Investigation of Conducted Immunity and Spatial Distribution of RF Currents for a 2-Sided PCB

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Abstract
Influence of the RF noise in automotive 12-volts power distribution network and its impact on electronic control unit is investigated. A magnetic near-field scanner is used to inspect the penetration of the injected RF currents on an automotive module. Spectral and spatial scans are useful in investigation of the power distribution robustness. It is anticipated that spatial view of conducted RF currents in a printed circuit board can result into design practices that enhances the EMI robustness of a product and its functional quality.

Keywords
Conducted Immunity (CI), Transient Waveforms, Near Field Magnetic probe, TEM Cell Radiated Immunity, EMSCAN, Direct RF Injection (DRFI).

I. INTRODUCTION
Automotive 12 volts DC power distribution network is constantly perturbed by transients as a result of the switched inductive electromechanical loads. Electronic control modules and DC motors all share the same power distribution network. In modern vehicle electronic modules provide critical functions in the operation of a vehicle. Electronic control units such as engine control unit, airbag and anti-lock brake system play key functions and are critical in the safety operation of the vehicle. All electronic modules installed in a vehicle receive their power from battery or ignitions line. Design engineers are required to understand the nature of these transients and provide protection mechanisms to react reliably to aforementioned events. OEM provides frequent revisions to their requirements to address the true nature of transient pulses and provide an accurate waveform signature that relates to the vehicle environment.

Automotive conducted immunity specifications and tests are designed to address the electronic module's robustness to a noisy 12-volt battery and ignition supply lines found in the vehicle power distribution network. OEM specifications provide various conducted immunity tests to address these issues. In the design world, engineers are confronted and challenged to meet the requirements provided by automotive OEM. Design of a product for automotive application has to be cost-effective and compliant with EMC and other electrical requirements. To meet these requirements, designers add several suppression components to assure product compliance. It is often thought that such robustness requirements are unrealistic. However, automotive design must account for reliability and in many situations it is a safety factor that cannot be ignored or neglected. A host of power dips and drops, and voltage transients, are captured in OEM specifications with various stress level to provide an accurate evaluation of vehicle environment. In addition, conducted RF injection by means of the bulk current injection (BCI) test technique, and direct RF injection (DRFI) to DUT pins, addresses RF susceptibility to power lines and I/O lines.These standards and requirements are in constant review and changes are introduced to address observed effects evidenced at vehicle environment. Conducted immunity tests could initiate reset and latch up reactions in the microcontrollers used in most automotive modules. ISO 7637 defines several transient pulses identified by automotive OEM. However, in recent years one OEM has introduced a number of transient waveforms, in addition to those of ISO pulses, to expose module's power distribution to vehicle-related disturbances. These transient events emanate as a result of contact arcing during deactivation of inductive loads. These waveforms do not possess precise amplitude and time requirements as defied by ISO waveforms, and can be classified as random in nature. One OEM has introduced additional waveforms as part of EMC validation requirements.

In this paper, we investigate the impact of the injected RF noise on the 12-volts power distribution network of an automotive module. A near-field scanning system is used to trace the RF current penetration within the printed circuit board components and PCB nets of the controller module. This technique is insightful for investigation of the robustness of power distribution network and its ability to withstand harsh automotive environment. An automotive electronic control module was selected for this investigation.

In order to understand the response of a circuit to the conducted transients on the power network, one must attempt to arrange a mechanism in which transients are time-mapped to the software execution of memory read and write cycles where there is a high degree of vulnerability. Consider if transients arrive at the power pins where a microcontroller is in the read or write cycle of a code to RAM, it may be the most critical moment that a micro may react unfavorably and cause a system crash or false data transfer. Time-mapping of the transients in typical CI tests are not considered in standard ISO pulse tests. A unit is

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placed in functional mode and transients are applied to power pins, without any consideration to such details.

Product assurance department of an automotive supplier in NA reported several situations; where most of the warranty return electronic control modules, and complaints, were as a result of a software failure. These units did not show any hardware failures or parametric degradation in its hardware components. It was discovered that regular CI tests did not result into similar failures. This required the introduction of additional waveforms that successfully replicate similar malfunctions and can be used by software engineers to test and validate the robustness of product under development.

