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EMC Chip-Level DESIGN AutomotiveProductDesign

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Abstract—**Integrated circuits (ICs) are often the sourceof thehigh-frequency noise that drives electromagnetic emissions fromelectronic products. A case study is presented where emissionsfromaprintedcircuitboardcontaininganautomotivemicrocontroller are reduced significantly through analysis of thecoupling mechanisms from the chip to the board and attachedcables.NoisegeneratedbytheICisexploredthroughmeasurementsinasemi-anechoicchamberandTEMcell,throughnear-fieldscans,andthroughmodificationstotheprinted circuit board. Noise is driven by the IC through bothpower and I/O connections. Results show that a ferrite in serieswith I/O power in this application reduced emissions by 10 dB ormore at critical frequencies. Possible causes for emissions fromthe IC and modifications that might reduce these emissions arediscussed.**

Keywords*-Electromagneticcompatibility;integratedcircuits;coupling;automotive;emissions*

INTRODUCTION

High-frequency noise from clocked circuits is inevitable.The switchingofinternalgatescauses periodicchanges involtages and currents that create noise on power and I/O linesat the clock frequency and its harmonics. This noise drives theboardandattachedcablestoradiate.Experiencesuggests,however, that there are both good and bad ICs in terms of theiremissions.Forexample,experimentshaveshown thereismorethan a 10 dB variation in the TEM cell emissions from similarmicrocontrollersmadebythesamemanufacturer[1].Variationsarelikelytobeevenhigheramongdifferentmanufacturersorimplementationtechnologies[2].OneICmaycause a particular board design to fail an emissions test whileanotherpin-for-pincompatibleICwillallowthedesigntopass.

The emissions driven by these ICs – that is, by the clockedcomponentslikemicrocontrollersandmemory–areparticularly challenging to deal with in automotive products.Profitmarginsarelow,sothat“standard”EMCdesignpractices like power and return planes, filtered I/O and powerlines, shielded enclosures, and even more than minimal

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powerbusdecouplinghavetobeapproachedwithcaretoavoidun necessary cost. In addition, electronic modules are attachedtolongcablesandareplacedveryclosetosensitiveRFreceivers, like an AM radio, so that even relatively small noisesourcescanbeproblematic.Becauseofpotentialsusceptibility issues,especiallytoRFreceivers,theemissionslimitsforautomotive products tend to be significantly more stringentthanthoseforotherindustries[3].

Issueswithautomotiveelectronicsaredrivingstandardization ofmethodstotestandsimulateintegratedcircuits(ICs)forEMC.StandardIEC61967,forexample,defines methods to measure the potential of an IC to causeradiated emissions through conducted, capacitive, or inductivemechanisms or to radiate emissions directly from the chip [4].TheICEM [5]andLECCS[6]modelsweredevelopedtomodelthenoiseconductedthroughtheICpowerdeliverynetwork in order to facilitate better prediction of board-levelemissions. Similar models are being explored to predict noisecoupledthroughI/O[7],[8],[9].

Thegoalofstandardizedmeasurementandsimulationtechniques is not only to allow design engineers to comparedifferent ICs, but is also to encourage IC manufacturers toproduce ICs that drive less emissions. Unfortunately, many ofthesameissuesthatprevent simpleEMCsolutionsattheboardlevel also prevent simple solutions at the chip level. On-chipdecoupling, for example, is an often-cited means of reducingemissions; however, this technique is not typically effectivebelow the LC resonant frequency of the chip and package.Above this frequency, doubling the on-chip decoupling willoften only result in a 6 dB or less reduction in emissions, butwith significant potential cost due to increased die area andwith reduced reliability and increased leakage current due totheadditionalgateoxide.Insomecases,theaddingdecouplingmay even cause an increase in emissions [10]. Similarly, therequirement that automotive ICs must function at temperaturesfrom -40 to +150 °C means that ICs must be designed withhightransitionspeedstomeettimingconstraintsatalltemperature levels. Emissions have been seen to vary in TEMcell measurements by as much as 5 dB from -40 to 100 °C [1].While we and others are developing design methods to reduceemissions,much workisstillneededinthisarea.

As integrated circuits will continue to drive emissions forthe foreseeable future, EMC engineers must continue to dealwiththeseemissionsattheboardlevel.Simultaneouslyminimizing emissions and cost is challenging. While little canbedoneabouttheemissionsfromtheICafteritismanufactured, the ability to handle these emissionscan beimprovedconsiderablywithagoodunderstandingofthenoise generated by the IC and the coupling paths to the board. Thefollowing paper illustrates this concept through a case study ofamicrocontrollerthatcausessystem-levelemissions.ThemicrocontrollerisstudiedintheTEMcell,in thesemi-anechoic chamber, with near-field scans, and with pin-currentmeasurements.Analysisisusedtoidentifythedominantcoupling mechanisms to the board and to mitigate couplingthrough minimal changes to the printed circuit board (PCB).ThemechanismsresponsiblefortheIC'semissioncharacteristics and chip design methods for reducing emissionsarealsodiscussed.

