-pressure monitoring system transmissions.



13. 3D modeling of the physical components takes into account the packaging parasitic effects.

This is especially important when analyzing the effect of SMT component bodies when installed on the PCB tracks. Unpredicted current losses from parasitics could be identified and designed around that, helping prevent undesirable inefficiencies and internal interference.

CONCLUSION

The use of a single integrated design environment, inclusive of circuit design software and EM planar and 3D FEM simulators, was critical in streamlining the design flow and enhancing optimization of the Sensata TPMS system. The software also allowed customized scripts to be utilized, enabling the designers to tweak the circuit components for even greater optimization. As the safety legislation and mandates continue, automobile manufacturers across the globe will need better performing TPMS. High-frequency software will become increasingly necessary to overcome the intensive design challenges introduced by the automotive industry.