II. Electronic Module Description

The electronic control module was designed on a 2-sided printed circuit board (1.6 mm thickness FR4 substrate, ε_r = 4.7). The high-density design utilized component placement on both sides of the PCB. High volume, cost conscious automotive world prevents multi-layer designs due to the cost reasons. Engineers are also challenged to design products exposed to extremely harsh thermal, mechanical and EMI threats. In this manner, automotive designs cannot utilize ground (return) planes as it would add to the PCB cost. The product under EMC investigation was designed with EMC robustness techniques and star configuration for power distribution network was adopted to operate reliably under EMC requirements. Microcontroller selected for this design required total of six decoupling capacitors, to be placed at three distinct power pins. A pair of 10 nF and 100 nF capacitors were mounted at each power pin. The clock frequency for the micro was set at 16 MHz in addition to a Phase Locked Loop (PLL) operating at 32 MHz (VCO).

It was decided to investigate the impact of the high frequency capacitors on conducted immunity and RF current distribution in the vicinity of the microcontroller. Unit #1 was fully populated with optimum placement of decoupling capacitors. For Unit # 2 we removed all six high frequency capacitors (1 nF and 100 nF).

III. Experimental Method

EMSCAN Nexus Plus is a magnetic near-field scanner system that is utilized at EMC laboratories to investigate electromagnetic emission of printed circuit boards (PCBs).

EMSCAN was utilized as shown in Figure 1 to measure the relative H-field in close proximity of each PCB. A CW RF generator (HP 8657A, amplitude 0 dBm) was connected to RF injection probe (FCC F-130A) as the RF source signal via a coaxial cable. By examining the spectral scan of both modules, it was observed that both modules did not exhibit any excessive spectral components at 110 MHz and 140 MHz. We decided to examine only these two frequencies for RF injection studies. The technique offered here can be extended utilizing the tracking generator of the spectrum analyzer, to sweep the power distribution network over a broad range of RF frequencies to identify the path and locations of RF currents flowing in the printed circuit board. The tracking generator of spectrum analyzers can be useful in determining resonances in a PCB and thus select those frequencies for RF injection. This may be explored at a different time. By exposing the module to 110 MHz and 140 MHz RF injection only, the Ignition and GND wires of each module was placed inside the injection probe.

The voltage measured at the spectrum analyzer does not contain the antenna factor of the EMSCAN antennas and cable loss factors. Therefore, it is not an absolute measurement of the field of each PCB. However, it can be used to understand the relative behavior of each PCB with respect to the RF current distribution impact. Each PCB was placed in close proximity of EMSCAN sensors facing the loop antennas of EMSCAN. The voltage was measured by spectrum analyzer only in the frequency range from 10 MHz - 200 MHz.

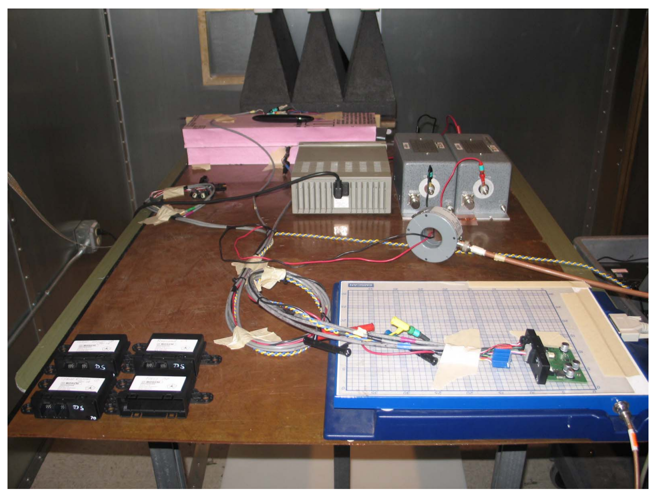

Figure 1. Near Field Scan and RF Injection Test Setup.

IV. Experimental Results

Spectral scan for both modules revealed the PLL's 32 MHz clock frequency and several other harmonics. Spatial scan for fully populated version indicated 32 MHz clock frequency currents in a highly confined, and in a very small physical area immediately under the microcontroller. This indicates the circulation of 32 MHz in the core of the microcontroller and cannot be resolved by external methods.

In Figure 2 spectral comparisons between a fully populated module (Unit # 1) and a reduced decoupling capacitor version (Unit # 2) is illustrated. It is clear that the reduced ver-

sion is elevated in noise floor by as high as 6 dB in the frequency range of 10 MHz – 200 MHz.
Therefore, the use of the decoupling capacitors, in addition to the reduction of radiated emission; has a great impact on the PCB noise floor.
Also, elimination of the decoupling capacitors provides an easier path for RF current penetration as will be shown.

