Microwave Journal

eBook

# Design Trends in Automotive Electronics and Radar Sensors

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## Table of Contents

# Introduction

## Design Trends in Automotive Electronics and Radar Sensors

Automotive electronics is experiencing a big boost from the trends toward more connectivity, autonomy and electrification. These trends started years ago with the addition of satellite radio and GPS but is quickly increasing with cellular connectivity, ADAS and autonomy being incorporated into more vehicles. Yole Development predicts a 23% CAGR from 2016-2022 for mmWave radar sensors growing to $7.5 B at the module level. The global automotive electronics market is predicted to grow from its current value of $270B to more than $400B by 2024 according to Global Market Insights, Inc. The development of intelligent vehicle technologies owing to the need for advanced safety and comfort parameters will drive the market growth according to the company.

Connecting vehicles to other vehicles (V2V) and to other devices/networks or everything (V2X), will enable new capabilities other than just communications and streaming services. It also would allow enhanced safety and traffic/navigation assistance where vehicles can connect to each other and avoid accidents and congested areas automatically – maybe traffic lights will become obsolete one day.

The promise of such capabilities will require advanced designs of the various electronics and sensors in vehicles. The eBook covers some of these topics starting off with high-resolution, wideband radar measurement challenges showing how to measure wider band radar sensor and signals. The next article by ADI addresses automotive radar and the congested spectrum dealing with the potential “urban electronic battlefield”. It discusses potential jamming and how to avoid it whether on purpose or not.

TDK covers another important subject in automotive electronics as the electric vehicle becomes more popular.  It discusses design challenges of infrastructure for automotive wireless charging as these stations are rolled out publically and become available in the future home. It discusses wireless power transfer and the design challenges and solutions to accomplish power transfer at the highest rates possible with today’s hardware.

Finally, all wireless applications need proper antenna design and testing so Copper Mountain Technologies, the sponsor of this eBook, covers characterizing and tuning antennas using low cost metrology grade VNAs and frequency extension systems to 110 GHz. Most current antenna measurement systems are relatively expensive but this low cost, turn-key system will enable companies to perform these measurements accurately at much lower levels of investment in equipment.

We hope that this topic intrigues engineers to learn more about the fast growing area of automotive electronics. We will have more follow-on eBooks covering this topic as we publish new articles. Thanks to Copper Mountain Technologies for sponsoring this one so you can download it for free.

*Pat Hindle*, Microwave Journal *Editor*

# Yole Reports Radar for Automotive is Entering A New Age

Yole Développement

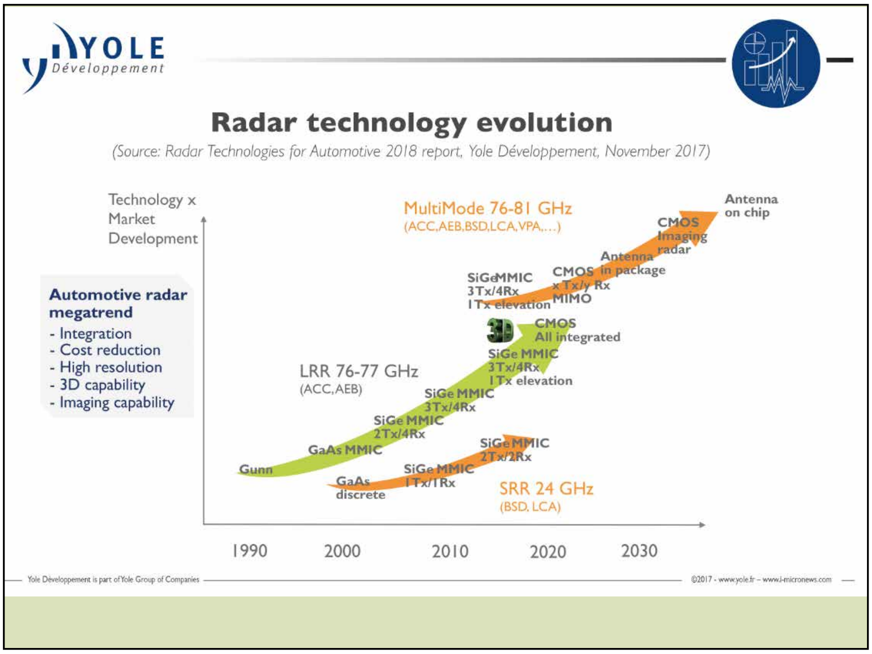
The automotive radar market is benefiting from a 23 percent CAGR between 2016 and 2022. AEB application is the main driver for the 77 GHz radar market growth. Yole Développement announces a global radar market reaching US$7.5 billion in 2022, at the module level.

"This growth should be accelerated with the autonomous car market," comments Cédric Malaquin, technology and market analyst, RF Devices & Technologies at Yole.

The market research and strategy consulting company Yole and its partners System Plus Consulting and Knowmade, are following the RF electronics industry taking into account technology evolution, market trends, the whole supply chain and the dedicated patent landscape. The companies propose a comprehensive understanding of the RF electronics industry with a wide collection of reports.

With the recent strong focus on safety, the market potential for ADAS has been extended to mid-end cars resulting in a production volume increase. Coupled to the fact that radars are well considered and employed by many brands: in 71 percent of cases for AEB.

Another trend with the advent of autonomous driving is the use of corner radar for the car 360 degree surveillance. These short and mid-range radar are supported by 24 GHz and more recently by 79 GHz module. The latest one being more suited for high resolution tracking which will be desirable for tasks such as target separation or even object recognition. Corner radars will be a must have for redundancy with other sensors such as camera or even Lidar for high-end robotic cars.




Indeed, the global LiDAR systems' market for automotive applications, is showing an impressive growth between 2017 and 2023: Yole announces a huge 43 percent CAGR during this period to reach US$5 billion in 2023, supported by a strong policy of investments.

"Strong investments are already noticeable at the IP level," comments Dr. Paul Leclaire, technology and patent analyst from Knowmade. "Indeed, since 2010, the patenting activity related to LiDAR for autonomous and robotic vehicles has shown an annual increase of 21 percent. Furthermore, while the IP landscape related to ADAS applications is consolidated, the robotic vehicles IP landscape is very competitive. For instance, the last five years have seen more than 50 newcomers entering the IP landscape related to high end LiDAR (solid state, 360 degree scanning, etc.) for 3D mapping."

A majority of OEM's integrates radar technology for new ADAS applications. Radar is often combined with other sensors as it provides valuable information to ensure better safety and helps in collision avoidance. OEM's demand is well supported by Tier1's offer with strong product portfolio. Analysts identified almost 50 active product references existing on the market. Market is very dynamic with strong competition and continuous product developments.

System Plus Consulting is strongly involved in the analysis of radar solutions. This year, the reverse engineering and costing company propose a detailed report on the world's first single-chip radar developed by Texas Instruments (TI).

"Ahead of its competitors in RFCMOS applications, TI has begun manufacturing highly integrated radar sensor chips–the latest of which is the AWR1642," asserts Dr. Stéphane Elisabeth, expert Cost Analyst, RF, Sensors & Adv. Packaging at System Plus Consulting. "But rather than integrating all transmitters, receivers and local oscillators in a single chip, TI went further and integrated a MCU and a DSP on the same chip."

System Plus Consulting and Yole interviewed Sneha Narnakaje, Automotive Business Unit Manager at Texas Instruments to explore TI's innovative solution and detail TI's market positioning.

In parallel, semiconductor's manufacturers deliver high performance solutions that enable mmWave radar to be operated in a reliable and accurate manner which is critical for safety functions. They propose a wide technology offer with GaAs, SiGe BiCMOS and RFCMOS platforms.

Innovative startups such as Metawave and Uhnder, bring disruptive technologies to the market to support high resolution sensor requirements either with ultra-thin steerable beam and AI engine for a deep learning approach or with unprecedented high channel number for high resolution imaging radar. Those innovations attract new comers in automotive radar field for instance with Magna and also well established players through the whole supply chain: Infineon Technologies, Denso, Toyota, Hyundai... It will certainly reshape the competition with the current leaders Continental and Bosch.

Regarding automotive 77 GHz radar chips, today it is mainly based on a 130 nm SiGe platform, with NXP and Infineon Technologies as the top suppliers. RFCMOS technology is entering the market with semiconductor companies such as TI with an intermediate technology node of 45 nm. And technology scaling has started with Analog Devices offering products based on advanced 28 nm CMOS nodes and also foundries that are positioning their advanced process capabilities in this ecosystem. For example, GLOBALFOUNDRIES and its 22FDX platform support innovative startup Arbe Robotics with a 4D high resolution radar for autonomous cars.

"It is exciting to see such a wide diversity of technology offerings, a clear confirmation of the automotive radar market's traction," comments Cédric Malaquin from Yole. "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," comments Claire Troadec, division director, Power & Wireless Division at Yole.■



# GCF, 5GAA Collaborate on Certification and Testing of C-V2X Tech

The Global Certification Forum (GCF) and 5G Automotive Association (5GAA) have agreed a collaborative framework under which they will combine their resources and expertise to accelerate the global introduction of Cellular Vehicle-to-Everything (C-V2X) products. The new partnership aims to address the current gap in certification capabilities and processes, thereby harmonizing C-V2X at a global level and reducing the time-to-market of C-V2X products.

C-V2X is set to become a central force for innovation in the automotive market, providing the platform which will enable vehicles to communicate with each other and with everything around them. Originally defined as LTE V2X in 3GPP Release 14, which was completed in June 2017, C-V2X provides one solution for integrated V2V, V2I and V2P and V2N operation. The shorter-range V2V, V2I and V2P modes support direct communication without necessarily relying on network involvement for scheduling, whilst the longer range V2N mode will deliver network assistance and commercial services requiring the involvement of a Mobile Network Operator (MNO). The data throughputs and latencies provided by 5G are critical to the performance of autonomous vehicle applications and hence C-V2X is designed to be fully compatible with 5G technologies.

Based on the C-V2X specifications defined in 3GPP Release 14, many car manufacturers and their suppliers in the key markets of the USA, Asia and Europe have been working on products which will come to market in 2019.

"As always, with the introduction of new and disruptive technology, standards and certification are critical to ensuring successful deployment," said Lars Nielsen, General Manager at GCF. "Our partnership with 5GAA means that together we are achieving the evolution into 5G with a proven success factor for self-driving and connected vehicles."

"We are extremely pleased to partner with GCF as a further step towards safe and successful C-V2X deployment," said Maxime Flament, CTO at 5GAA. "This aligns perfectly with our mission to accelerate the global deployment of intelligent transport and communications solutions and make transportation of the future safer and more reliable."