I. INVESTIGATIONOFEMISSIONS

Analysis was performed on a printed circuit board with aknownemissions problem. Thesource ofemissionswas a32-bit microcontroller used in automotive applications like theHeat, Ventilation and Air conditioning Control (HVAC), Anti-lockBrakingSystem(ABS),electro-mechanicalbraking,ElectronicStabilityControl(ESP),andotherautomotivesystems. Emissions occur at the system clock frequency and itsharmonics.Thefollowingexperimentswereperformedwithaninternal clock speed of 32 MHz (external 4 MHz), using onlyinternal memory, and without active switching of I/O. ThefrequenciesofinterestrelatetothecoreratherthantheI/O.

Radiated emissions from the board were captured in a 3-meter semi-anechoic chamber as shown in Fig. 1. The deviceundertestwasplacedonaStyrofoampadontopofaturntable.Powerwas supplied through a short cable by a DC powersupply. Emissions were measured with a log-periodic antenna.The outputof the antennawas connected to a25 dB pre-amplifier through a 50-ohm coaxial cable. The output of thepre-amplifier was connected to a Rohde & Schwartz FSEBspectrumanalyzerandoscilloscope.Measurementswere performed both with and without ferrite clamps on the powersupply cable. The device was rotated and antenna polarizationchangedduringthemeasurement.Themaximumradiationoverthetestisreported.

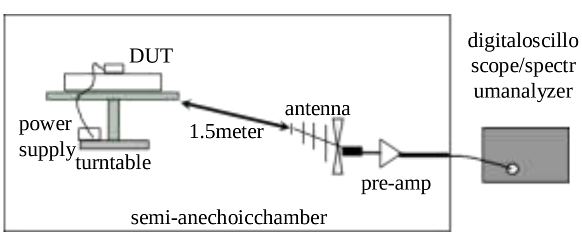


Figure1.Measurement ofemissionsin3-meter chamber.

The measured emissions are shown in Fig. 2. While notmeasured exactly according to the class B FCC requirements,one can readily calculate that the device is on the boundary offailingclassBradiatedemissions.Forexample,at96MHz,theradiatedpoweris-47dBm.Consideringthe25dBamplifier,a 8.2dB(m^{-1})antennafactor,andthemeasurementdistancefromthe antenna,the measuredfieldstrength at3 mshould beapproximately40dBuV.TheclassBFCClimitsis43.5dBuV. ThedevicewouldlikelyfailanautomotiveEMCtest,as automotivestandardsaretypicallymuchmorestringentthanFCCrequirements,especiallyinthe30-400MHzband[3].

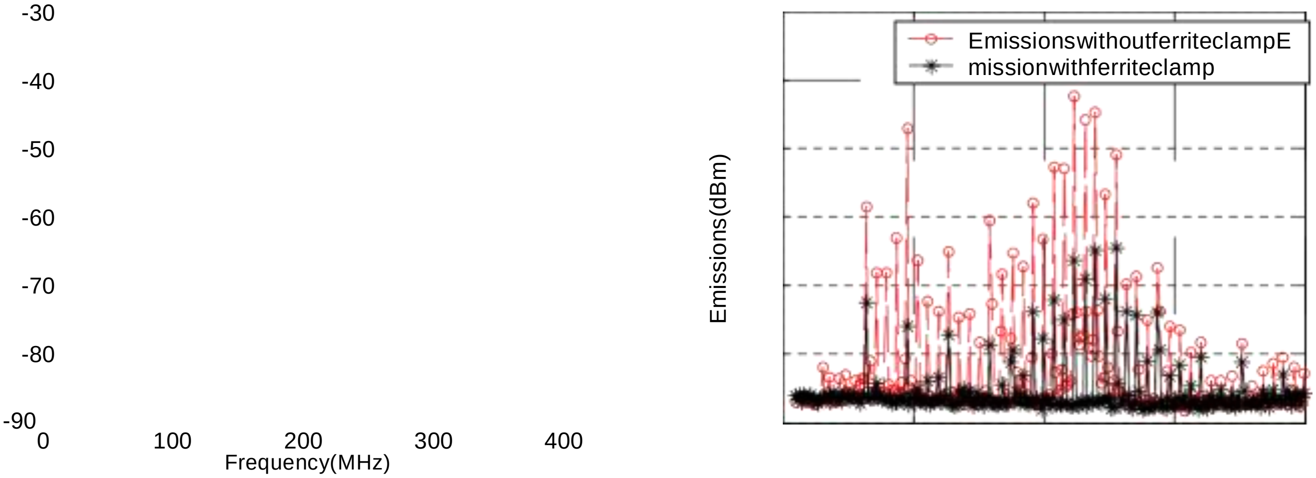


Figure 2. Measured emissions in semi-anechoic chamber from the board andpower cable,withandwithout ferriteclampsattachedtothepower cable.