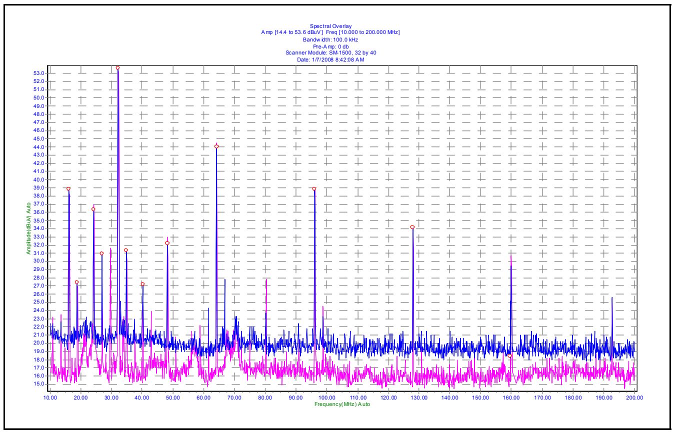

Figure 2. Spectral View for Fully Populated PCB vs. Reduced Decoupling Version.

In Figure 3 spectral scan of a fully populated module (Unit # 1) injected with a 110 MHz (0 dBm) RF signal is shown. The measured amplitude of the 110 MHz RF current is 56 dBμV.

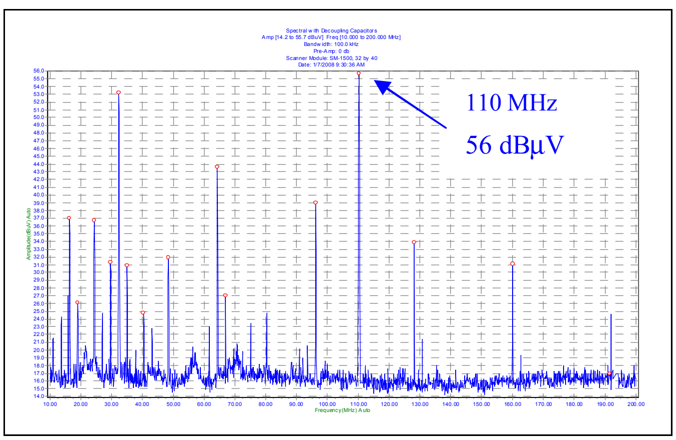

Figure 3. Spectral View for Fully Populated PCB Injected with 110 MHz RF Current.

In Figure 4 the spatial scan of a 110 MHz RF current on Unit # 2 with removed decoupling capacitors is illustrated. It is evident that the removal of the decoupling capacitors has a profound effect on the penetration of the RF currents into a PCB real estate where microcontroller and other sensitive circuits may reside. The removal of decoupling capacitors resulted into a less stable unit with abrupt reset indications. It is clear that the removal of high frequency capacitors results into the circulation of high frequency RF currents that may be detrimental to the analog circuits and the other microcontroller circuits (analog ports and reset circuitry). Spatial color plots range from 20 dBμV (Blue) to 55 dBμV (Red).

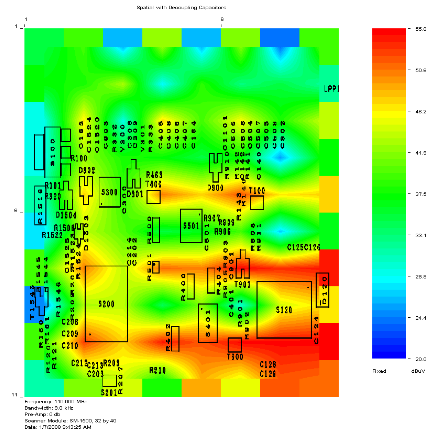

Figure 4. Spatial View of 110 MHz RF Current for the Reduced Decoupling Version (20 dBuV - 55 dBuV).

In Figure 5 the spatial scan of a 110 MHz RF current on the Unit # 1 (fully populated module) is shown. The color level assigned to the spatial scan is the same as in Figure 3. It is clear that the amplitude of 110 MHz is substantially less in this case, and it is a key factor to the reduction of the circulation of RF currents.

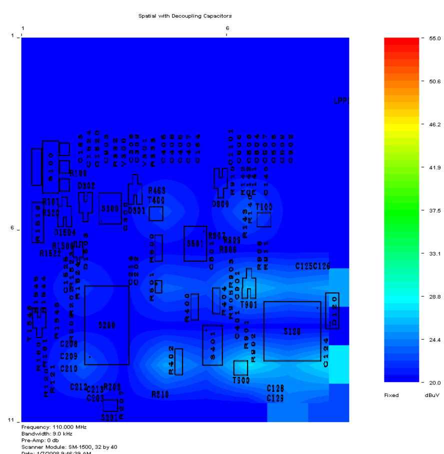

Figure 5. Spatial View of 110 MHz RF Current for the Fully Populated Version (20 dBuV - 55 dBuV).

