Automotive EMI Reduction Techniques, Applications and Solutions

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TI training - summary

EMI Techniques for Automotive Applications:
The world is hurtling towards *Electric Vehicles* and *Autonomous Cars*. Semiconductor content of cars is expected to increase ~ 10x by 2025. In this presentation we show challenges in EMI for new increasing demanding automotive systems like ADAS, cameras, instrument cluster and infotainment. Then we show the EMI mitigation techniques like filtering, spread spectrum and E-field shielding and compared the results.

What you'll learn:

1. In this training, you will learn about new automotive application trends
2. You will learn EMI noise sources and about near E-Field coupling
3. Introducing EMI mitigation techniques, like switch node shaping, spread spectrum, E-Field shielding techniques.
4. EMI measurement that show how much all of these techniques will reduce and help to pass CISPR 25 are presented.

Course details:

- Type: PPT Presentation
- Duration: 1:30h / English
- Audience: FAE, Apps, System Apps

TI Products and Solutions:

- 2.1MHz LM53601
- 2.1MHz LM53603
- 2.1MHz LM53635
- 400kHz LMS3655

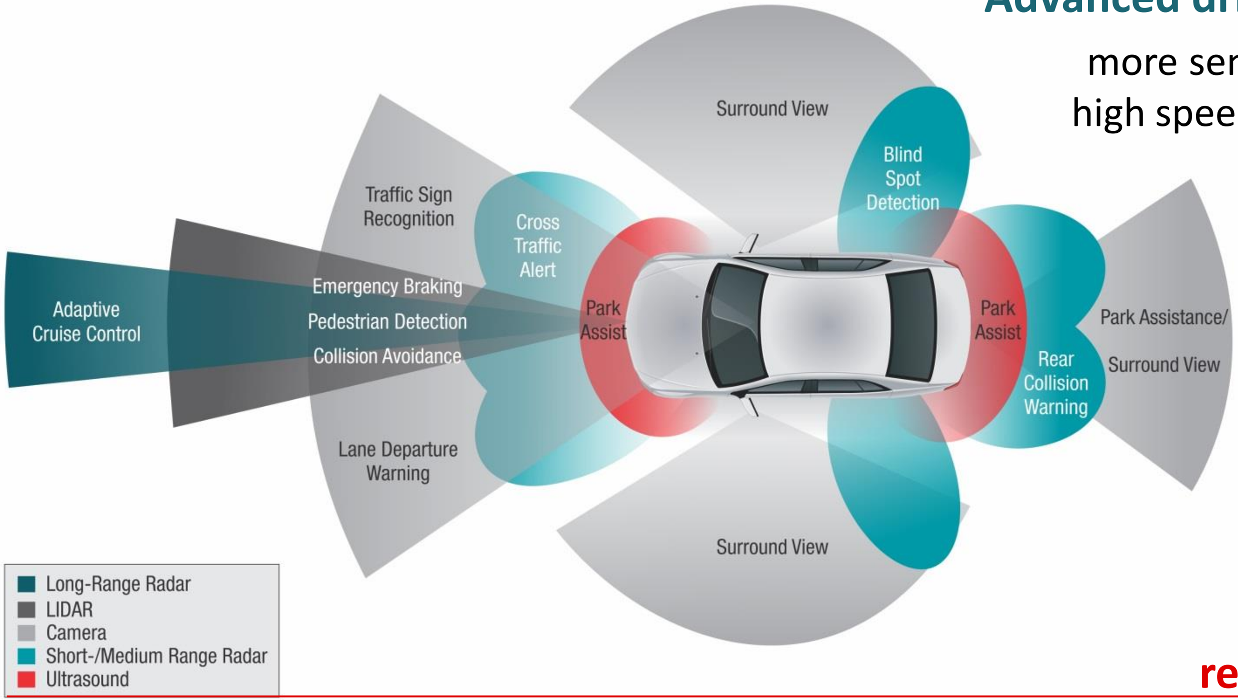
Detailed agenda

1. **New automotive system trends evolving EMI needs and challenges**
   a. ADAS and Infotainment applications
   b. Switching above AM-band 400kHz to 2.1MHz, solution size
   c. Switch node noise challenges, switch node shaping

2. **EMI noise source model and reduction methods / techniques**
   a. Automotive DC/DC conversion noise source model for Buck
   b. Why conducted EMI is essential for passing radiated tests
   c. Differential and common mode noise sources and reduction techniques

3. **EMI examples for automotive system applications**
   a. 2.1MHz LM53603 comparison between 2-stage filter, CM choke and E-field shielding
   b. 2.1MHz LM53601 comparison between spread spectrum versus E-field shielding
   c. Integrated Buck module comparison between partial and full E-field shielding

1. New automotive system trends – ADAS



Advanced driver-assistance systems:

more sensors and systems in the car
high speed image / data links / clocks
24GHz and 77GHz radar
complex wire harness
signal to noise ratio
safety relevant

Autonomous driving requires best in class EMI.

1. New automotive trends for cameras

12V Battery

CISPR25 class 5

module

- ADAS requires more camera modules around the car arranged.
- Camera metal enclosures changes to cheaper / lighter plastics.
- Smaller module solution size is required.
  Use ICs that need a smaller EMI filter to pass CISPR.
  -> Solution: 2.1MHz and Spread Spectrum will need small FB filter only

Trend to lighter and cheaper wire harness for power, control and data wire.