Eliminating emissions efficiently requires determination oftherootcauseoftheproblem.Asnoiseoccursatthemicrocontrollerclockfrequencyandits harmonics,andnoother device on the PCB is clocked, the noise generator isclearlythemicrocontroller.Themicrocontrolleritself,however, cannot radiate electromagnetic energy well at lowfrequencies because the structures on the chip and package aretoo small to serve as efficient antennas. Noise must be coupledto the PCB and attached cables through electric or magneticfields or conducted through power or I/O pins, where it canthenberadiatedbythelarger,betterantennasofthesystem.

A. CouplingThroughI/O

Noise conducted on I/O lines can be a serious problemwhen the I/O is attached directly to a cable. The possibility ofhigh-frequencyswitchingnoiseonlow-speedI/Olinesissometimes overlooked by PCB designers. To show if noise iscoupled internally from the core to the I/O and then conductedoutofthepackagethroughI/Opins,measurementswereperformedinthesemi-anechoicchamber whena1mcablewasattached directly to the I/O and ferrite clamps were placed onthe powercable. I/O were configured either as input or asoutputcontinuouslydrivingahigh orlowvoltage.

Measured emissions are shown in Fig. 3. Emissions with awire attached to I/O are generally higher than when no wire isattached and the powerlineclamped,asshowninFig.2.EmissionswhenI/Oisconfiguredasinputaremuchlower thanwhenI/Oisconfiguredasoutput.Highestemissionsaregenerallyobservedwhenthemicrocontrollerisdrivinganoutput high. When the I/O drives a high or low voltage, aconduction path exists between Vddio or Vssio, respectively,and the I/O output pin. Since emissions increase on an outputhigh or low, coupling is probably occurring between the coreandVddioorVssiowithintheIC.

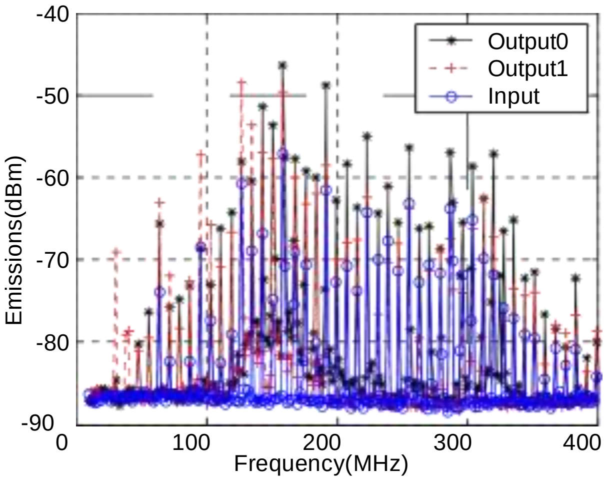


Figure 3.Measured emissions in semi-anechoic chamber from the boardwhena1mwirewasattacheddirectlytotheI/O.

Twoimmediatesolutions thatcouldbeimplementedtoreduceemissionsfromnoiseonI/OaretofiltertheI/O,especially the outputs, or to buffer the I/O before it leaves thePCB. While these solutions are likely to be effective, neither isideal due to the extra costs involved, particularly if there are alarge number of I/O. Other simpler solutions may be available.For example, if noise is being capacitively coupled from VddtoVddiowithinthechip,thennoisemightbereducedbybetterdecoupling of Vdd. A better understanding of the couplingmechanismsshouldbeacquired,however,beforesuch solutions are pursued. One such simple solution presents itselfinthenextsection.

B. Coupling ThroughPower Pins

Switching noise from the core may also be coupled to theboardthroughpowerpincurrents.SuchamechanismisindicatedindirectlyinFig.2,sincenowiresareattachedtoI/O.To further demonstrate this possibility and better understandthecouplingmechanism,emissionsweremeasuredinthesemi-anechoic chamber when the power cable was clamped with aferrite and 50 cm wires were attached to the return plane of thePCBtocreateadipole-likeantenna,asshowninFig.4.Emissionsweremeasuredwhenthewireswereattachedfirstinthe X direction then the Y direction (i.e. the attachment pointswererotated90ºaboutthePCB).

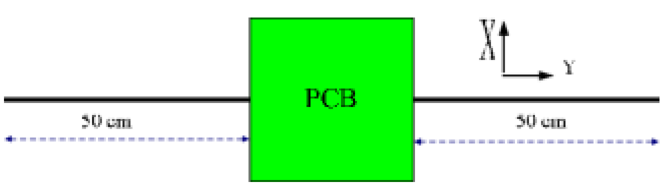


Figure 4.Wires were attached to the return plane to test the influence ofpower-busnoise.