In Figure 6 we illustrate another example for the amplitude of the injected RF current (140 MHz) into the power distribution network of Unit # 1 (fully populated module).

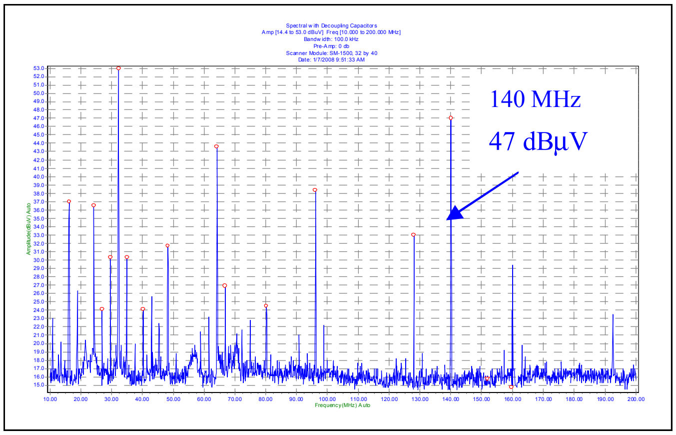

Figure 6. Spectral View for Fully Populated PCB Injected with 140 MHz RF Current.

In Figure 7 we illustrate spectral content for injection of 110 MHz and 140 MHz RF current into the power distribution network of Unit # 2 (reduced decoupling module). We use EMSCAN's spectral overlay capability to investigate the amplitudes of two RF signals simultaneously.

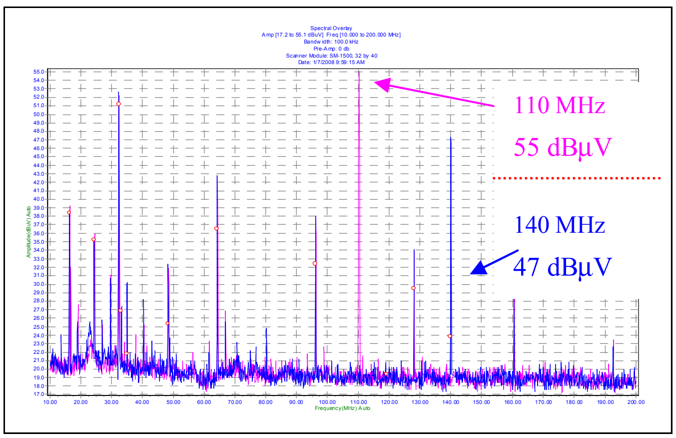

Figure 7. Spectral View for Reduced Decoupling Version Injected with 140 MHz RF Current.

Figure 8 shows the injected RF currents at 140 MHz into the power distribution network of a fully populated module, and a reduced decoupling version. The spatial scan was set between 135 MHz – 145 MHz with spectrum analyzer's RBW (Resolution Bandwidth) set at 10 kHz (RBW for all other spectral scans were at 100 kHz). It is clear that Unit # 2 has higher vulnerability to the injected RF currents compared with Unit #1.

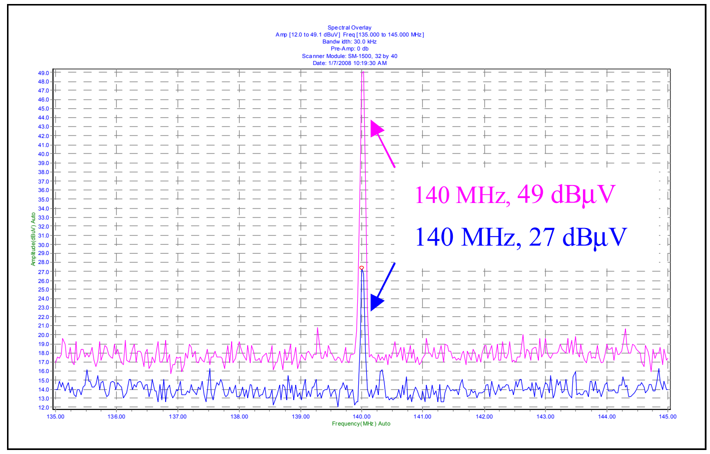

Figure 8. Spectral View for Fully Populated vs. Reduced Decoupling Version PCB (injected with 140 MHz).