- More compact / packed PCBs can cause near field noise coupling.
- Display wires and clocks
- High Speed processor next to it
- Analog link changes to digital link

2. New automotive trends for Infotainment

12V Battery

CISPR25 class 5

Complex wire harness:
- Power cables
- Display links
- Speaker cables
- USB power
- RF antennas
- CAN bus

- Multiple RF modules Bluetooth, LTE, FM, satellite, GPS
- High speed processors, graphic chips and clocks
- High resolution displays higher faster frequencies
- Small motors in cluster

- Telematics and emergency call
- Output wires to speakers
- Output wires to USB
- Interference with external phone or consumer devices

USB power

USB cable

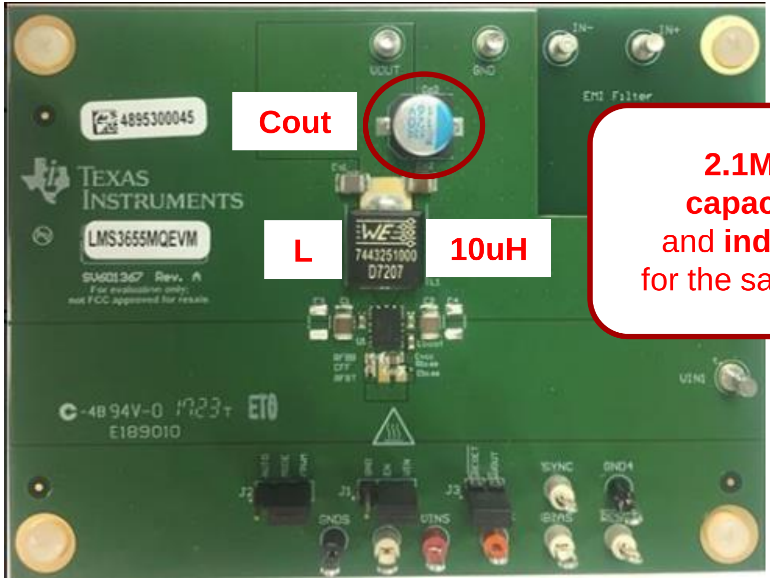
Media device

2. End equipment EMI requirements

End equipment	PCB & Layout	Schematic	Components	IC topology
- **Input power source** battery or generator DC or AC 12Vin, 24Vin or 48Vin standard - **Cables** what type, gauge / stranded, twisted pair or shielded, total length of wires, what signals like clocks? - **Enclosure & Connectors** - **Load** internal or external (e.g. USB)	- PCB total size - PCB numbers of layers and stack-up - Component placement - routing of noise signals - shielding - position of connectors	- EMI filter design - Switch node snubber - Noise filter - Rboot - Cin and Cout **Trend is switching above AM band from 400kHz to 2.1MHz**	- EMI Inductors - CM Chokes - EMI Shields - EMI Beads - EMI Caps - EMI Cable - EMI Connector	- LDO versus Buck - Controller versus integrated Converters - Non-Synchronous Buck versus synchronous Buck - Multiphase to reduce ripple noise
Each end application has it's own EMI challenges and solutions.	PCB layout and component placement is EMI critical.	Use noise reduction and switch node shaping techniques to reduce EMI.	Trend to lower BOM cost.	EMI optimized power architecture.

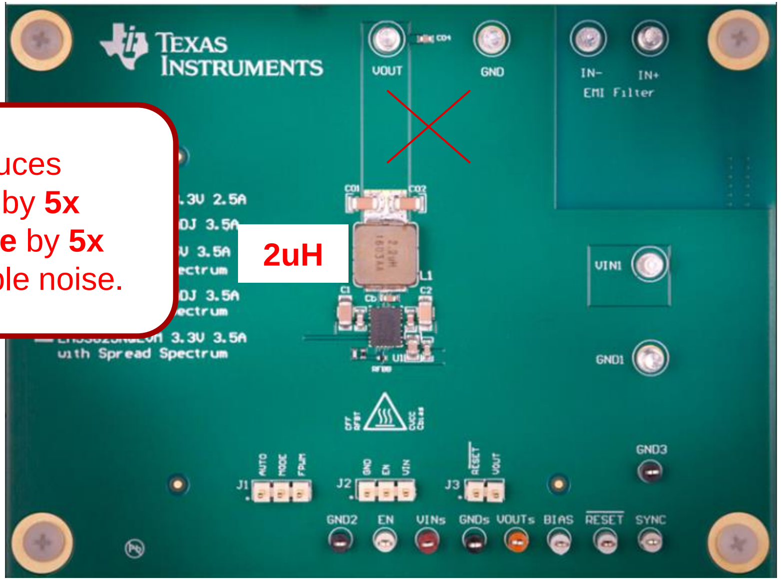
Trend → 2.1MHz for smaller solution size

400kHz @ 5.5A



LMS3655-Q1

2.1MHz @ 3.5A

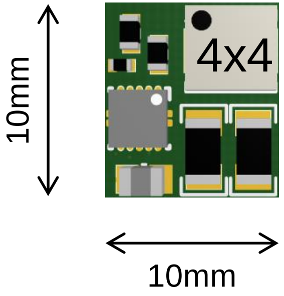


2.1MHz reduces **capacitance** by **5x** and **inductance** by **5x** for the same ripple noise.