The GCF certification scheme has been running since 1999 and has constantly evolved in alignment with developments in mobile technologies and the changing needs of the industry. GCF's certification portfolio already covers LTE sidelink, a key technology for automotive applications, supporting vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) use cases, and GCF is therefore the natural partner for 5GAA on C-V2X certification.

The framework agreed by the two organisations will enable 5GAA and GCF to work together to ensure the certification needs of the C-V2X industry are identified and prioritised and that test cases and associated capabilities are developed in-line with the needs of this rapidly emerging market.

The 5G Automotive Association (5GAA) is a global, cross-industry organisation bridging the gap between automotive, technology and telecom industries, promoting the C-V2X technology as a comprehensive platform for connected vehicles, safety and transportation. With 110 members, the organisation is committed to helping define and develop the next generation of connected mobility and automated vehicle solutions.■

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# High-Resolution, Wideband Radar Measurement Challenges

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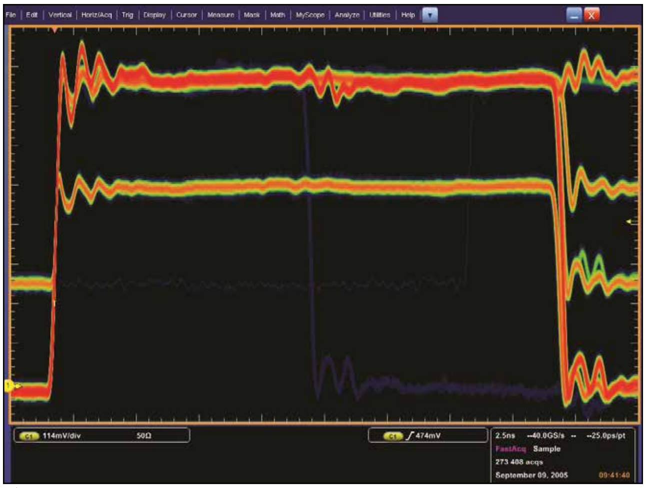
High-resolution radars have a diverse set of uses in both commercial and military applications, ranging from automotive vehicle awareness to advanced target ID, surveillance and ballistic missile defense. These applications drive the need for wide instantaneous bandwidth radar. Understanding how a radar behaves in the frequency and time domain helps determine its overall performance, especially when dealing with short-duration pulses or the performance of frequency modulation on longer pulses.

Fundamentally, radar can be characterized as a time domain phenomenon. In its simplest form, it is the time it takes a transmitted signal to illuminate a target and "reflect back" to the receiver. The signal can be continuous wave (CW) or a sequence of pulses, depending on the specific mission. Pulse rise and fall times, the type of modulation and the behavior of the transmitter amplifier can create a range of responses in the frequency domain. The radar signal needs to be tested in congested—even contested—environments, and a key task is to verify immunity to signal interference, jamming and clutter effects.




▲ **Fig. 1 The fast acquisition mode can show a single, narrow pulse.**

Time domain measurements are traditionally performed with oscilloscopes, while spectrum analyzers are best suited for frequency domain measurements. However, advancements in measurement instrumentation architectures have shaken this up a bit. Now, broadband frequency domain analysis can be performed with an oscilloscope, and the time domain behavior of a frequency modulated signal can be analyzed using a spectrum analyzer. This article explores the trade-offs with each instrument.

## RESOLUTION: TIME, MODULATION AND FREQUENCY

Radar resolution can be improved by using a very narrow pulse (in time); however, the amplification of short-duration pulses can be challenging, so techniques such as modulating a longer pulse with a frequency ramp, termed linear frequency modulation (LFM), are used. Frequency modulation does not necessarily have to be linear; in some cases, an exponential waveform may be better suited to a particular application.

Fast time domain events, such as radar pulses, exhibit sin(x)/x behavior in the frequency domain. If a pulse is short, the main lobe of the sin(x)/x function has a broader frequency response. If the pulse is wide, the lobe has a narrow frequency response. This affects the choice of transmission frequency: A short-duration pulse will require a large amount of spectrum, so a high carrier frequency should be used. Longer pulses require less spectrum and can be transmitted at lower frequencies. How often the pulse is repeated, termed the pulse repetition frequency (PRF), depends

▲ Fig. 2 Discovery of a single transient glitch in a train of pulses.

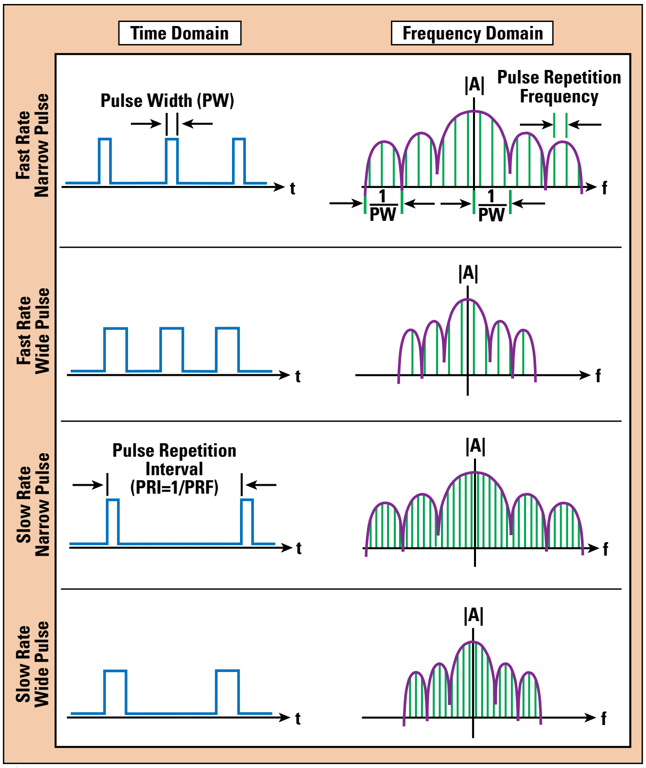
on the radar's mission. Low PRFs are better for detecting targets greater than 50 km range, and high PRFs are better for closer targets. As a rule, a low PRF radar uses longer pulses and transmits at lower frequencies, such as in the VHF band, and high PRF radars use narrow pulses and transmit at higher frequencies.

When modulation is added, further frequency and time domain interactions are observed. For example, a 4 GHz bandwidth LFM chirp gives a resolution of around 6 cm, which is ideal for imaging applications. However, adding this type of modulation to a pulse will add ±2 GHz of FM modulation to the sin(x)/x frequency response, making a logical transmission frequency in the mid 30 GHz part of the spectrum.

## TIME DOMAIN MEASUREMENTS

Traditionally, the oscilloscope has been the primary tool for examining varying voltage versus time. This is key to understanding pulse or pulse train behavior. Oscilloscopes are available with various levels of performance; a basic oscilloscope may have a bandwidth of 200 MHz, so it is a good tool for analyzing pulses with a frequency response less than 200 MHz, i.e., either unmodulated pulses or lower frequency pulses with slow modulation. However, the limited bandwidth of entry-level oscilloscopes means that degenerative effects such as intermodulation will be filtered out.

A modern, high performance oscilloscope can have bandwidths up to 70 GHz, providing the capability to capture multiple harmonics and other frequency-based distortion mechanisms. Without using a detector, oscilloscopes can capture and analyze the transmit frequency to help understand the behavior of both short-duration pulses, or impulses, and wideband signal modulation. For short-duration pulses and impulses, enhancements in architecture have improved the oscilloscope's ability to analyze these signals using a fast acquisition mode. This reduces the dead time between waveform acquisitions, enabling the capture and display of transient events. Fast acquisition combined with persistent waveform features can display phenomena at varying intensity to reflect the rate of occurrence. ***Figure 1*** shows a single pulse captured multiple times, with a




▲ Fig. 3 Relationship between spectrum and pulse width and PRF.

persistence heat map technique used to show the rate of occurrence. Frequent occurrences are shown in red and infrequent events displayed in yellow to blue, for the most infrequent. The display identifies a number of intermittent pulses with lower amplitude and, occasionally, a pulse of shorter duration in blue. ***Figure 2*** shows a string of "good" pulses with an occasional anomaly displayed in blue.

Traditionally, oscilloscopes triggered on a simple edge or voltage level. Today, using a digital probe, the trigger can be a pattern of logic; for example, when a specific word appears on a bus, the scope can be triggered to make an analog measurement in the time domain. A mixed domain oscilloscope can add a further trigger advantage, providing the ability to simultaneously trigger and acquire signals across multiple channels. This results in time-correlated and seamless acquisitions in the analog, digital and RF domains, providing the ability to observe how the spectral and vector properties of the RF signal vary over time, along with the analog and digital signals. Complementing the advanced trigger system, a fully-automated suite of pulse timing measurements available for oscilloscopes can lead to more consistent results. Single-button selection of rise time, fall time, pulse width and other parameters simplify the measurement process and save time.

## FREQUENCY DOMAIN MEASUREMENTS

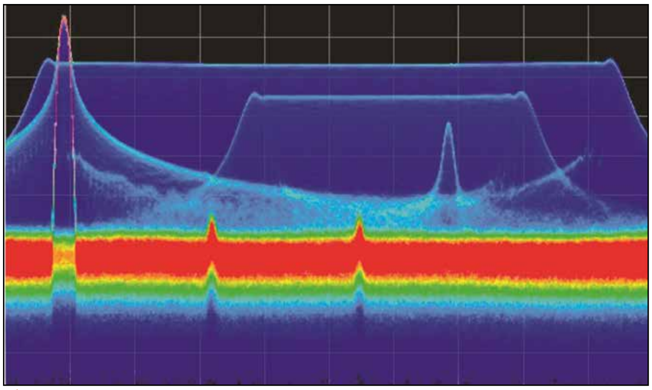
The measurement of frequency domain characteristics of a transient, pulse-based system requires a specific type of spectrum analysis. While swept spectrum analyzers offer wide frequency and dynamic range, advances in analog-to-digital converters (ADC) and signal processing technology provide many of the same benefits while performing wide bandwidth, time domain acquisition, then post processing with a fast Fourier transform (FFT). Time domain acquisitions allow for very fast visualization of signals, referred to as real-time. Beyond speed, the advantages of real-time measurement capability are high quality persistence displays, frequency domain triggering and waveform storage, providing higher levels of measurement capability and insight.

***Figure 3*** shows the relationship between the sin(x)/x spectrum in the frequency domain and a pulsed radar signal in the time domain. Longer pulses have smaller lobes, while shorter pulses have wider lobes, as discussed earlier. Because of the inverse relationship between frequency and time, it is possible to determine basic pulse timing parameters using the spectrum analyzer frequency domain display. The pulse repetition time or pulse period is the inverse of the frequency spacing between the finely-spaced lines within the larger spectrum envelope, and the pulse width is the inverse of the frequency spacing between the nulls in the spectrum envelope. Real-time and persistence display technologies allow observation of the frequency and frequency response and improve the ability to view the PRF.