V. TEM CELL Radiated Immunity

Control Unit # 1 and Unit #2 were exposed to Radiated Immunity at 200 V/m field strength (TEM Cell). Unit # 1 continued to operate as intended without any functional deviations. However, Unit #2 exhibited microcontroller reset activation. Unit # 2 recovered to its intended function after field was removed and resumed its normal operation. The failures occurred at 3 MHz, 16 MHz, 32 MHz, 52 MHz, 64 MHz, 100 MHz, 108 MHz, 140 MHz and 160 MHz. It is clear that the removal of high frequency capacitors have adverse effects during exposure to RF fields that may result into circulation of RF currents in the analog ports of the microcontroller. Figure 9 illustrates the TEM Cell test setup.

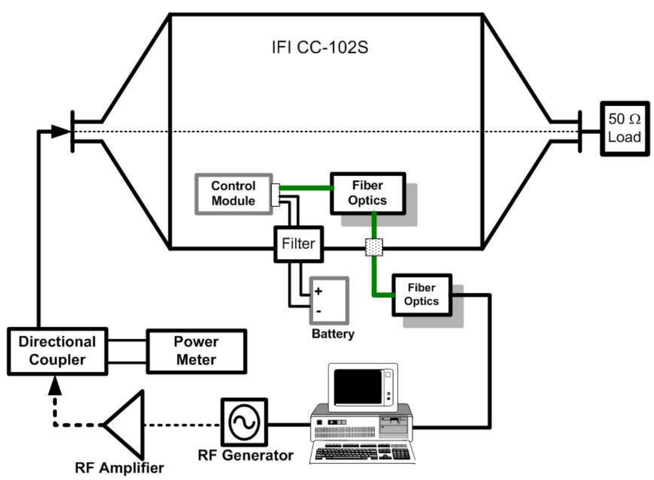

Figure 9. TEM Cell Radiated Immunity Test Setup.

VI. Pulse A2 Conducted Immunity

Control Unit # 1 and Unit #2 were exposed to Pulse A2 (Ford Motor Company, EMC Pulse A2). Unit # 1 continued to operate as intended without any functional deviations. However, Unit #2 exhibited malfunctions and microcontroller reset activation. Unit # 2 did not recover to its intended function after Pulse expiration and required power re-cycle to resume its normal operation. This compares to the 110 MHz RF circulation current failure scenario. Although, spectral content of Pulse A2 pulse is well below 110 MHz band. However, it is clear that the removal of the high frequency capacitors has adverse effects during CI pulse A2 injection, and may result into circulation of RF currents in the analog ports of the microcontroller. Figure 10 illustrates the pulse A2 waveform details. It is clear that ISO pulses are not designed to identify similar events.

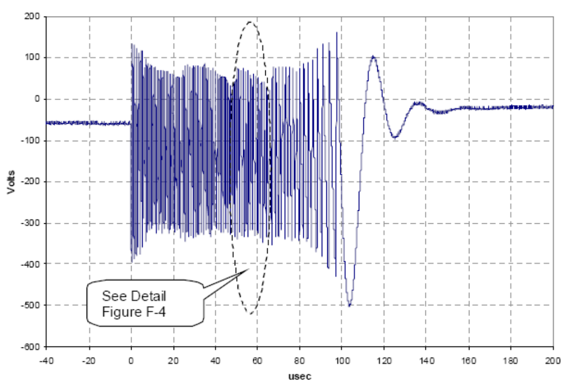

Figure 10. Ford Motor Company Pulse A2 "Showering Arc".

VII. Conclusion

Circulation of RF currents in large areas of the printed circuit board must be avoided in order to prevent microcontroller reset and other functional deviations. In particular, analog circuits and analog ports of microcontrollers are highly susceptible to the presence of RF currents. It was shown that the RF current circulation was 18 dB higher for Unit # 2, compared with Unit #1 (fully populated version). By placement of high frequency decoupling capacitors in close proximity of the microcontroller power pins, one can prevent and control the high frequency current circulations and resolve functional problems. This study is a basic consideration to the function of high frequency decoupling capacitors, as a mitigation solution for the radiated emission, and RF immunity (conducted and radiated). It is also important to note appropriate implementation, and placement of decoupling capacitors is critical for 2-sided printed circuit boards. Spatial view of the circulating RF currents in printed circuit board is useful in detection and troubleshooting stage. It was shown that the removal of decoupling capacitors elevated the PCB noise floor by as much as 6 dB

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