LM53635-Q1

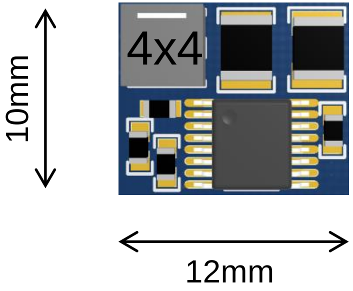
2.1MHz solution size advantage for low power

LM53601-Q1
2.1MHz @ 1A
WSON package



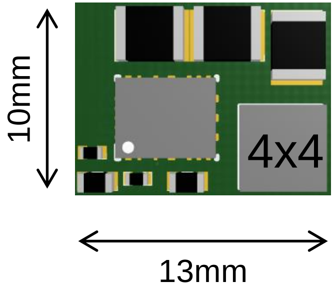
Cout= 1x22uF
Cin = 1x10uF

LM53602-Q1
2.1MHz @ 2A
TSSOP package



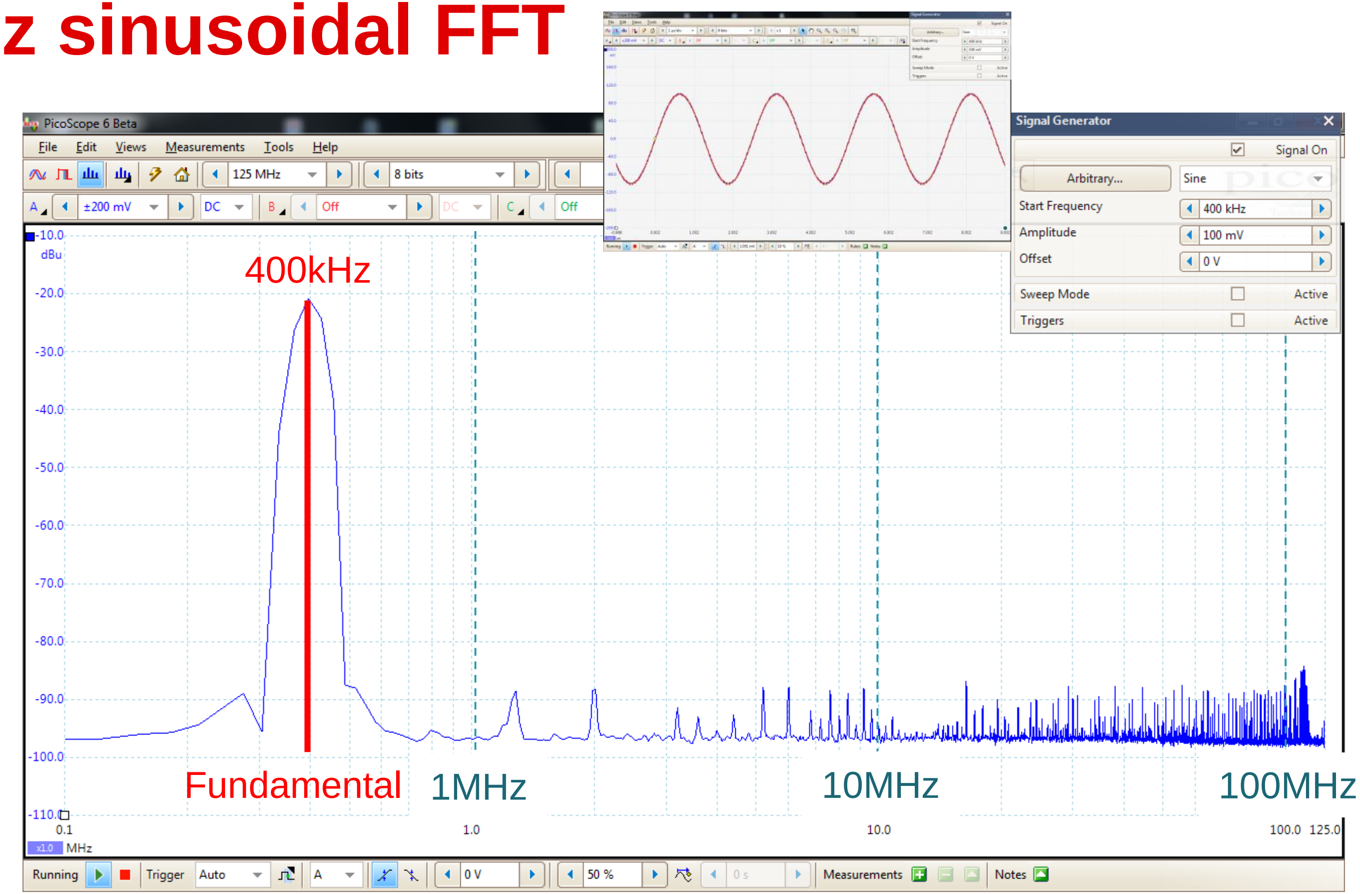
