Multiscale Modeling, Simulation, and Validation of a Synchronous Step-Down DCDC Converter

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IEEE

Agenda

1 Introduction

2 Why do we need modeling?

3 When to use modeling?

4 What to model?

5 How to model?

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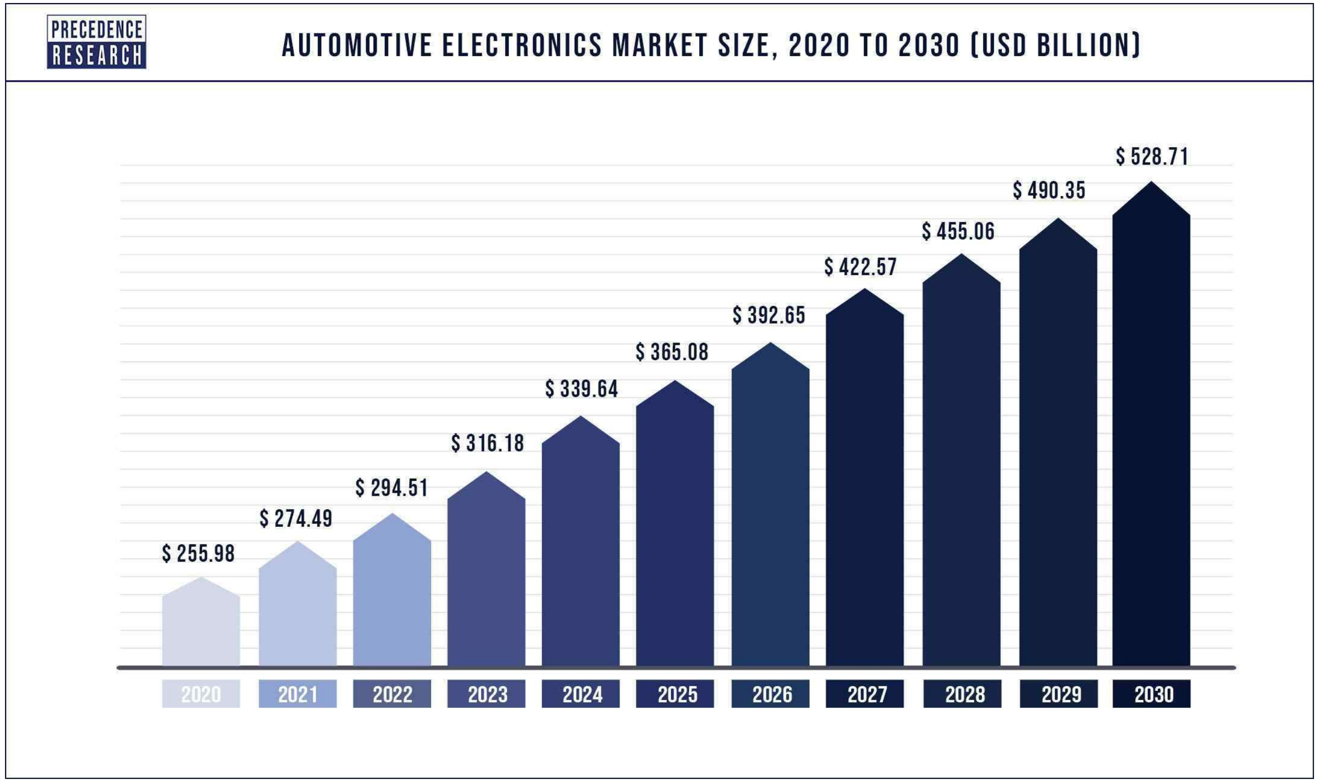
Introduction: Automotive EMC Compliance

Proliferation of automotive electronics

- The global automotive electronics market size was estimated at US$ 274.49 billion in 2021 and is predicted to hit over US$ 528.71 billion by 2030.
- Electronics is at the heart of the automotive industry → "future of mobility".
- Automotive electronics refers to electronic systems and components in vehicles for various purposes.
- What are the key **drivers** of automotive electronics market?



Source: *https://www.precedenceresearch.com/automotive-electronics-market.*

Drivers of automotive electronics

Hybrid and electric vehicle powertrain systems

Enabling longer distances between charges, higher performance and safer, more affordable vehicles

Advanced driver assistance systems

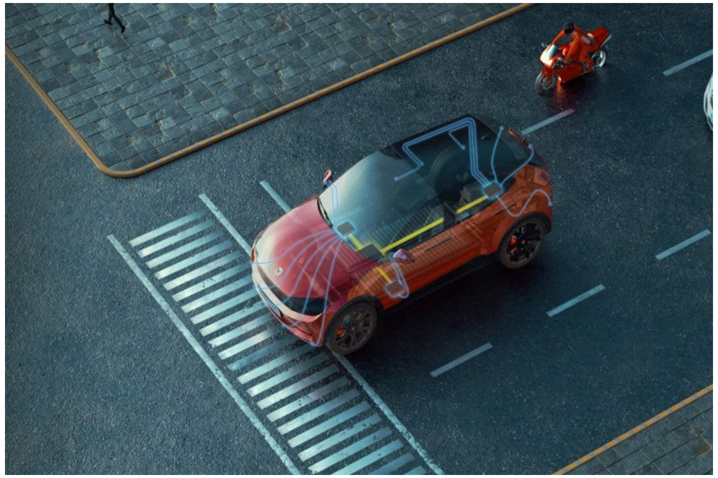
Creating a safer driving experience while building the foundation for the fully autonomous vehicle

Infotainment and cluster

Making the driving experience smarter and safer through advanced display communication and connectivity capabilities

Body electronics and lighting

Optimizing comfort and convenience in and around the vehicle with innovative analog and embedded processors



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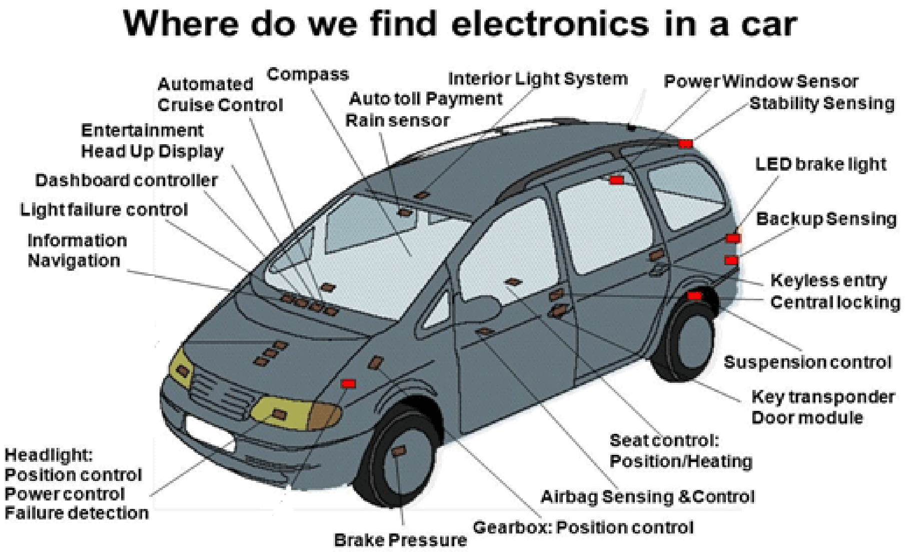
Automotive systems – safety critical

- With proliferation of electronics in automotive, **EMC/EMI** problems are being exacerbated[1].
- Increase potential of causing unintended changes in automotive system operations – or even failure!
- Incomplete or nondeployment of air bags due to EMI noise coupling to the ECU[2,3]



- Immunity to EMI has become a serious aspect of vehicle testing, with conformance to standards mandated in most countries around the world.
- In order to comply with the current quality standards of the automotive industry, IC suppliers will need to adhere to more stringent EMC standards imposed by the automobile industry.

[1] Momidi, K., "Electromagnetic compatibility in Electric Vehicles - Sources of EMI and Guidelines to reduce it", https://circuitdigest.com/article/electromagnetic-compatibility-in-electric-vehicles, August 13, 2019.

[2] Shepardson, D., "Toyota to recall 3.4 million vehicles worldwide, air bags may not deploy in crashes", https://www.reuters.com/article/us-toyota-recall-idCAKBN1ZK2TZ January 21, 2020

[3] Corbett F., D., "EMC challenges in connected cars", https://www.ttieurope.com/content/dam/tti-europe/about/distribution-center/TTI_Whitepaper-EMC-challenges-in-connected-cars.pdf.

Why do we need modeling?

Automotive EMC requirements

- In order to release an electronic device on the market, the device is required to comply with regulatory EMC industry standards.
- EMC standards define terms, rules, test methods, frequency range, **emission** limits and **immunity** levels for Electromagnetic Compatibility (EMC).
- Emission and Immunity standards for both Conducted[4] and Radiated[5].

Table 1: Typical product EMC standards for **Conducted** Emissions[4]

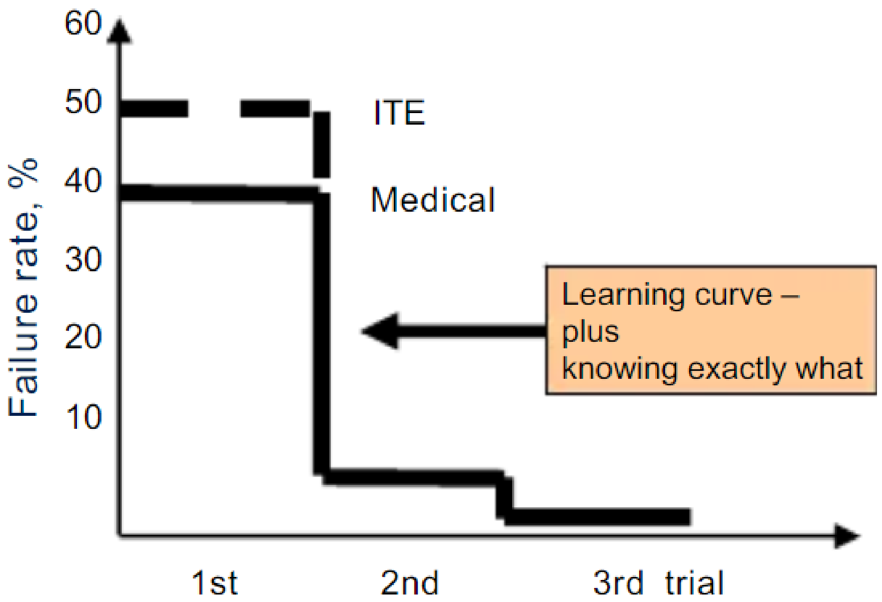
Product sector	CISPR standard	EN standard	FCC standard
Automotive	CISPR 25	EN 55025	–
Multimedia	CISPR 32	EN 55032	Part 15
ISM	CISPR 11	EN 55011	Part 18
Household appliances, electric tools and similar apparatus	CISPR 14-1	EN 55014-1	–
Lighting equipment	CISPR 15	EN 55015	Part 15/18

Table 2: Typical product EMC standards for **Radiated** Emissions[5]

Product sector		IEC/CISPR standard	EN standard	FCC standard
Vehicles, boats & devices with internal combustion engines	Off-board receivers	CISPR 12	EN 55012	–
	On-board receivers	CISPR 25	EN 55025	–
Multimedia Equipment		CISPR 32	EN 55032	Part 15
ISM		CISPR 11	EN 55011	Part 18
Household appliances, electric tools & similar apparatus		CISPR 14-1	EN55014-1	–
Luminaires, lighting equipment		CISPR 15	EN 55015	Part 15/18
Equipment with no product-specific standard	Commercial/light-industrial	IEC 61000-6-3	EN 61000-6-3	–
	Heavy-industrial	IEC 61000-6-4	EN 61000-6-4	–

[4] Hegarty, T., "An overview of conducted EMI specifications for power supplies", Texas Instruments, Inc. Application Note, SLYY136, 2018.
[5] Hegarty, T., "An overview of radiated EMI specifications for power supplies", Texas Instruments, Inc. Application Note, SLYY142, 2018.

Challenges in Meeting EMC Compliance



https://www.scribd.com/document/182259827/Intertek-WP0307-pdf

What Percentage of Products Fail EMC Tests the First Time?

Improve Your Success Rate.

Surprisingly, there is not much information out there about electromagnetic interference testing failure rates. It is surprising because so many products fail.

50% to 90% Failure Rate

A report by Intertek Testing Services, Boxborough, MA, estimates that 50% of devices fail EMI testing on the first try. Intertek, notes that after the initial 50% failure rate, between 5% and 7% fail retest, and 1% to 2% fail a third time.

A second Intertek report states, "Over 90% of electrical medical devices that Intertek has tested have failed to comply with the required standards on the first submission." The biggest reason? 97% fail EMC testing the first time.

How to ensure an EMC-compliant ecosystem?

- Multiple sources of EMI (electromagnetic interference) → automotive ICs.
- An EMC-compliant ecosystem depends on starting with careful engineering design decisions and a thorough understanding of the fundamental EMC techniques.
- In-house EMC **Pre-compliance testing** allows you to cost-effectively reduce your time to market and certifies your product passing final compliance testing[6]. Compliance testing – done at a certified lab (costly, time-consuming)[7]
- **EMC simulation and modeling** tools are essential for electronic engineers who want to design, test, and optimize their products for electromagnetic compatibility.
- **Combining pre-compliance and EMC modeling** can help you save time, money, and resources by allowing you to predict and prevent potential EMC issues before they become costly problems.

[6] Keysight, https://www.keysight.com/us/en/solutions/manufacturing-test/fundamentals-of-emc-pre-compliance.html

[7] Benjamin Dannan, "Addressing EMC Challenges with In-house EMC Pre-compliance Testing, https://www.signalintegrityjournal.com/articles/1633-addressing-emc-challenges-with-in-house-emc-pre-compliance-testing.