As shown in Fig. 5, emissions at many frequencies tend tobe lower when wires are placed in one direction compared totheother.Thisresultindicatesapossiblecurrent-drivenradiationmechanismmayberesponsibleforasignificant portionoftheemissions.Thecurrent-drivenradiation mechanismisillustratedinFig.6.Currentflowfromthepower-plane,thoughtheIC,andbacktothereturnplanecausesmagnetic flux to wrap the board. This flux induces commonmode voltages that drive the board and attached cables [11].Emissionsoccurwhencablesareorientedinthesamedirectionas the current loop. It is reasonable to assume these currentsoriginate from power and ground pins, since these currents aregenerallylargest,andthatcurrentsareflowingfromoneside ofthe package to another to create a large loop area.Neitherassumption, however, is guaranteed. For example, power andground pins are typically placed next to one another. Mutualinductancebetweenthemencouragesthehigh-frequencycurrent entering through one pin to leave through the adjacentpin,thuscreatingzeronetcurrentacrossthepackage.

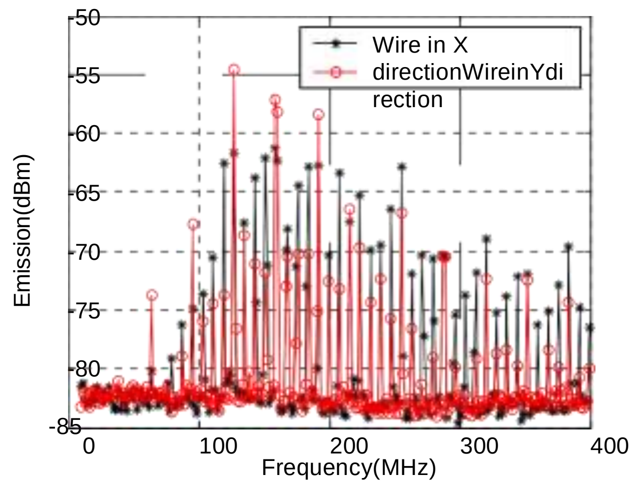


Figure 5.Measured emissions in semi-anechoic chamber when wires wereattachedtothereturnplane.

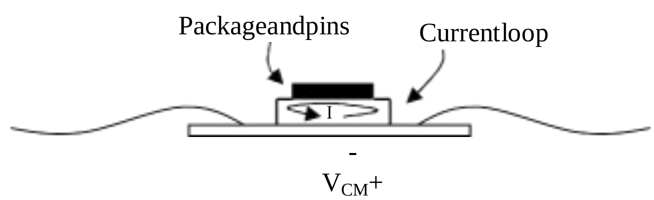
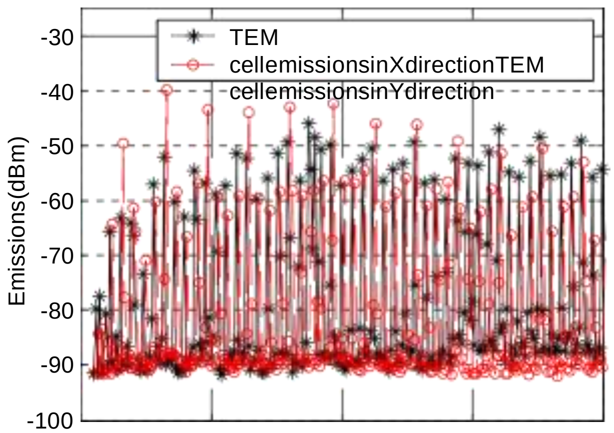


Figure 6.Current flowing across the package can cause common modevoltagesandcurrentsthatdriveemissionsontheboardandattachedcables.

Tovalidatethishypothesis,measurementsofthemicrocontroller (alone) were taken in a TEM cell followingrecommendationsinIEC61967[4].TheresultisshownInFig.
7. As expected, the same orientation relative to the attachedcablesthatcausedhighestemissionsinthesemi-anechoicchamberalsocausedthehighest emissionsintheTEMcell.