Cout= 1x47uF
Cin = 1x10uF

LM53625-Q1
2.1MHz @ 2.5A
Hot Rod™ package

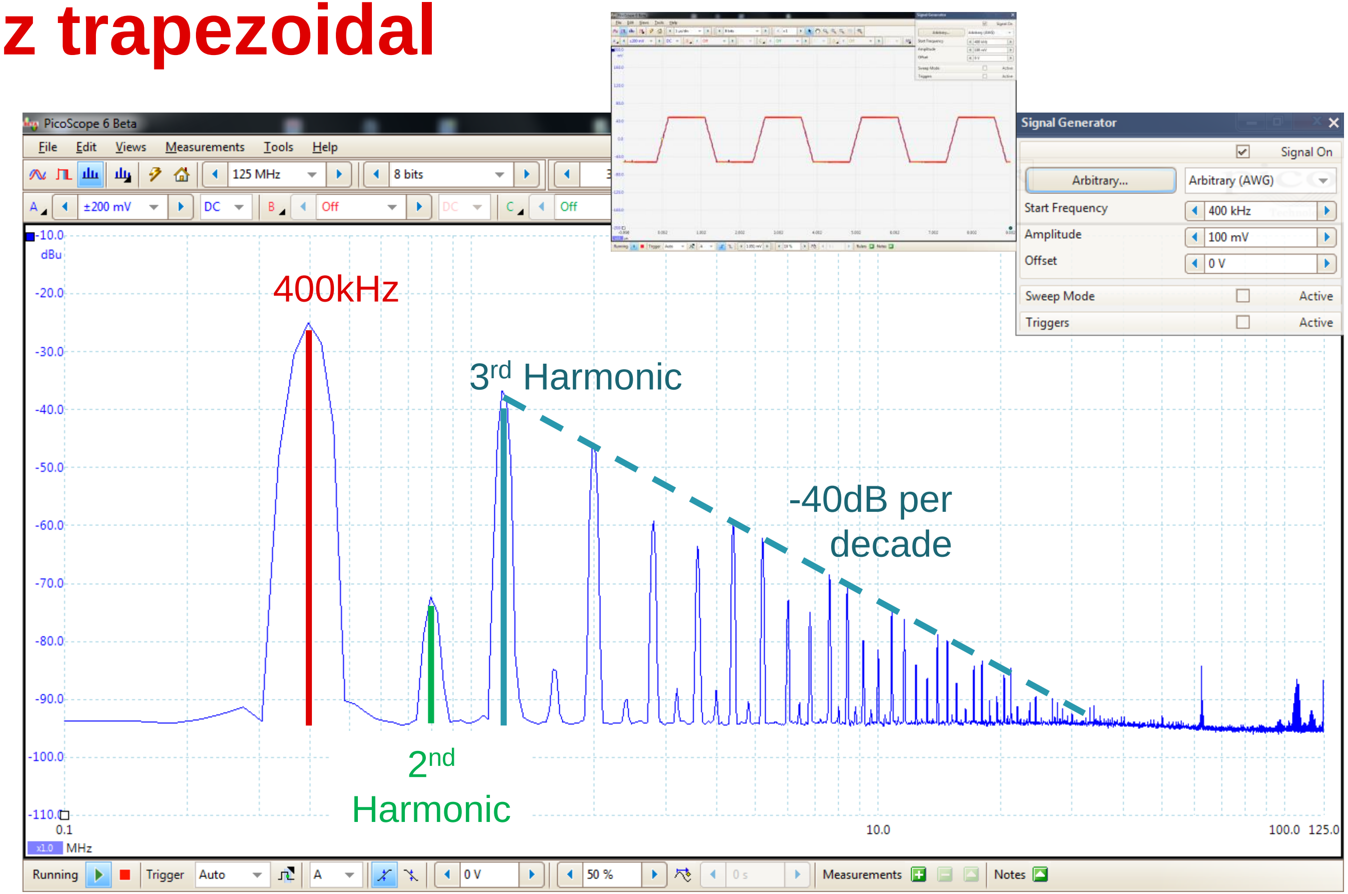


Cout= 2x22uF
Cin = 1x10uF

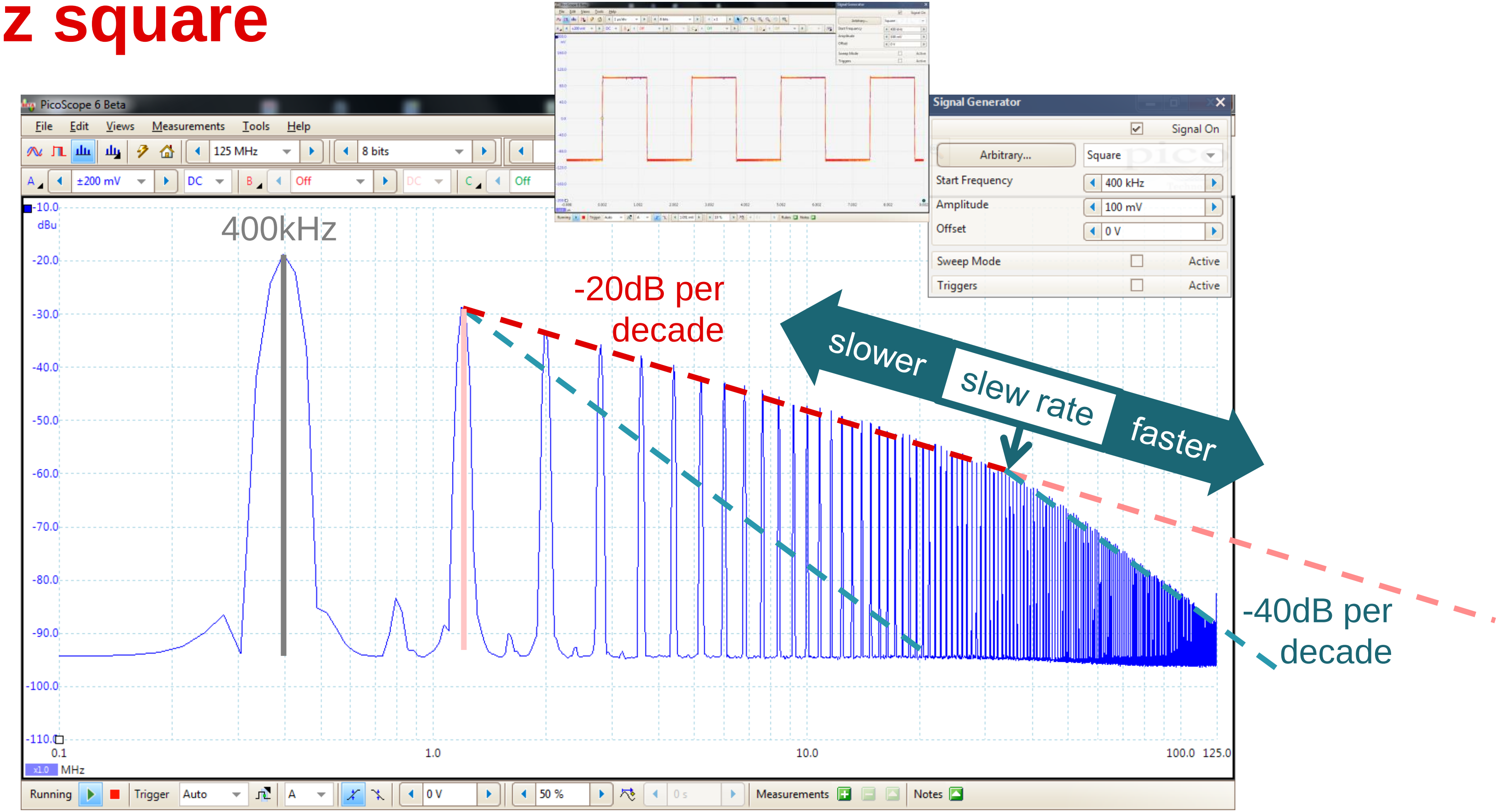
400kHz sinusoidal FFT



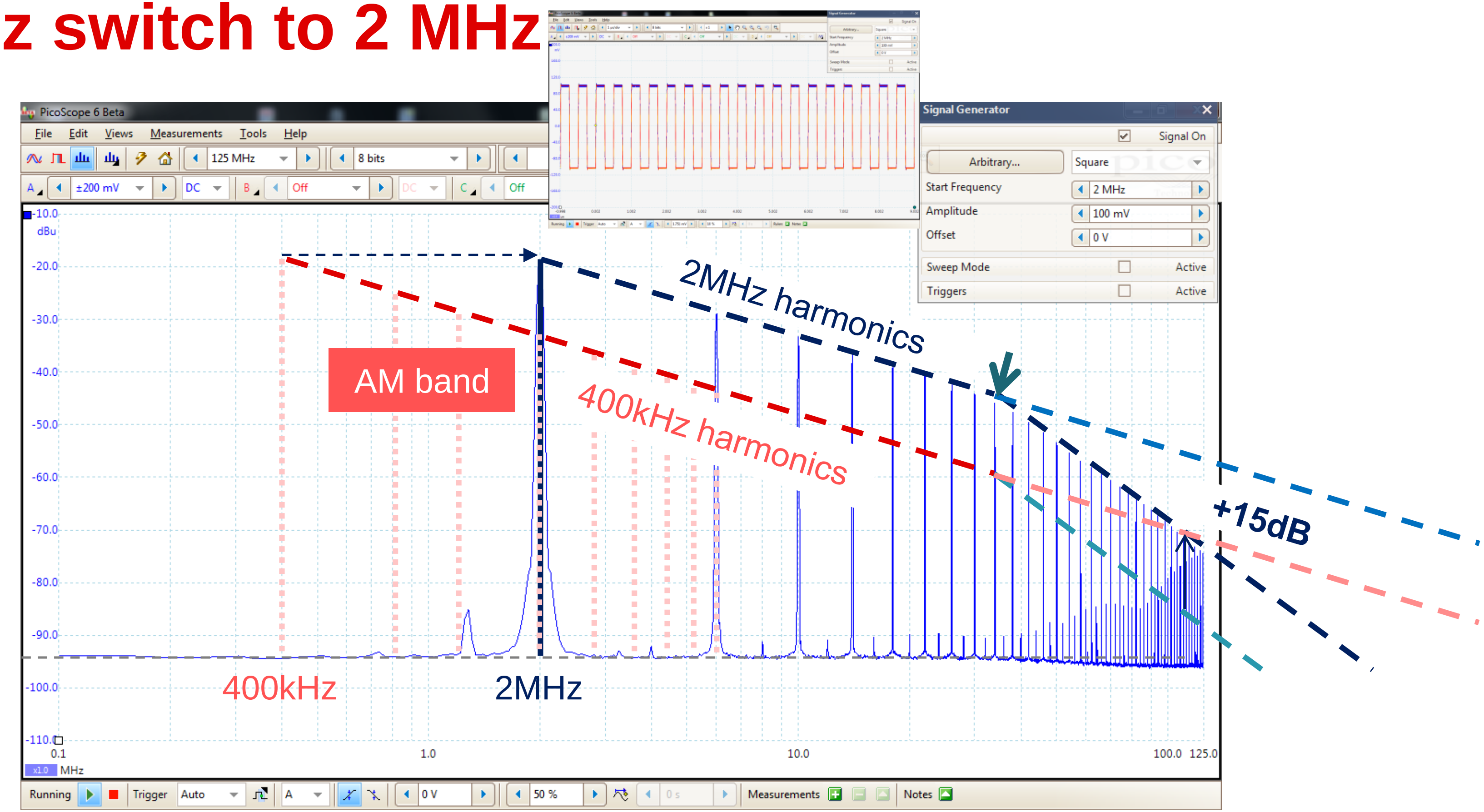
400kHz trapezoidal