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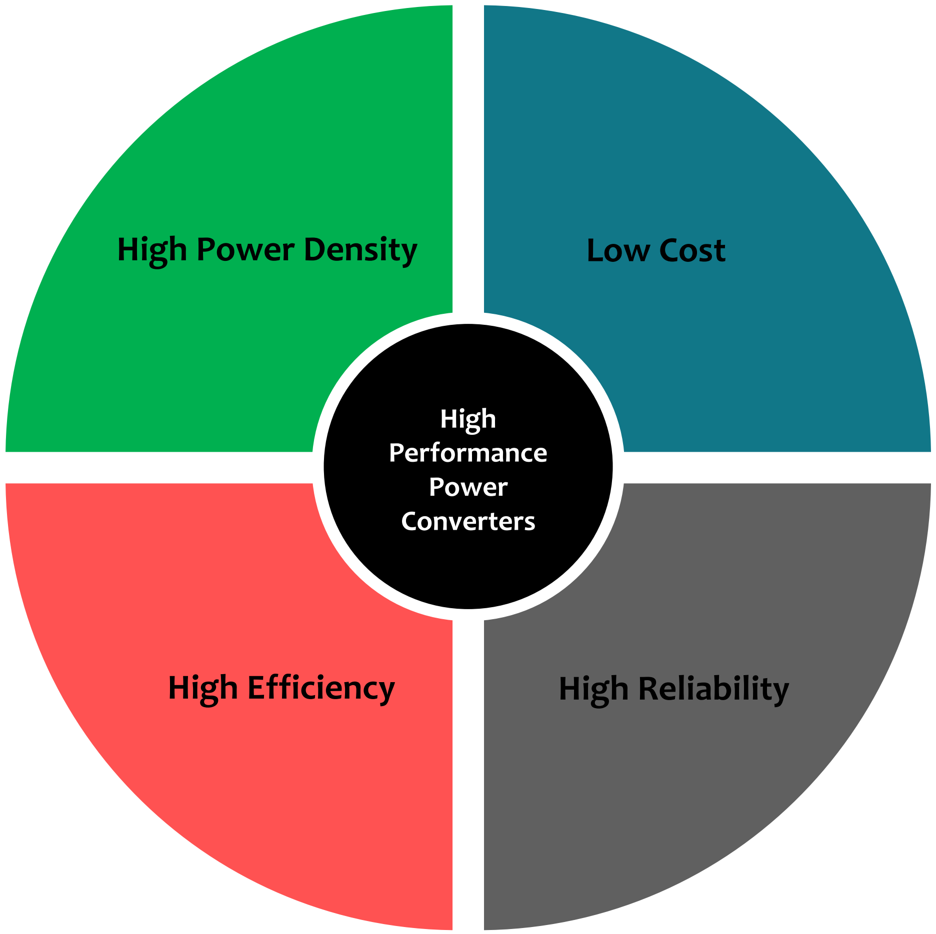
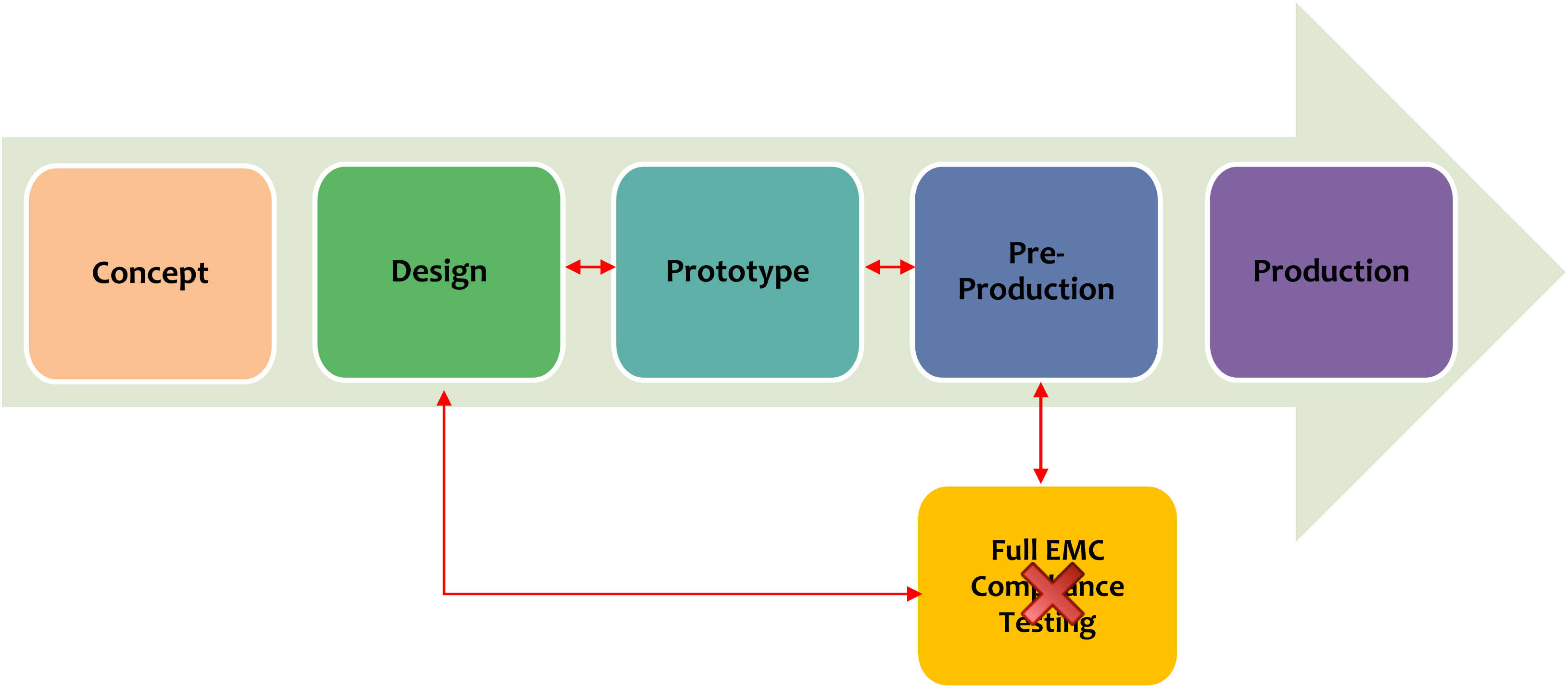
When to use modeling?

The ask from management

- **Design:** Low-EMI DCDC source-synchronous converter.
- Power converters trend → Smaller, Faster, Robust, and Cheaper
- High power density, efficiency, reliability, and **low-cost** solution
- Power density – amount of power processed per unit of volume in units of watts per cubic meter (W/m3) or watts per cubic inch (W/in3)
- Efficiency – Lowest loss (resistive + switching) + package parasitics) → system (including package and PCB)
- Meet/exceed automotive EMC regulatory standard (e.g. CISPR25)
- First-pass design success!



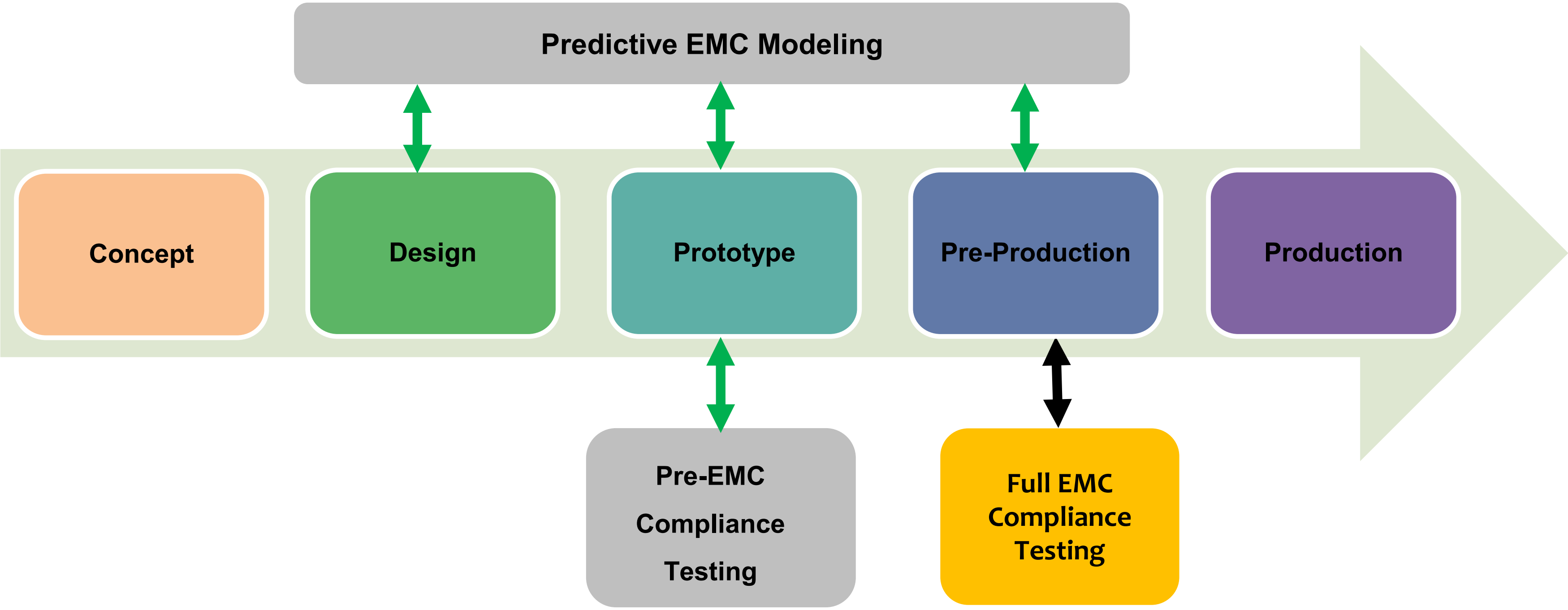
Traditional EMI/EMC IC design sign-off flow



Financial/Business Impact

- TTM (Time-to-Market)
- Multiple design iterations
- Increase design cycle

Improved EMI/EMC IC design sign-off flow

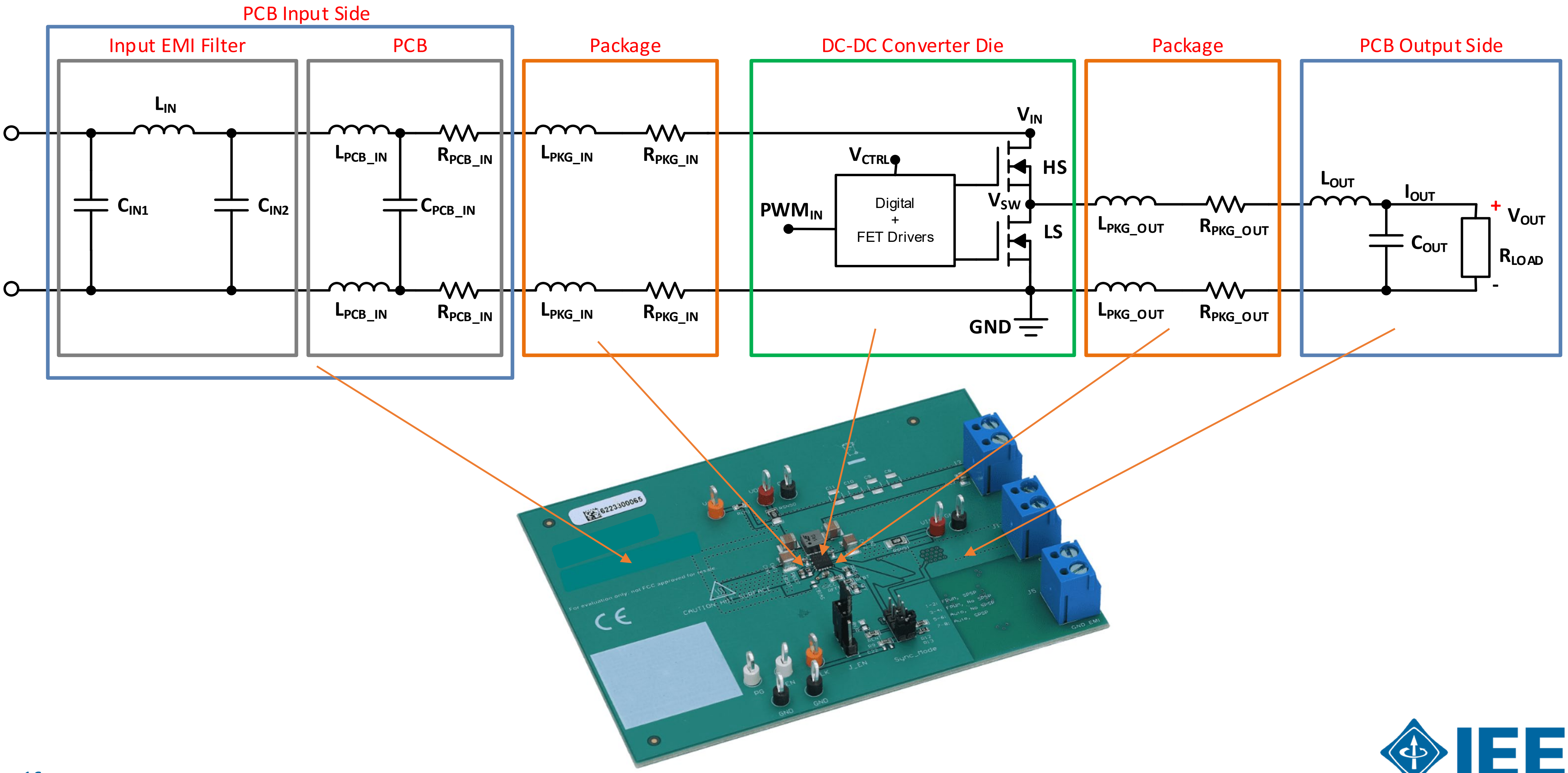


Financial/Business Benefits

- √ First-time design success
- √ Reduced iterations
- √ Shorten design cycle

What to model?