The architectures of spectrum analyzers and oscilloscopes differ. The bandwidth of an oscilloscope is usually a function of the ADC technology and sample rate of the system, while a spectrum analyzer uses some form of frequency conversion (usually super heterodyne) to create an intermediate frequency that is centered around the frequency bandwidth of a narrow ADC. As bandwidth is inversely proportional to dynamic range, the spectrum analyzer has a better dynamic range, allowing the user to view very small signals in the presence of large signals. In comparison, an oscilloscope with a bandwidth of 18 GHz will have lower dynamic range than a spectrum analyzer with a frequency range of 18 GHz. However, the 18 GHz oscilloscope captures the whole instantaneous bandwidth (DC to 18 GHz), while the spectrum analyzer captures a narrower instantaneous bandwidth—±400 MHz around a center frequency of 9 GHz, for example.

Just as an oscilloscope can translate time domain data by performing an FFT and displaying the frequency domain spectrum, a spectrum analyzer can show measurement information in the time domain. Once the spectrum analyzer is tuned to an appropriate center frequency, the required measurement data can be displayed in either the frequency or time domain. As the time domain measurement on the spectrum analyzer is limited by the bandwidth of the ADC, the maximum LFM that can be observed in the time domain will be limited; in the example of the spectrum analyzer with an instantaneous bandwidth of ±400 MHz around a center frequency of 9 GHz, the maximum LFM sweep will be 800 MHz.

Another feature of the spectrum analyzer is adjustable acquisition bandwidth to make more selective measurements, by using a resolution bandwidth filter. This effectively reduces the displayed noise level. For example, a 3 kHz resolution bandwidth filter has a noise floor of 10 dB lower than a 30 kHz resolution bandwidth filter.



**▲ Fig. 4 Using a phosphor emulation display reveals multiple chirps in one band.**

New is not necessarily best; many newer spectrum analyzer models emulate the displays of cathode ray tubes (CRT) used on spectrum analyzers before the advent of digital displays. A CRT uses a magnetically-controlled electron gun that fires electrons onto a phosphor-coated screen. The electrons initially illuminate the screen and the image slowly decays with time. ***Figure 4*** shows a typical display using a phosphor emulation technique. Without phosphor emulation, the screen shows just the large LFM signal, with the CW signal "popping out" the top on the left. Phosphor emulation enables a second, lower power LFM signal with several single frequency, pulsed carriers and two CW interferers to be seen.

As with an oscilloscope, spectrum analyzers are available with automated pulse measurements that increase signal detail and measurement repeatability. In some cases, a spectrum analyzer will have more advanced capabilities:

- Storing up to two hours of data
- Finding the pulses within the signal
- Measuring a full set of parameters for each pulse, such as timing, frequency and phase
- Processing the results to display trends or identify the transmitter.

## PICKING THE RIGHT INSTRUMENT

High-resolution radar employs wideband techniques, either short pulses, impulses or a modulation technique such as LFM. Both oscilloscopes and spectrum analyzers are good tools for measuring performance in the time and frequency domains and can have equivalent measurement capability; however, the difference in instrument architecture makes one more optimal for some measurements than the other. An oscilloscope can have an extremely wide acquisition bandwidth in the tens of GHz, at the cost of dynamic range and sensitivity, which makes it ideal for capturing fast transient events such as narrow pulses, impulses and large frequency sweeps. A modern spectrum analyzer can tune to a specific frequency and acquire a signal in the range of a few tens of MHz up to 1 GHz, with better dynamic range and sensitivity, making it an ideal tool for broadband spectrum analysis, spurious signal searches, intermodulation and harmonic analysis.■

# Automotive Radar and Congested Spectrum: Potential Urban Electronic Battlefield

Sefa Tanis
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As automotive radars become widespread, the heavily occupied RF spectrum in an urban environment will resemble an electronic battlefield. Radar will face a combination of unintentional—even intentional—jamming, and designers must implement counter-jamming techniques like ones used in electronic warfare (EW). An automotive radar can experience either denial or deceptive jamming. Denial jamming blinds the victim's radar, reducing the signal-to-noise ratio (SNR) and, as a result, the probability of target detection is degraded. Deceptive jamming makes the victim's radar "see" targets that are really false. The victim's radar loses the ability to track the real targets, and vehicle safety is compromised. These jamming attacks could originate from mutual interference between automotive radars or be deliberate, by simply pointing a strong continuous wave (CW) signal into the victim's radar using inexpensive hardware.

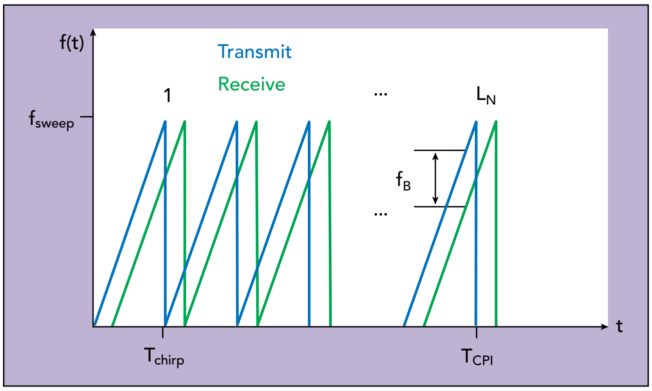



**Fig. 1 FMCW chirp sequence waveform.**

While current jamming avoidance techniques may be adequate today, with the proliferation of radar sensors, more resilient mitigation techniques will be needed, either stand-alone or in conjunction with other approaches. Such techniques include time/frequency domain signal processing or complex radar waveforms.

## JAMMING FMCW RADAR

The waveform is a critical system parameter that determines the radar's performance in the presence of jammers. Automotive radars in the 77 GHz band mainly use FMCW waveforms, where a CW signal is linearly swept or "chirped" in frequency across the RF band (see ***Figure 1***). The frequency difference or beat frequency ($f_B$) between the transmit and receive signals is proportional to the distance to the target (R) and can be determined by

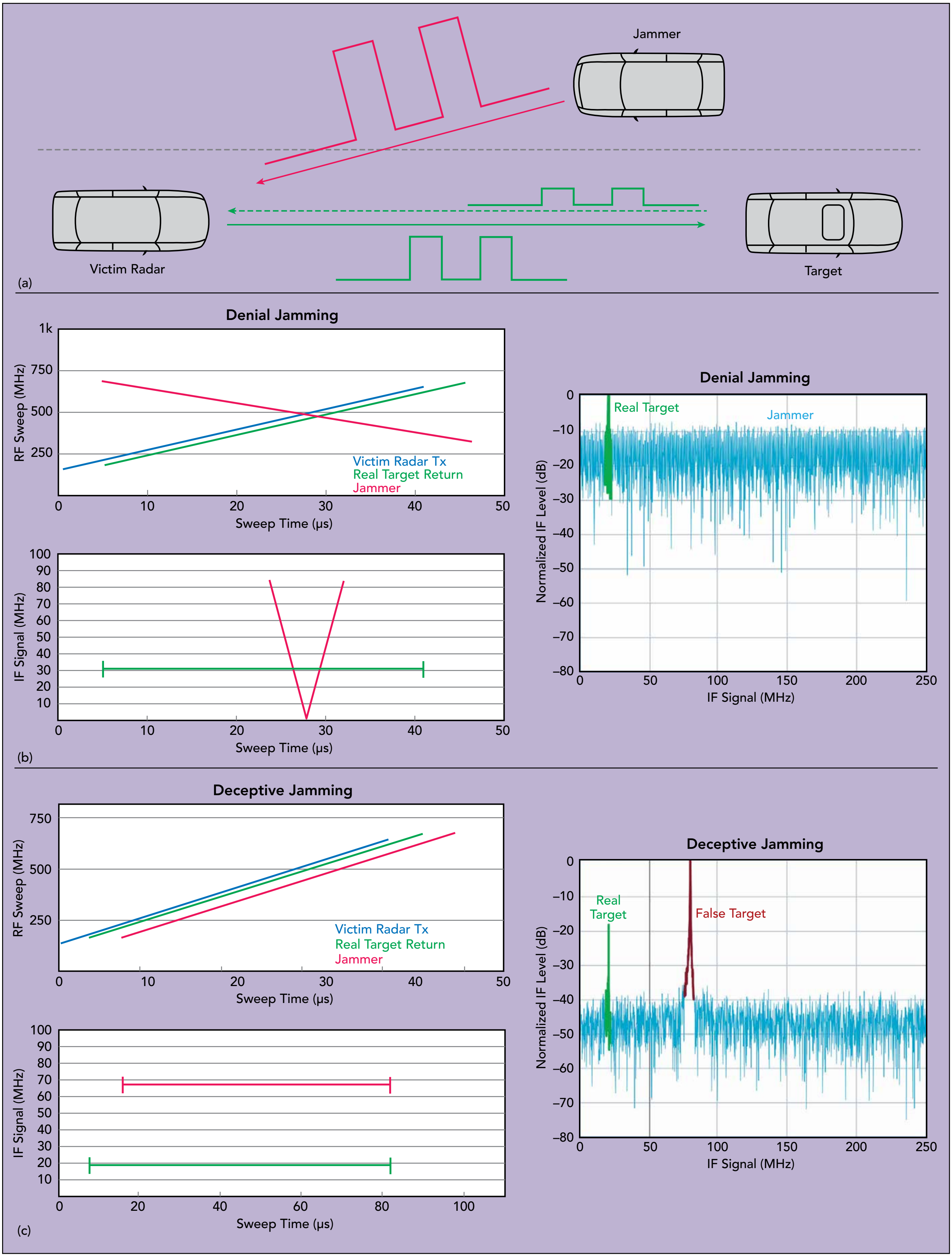
$$f_B = \frac{2}{C}\frac{f_{sweep}}{T_{chirp}}R\ ,$$

where $f_{sweep}$ is the change in frequency and $T_{chirp}$ is the time for the frequency sweep.

Unintended jamming can occur in a dense RF environment when FMCW radar sensors are operating in the same portion of the frequency band. A typical automive jamming example is shown in ***Figure 2a***.