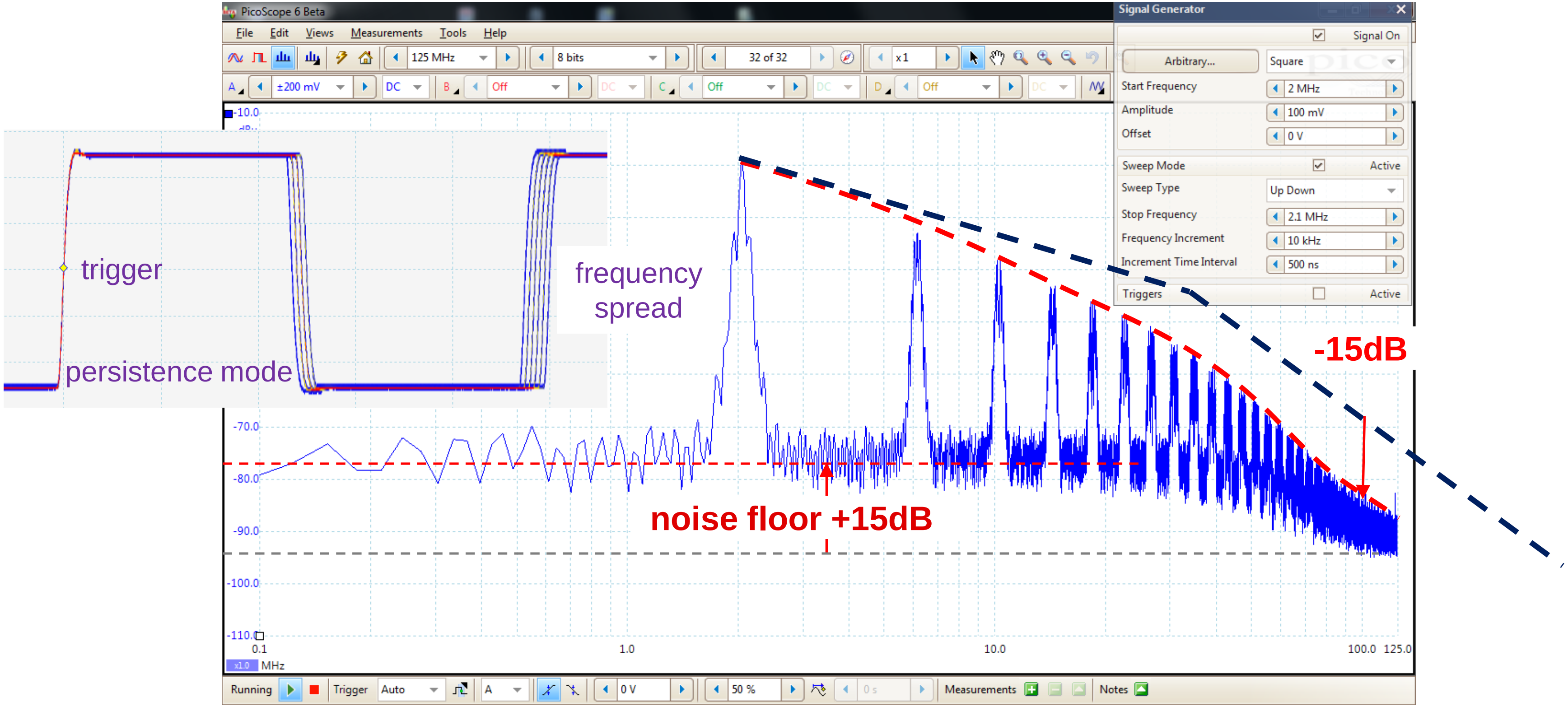
400kHz square



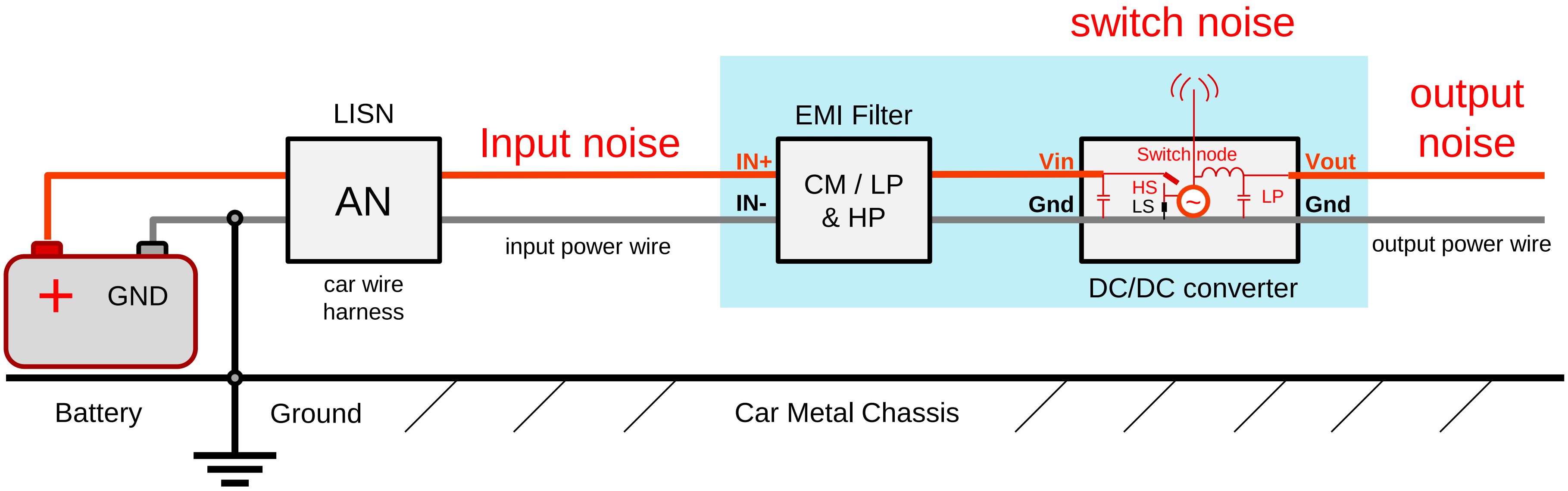
400kHz switch to 2 MHz



2 MHz square with spread spectrum



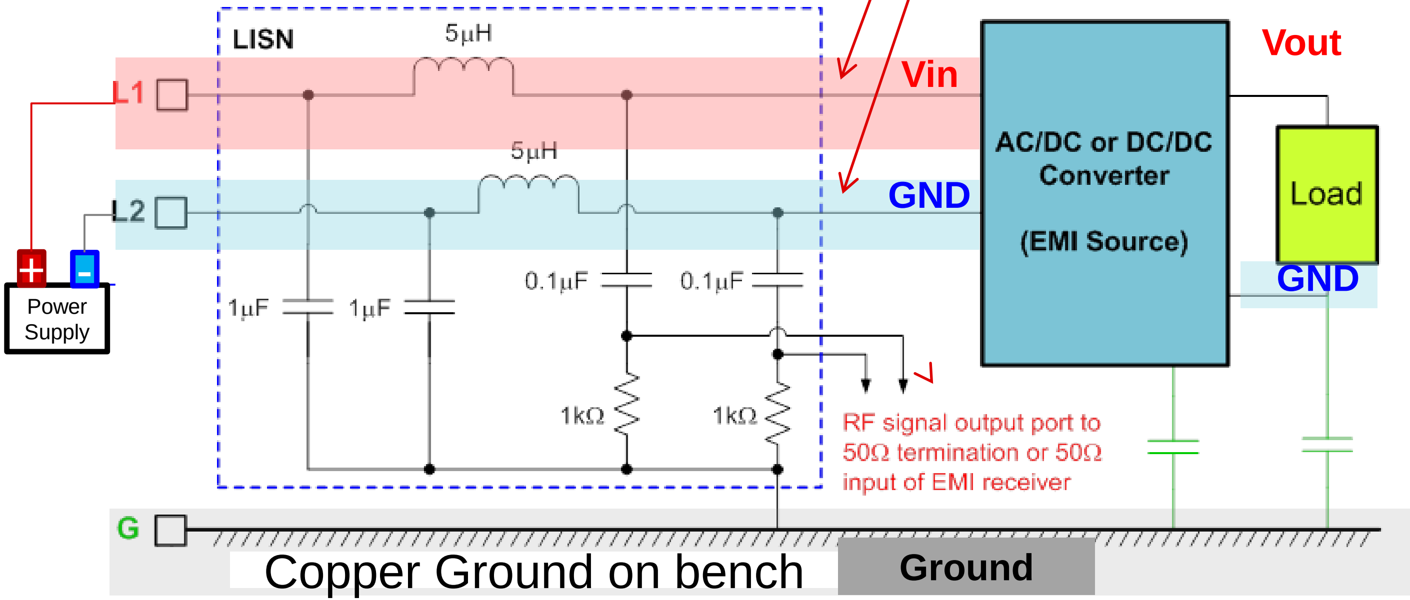
Automotive EMI noise source model for Bucks



About AN = LISN