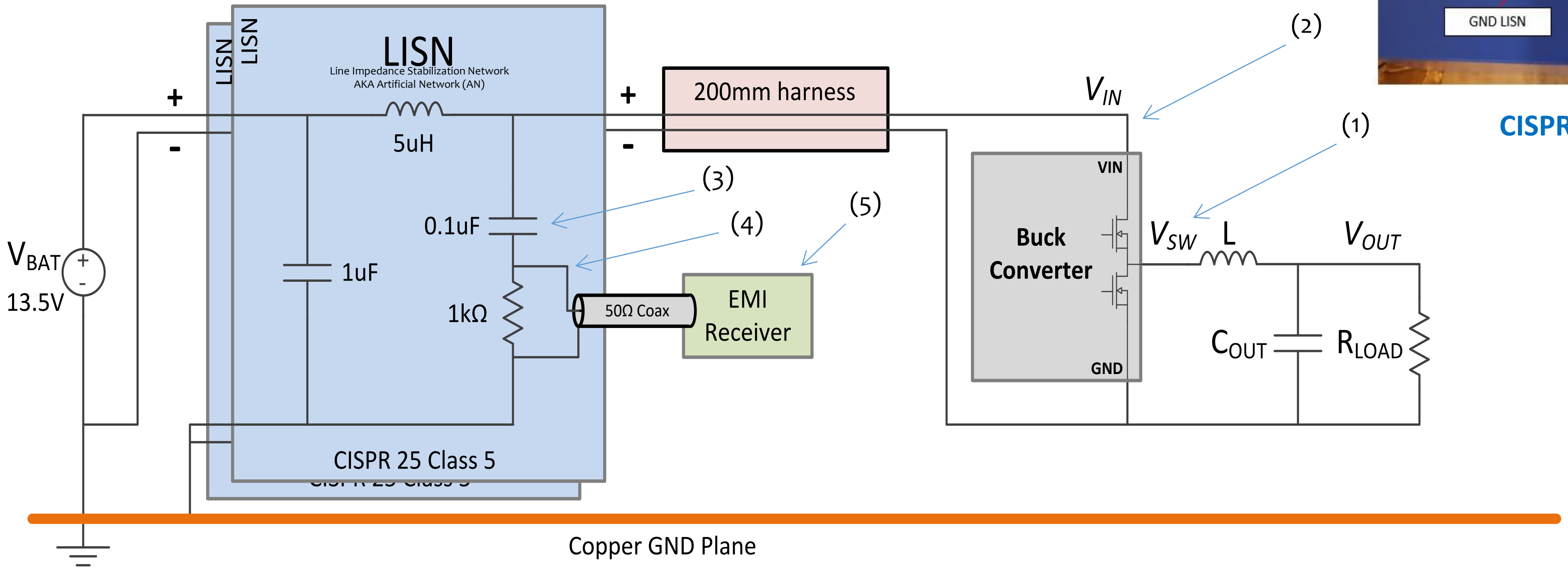
DCDC converter system (system modeling)

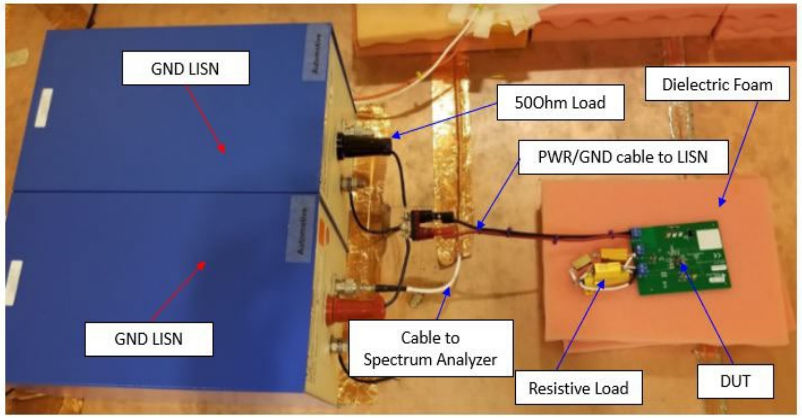


Automotive IC EMC Testing (Conducted Emission)

(1) Switching causes → (2) V_{IN} ripple which is →(3) DC blocked to allow → (4) AC signal to reach → (5) EMI receiver

CISPR 25 Class 5 – Conducted EMI Test Setup[8]





CISPR 25 CE Measurement Set-up[9]

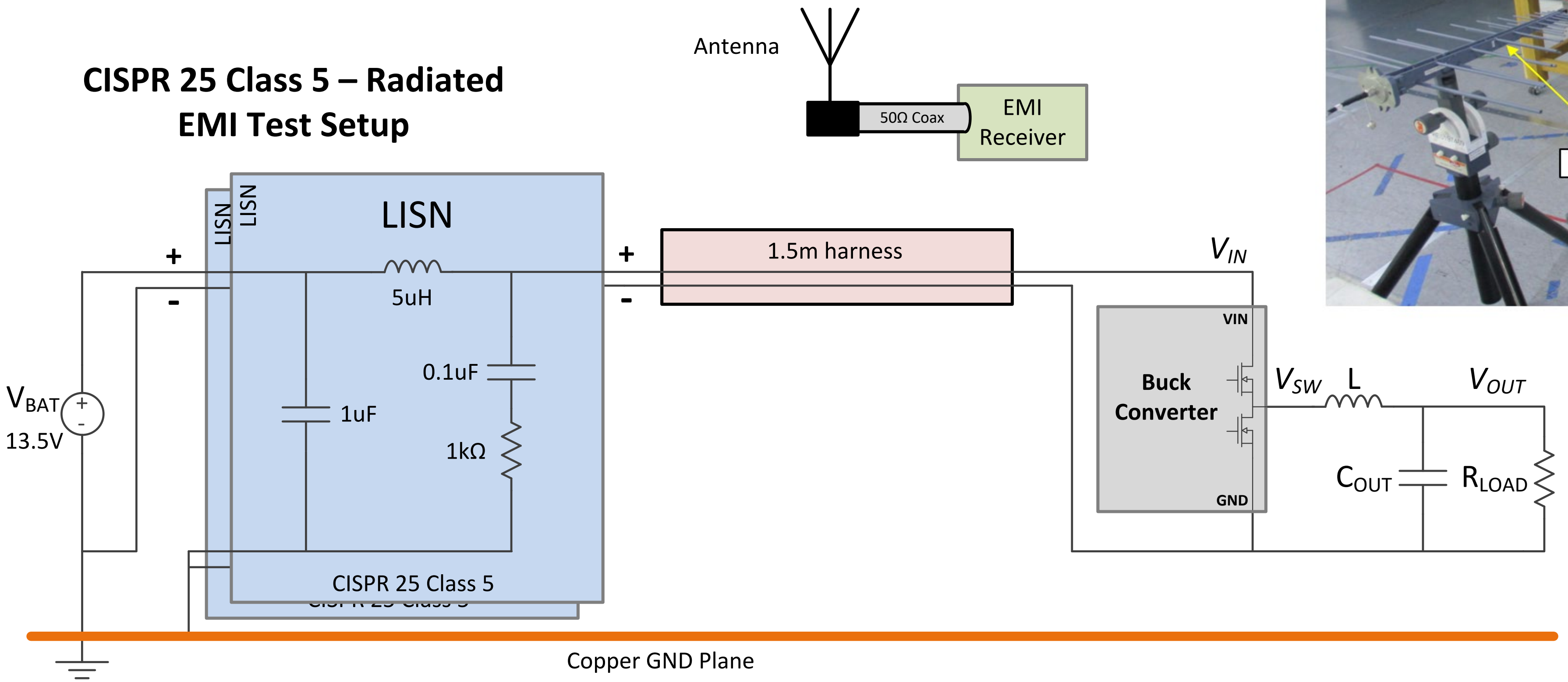
[8] Jaffe, S., "Practical Buck EMI Debugging for Automotive Applications", Application Note, 2019.

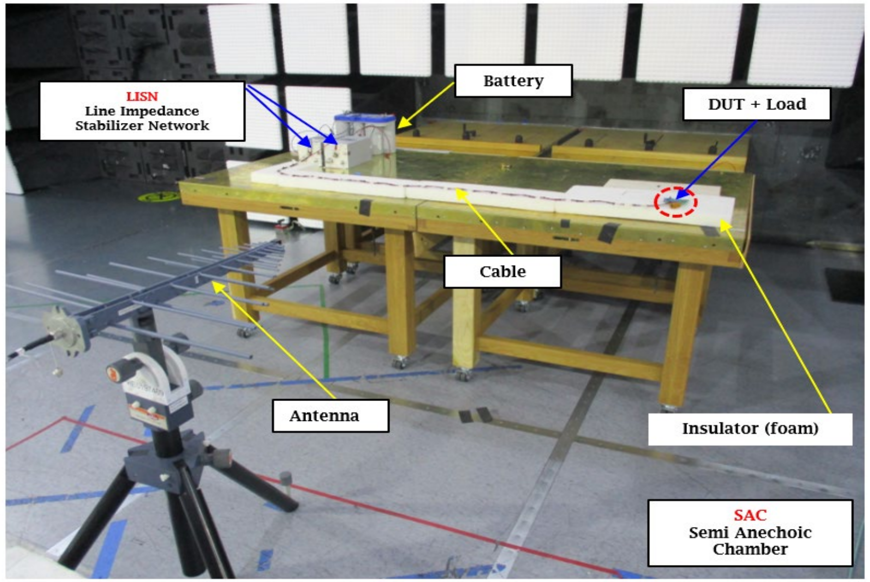
[9] Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers." CISPR 25:2016, fourth edition (or EN 55025:2017). CISPR: Geneva, Switzerland, October 2017.

Automotive IC EMC Testing (Radiated Emission)

Near field (electric/magnetic) coupling to antenna (→~300MHz)
Far field (electromagnetic) radiation to antenna (>~300MHz)

CISPR 25 Class 5 – Radiated EMI Test Setup





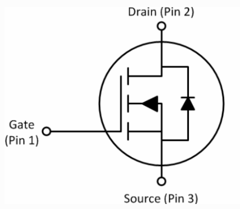
Measurement Set-up[9]

[9] Vehicles, boats and internal combustion engines – Radio disturbance characteristics – Limits and methods of measurement for the protection of on-board receivers." CISPR 25:2016, fourth edition (or EN 55025:2017). CISPR: Geneva, Switzerland, October 2017.

Evolution of Modeling: Multiscale Modeling

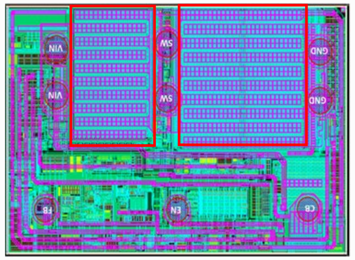
- Multiscale modeling is the field of solving problems which have important features at multiple **scales of time and/or space**[10]**.**
- It is a technique in which multiple models at different scales are used simultaneously to describe a system. A broad range of scientific and engineering problems involve multiple scales. An example of multiple scale is the design of a DCDC converter.