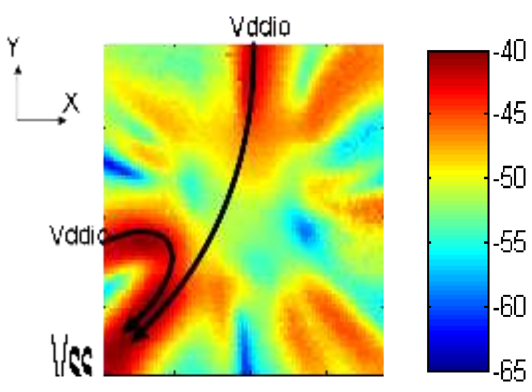
Near magnetic-field scans above the IC were conducted tolocate the source of these “common-mode” currents, followingmethods describe in [12], [13]. The magnitudes of the near-magnetic fields are shown in Fig. 8. Phase is shown in Fig. 9and Fig. 10. As shown in these figures, there are particularlystrong magnetic fields close to two Vddio pins and to a Vsspin. Examination of phase indicates the direction of currents.For fields in the y-direction (Fig. 9), the phase changes signbetweentheVddioandVsspin,indicatingthedirectionof current is changing and that current flows from the Vddio tothe Vss pin. This current loop is relatively small so is unlikelyto generate significant common-mode noise across the PCB.Forfieldsinthex-direction(Fig.10),thephaseremainsconstant from one Vddio pin to the Vss pin, indicating currentflowsinonedirection,fromonepintotheother.This“commonmode”currentacrossthepackageisrelativelystrongand covers a large loop area, making it a prime candidate fordriving emissions on the PCB, especially for wires attached inthey-direction.



0 100 200 300 400

Frequency(MHz)

Figure7.TEMcellemissionsfortwoorientationsoftheIC.



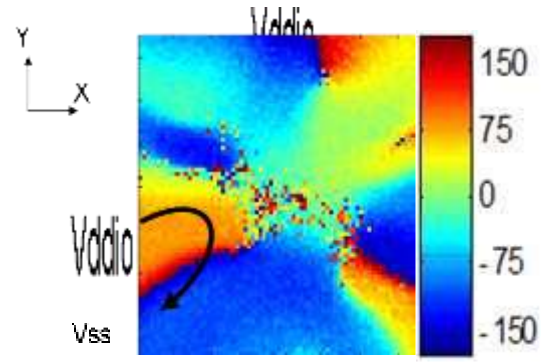


Figure 9.Phase in degrees of the near-magnetic field over themicrocontroller at 64 MHz. Phase is shown for fields oriented in the y-direction(i.e.verticallyforthepictureshown).

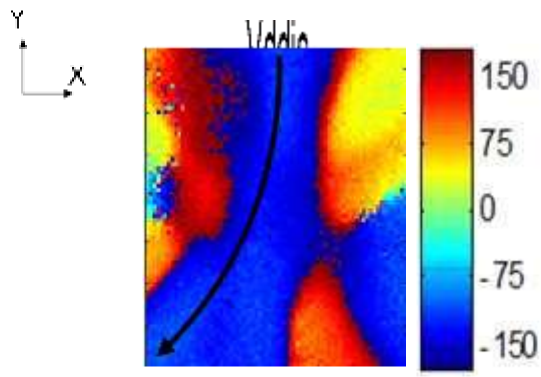


Figure 8.Magnitude in dBm of near-magnetic field over the microcontrollerat64MHz.Currentsappeartoflowinthedirectionofthearrows shown.

Vss

Figure 10.Phase in degrees of the near-magnetic field over themicrocontroller at 64 MHz. Phase is shown for fields oriented in the x-direction(i.e.horizonatallyforthepictureshown).

The magnitude ofcurrentswasfurtherverifiedusing aspecialized near-field loop probe. Since the pin-pitch of themicrocontroller was very small (approximately 0.4 mm) andpowerandreturnpinswereconnectedimmediatelytothepowerand returnplanesof the board, a conventional loopprobe could not be used effectively. The fields measured by aloop placed on top of a pin would not measure only fieldsgenerated by that pin, but of many pins in the nearby area. Tobetter identify currents from a single pin, a special-purposeprobe was built from a slotted coaxial cable probe as shown inFig. 11. Magnetic flux from the pin enters the slot and wrapsthe inner conductor. A hybrid was used to distinguish betweencommon- and differential-mode currents and hence distinguishbetween inductive and capacitive coupling. Because the slot isverysmall,theprobe isabletofocusrelativelypreciselyonthefields generated by asingle pin. Measurements at 64 MHz(twice the system clock) using this probe validated near-fieldscan results and indicated that currents through Vddio were20% or more of currents through Vdd. If Vdd and Vddio areinternally well decoupled, then currents should be confined toVdd.

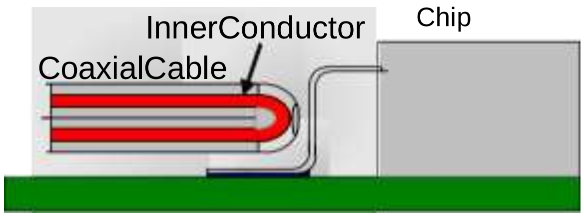
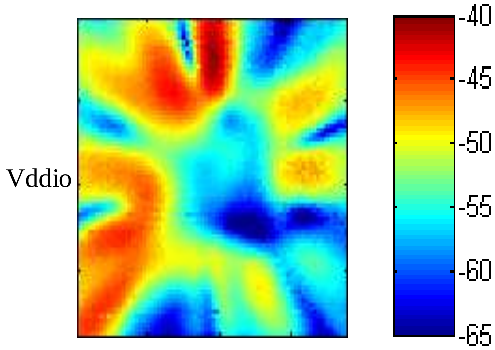


Figure11.Slotted coaxialcableprobe.