LISN or Artificial Network (AN)
Represents the wire harness and terminates the test setup

~50 Ω equivalent input impedance on each port over relevant frequency range.



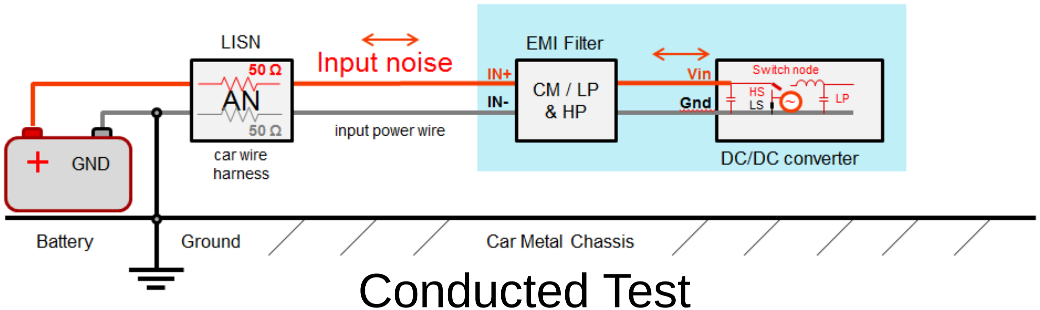
Spectrum Analyzer measures the noise from:

1. **Vin** to **Ground**