### Denial Jamming

An arbitrary FMCW jamming signal that falls in the receiver bandwidth of the victim's radar raises the noise floor (see ***Figure 2b***). Called denial, this jamming may cause small targets—those with small radar cross sec-




▲ **Fig. 2 Driving scenario (a) with denial jamming (b) and deceptive jamming (c) of an FMCW radar.**

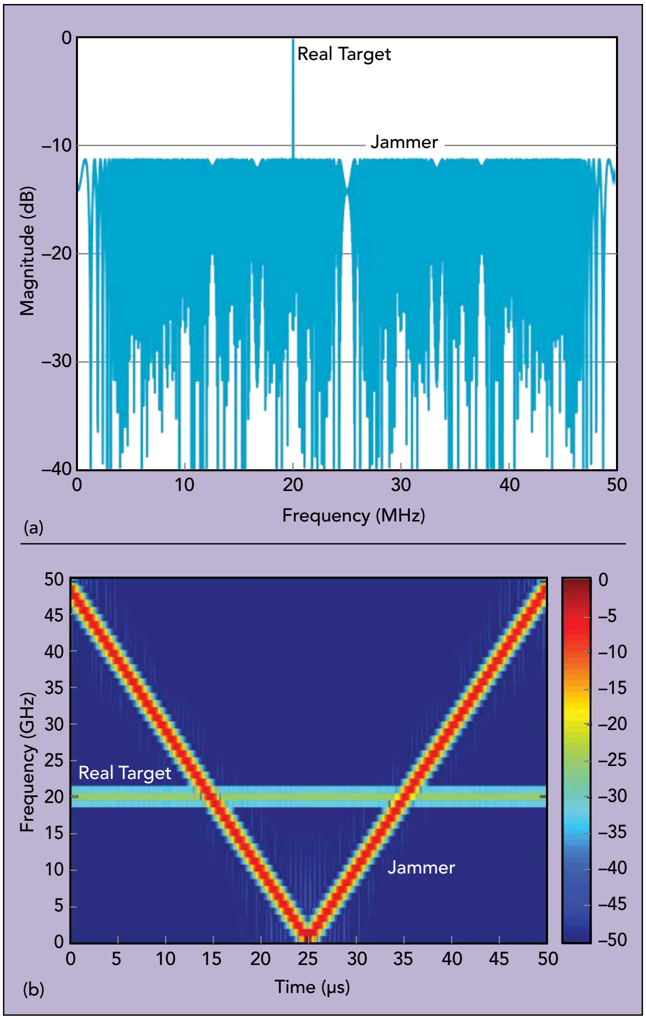



**Fig. 3 FFT (a) and STFT (b) of the radar echo IF waveform with jamming.**

tion (RCS)—to disappear, due to the poor SNR. A denial attack could be purposeful, by simply beaming a strong CW signal into the victim's FMCW radar.

### Deceptive Jamming

If the swept frequency of the jamming signal is delayed and synchronized with the victim's radar, the impact is a false target generated at a fixed range (see ***Figure 2c***). This technique is commonly used by EW jammers. However, this can occur unintentionally with an oncoming automobile having a similar FMCW radar, although the probability of time alignment between the victim and jamming radars is small. Nonetheless, a jammer delay offset less than the maximum range delay of the victim's radar could look like a real target. For example, a radar with 200 m maximum range would require sweep alignment of less than 1.3 μs. Such a deceptive attack could be intentional using sophisticated EW equipment mounted on the oncoming automobile.

Generally, deceptive jamming is based on retransmitting the victim radar's signal with a systematic change in delay and frequency. This signal can be noncoherent, in which case the jammer is called a transponder, or coherent, termed a repeater. Repeaters receive, alter and retransmit one or more jamming signals, while transponders transmit a predetermined signal when the desired victim's signal is detected by the jammer. A sophisticated repeater-based attack typically requires a digital RF memory (DRFM). A DRFM is capable of carrying out coordinated range delay and Doppler gate pull-off attacks, with the false target range and Doppler properties maintained to deceive the victim's radar.

## JAMMING MITIGATION

Basic radar jamming mitigation techniques rely on avoidance. The objective is to reduce the probability of overlap in space, time and frequency, using methods such as:

- Spatial: Using a narrow and electronically-scanned beam to reduce the risk of jamming. A typical field of view for long-range automotive cruise control radar is ±8 degrees. Nonetheless, a strong jammer could be effective via the antenna sidelobes.
- Temporal: Randomizing the FMCW chirp slope parameters to avoid periodic jamming.
- Spectral: Randomizing the FMCW chirp start and stop frequencies to reduce the probability of overlap and jamming.

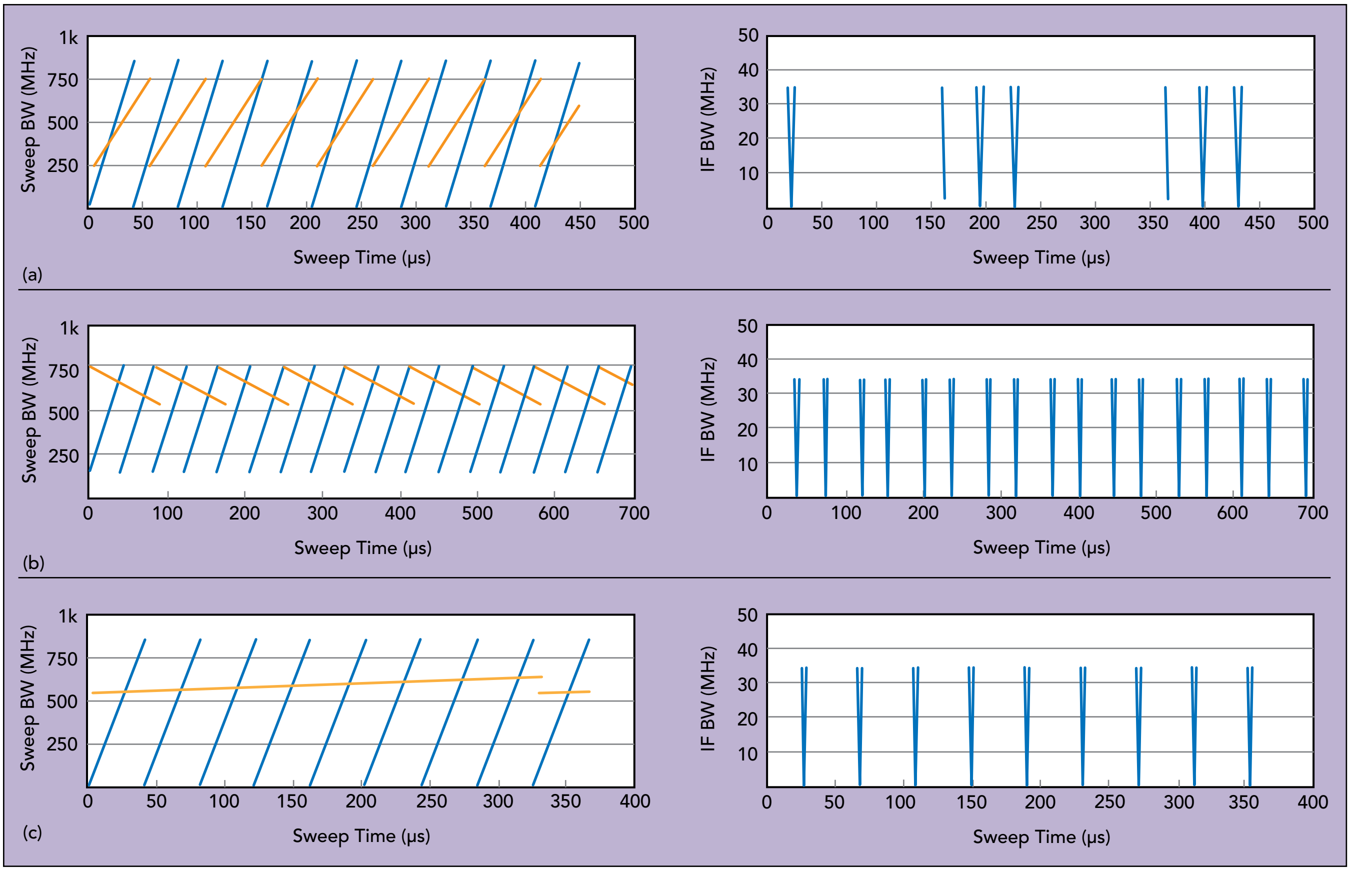
The basic methods of randomization would avoid accidental synchronization with other radars but might not be as effective in dense RF environments. The growing number of radar sensors will require more sophisticated techniques to mitigate possible jamming.

### Detect and Repair

An alternative method to avoid jamming is to repair the received waveform using signal processing algorithms. Time/frequency domain techniques can be effective against denial type jamming. In the oncoming automobile scenario (see Figure 2), the jammer sweeps all frequency bins for a very short time duration. This fast time-varying signal manifests itself as a raised noise floor in the fast Fourier transform (FFT) domain. Time/frequency domain signal processing transfers the signal to another domain where it is easier to filter out the jamming.

For time-varying signals, a short time Fourier transform (STFT) provides more information than a regular FFT, and STFT-based techniques can be used for countering narrowband jamming (see ***Figure 3***). The STFT essentially moves a window through the signal and takes the FFT of the windowed region. The signal is filtered in the frequency domain to remove the jammer components before being transformed back to the time domain. ***Figure 4*** shows a typical FMCW jamming scenario of overlapping RF chirp sequences and the IF signals obtained using STFT processing. The plots on the right show the beat signal from mixing the radar (blue) and jamming (orange) signals. A horizontal line indicates a target, while V-shaped vertical lines indicate the presence of a jamming signal. Similar or opposite direction FMCW jamming or a CW-like slow chirp have similar effects on the IF signal. In all these jamming scenarios, the fast moving V-shaped IF signal raises the noise floor in the regular FFT domain, as was seen in Figure 3.

Amplitude-based masking can be used to filter out jamming in the STFT domain. This assumes, of course,




▲ **Fig. 4 Radar and jammer chirps (left) and STFT-processed IF (right) for similar direction (a), opposite direction (b) and CW interference (c) scenarios.**

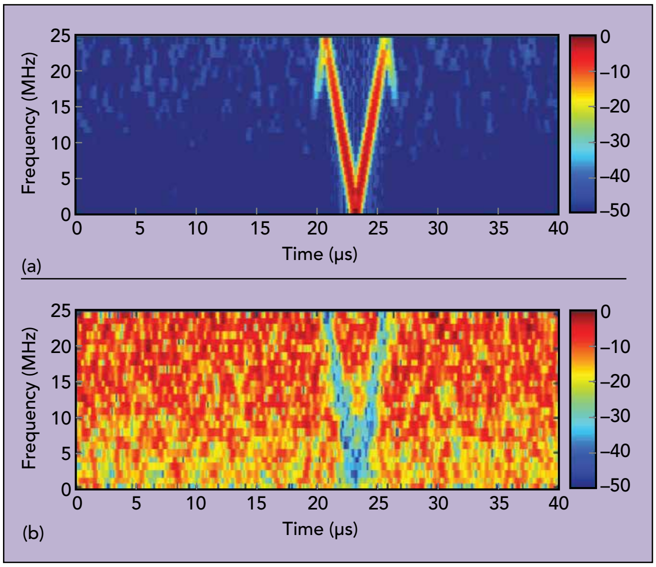
that the victim's radar front-end and quantization have enough dynamic range to linearly process the stronger jammer signal and the small intended target at the same time. ***Figure 5a*** shows the STFT signal with a strong jammer, and ***Figure 5b*** shows the STFT after amplitude-based masking. Without processing, multiple real targets will not be visible in the presence of a strong jammer; however, amplitude-based masking excises the V-shaped jammer in Figure 5b, enabling the low SNR targets to be discerned when transformed back to the time domain.