Power MOSFET



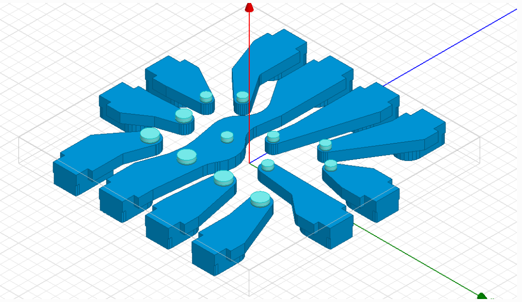
Nanometer

Chip



Micrometer

Package

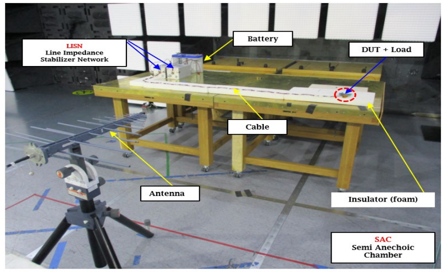


Millimeter

PCB

Centimeter

System

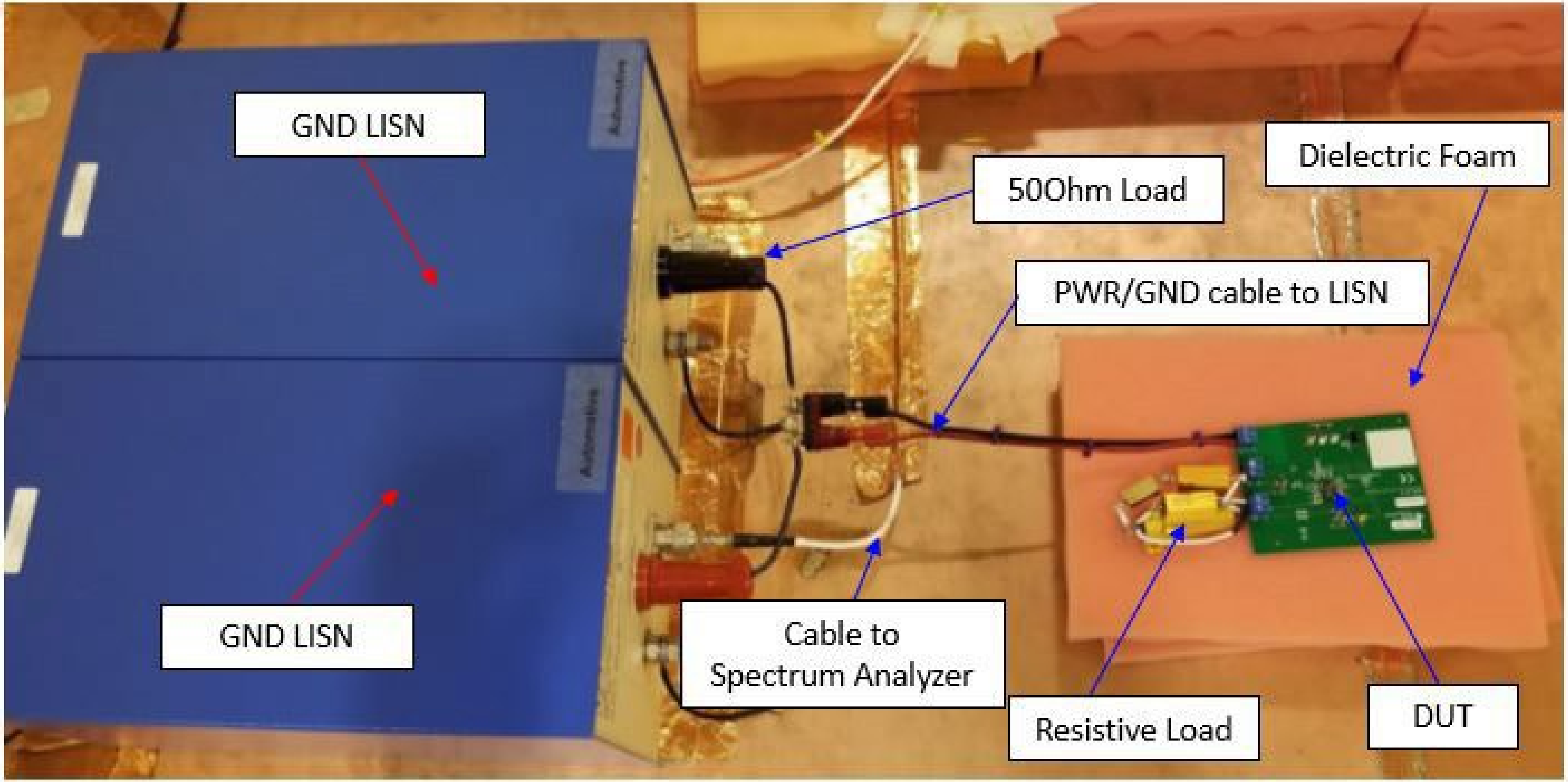


Meter

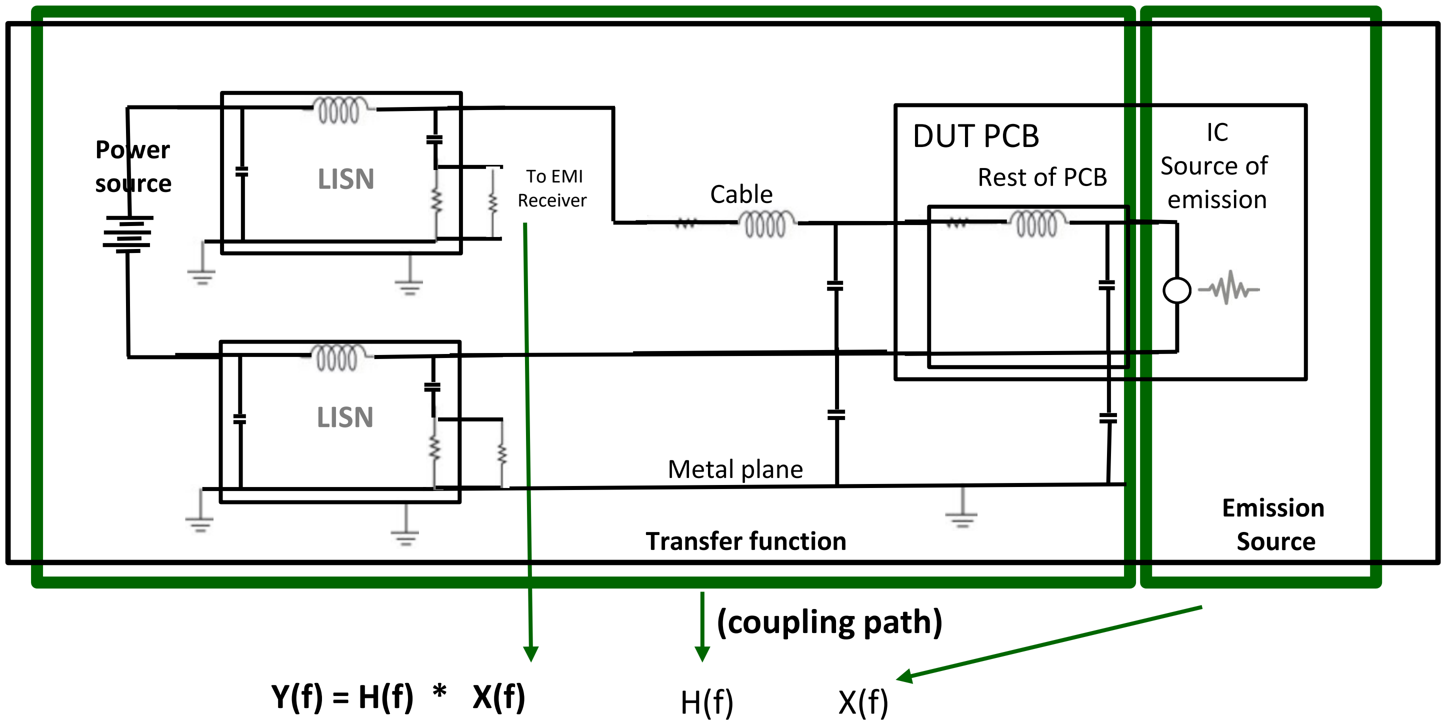
[10] Zhang Q. and Cen S., "Multiphysics Modeling: Numerical Methods and Engineering Applications", Tsinghua University Press Computational Mechanics Series, 1st Edition - December 15, 2015.

How to model?

Conducted Emission (CISPR25 Voltage Method)

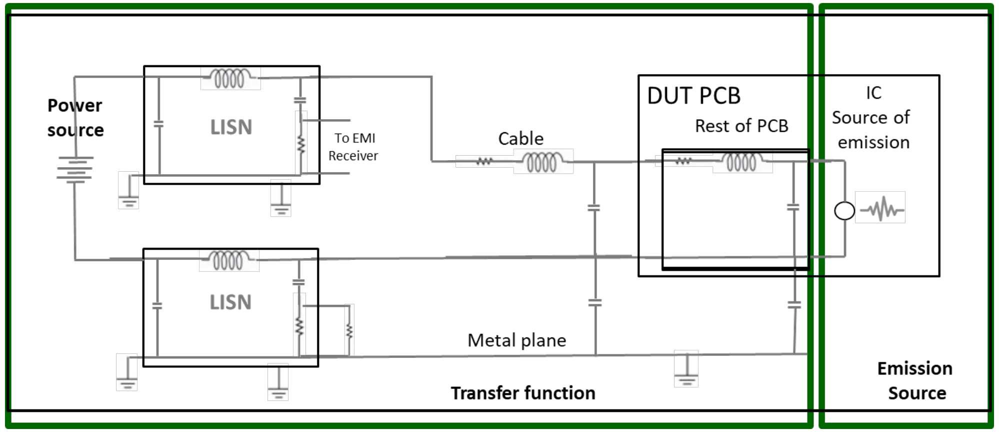


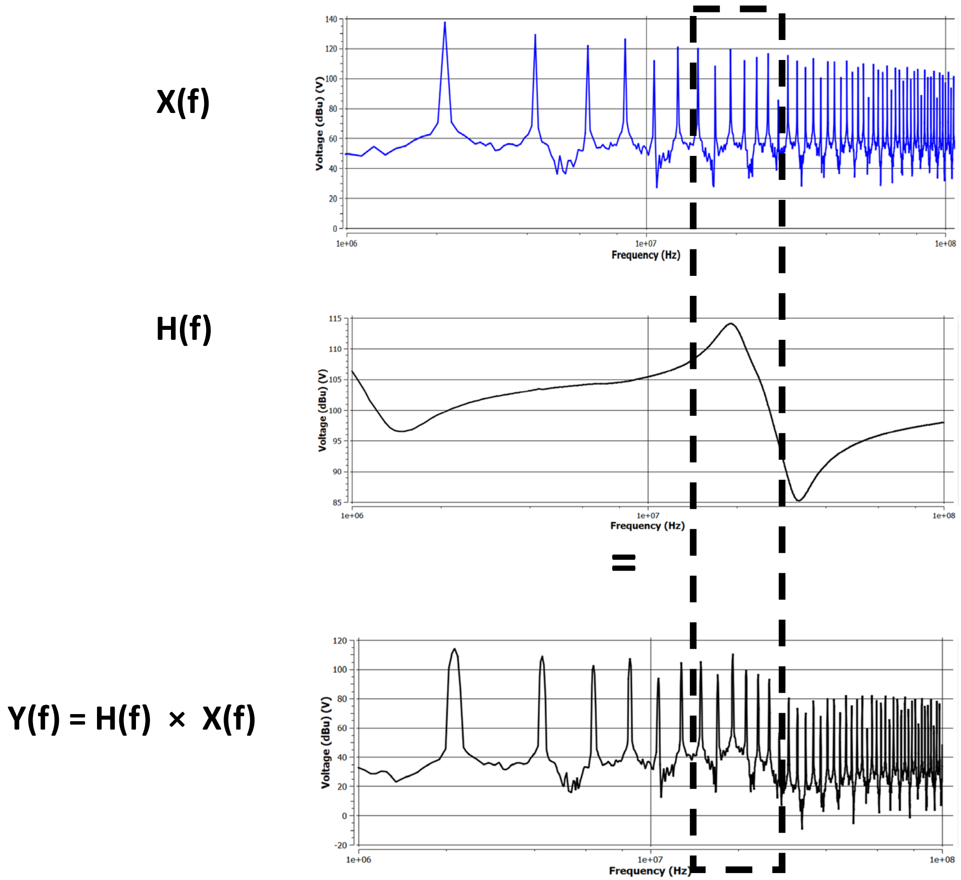
Conducted Emission (CISPR25 Voltage Method): Modelling



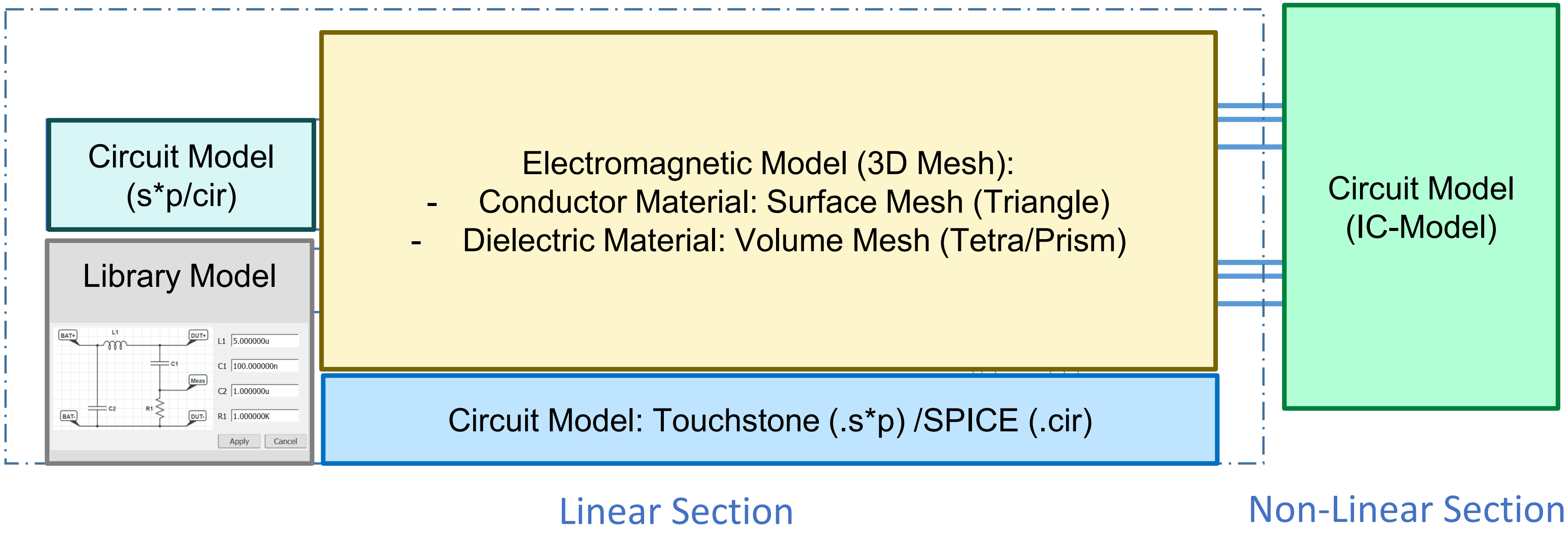
Y(f) = H(f) * X(f)