2. **GND** to **Ground**

50 Ω

Two EMI tests for CISPR 25

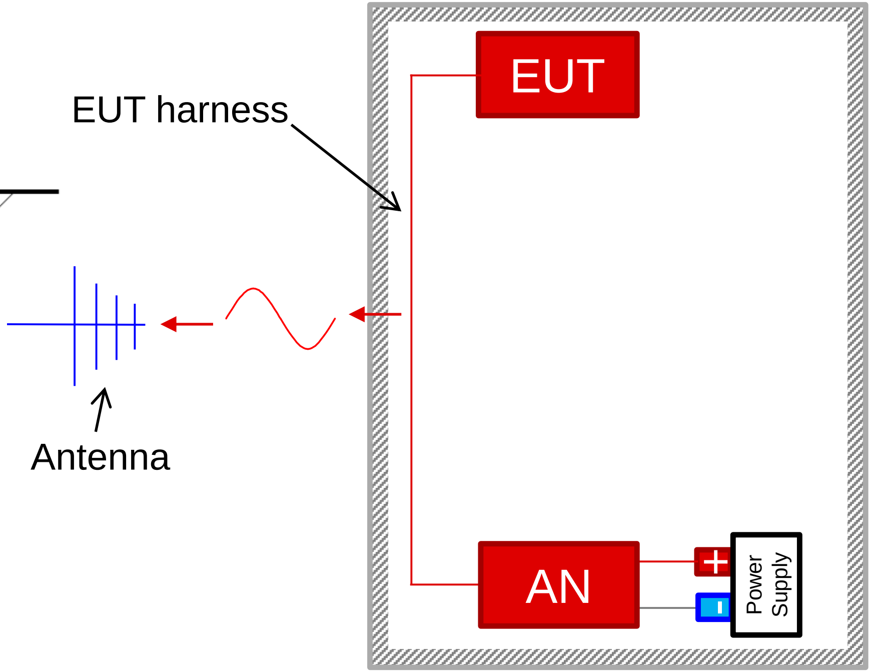
1. **Conducted testing: Measures voltage ripple on input harness.**
   a) **EUT is close to the measuring apparatus – the harness is short**
   b) **Measured quantity is voltage, dBµV**