While STFT-based jamming mitigation can be used against strong jammers in denial jamming scenarios, with deceptive jamming attacks, STFT alone cannot authenticate whether the return signal is real or false.

## Encrypted RF

The simple countermeasure to reduce the impact of deceptive jamming from repeater attacks is using a low probability of intercept (LPI) radar waveform. The objective of an LPI radar is to escape detection by spreading the radiated energy over a wide frequency spectrum, usually via a quasi-random sweep, modulation or hopping sequence. FMCW is a type of LPI waveform, and if phase coding or encryption is used with the frequency chirp, it is possible to further reduce the probability of a DRFM intercepting the radar signal. An encrypted RF signature unique to each radar sensor can authenticate the return signal.

***Figure 6*** shows a use case where two identical radars are on two different automobiles, and the frequency offset and delay between them generates a false target in the victim's radar. The jamming radar is time aligned with the victim radar, i.e., having the same chirp slope and a short offset. Phase-coded FMCW radars will provide high jamming robustness in this case, and the use of orthogonal codes will also make MIMO radar operation possible, by enabling multiple simultaneous transmit waveforms.




▲ **Fig. 5 STFT chirp return with strong interference (a) and after amplitude-based masking (b).**

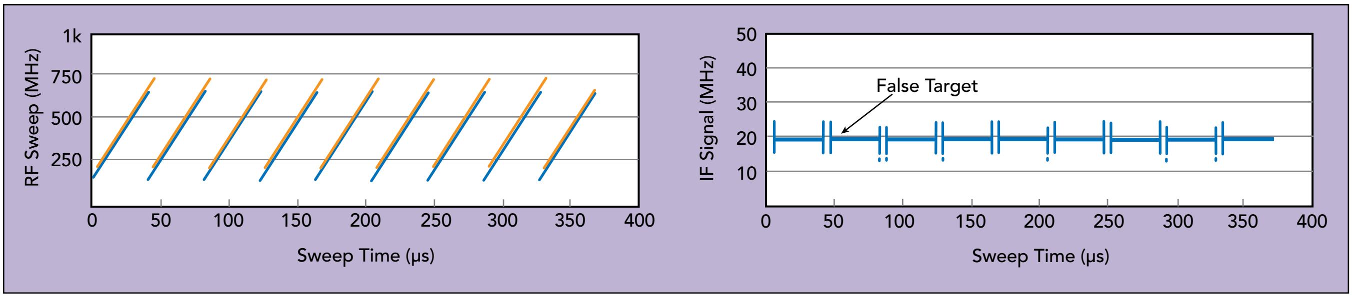



Fig. 6 Jamming due to identical radars with frequency offset and delay.

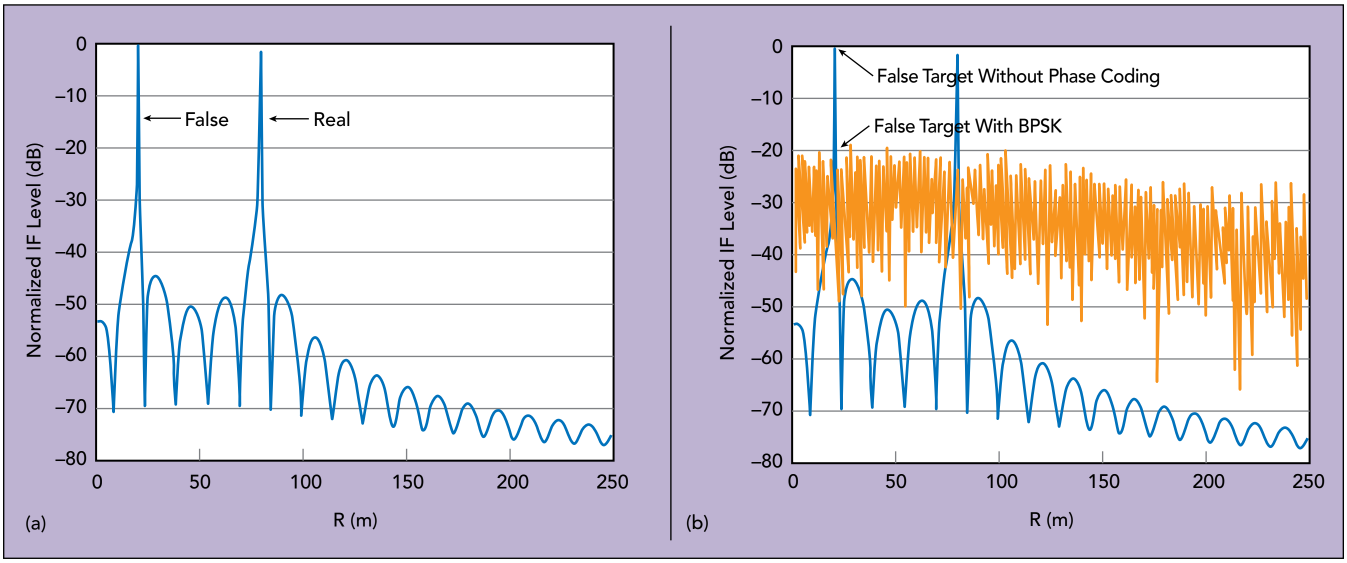



Fig. 7 Radar return without phase coding, showing false and real targets (a). Phase coding reduces the false target by some 20 dB (b).

The requirements for coding are:

- Code length: The code length should achieve minimal range sidelobe levels with short sequences. A pseudo-random-noise (PRN) sequence length of 1024 results in a peak sidelobe level (PSLL) of about 30 dB, i.e., $10 \bullet \log_{10}(1024)$. Transmit codes together with receive filter weights can be optimized to improve the PSLL at the expense of SNR.
- Good cross-correlation properties: Cross-correlation coefficients of the members of a set should be zero to achieve separation between sensors.
- Doppler resistance: Phase-coded radar performance can suffer from the Doppler shift. Binary codes are Doppler intolerant, while polyphase codes degrade less rapidly.
- Available number of different codes: A large family size is better to assign a unique code to each radar sensor.

***Figure 7a*** illustrates a radar echo with no phase coding, where the jamming signal appears as a false target. When the transmitted FMCW waveform is phase-coded with a PRN sequence, the jamming signal is suppressed, as shown in ***Figure 7b***. The dynamic range is compromised with this method; however, the radar signal processor could use phase-coded FMCW for a few chirps to flag a false target, then switch back to normal operation.

**TABLE 1**

**JAMMING MITIGATION FOR FMCW AUTOMOTIVE RADAR**

| Jamming Type | Denial | Deceptive | |
|---|---|---|---|
| Jamming Hardware | Another Radar Sensor or a Simple CW Generator | DRFM (Coherent) | Transponder (Noncoherent) |
| Impact on Victim Radar | Poor SNR | False Target | |
| Resilient Mitigation Technique | STFT | Phase-Coded FMCW | |
| Mitigation Principle | Repair the Radar Return Waveform | Escape Detection | Processing Gain of the Coding Sequence |
| Mitigation Effectiveness | High | Moderate | Good |

## FUTURE TRENDS

In congested automobile radar environments, jamming can be mitigated using advanced signal processing algorithms and complex waveform generation techniques. STFT-based signal processing can be used against denial attacks. Phase-coded FMCW provides an additional layer of resistance to both noncoherent and coherent deceptive attacks by using processing gain and interception avoidance. ***Table 1*** summarizes these mitigation techniques. The jamming mitigation principles for automotive radar are also applicable for other radar sensors: robotics, road tolling, GPS and UAV landing or collision avoidance systems.

Currently, automotive radar sensors are operating in a non-cooperative mode, i.e., not communicating with each other. Although a cooperative mode of operation requires industry-wide harmonization, the arbitration between radar sensors would help resolve interference. A future radar concept including sensor cooperation is the fusion of communication nodes and radar sensors. Future radars with complex waveforms offer the possibility to include information in the radar signal, enabling the same hardware to be used simultaneously for radar and communications (RADCOM). Such a capability has the following benefits:

- Multi-user capability without interference.
- Coding the radar signal with OFDM or similar communication codes enables information to be contained in the radar signal.
- Simultaneous RADCOM.

5G mmWave transceivers with multi-GHz bandwidth and beam steering capabilities are candidates for use in a RADCOM system.■

# Design Challenges of Infrastructure for Automotive Wireless Charging

Armando Medina, James Wooten, and Ganesh Kudva
*TDK RF Solutions, Inc.*

In October 2018, the world's first electric vehicle (EV) equipped with remote wireless charging was rolled out in Germany, with plans for expanded release in the United States, the United Kingdom, Japan, and China.[1] This EV represents decades of technological development towards plug-less EVs that many believe bring us one step closer to a future with dynamically self-charging autonomous vehicles.

Wireless technologies, including EVs with wireless power transfer (WPT), are proliferating rapidly: ABI Research predicts that the number of wirelessly chargeable devices will exceed 700 million by 2020. The number of EV models (both plug-in and wireless) is expected to grow, too, from 155 in 2017 to 289 by 2022[2], an expansion driven by stringent carbon emissions requirements and government-mandated initiatives worldwide.

One regularly cited inhibitor to even faster adoption is the need for a public charging infrastructure that is universally available. The technical teams behind these infrastructures are working diligently to both increase the number of currently available plug-in stations as well as drive technological innovation and drive down costs to deliver wireless charging infrastructures available in both public and private spaces.

This article examines several of the technical challenges that must be solved to bring this to fruition. First, let's review the current state of WPT in general, and in automotive applications specifically.

## WIRELESS POWER TRANSFER

The mainstream WPT methods are electromagnetic induction and magnetic resonance. Both approaches realize contactless power transfer by using power-receiving coils to capture the magnetic field generated at the power transmission coils.