Basedonthese results,emissions mightbereducedbyeitherreducingthecurrentflowingfromVddiotoVssorreducing the size of the loop. To this end, a ferrite was placedinserieswiththeVddiosupplytoincreaseitsimpedanceat lowfrequencies (around 100 MHz). A near magnetic-field scanafter inserting the ferrite is shown in Fig. 12. A strong field isnow measured at the top of the IC, but now the field resultsfrom current flowing through Vssio instead of Vddio. Vddioand Vssio are right next to each other at this location. Whenmeasuring the near-magnetic field distant from the pin, as inthis case where the package prevents the probe from reachingthe lead frame, the near-magnetic field roughly indicates thesumoffieldsgeneratedbynearbypins.InFig.8,fieldsgeneratedbycurrentsenteringtheICthroughVddiooverwhelmed those generated through Vssio. After the ferritewasinserted,currentsthroughVssiodominatedthemeasurement. The ferrite significantly reduced current throughVddioandredirectedpackagecurrentssuchthatthetotal “common mode” current flowing across the package was alsoreduced.



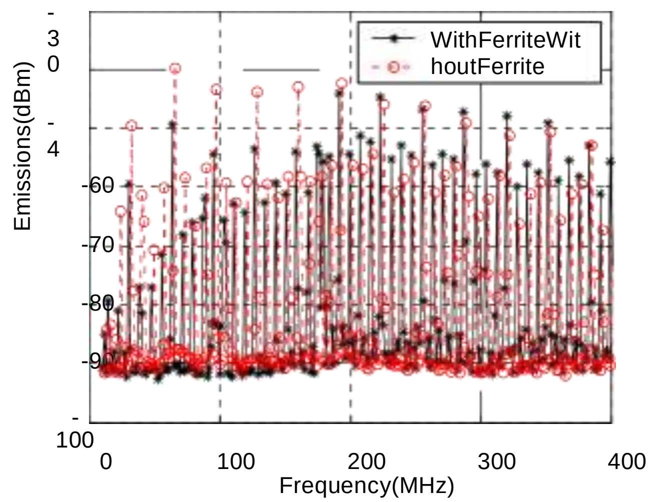
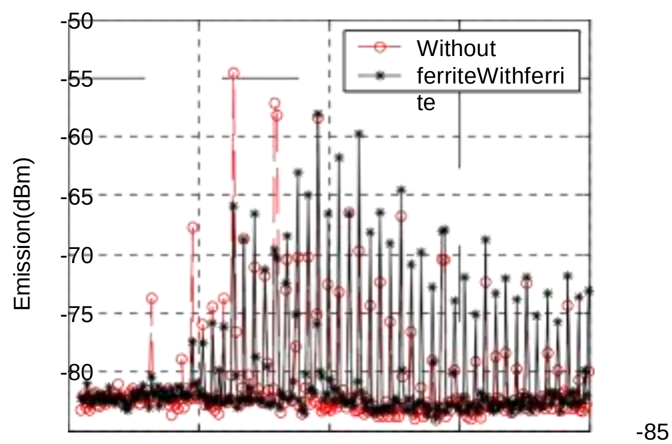


Figure 13. TEM cell emissions in Y direction with and without ferrite placedinserieswithVddio.



0 100 200 300 400

Vss

Figure 12. Magnitude in dBm of near-magnetic field over the microcontrollerat64MHzafterinsertingaferriteinserieswithVddio.

Follow-up measurements in the TEM cellshow that, asexpected, the ferrite reduced TEM cell emissions in the Y-direction (the direction causing greatest emissions) by up to 10dB for frequencies below 200 MHz (Fig. 13) but had littleinfluenceonemissionsintheXdirection.Similarly,measurementsinthesemi-anechoicchamberwithwiresattached to the power return plane in the Y direction (Fig. 14)or with power cables attached (Fig. 15) show a reduction

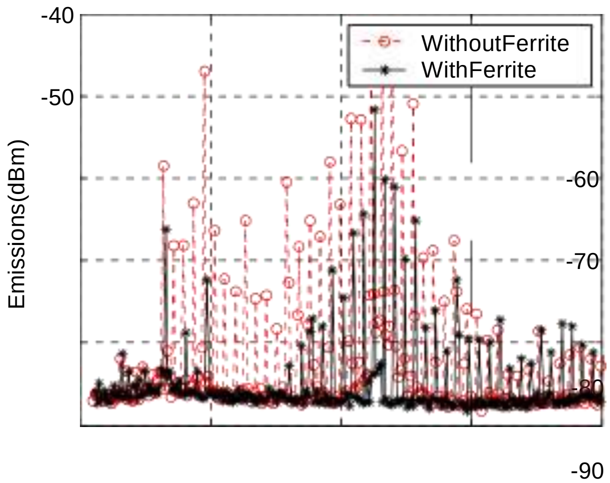
Frequency(MHz)

Figure 14. Measured emissions in semi-anechoic chamber w

inemissions of 10 dB or more at most frequencies below 200MHz.