Conduced Emission (CISPR25 Voltage Method): Modelling

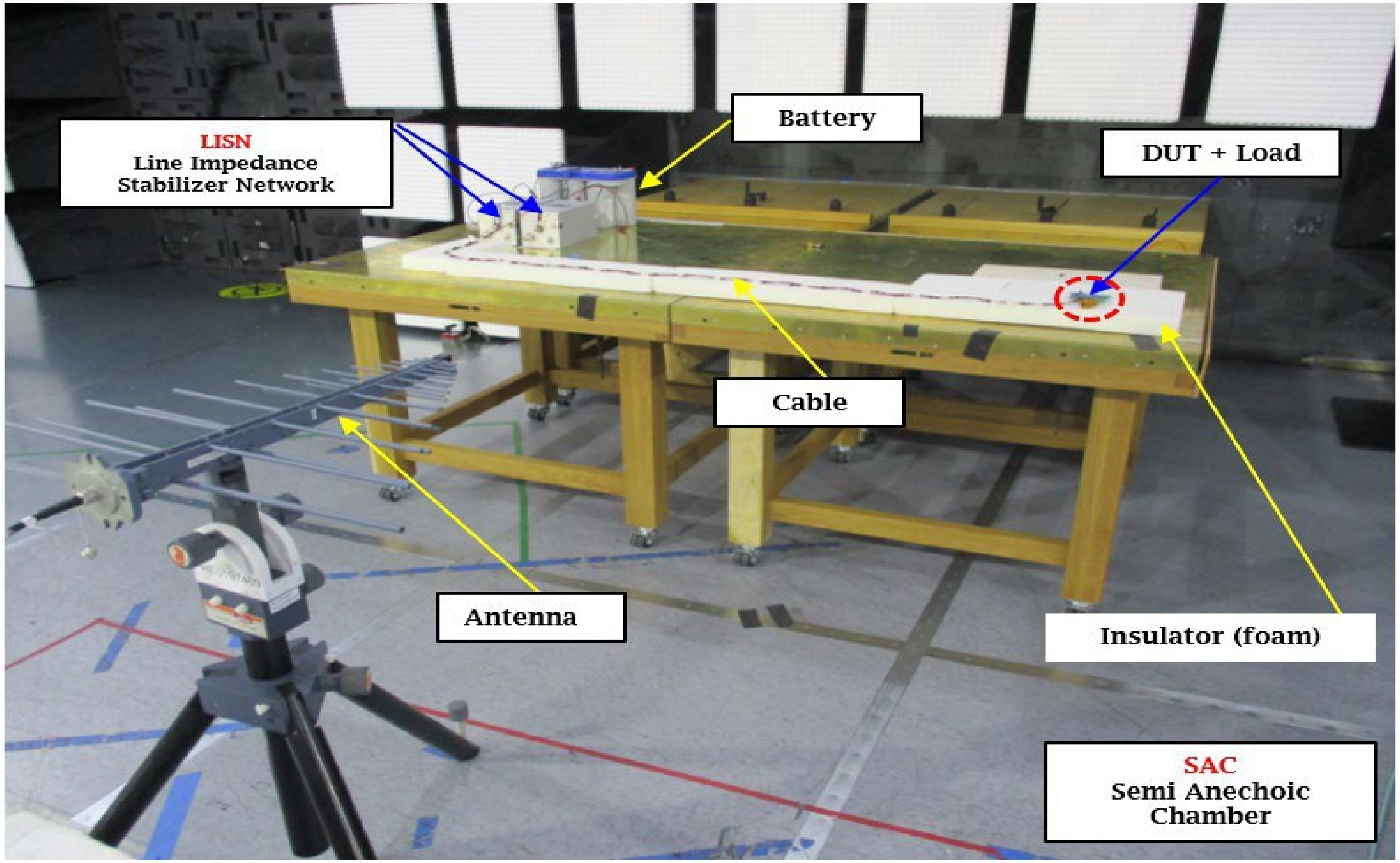




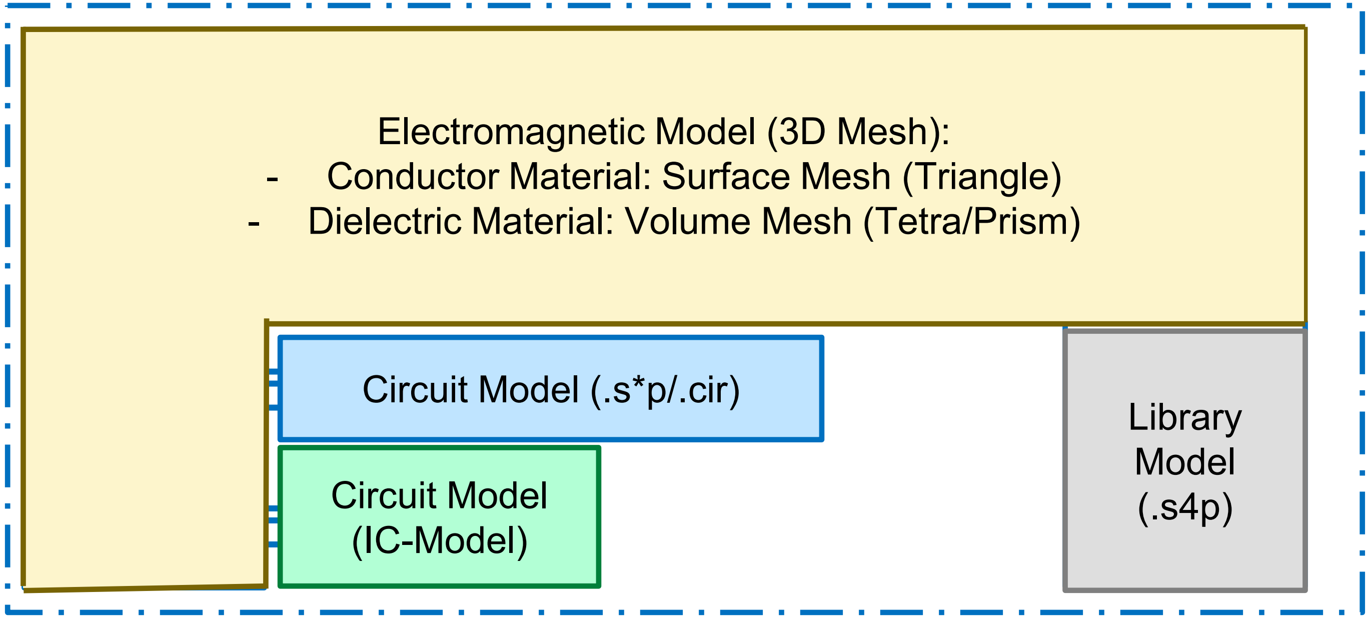
Conducted Emission (CISPR25 Voltage Method): Modelling



Radiated Emission (CISPR25)



Radiated Emission (CISPR25): Modelling



Sources of EMI noise: IC-Models

IC-Models: Inspired by IEC-62433

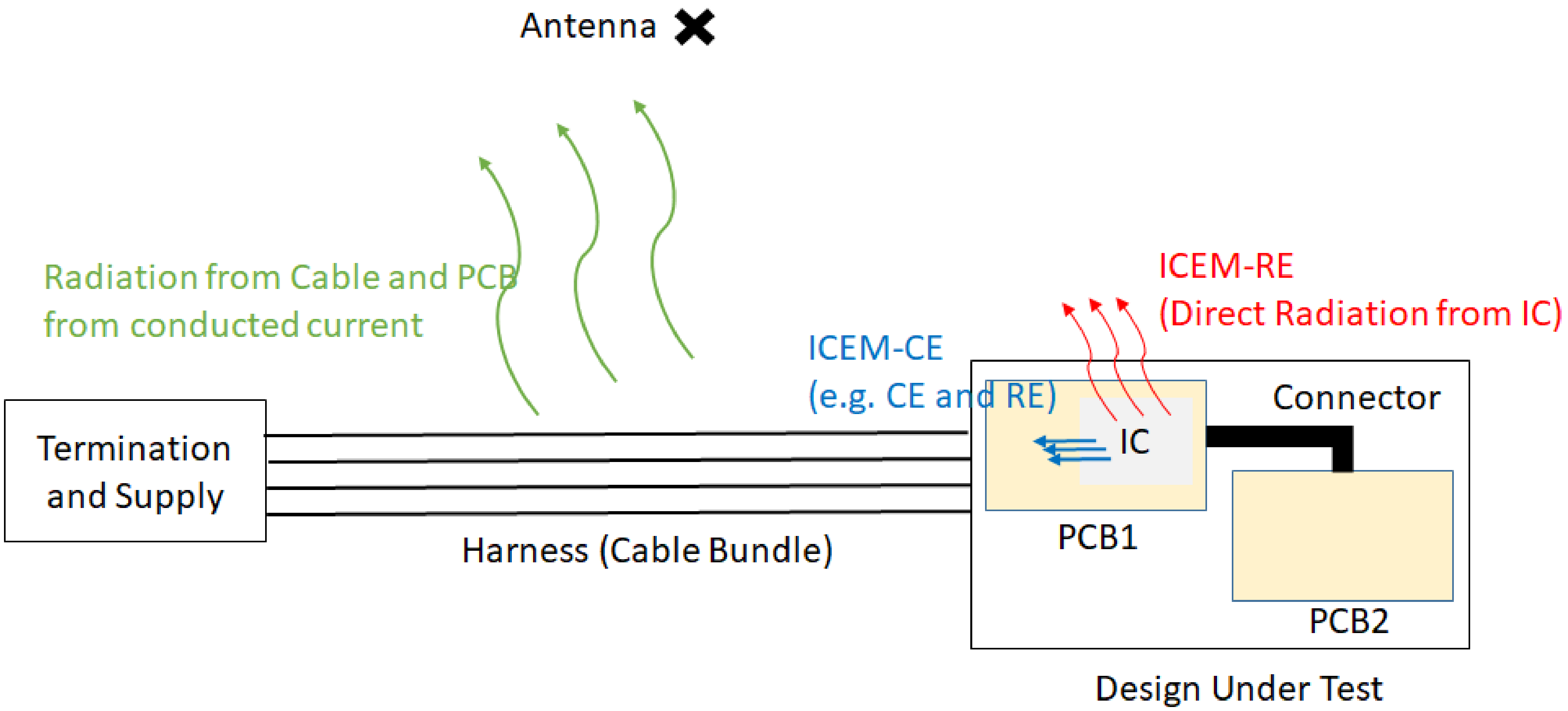
	Conducted	Radiated
Emission	Conducted Emission (CE) IEC-62433-2 (ICEM-CE)	Radiated Emission (RE) IEC-62433-2 (ICEM-CE) IEC-62433-3 (ICEM-RE)
Immunity	Bulk Current Injection (BCI) IEC-62433-4 (ICIM)	Radiated Immunity (RI) IEC-62433-4 (ICIM)

[1] IEC 62433-2:2017, Edition 2.0, “EMC IC MODELLING – Part 2: Models of integrated circuits for EMI behavioral simulation – Conducted emissions modelling (ICEM-CE)”.

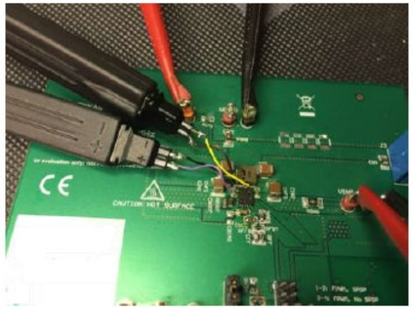
[2] IEC 62433-3:2015, “EMC IC MODELLING – Part 3: Models of integrated circuits for EMI behavioral simulation – Radiated emissions modelling (ICEM-RE)”.

[3] IEC 62433-4:2016, “Models of integrated circuits for RF immunity behavioral simulation for Conducted immunity modelling (ICIM-CI) - Edition 1.0;”

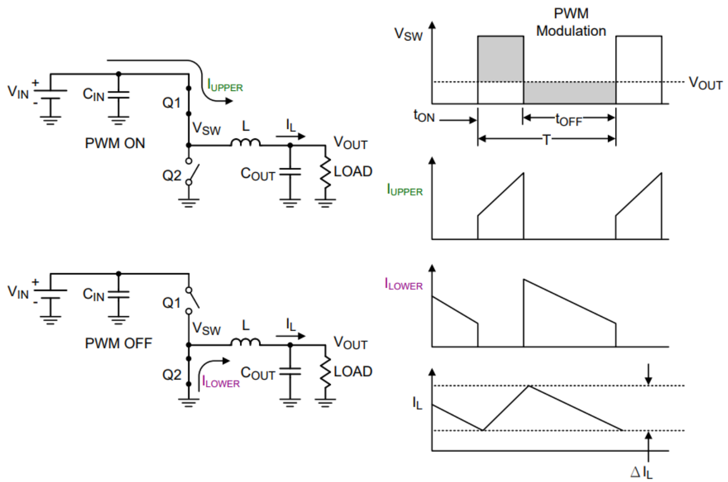
ICEM-CE vs. ICEM-RE



ICEM-CE: Working models



- Model-1: IC-pin waveforms
  - Model-1A: From SPICE simulations
  - Model-1B: From PCB measurements using oscilloscope



- Model-2: Equation-based waveforms

- Model-3: Measurements from IC-level EMC Tests (1-150Ohm setup)

ICEM-CE from IC-level Tests

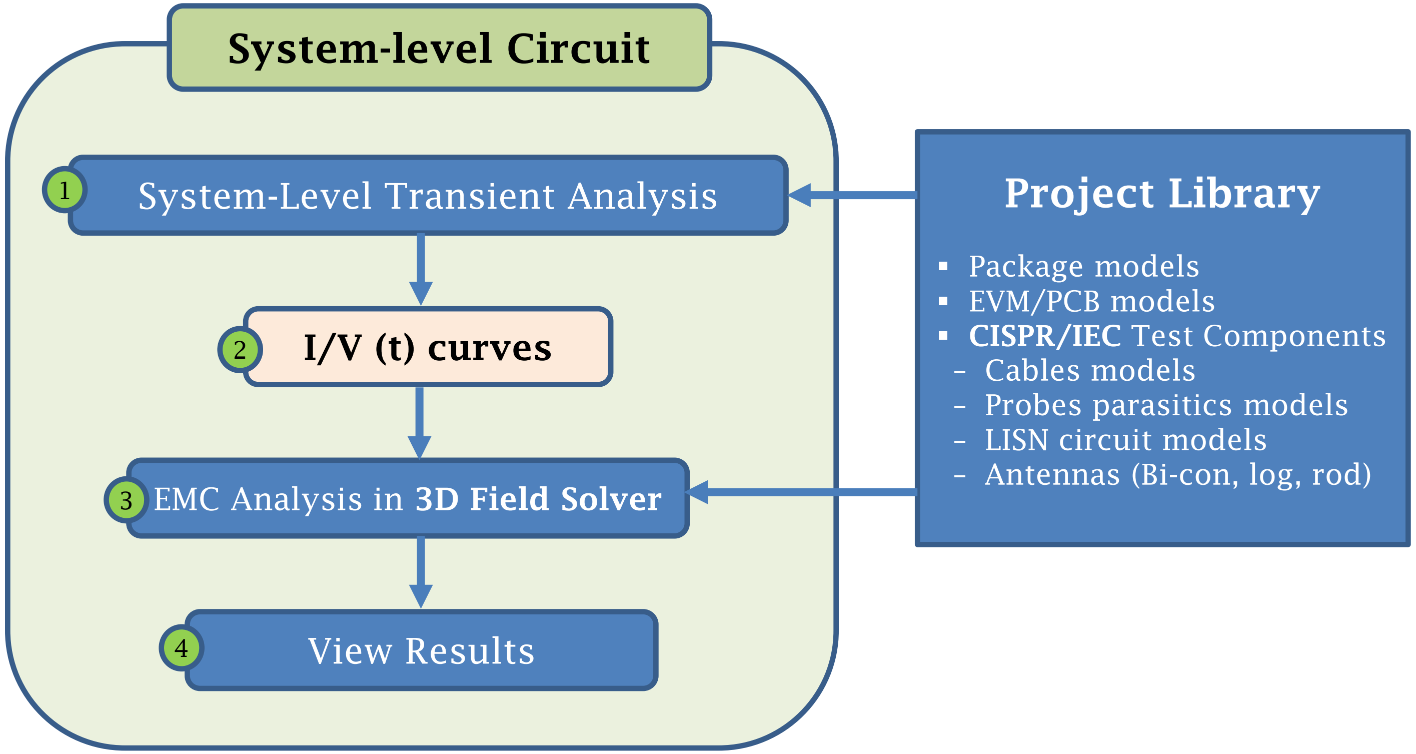
		CONDUCTED EMISSIONS	CONDUCTED IMMUNITY	RADIATED EMISSIONS	RADIATED IMMUNITY
OEM		Vehicle testing AND Inter-Vehicle Issues			
COMPONENT LEVEL TEST	Auto	CISPR 25 Voltage method Test CISPR 25 Current method Test	ISO 11452-4 (BCI)	CISPR 25	ISO 11452-2 (RI)
	D&A	MIL-STD-461G CE101 MIL-STD-461G CE102	MIL-STD-461G CS 114	MIL-STD-461G RE102 MIL-STD-461G RE101	MIL-STD-461G RS103
	Ind	CISPR32 CE	61000-4-6	CISPR32/CISPR11	61000-4-3
		↑	↑		
CHIP LEVEL TEST		1-150 Ω Test (Requirement till 3 GHz)	Direct Power Injection Test (DPI)	Strip line Test as per 62132-8 standard TEM Cell Test	Strip line Test as per 61967-8 standard TEM Cell Test

ICEM-CE Modelling: Comparison

	SPICE	PCB-measured	Equation	1-150Ω
Pre-tapeout (IC-design stage)	☑		☑	
Pre-EVB	☑		☑	
Pre-customer PCB	☑		☑	☑
Post-Failure Analysis (high accuracy)	☑	☑	☑	☑