Common electromagnetic induction examples include electric shavers and cordless phones. While electromagnetic induction offers a simple principle and structure, plus low-cost system manufacturability, these systems are also prone to a drastic drop in power transmission efficiency as the distance increases between the power transmission and the receiving coils.[3]

On the other hand, magnetic resonance-based WPT transmits power via a capacitor in the power transmission and in the receiving sides to form LC resonance circuits, tuning both sides to resonate at the same frequency. This gives the systems an ability to maintain power feeds even with greater inter-coil distances, and/or when the centers of the coils are slightly shifted.[3]

Because magnetic resonance systems provide greater ranges of power transmission, and have demonstrated the potential for EV battery charging while in motion, this WPT technology has been in the spotlight in recent years as a solution for the automotive industry.

The automotive WPT applications currently consist of an external power pad that likely sits on top of the ground or may be embedded in the ground. The pad or

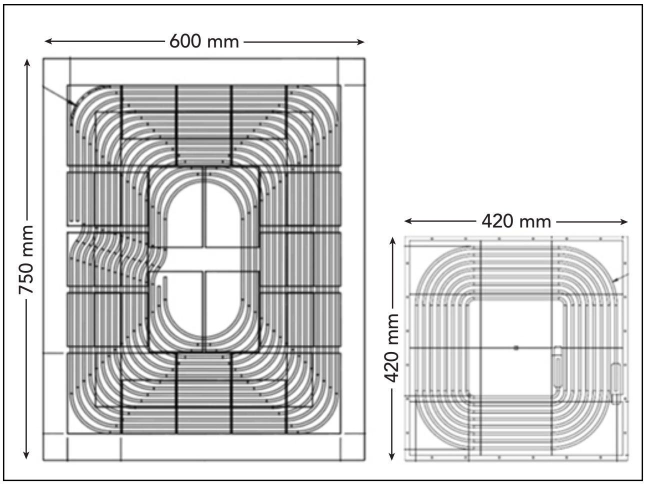



Fig. 1 **Circular WPT3 Ground Assembly and Vehicle Assembly.**

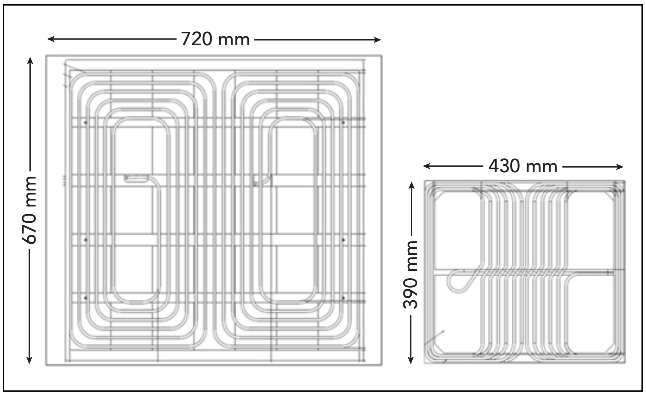



Fig. 2 **DD Universal (WPT1-WPT3) Ground Assembly and Vehicle Assembly.**

plate has a circular coil that converts alternating electrical current into magnetic waves. A partner power amplifier controls this current and wave frequency. Inside the EV, a receiver located near the car's power management system has a coil that's tuned to receive magnetic waves at the same frequency as the source coil. The receiver converts the magnetic energy back into electric current to be stored in the car's battery.

This approach relies on magnetic resonance because it loses little power (typically 7% to 10%) as it moves through the air, and is therefore considered to be highly efficient.4 WiTricity has commercialized a magnetic resonance WPT for automotive applications and TDK announced in early 2018 that it is working with WiTricity and automakers to develop a wireless charging system for electric vehicles, with an eye toward making easy, cable-free charging a commercial reality by 2021.[5]

## THE NEED FOR STANDARDS

The Society of Automotive Engineers (SAE) International has working groups around the world developing national standards on which automotive wireless charging systems can be based. The goal of the standards is to ensure that both private and public charging systems work with a myriad of different EV models.[6]

In November 2017, SAE International published its J2954 Recommended Practice (RP), the first industry-wide specification for WPT for EVs with motors of up to 11 kW power levels (WPT 3).[7] The current version addresses unidirectional charging, from grid to vehicle, with the caveat that bidirectional energy transfer may be evaluated for a future standard.

As part of its specification, the RP provides a standardized test stand (first up to WPT 2 power levels) to give EV manufacturers and infrastructure companies the means for testing performance and validation of their products and new developments. According to the J2954 RP, the test stand is based on circular topology, but also provides a way to demonstrate compatibility to other topologies such as a "double D" design (See ***Figures 1*** and ***2***).

The J2954 states that WPT systems have two main components: a Ground Assembly (GA) unit and a Vehicle Assembly (VA) unit. The GA contains a grid-connected Power Factor Correction (PFC) converter, followed by a DC-AC inverter, a filter, and an impedance matching network (IMN) connected to a GA coil. The VA consists of a VA coil connected to an IMN and filter, a rectifier, and an optional impedance converter that produces suitable voltages and currents to the connected battery. During charging, the magnetic energy created by the GA coil is coupled to the VA coil.[7]

The adopted minimum common alignment method is executed by means of low power excitation (LPE). LPE is the method whereby the SAE J2954-compliant GA coil is excited at a low current to induce a detectable signal on the VA. The J2954 specifies a power-transfer-enabled vehicle ground clearance of up to 10 inches (250 mm), with a side-to-side tolerance of +/-4 inches (+/- 100 mm) and a front-to-back tolerance of +/-3 inches (+/-75 mm). This alignment assists drivers to stay within the charging range—and the future's autonomous vehicles with finding parking spots—even in inclement weather conditions like rain or snow.

SAE International published a technical paper with bench test results from automobile and wireless charging suppliers measured at the U.S. Department of Energy (DOE) Idaho National Labs and TDK. The test report confirmed that WPT can be achieved at full power and with a high efficiency of up to 93% (grid to battery) with both matched and unmatched coil topologies, as well as charging between different power ranges (3.7 to 7.7 kW).[7]

In the months following the RP announcement, additional tests have been conducted—including in-vehicle field testing—for final validation. To date, 3.7, 7.7 and 11.1 kVA systems have been tested per the SAE standards, and 22 kVA units are under consideration. Very recently, 120 kVA systems have been demonstrated in a laboratory environment. Wireless power transfer rates have reached up to 90% percent efficiency compared to wired power transfers, even though the standards recommend a minimum 80% efficiency at offset positions of alignment.

Engineers developing optimal WPT especially in the public domain are grappling with the following questions:

- How much alignment must a car have with a wireless charging plate?

- How do materials like cement (in a garage floor) or asphalt (in a public space) affect the performance of a charging plate coil?
- How does the angle of the coil in an EV impact its charging capability when aligned with the charging plate coil?
- How will coils interact with one another in public spaces (e.g., where there are several parking spaces with chargers)?

Answers to these questions lie in the following aspects of automotive WPT. We'll describe how each works, outline the current technical inhibitors, and present a snapshot of test data showing advancements toward overcoming the challenges.

## MAGNETIC RESONANCE[8]

The magnetic resonance method of WPT helps overcome the problem of a drop in efficiency when the distance increases between the power transmission coil and the power reception coil. The extent of magnetic coupling between the transmission and the reception sides is expressed by a value known as the coupling coefficient or k. If the inductance of the power transmission coil and the power reception coil are L1 and L2 respectively, and the mutual inductance is M, the coupling coefficient k is expressed by the following formula:

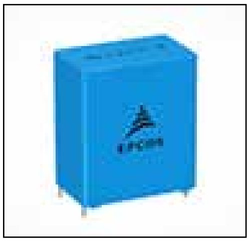


Fig. 3 A typical capacitor used in WPT.

$k = M/\sqrt{L1 \times L2}$

The coupling coefficient is a value in the range of 0≤k≤1, and it is ideally equal to 1 (=100% transmission efficiency) in the absence of leakage flux.7 In the magnetic resonance method, the capacitors are inserted on both the power transmission and the power reception sides to form an LC (inductor and capacitor) resonance circuit (see ***Figure 3***). Power is transferred by matching the resonance frequency on both sides. Thus a high transmission efficiency can be obtained even when the coupling coefficient is low, typically <0.5.

The maximum transmission efficiency in the magnetic resonance method is expressed as a function of the product of the coupling coefficient (k) and the Quality factor (Q) of the coil (kQ product). Even if the coupling coefficient is low, high-transmission efficiency can be obtained by increasing the coil's Q. However, several problems need to be overcome to implement the magnetic resonance method of WPT.

## INHIBITORS

The coil's Q-value is expressed as Q=2πfL/R (where f is the resonance frequency, L is the coil inductance, and R is the coil's AC resistance component). According to this formula, if inductance is increased by expanding the coil's diameter, or by increasing the number of turns of the coil, then theoretically, Q will be increased. However, since the resistance component also increases in this case, it is necessary to optimize the shape and the size of the coils during coil design in order to balance both.