II. DISCUSSION

Understanding noise coupling mechanisms between the ICandprintedcircuitboardandattachedcablescanbeveryhelpf ulforreducingsystem-levelemissions.Couplingmechanisms, however, may sometimes be complicated. In thiscase,acurrent-drivenradiationmechanismdominatedemissions at low frequencies and adding a ferrite in series withVddiosignificantlyreducedemissions.Eveninthiscase,h owever,"obvious"reductionstrategiesmayfailtowork.Lifting the Vss pin on the bottom left of the package, throughwhich most "common mode" currents apparently return, hadless than a 2 dB influence on emissions because these currentsshiftedtoothernearbyVsspinsandcausedequallybadc oupling to the board. Adding a ferrite to Vddio may also notbe reasonable, as it may prevent proper operation of the I/O,especiallyifseveralI/Oareswitchingsimultaneously.Ident ifying the current-driven radiation mechanisms, however,doessignificantlyimprovetheengineer'sabilitytocra fta solution. For example, since coupling occurs due to currentfrom Vddio to Vss, one would not expect emissions to reducewithimprovedpower-busdecoupling.Forthisboard,removingall SMT power-bus decoupling capacitors changed emissionsbyonlyabout2dB. Atfrequenciesbeyond200MHztheferritehad little influence on emissions both because the ferrite wasless resistive at higher frequencies but also because couplingmechanisms were different. Results in Fig. 5 and Fig. 7 bothindicate the coupling mechanism change at higher frequencies.Near-field scans of the IC show similar results. We have notthoroughly investigated these mechanisms, but it is reasonableto assume mechanisms change as frequencies exceed the LCresonanceofthechipandpackage,becauseinductancebecomesanincreasinglyimportantdeterminantofcurrentreturn paths and the relative importance of capacitive couplingfromthechiptoboardincreases.



asaninput, emissionsdroppedbyabout10dBbelow200MHzwhen a ferrite was added in series with Vddio (Fig. 16). Whenthe I/O was configured as an output, however, inserting theferrite had little influence on emissions (Fig. 17). It is possiblethatthesamecurrentdrivenmechanismdominatingmeasurements when wires were connected to the return planealso dominated emissions when I/O was configured as input,but when the I/O was configured as output, noise conducteddirectly through the I/O dominated emissions. Noise on I/Ooutputscanpresentasignificantchallenge.

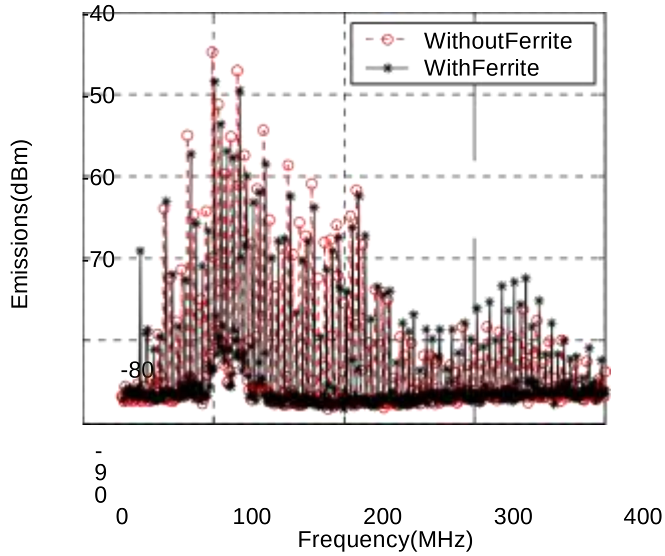


Figure 17. Measured emissions in semi-anechoic chamber when a 1 m wirewasattachedtoanI/Ooutputdrivenhigh.

Ideally,emissionsproblemscouldberesolvedthroughc

Figure 15. Measured emissions in semi-anechoic chamber when power cablewasattachedasnormal.