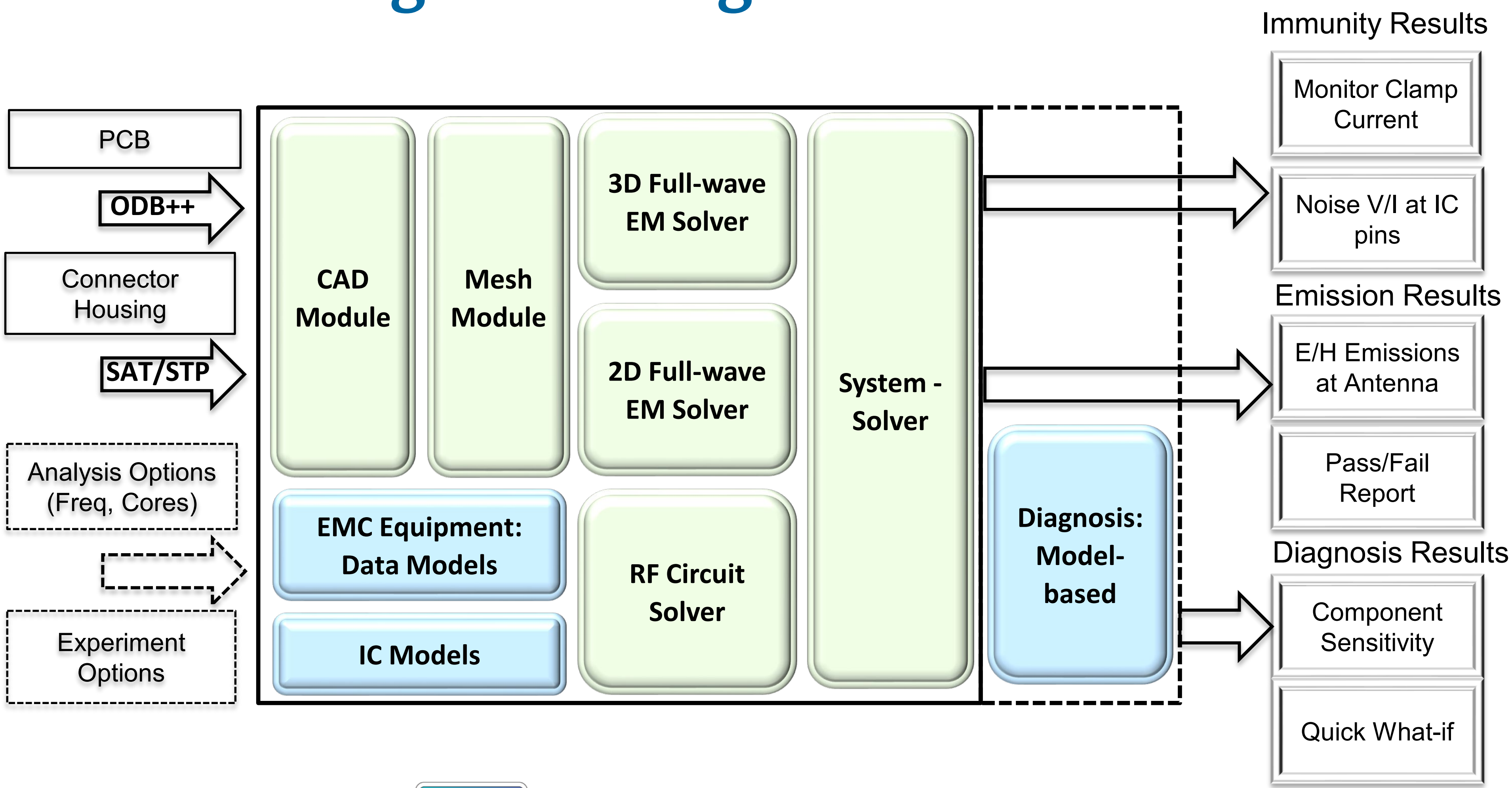
Confidentiality		☑	☑	☑

System-level modeling flow



- **Methodology:**
  1. **Step 1:** System-level TRAN analysis in circuit analysis tool (SS, multi-cycles) – include package + PCB + load models
  2. **Step 2:** Export (I/V) curves for power stages (HS + LS FETs). ASCII and .XLS formats are supported
  3. **Step 3:** Use I/V curves to run field analyses
  4. **Step 4:** View results in circuit analysis tool

EMC Modelling: Block Diagram



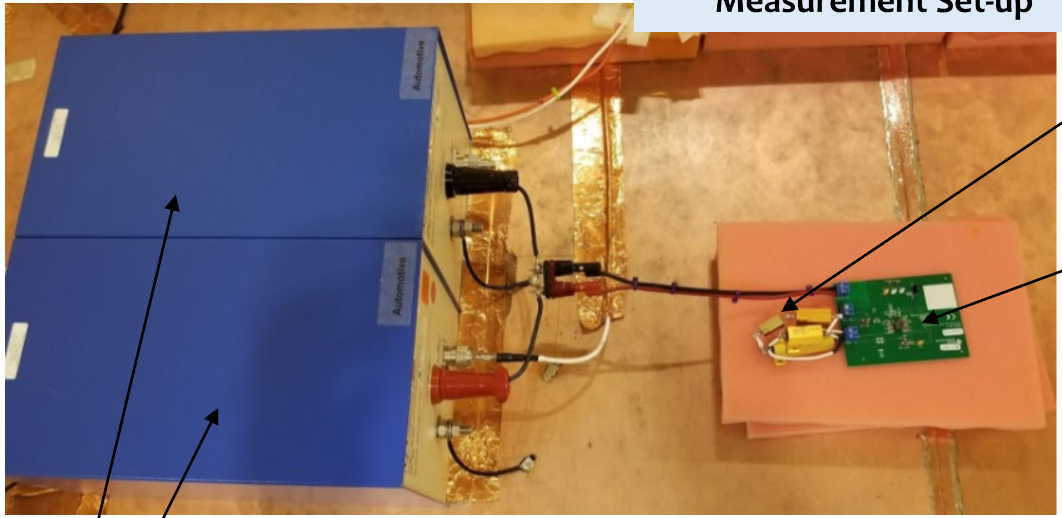
Compliance-Scope®
Virtual EMI/EMC Laboratory