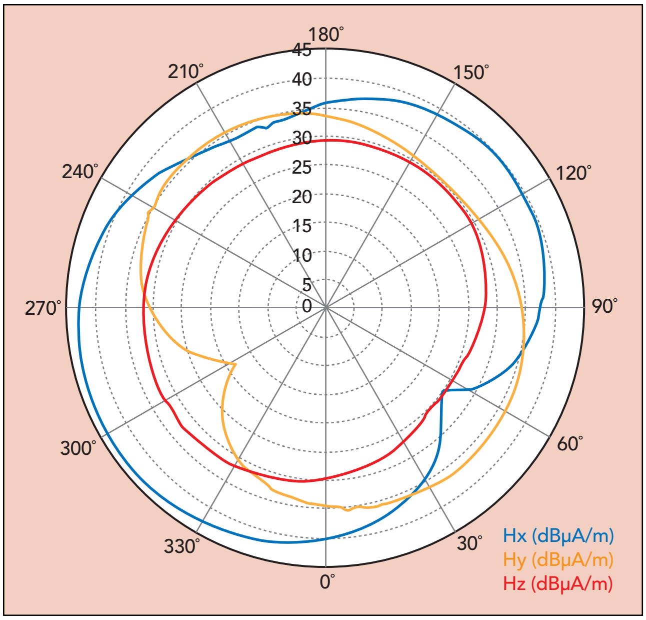



**Fig. 4 Coils Matched [0,0] Aligned, Nominal Frequency Sample Azimuth Measurements.**

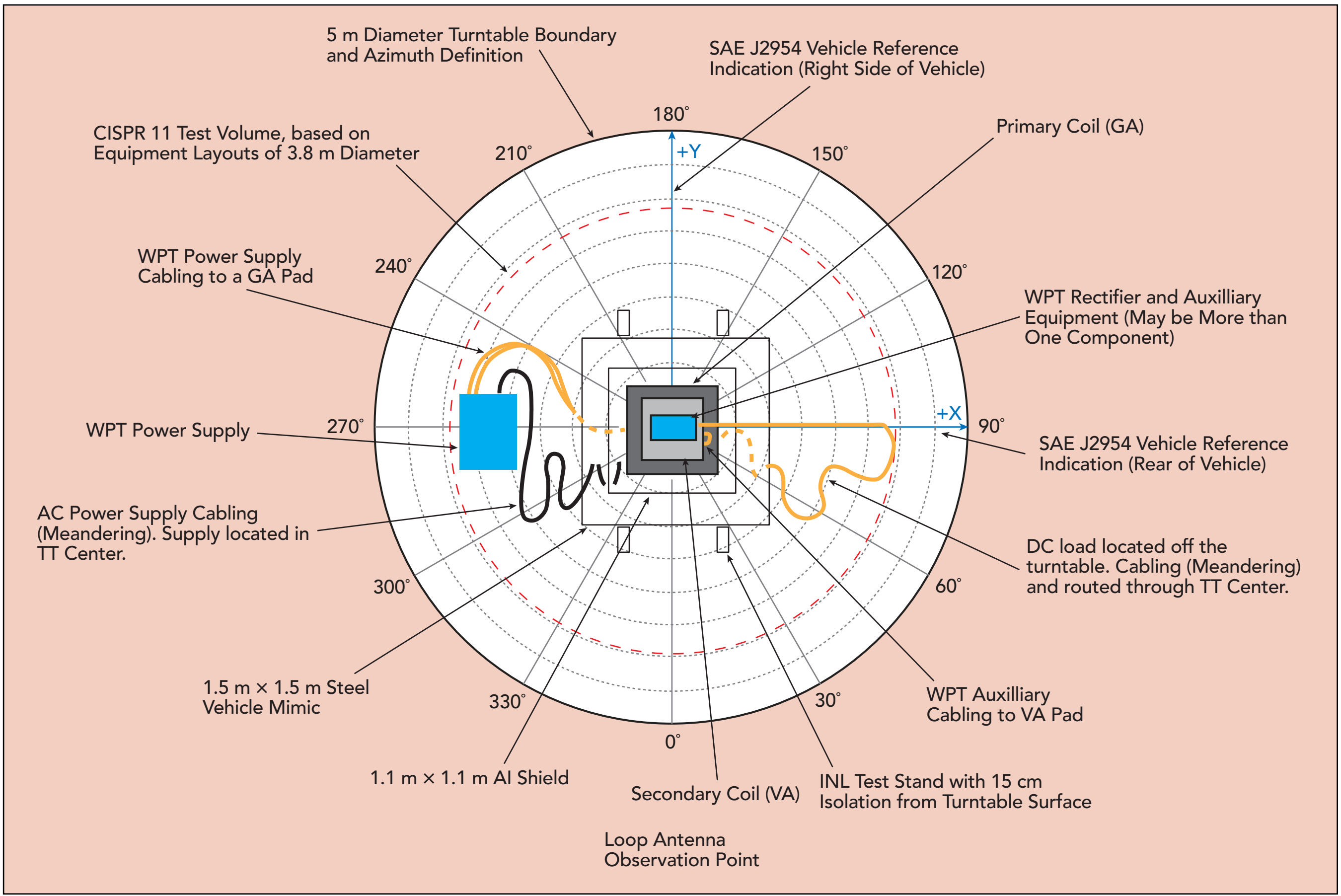
**TABLE 1**

**COILS MATCHED [0,0] ALIGNED, NOMINAL FREQUENCY SAMPLE SPECTRUM ANALYZER MEASUREMENTS**

| | EMI (dBμA/m) | Angle (°) |
|---|---|---|
| Max Hx: | 43.94 | 306 |
| Max Hy: | 36.51 | 36 |
| Max Hz: | 32.56 | 298 |

Furthermore, in the magnetic resonance method, maximum transmission efficiency may be obtained when the power transmission and the power reception coils are placed at an optimum distance from each other. However, reducing this distance may cause the transmission efficiency to drop instead of increasing. This is due to deviations from the optimum distance when the mutual inductance M changes, causing the coupling coefficient and the resonance frequency to change. Additionally, the stray capacitance from the objects around the coils also affects the resonance frequency, resulting in an untuned, non-optimized system. Hence, a special circuit is typically required to automatically track and tune the circuit for the maximum efficiency. There are various techniques to compensate for these fluctuations in the resonance frequency, but this is the most important technical consideration in the magnetic resonance method, along with the coil design technology.

Simulated and measured data cannot be provided, but the typical resonant frequency of the WPT system is 81.38 – 90 kHz. The EMF fields are governed by International Commission on Non-Ionizing Radiation Protection (ICNIRP) 2010 standards. Field strengths vary depending on the regions specified for WPT systems. In the driver area and around the vehicle it is restricted to 21.2 micro-tesla. The field strengths are governed by the ICNIRP 2010 standards. ***Figures 4 and 5*** show




▲ **Fig. 5 Test Setup Top View.**[6]

the nominal frequency sample azimuth measurements with sample spectrum analyzer and EMI measurements shown in ***Tables 1*** and ***2.***

## ELECTROMAGNETIC COMPATIBILITY (EMC)

Electromagnetic compatibility (EMC) means that a device is compatible with (i.e., no interference is caused by) its electromagnetic (EM) environment, and it does not emit levels of EM energy that cause electromagnetic interference (EMI) in other devices in the vicinity. The EMC in the WPT world includes the compatibility of the electronics in a vehicle to be able to work properly in the presence of strong magnetic fields generated by the WPT systems. Furthermore, the potential for a negative effect, if any, of these signals on human beings in the vehicle is worth a mention here.

The increasingly advanced electronics that are being incorporated into EV-component-level systems will need to be designed with the EMC in mind to ensure the reliability and safe operation of the vehicle. Each system component needs to coexist in the EM environment introduced by the EV systems as a whole (see ***Figure 6***). These electrical system components introduce radiated or conducted EM energy of their own. For example, an intentional radiator such as a WPT system transmitter (e.g., transmission coil) can generate a strong signal at a specific frequency of operation that may couple with other vehicle electronic systems such as navigational and communication systems, resulting in operational failures. These types of interferences are introduced via coupling through wiring harnesses or PCB traces. The EMC circuits, such as filters, are designed for each system component to mitigate any potential EMI. These

**TABLE 2**

**COILS MATCHED [0,0] ALIGNED, NOMINAL FREQUENCY SAMPLE EMI RECEIVER MEASUREMENTS**

| Detector | $H_x$ Trace (dBμV) | $CF_{rc}$ (dB) | $H_x$ EMI (dBμA/m) |
|---|---|---|---|
| Pk | 53.4 | –10.17 | 43.23 |
| QP | 53.0 | –10.17 | 42.83 |
| Average | 53.3 | –10.17 | 43.13 |
| **Detector** | **$H_y$ Trace (dBμV)** | **$CF_{rc}$ (dB)** | **$H_y$ EMI (dBμA/m)** |
| Pk | 46.8 | –10.16 | 36.64 |
| QP | 46.3 | –10.16 | 36.14 |
| Average | 46.6 | –10.16 | 36.44 |
| **Detector** | **$H_z$ Trace (dBμV)** | **$CF_{rc}$ (dB)** | **$H_z$ EMI (dBμA/m)** |
| Pk | 43.0 | –10.16 | 32.84 |
| QP | 40.2 | –10.16 | 30.04 |
| Average | 41.1 | –10.16 | 30.94 |

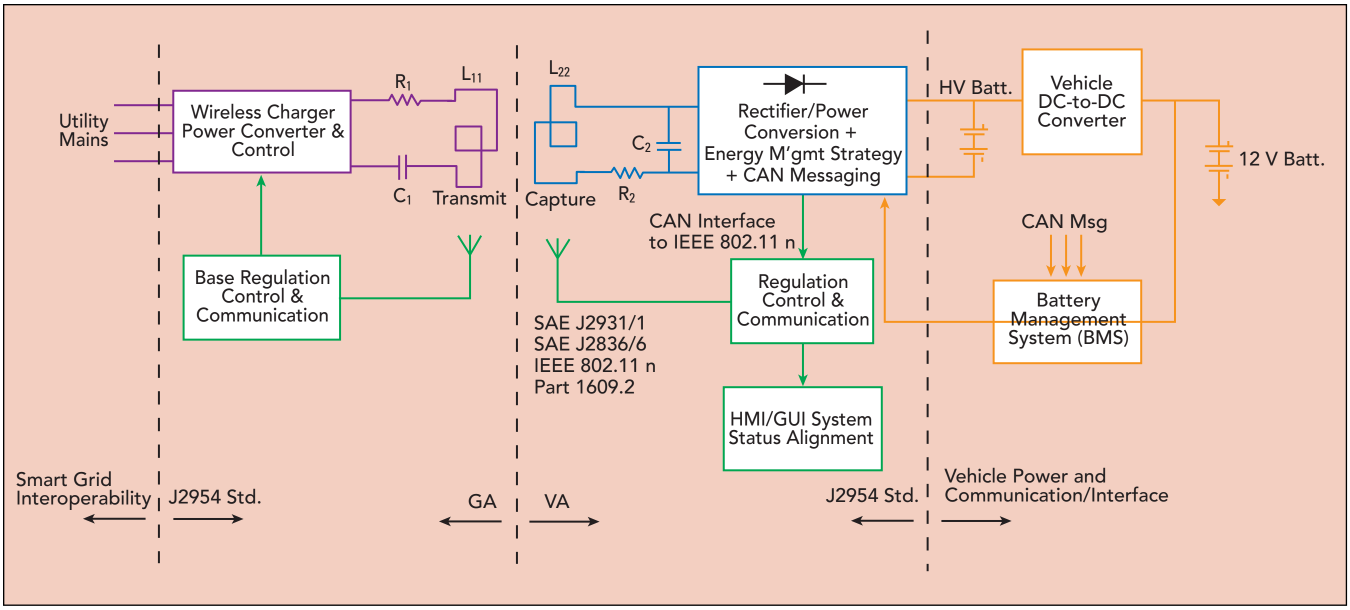



**Fig. 6 Block diagram of a single WPT charging station.**

circuits include capacitors, inductors, resistors, and combinations thereof. Other electronic components that will help mitigate such interferences are ferrite materials in the forms of beads, clamps, toroids, sheets, and specifically designed ferrite material for wiring applications.