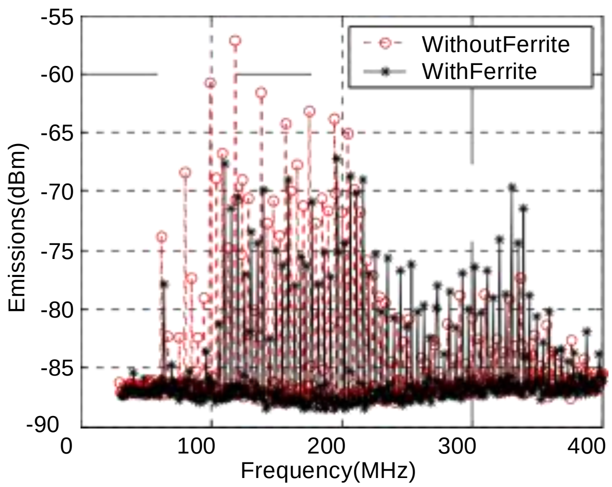


Figure 16. Measured emissions in semi-anechoic chamber when a 1 m wirewasattachedtoanI/Oinput.

EmissionsthroughI/OwasdependentontheI/Oconfiguratio n.Whena wirewasattachedtoI/OandI/Owasset

arefulICdesign.Inthiscase,however,achip-levelsolutionisdifficulttorecommendbecausethereasonsf orcoupling

between the core and I/O and the tendency for currents to flowthroughonlyafewpowerpinsarepoorlyunderstood. Asimpleanalysis of the passive characteristics of the IC does not showanobviouscouplingmechanism.Toanalyzethesemecha nisms, a circuit model of the on-chip power deliverynetwork was derived from off-chip measurements (Fig. 18).Theinductanceisapproximate.Thebestreturnpathforswit chingcurrentsgeneratedbetweenVddandVssiseitheron-chip, through the on-chip 8.4 nF decoupling capacitor, or off-chip,throughVddandVsspins.Forexample,saytheon-boarddecouplingis10nF.At64MHz,theimpedanceseenbyswi tching current throughthe Vdd/Vss pins is around 0.25ohms. The impedances from Vdd to Vddio and from Vddio toVss are both around 6 ohms. The current through Vdd/Vssshould be many times the current through Vddio. Resonancebetween on-chip decoupling capacitors and package inductancecanresultinsignificantcurrentatsomefrequencies, butresonancewouldfacilitateamuchmorenarrow-bandphenomena than seen here and measurements of the IC do notsupportthispossibility. Simulationsofcore-noisebetweenVddand Vss similarly did not predict the noise problems observed.Preliminary investigations suggest a possible active, non-linearcoupling mechanism, for example a voltage controlled currentsource from Vdd to Vddio/Vss resulting from parasitic PNP orNPN transistors between active P^+ or N^+ regions and the wells.Anotherpossibilityisthatthedistributedresistanceofthe power delivery network, which can be on the order of ohms,may play a role in the current distribution at the observedfrequencies.Further research is needed to investigate thesehypotheses.

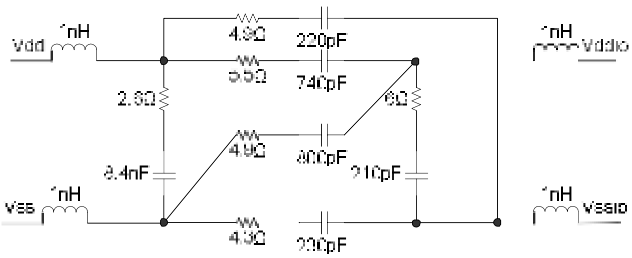


Figure18.Circuitmodeloftheon-chippower deliverynetwork.

Oncetheon-chipcouplingmechanismsarebetterunderstood, one can work to mitigate emissions through betterlayoutand designof the IC. Emissions canbe reduced byreducingthenoisesource,removingthecouplingpathfromthe core to I/O, or providing a better on-chip return path for noisecurrents [8]. While the coupling path is not known, emissionsmight also be reduced by reducing the noise magnitude usingasynchronous logic [14] or low-power logic design [15]. Abetter return path for noise currents might be accomplished byaddingdecouplingbetweenVddioandVssio,thoughthissolutionshould be approachedwithcare until the couplingmechanismsarebetterunderstood.Addingdecoupling betweenVdd and Vss may not help and is not an attractive solution inthis case, since 8.4 nF of additional on-chip capacitance wouldbe required to only double existing on-chip decoupling andwould be prohibitively expensive. Other mitigation approachesarealsopossible[8].

III. Conclusion

Understanding how an IC drives emissions allows one tointelligently pursue board-level emissions mitigation strategiesaswellastoimproveICdesign.Noiseandcouplingmechanismscanbedeterminedthroughspecializedmeasurements in the semi-anechoic chamber, through TEMcell measurements, near-field scans, pin current and voltagemeasurements, models of the IC, and many other techniques.Here,analysisrevealedthatemissionswereprimarilydrivenbyacurrent-loopacrossthepackage.Placingaferriteinthecurrentpathallowedemissionstobereducedby10dBormoreatmanyfrequenciesby reducingandredistributinghigh-frequency currents. Such analysis techniques are also useful tothe IC designer, who may use this information to reduce thesourceofthenoiseortoeliminateon-chipcouplingpaths.

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