IEEE

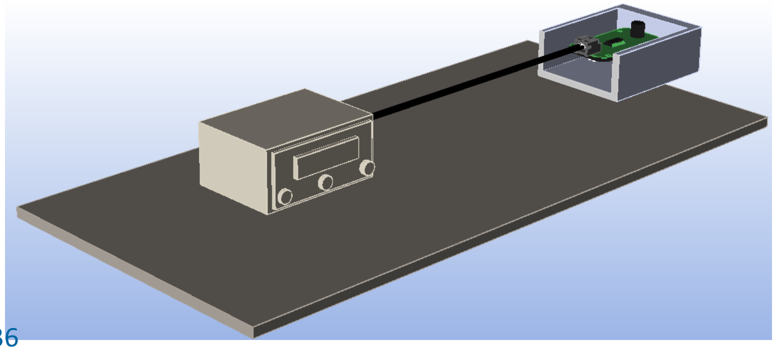
Hardware to Simulation Correlation

Methodology validation: CISPR 25 Conducted Emission

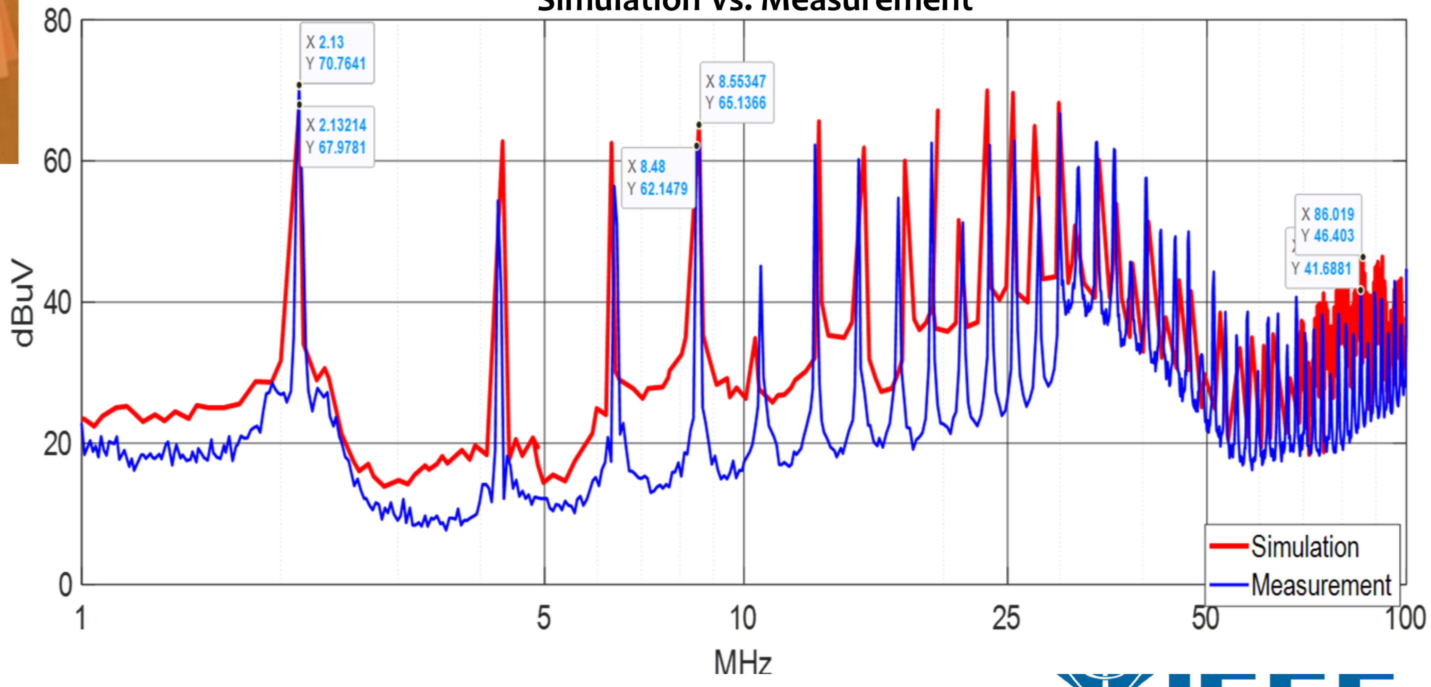
CISPR25 CE Measurement Set-up



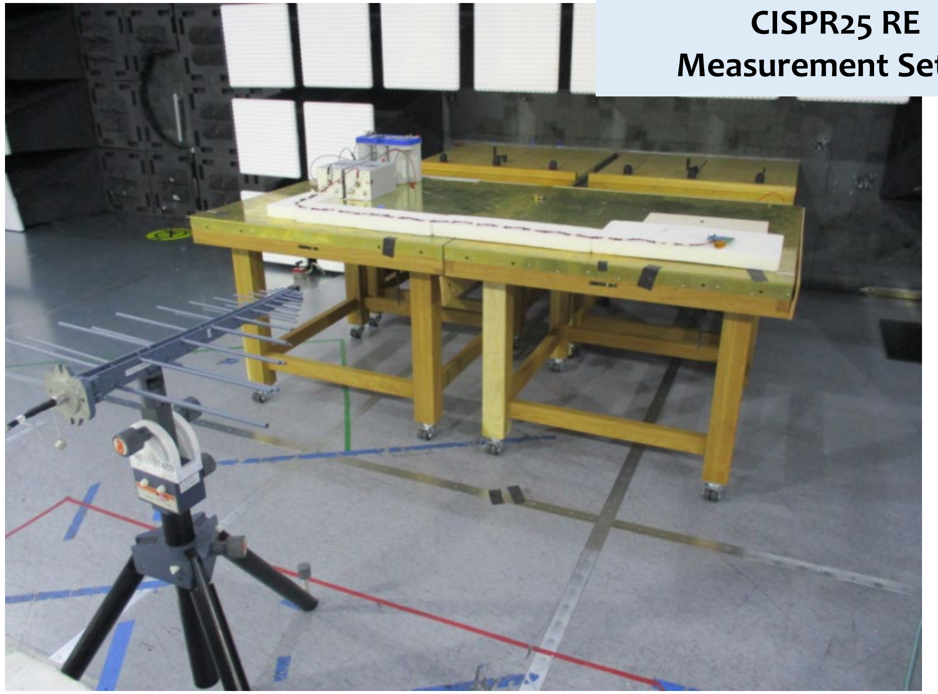
CISPR25 CE Simulation Set-up



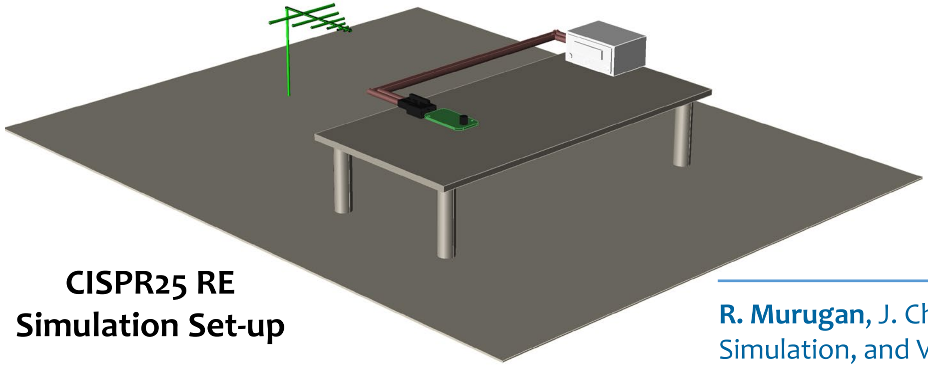
CISPR25 CE Simulation Vs. Measurement



Methodology validation: CISPR 25 Radiated Emission

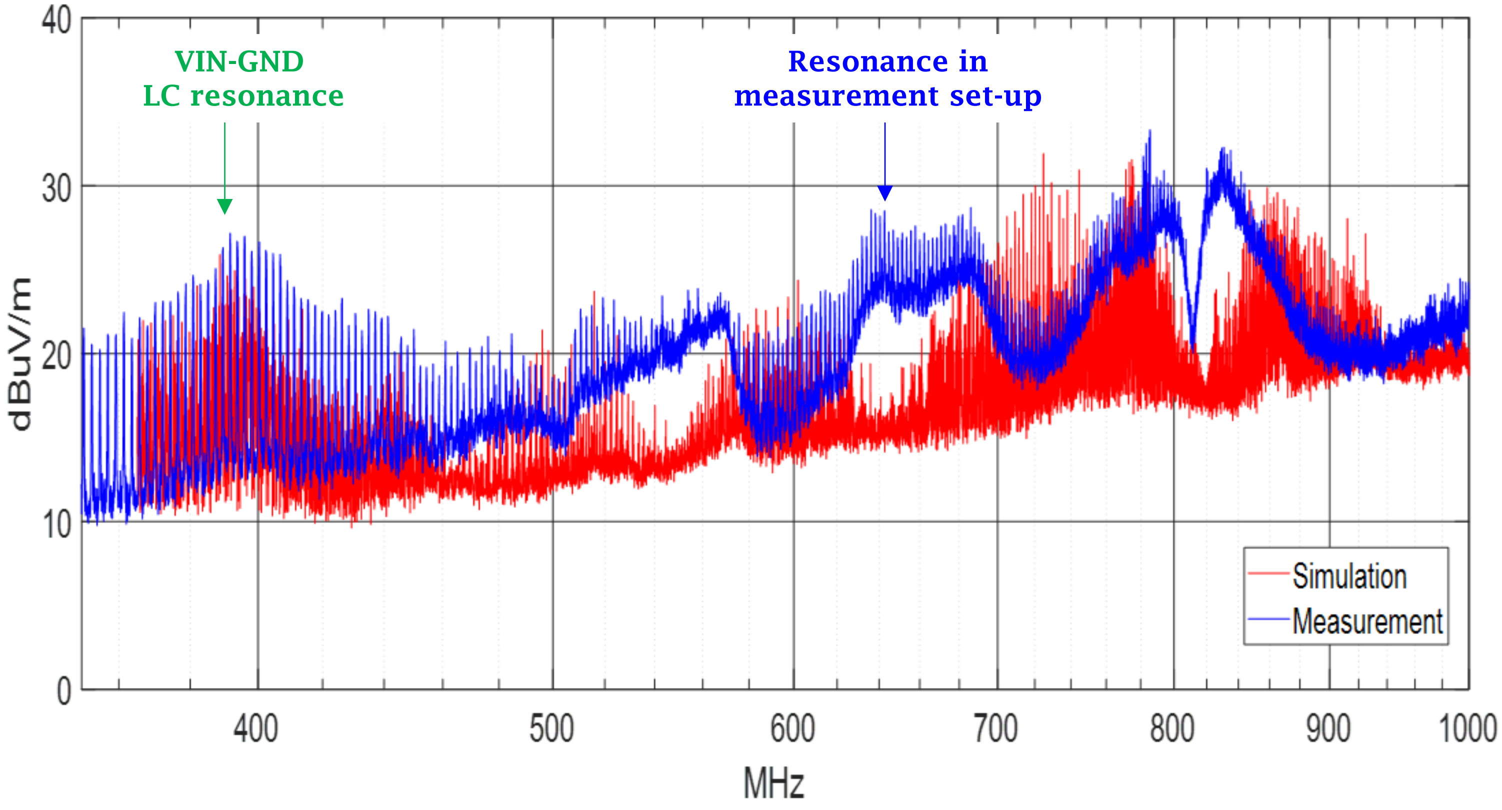


CISPR25 RE
Measurement Set-up



CISPR25 RE
Simulation Set-up

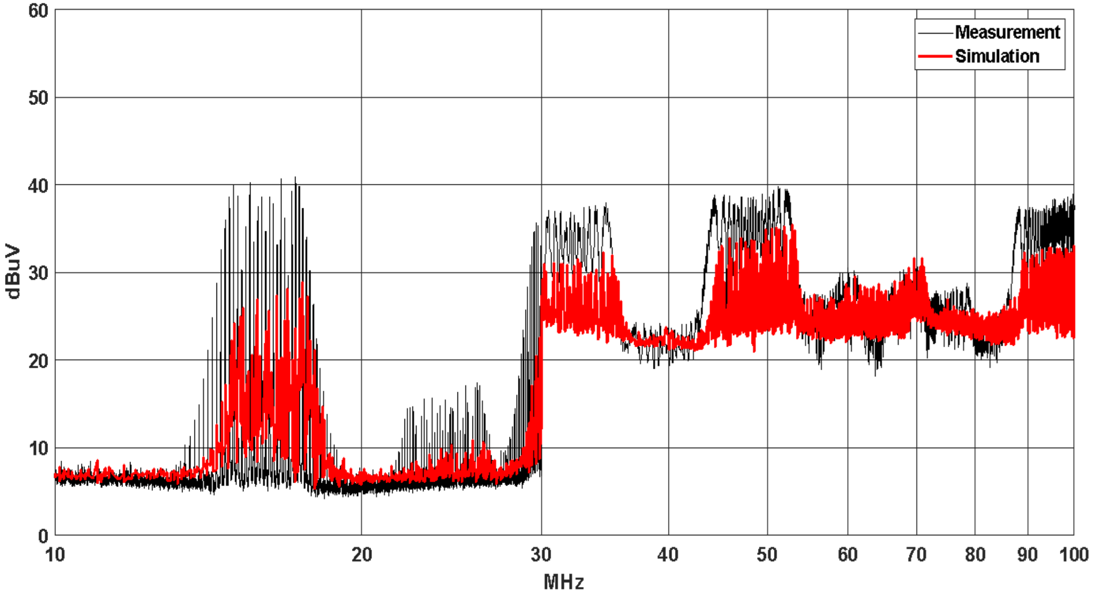
CISPR25 RE
Simulation Vs. Measurement

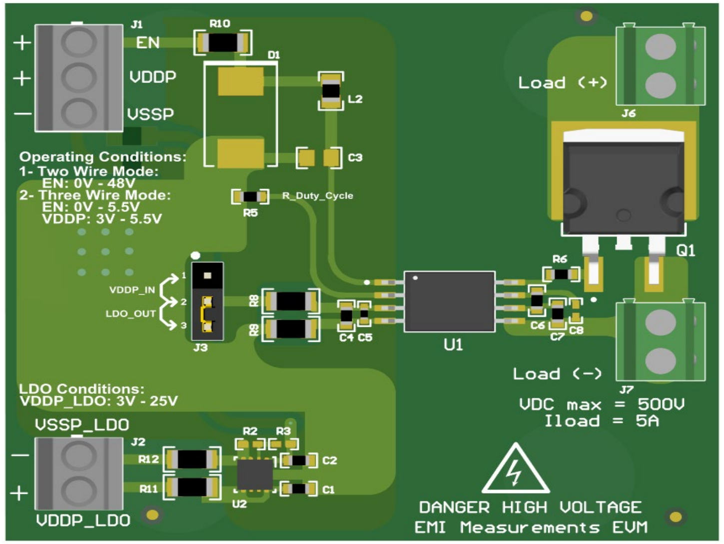


R. Murugan, J. Chen, A. Tripathi, B. P. Nayak, H. Muniganti and D. Gope, "Multiscale EMC Modeling, Simulation, and Validation of a Synchronous Step-Down DC-DC Converter," in IEEE Journal on Multiscale and Multiphysics Computational Techniques, vol. 8, pp. 269-280, 2023, doi: 10.1109/JMMCT.2023.3276358.

Conducted Emissions: Reinforced Isolated Switch Driver

LISN Voltage

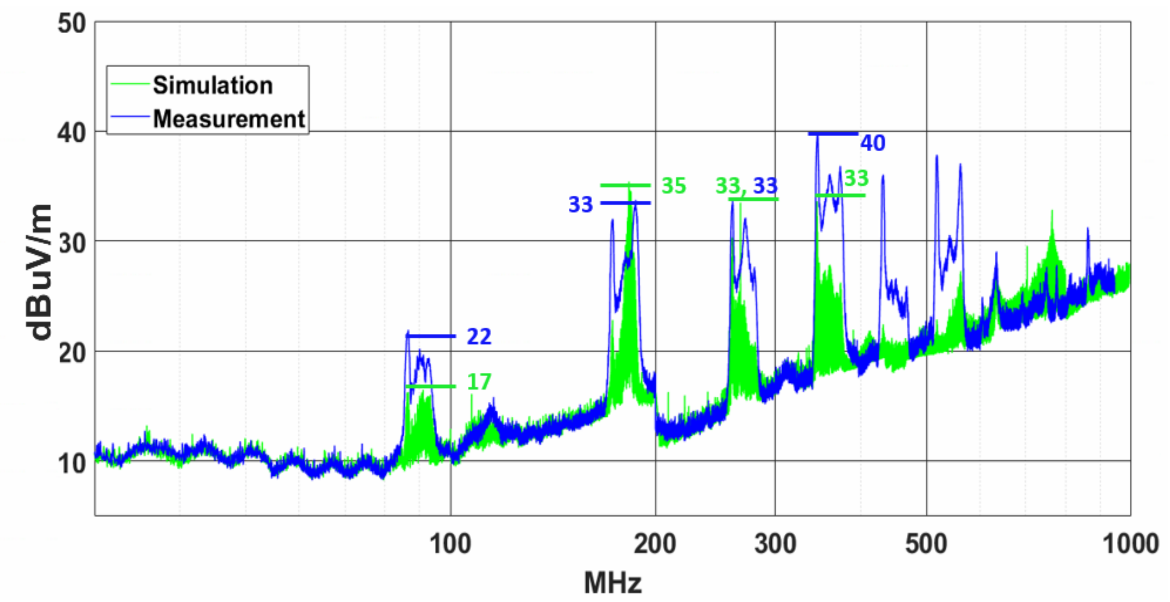


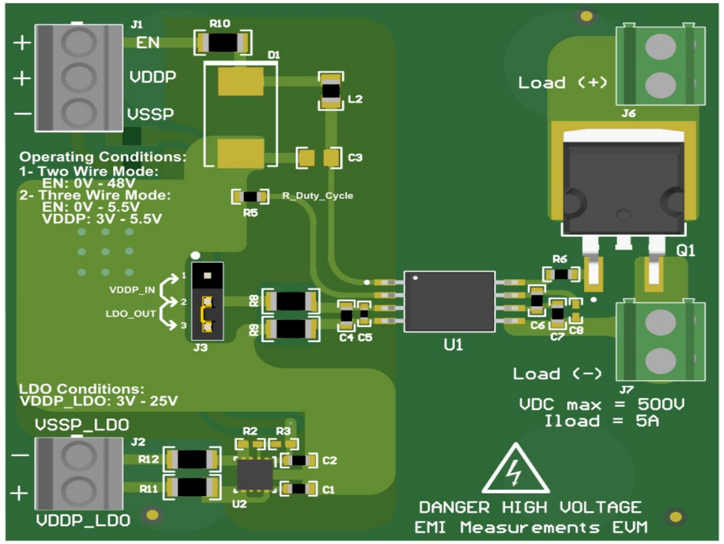


J. Chen, R. Murugan, S. Saw, F. Lauzurique, J. Broze, C. Greenberg, A. Triano, B. Nayak, H. Muniganti, J. Sivaswamy and D. Gope, "CISPR 25 Radiated Emission Simulation and Measurement Correlation of an Automotive Reinforced Isolated Switch Driver," *2022 IEEE 31st Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS), San Jose, CA, USA, 2022, pp. 1-3, doi: 10.1109/EPEPS53828.2022.9947145.*

Radiated Emissions: Reinforced Isolated Switch Driver

Electric Field Vertical





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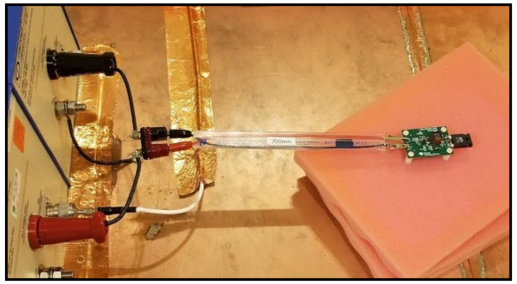
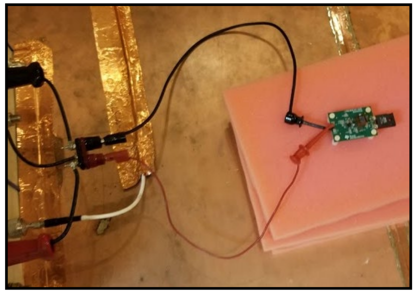
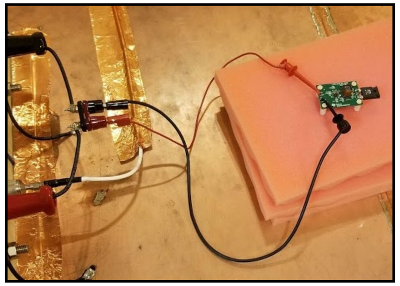
Lessons learned

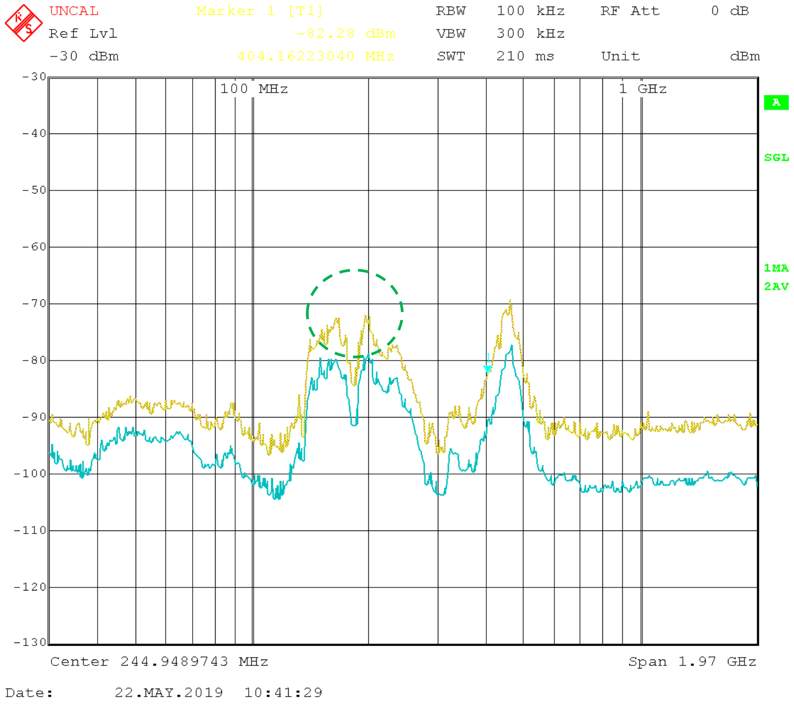
Sensitivity of Cable for CE Measurements