A WPT system supplies power at a specific rate according to the position of the VA coil within the required range relative to the GA coil. The power transfer will cease in the event of any out-of-specification circumstance. Furthermore, the power transfer needs to meet the efficiency targets at the full specified rated power. The WPT mechanisms are composed of the following components:

- Ground Assembly Mechanism:
  - *High-frequency power inverter*
  - *Filter*
  - *Transmit coil*
  - *Regulation control and communication*
- Vehicle Assembly Mechanism:
  - *Receive coil*
  - *Filter*
  - *Rectifier*
  - *Regulation control and communication*
- Secondary Energy Storage Mechanism:
  - *Secondary energy storage system*
  - *Battery management system components*
  - *In-vehicle communication modules*

## CONCLUSION

Many believe plug-less EVs will be a key to realizing a future with ubiquitous self-charging autonomous vehicles. For mass adoption to occur, there needs to be an accompanying public charging infrastructure that is universally available. Global industry leaders including TDK are working to define a clear set of WPT standards, including those governing EMC. Engineers developing optimal WPT for public spaces are grappling with issues such as the necessary degree of alignment precision between the charging plate and the EV, the effects of materials on EMC, the optimum coil angles, and the consequences of interaction among multiple coils in proximity together in public spaces. They are considering what effect EM signals may have on human beings in and around the wireless EVs. Pursuing ongoing research, development and testing of new methods, materials and designs, engineers around the globe are racing to solve the complex issues of WPT for the automotive industry.

## SUMMARY OF AUTOMOTIVE WPT PROS AND CONS:

**Pros:**

1. Convenience: There is no need for manual charging, or connecting/disconnecting cables.
2. Lower lifetime costs: There are fewer mechanical parts with the potential to break down and require repairs/replacement. There is reduced potential for rust or corrosion due to weather on cables or receptacle.
3. Safety: There are no exposed high voltage or power outlets.
4. Automatic: Autonomous vehicles are self-charging.

**Cons:**

5. Lower efficiency: Currently, WPT is lower efficiency than wired options.
6. Longer charging: WPT currently requires longer charging times than wired options.
7. High upfront or setup costs: There are costs for updating the power infrastructure as mentioned above, installation of ground assemblies, etc.
8. Susceptibility to weather: Extreme weather conditions could affect charge efficiency and/or the general ability to charge. ■

# Characterizing and Tuning Antennas Using an Automated Measurement System and a VNA

Copper Mountain Technologies
*Indianapolis, Ind.*
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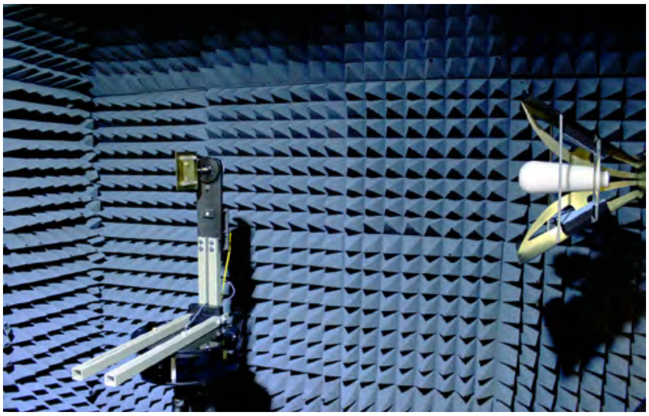
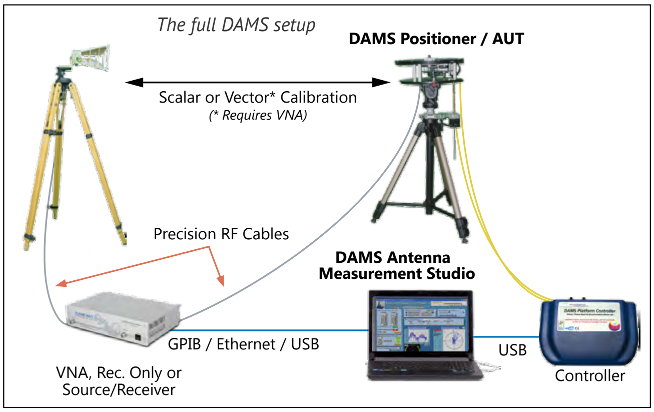
*Diamond Springs, Calif.*

## APPLICATION PROFILE

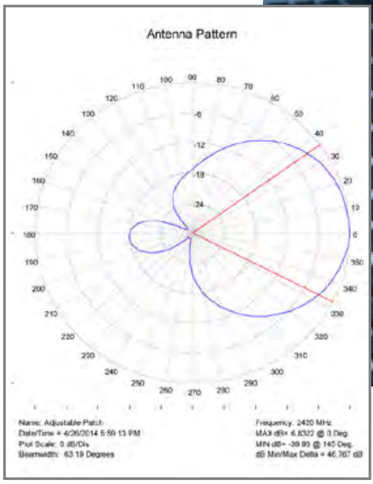
As the number of devices featuring wireless connectivity grows, ensuring their performance specifications while staying within regulatory requirements becomes even more important. Antenna pattern measurement is a critical step in the design process of antennas and wireless devices. Compact antenna measurement systems combined with a high performance VNA are necessary to characterize parameters such as pattern, gain, VSWR, and efficiency. These results are used to validate simulated designs and identify possible performance issues before final testing. By using an in-house measurement system, multiple design revisions can be tested and precertified without the high cost of using an accredited or certified measurement facility for each test. Other considerations like portability and low cost are important to engineers in various environments like defense or education, respectively.






## CHALLENGES

Making accurate antenna measurements carries a number of challenges, some of the most important being dynamic range, calibration, and speed. A sufficient dynamic range will allow the antenna to be measured accurately at both minimum and maximum signal level with a minimal amount of trace noise. Older network analyzers can reach a reasonable dynamic range and reduced noise by reducing the IF bandwidth but the ana-



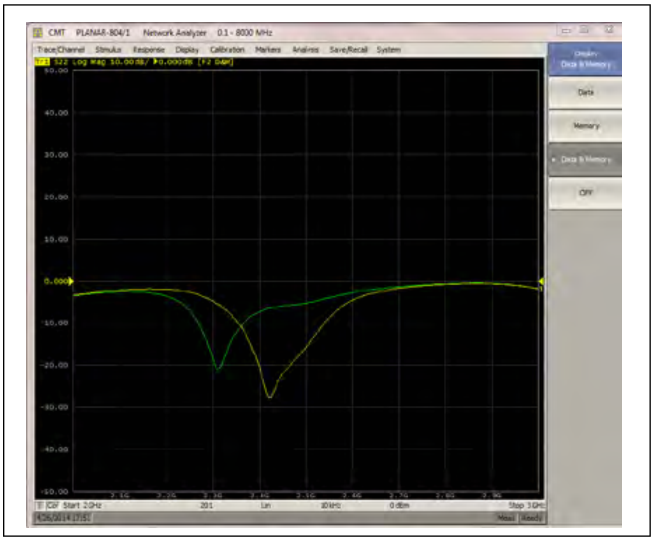


**Left: the AUT is tuned at 2420 MHz**
**Right: the VNA and DAMS software operate in tandem on a PC**

lyzer speed is greatly reduced, a single sweep can take many seconds to complete. PC-based VNA's offer the benefit of greater initial dynamic range, higher speeds, and direct data transfer.

## APPLICATION: CHARACTERIZING THE ANTENNA

In this example, an unknown 2.4 GHz antenna is characterized, with a configuration consisting of: Diamond Engineering DAMS 5000 positioner with an FSM spherical mount, RF cables, a calibrated reference antenna, a Copper Mountain Technologies Planar 804/1 VNA, and a computer (PC) running the measurement and VNA software. To begin, the VNA is set to the antenna's frequency range, all RF cable loss (including positioner) is calibrated out using the VNA's built in 12 term calibration. Once the calibration is complete the AUT is mounted to the positioner's RF Rotary Joint and the reference antenna is connected then positioned at the appropriate distance (typically 1 or 3 meters). Now that the antennas are connected and the VNA is set to transmission (S12 or S21), the VNA will show the response of the entire link. At this point the user can note the signal response on the analyzer; if the polarization is correct and the AUT is at a point of high signal, the VNA should show a strong profile with little trace noise. Depending on the type of antenna being measured, the antenna can be manually positioned to a point of lowest signal to confirm that the signal is still above the noise floor and the trace noise is acceptable for testing requirements. After the setup is verified, the DAMS antenna measurement software is used to make a measurement. The software indexes the antenna to every physical point and executes a transmission sweep on the VNA. Optionally, VSWR data can be automatically collected at every point. Once complete, the entire data set can be viewed, processed and exported.



**The yellow trace shows S22 of the AUT after tuning**

## POST-MEASUREMENT ANALYSIS AND TUNING

Analyzing the measurement data may reveal certain problems such as low gain, pattern distortion, or frequency response issues. Since the Planar 804/1 VNA is still fully calibrated it can be used to tune and troubleshoot the antenna in real time. For live antenna tuning, the analyzer is switched to S22 mode, and the user can make small modifications to the antenna while seeing the results immediately displayed. To identify multi-path and unwanted environment reflections, the VNA can be switched to S21 Time Domain mode. Reflections outside of the direct path will show up as unusually large spikes indicating that the signal is being reflected. The absorber can now be placed to block the unwanted reflections. After changes have been made to the antenna and/or the test setup, another measurement can be made quickly to verify and record these changes. The end result is a refined antenna design with accurate, publishable test data.

## INCORPORATING A PC-BASED VNA

Several specific features and modes of the analyzer were key in this application, including transmission, reflection, VSWR, dynamic range, Time Domain, and sweep speed. All of these are crucial for the measurement and design of antennas and related systems. Antenna measurements contain a large amount of data: a single polarization full spherical measurement using 10 degree resolution and 51 frequencies contains over 33,000 data points. The ability to automate these measurements using the Planar 804/1 VNA scripts and DAMS 5000 positioner saved many hours compared to manual testing. In this application the VNA's high measurement speed of 100 µs enabled real-time tuning and fast data collection.

## SUMMARY

Complete antenna measurement and characterization can be quickly achieved using a compact antenna measurement system powered by a PC-based VNA and the DAMS studio. Traditional pattern measurement systems often use a separate source and receiver, limiting measurements to either single frequency or stepped CW modes of operation. The test equipment for these systems is often dedicated and limited to just the measurement of the antenna without parameters such as phase and VSWR. The Planar 804/1 VNA contains all of the tools and capability required for the measurement, design, and tuning of the antenna. Fast, broadband vector based measurements with low noise and high dynamic range are essential for the wireless technology of today and tomorrow. Combining a compact antenna measurement system with the flexibility of an automation ready, PC-based VNA from Copper Mountain Technologies provides a low cost solution that greatly reduces development time and increases product performance. ■

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