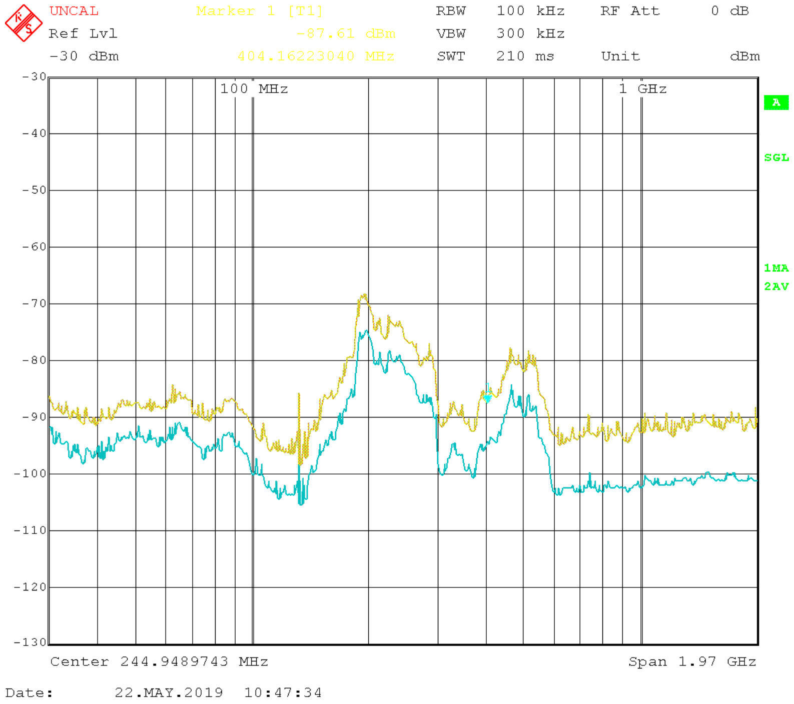


CISPR 25 CE Meas.
DCDC Converter
V_{IN} = 13.5V
V_{OUT} = 5V
I_{OUT} = 0.5A
F_{SW} = 250kHz

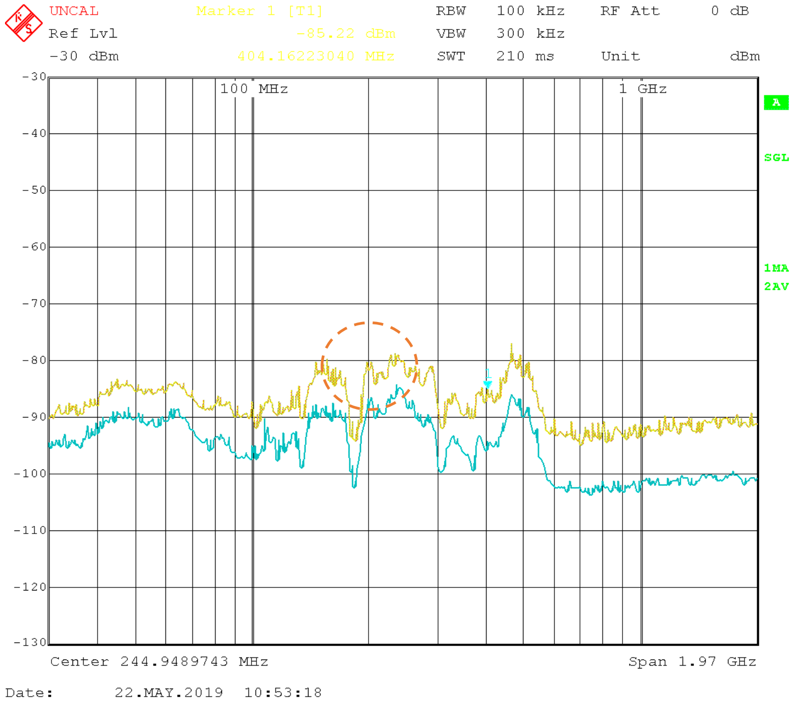




- Typical cable
- Parallel wires
- 200mm long max by spec
- Slight separation

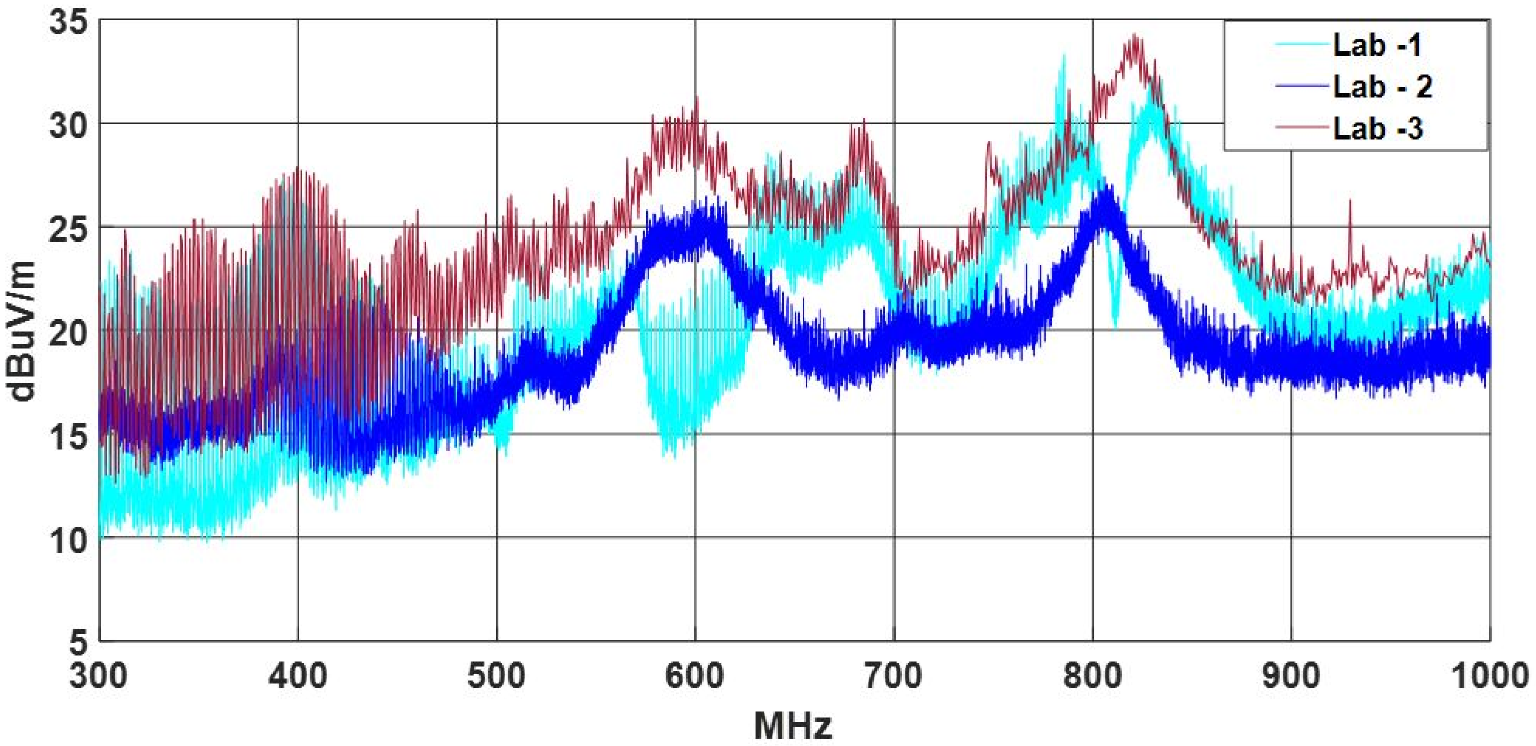


- Cables making large loop
- Counter clockwise differential mode current



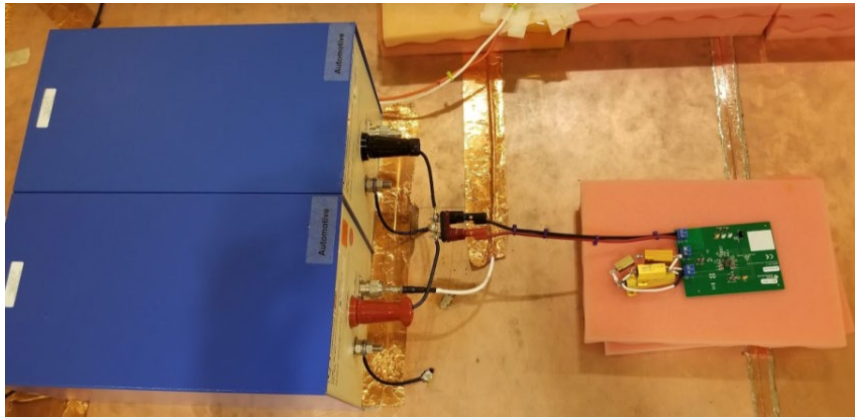
- Cables making large loop
- Clockwise differential mode current

Certified 3rd party EMC Labs Measurements – CISPR 25[12-15]



[12] F. Lafon, J. Davalan and R. Dupendant, "Inter-laboratory comparison between CISPR25 chambers, identification of influent parameters and analysis by 3D simulation," 2015 Asia-Pacific Symposium on Electromagnetic Compatibility (APEMC), 2015, pp. 71-74, doi: 10.1109/APEMC.2015.7175291.
[13] F. Lafon et al., "Investigation on dispersions between CISPR25 chambers for radiated emissions below 100 MHz", EMC Europe 2014.
[14] D. Kumar and P. Sudhakar, "Inter laboratory comparison (ILC) of conducted emission measurements," in IEEE Electromagnetic Compatibility Magazine, vol. 7, no. 3, pp. 52-59, 3rd Quarter 2018, doi: 10.1109/MEMC.2018.8479339.
[15] S. Baisakhiya, A. Albin, B. Subbarao, "Interlaboratory comparison of radiated emission measurements. 2008 10th International Conference on Electromagnetic Interference & Compatibility", 283-285, 2008.

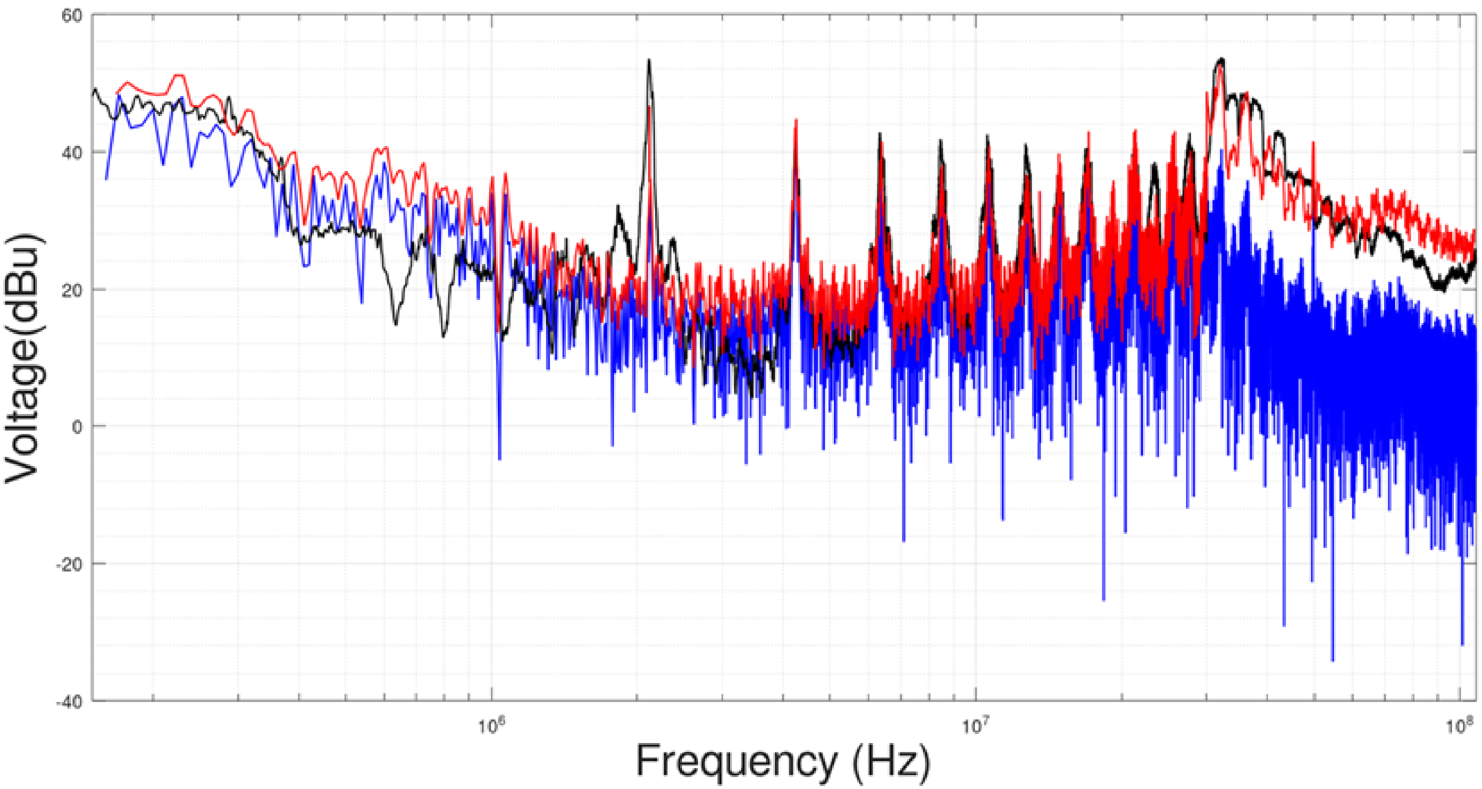
EMI-Receiver Effect



☑ Enable EMI Receiver Peak EMI - RX Type = CISPR_16_1_1

	Start Frequency	End Frequency	RBW
Band A	9000	150000	200
Band B	150000	3e+07	9000
Band C	3e+07	3e+08	120000
Band D	3e+08	1e+09	120000
Band E	1e+09	1.8e+10	1e+06

OK Cancel



Simulation result without EMI receiver model
Simulation result with EMI receiver model
Measurement data

Summary

- As more stringent regulations are put in place, electromagnetic compatibility (EMC) is becoming more relevant than ever before.
- Meeting EMC regulatory standards is a system-level requirement – optimizing the package and PCB, for low EMI, is critical.
- EMC modeling methodology developed here can be applied both at Pre-silicon and Post-silicon stages of the design process.
- Predictive EMC modeling coupled with Pre-EMC compliance testing will provide for an improved EMC product design and development.