Conducted Test

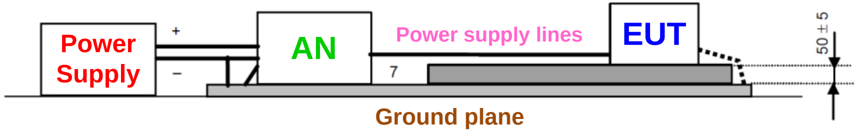
2. **Radiated testing: Measures electric field near the EUT and harness.**
   a) **The EUT and harness are approximately 1 m from the antenna**
   b) **Measured quantity is electric field dBµV/m**
   c) **Over most frequencies of interest for DC/DC conversion, this is not a far field measurement**

Radiated Test

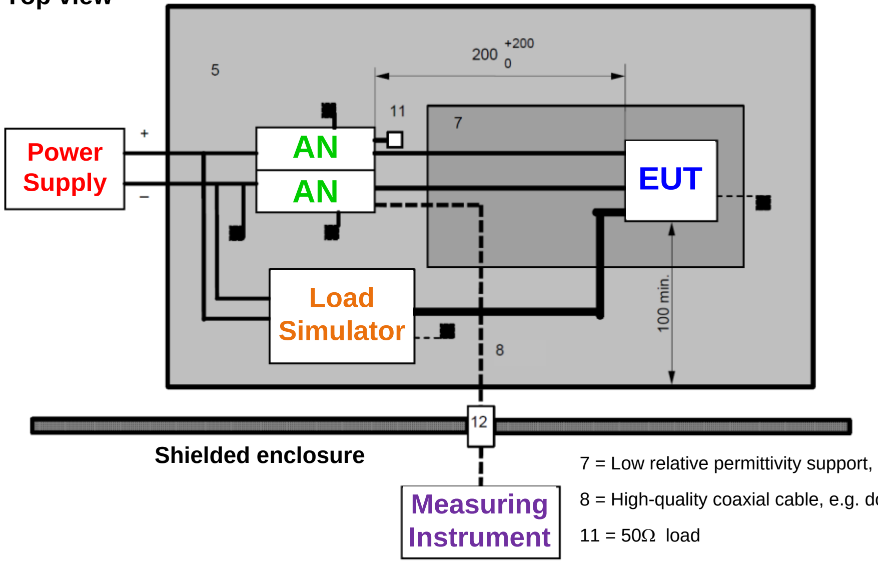


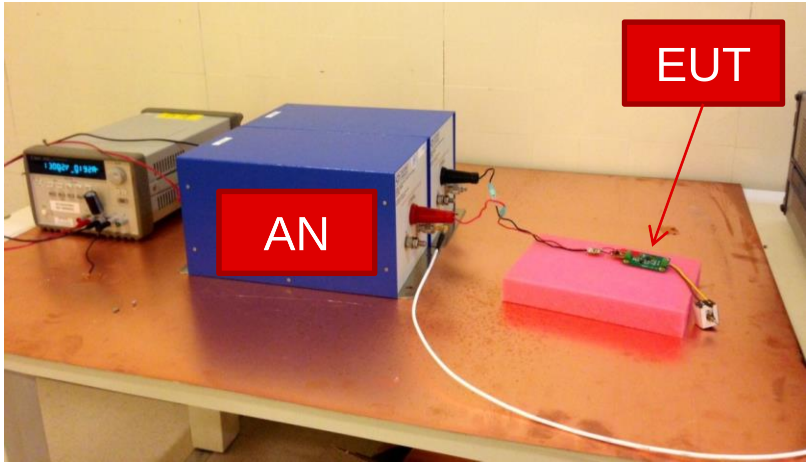
About Conducted EMI

Side view



Top view





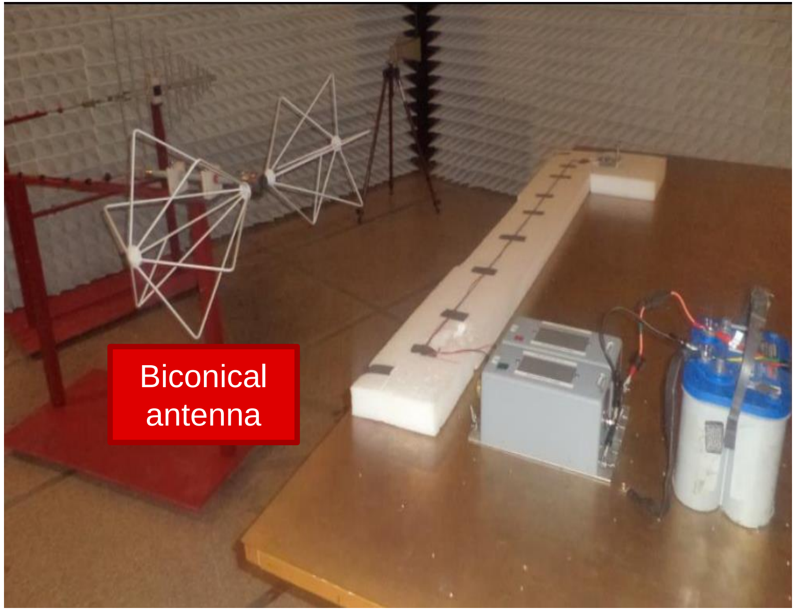
7 = Low relative permittivity support, $\varepsilon_R < 1.4$

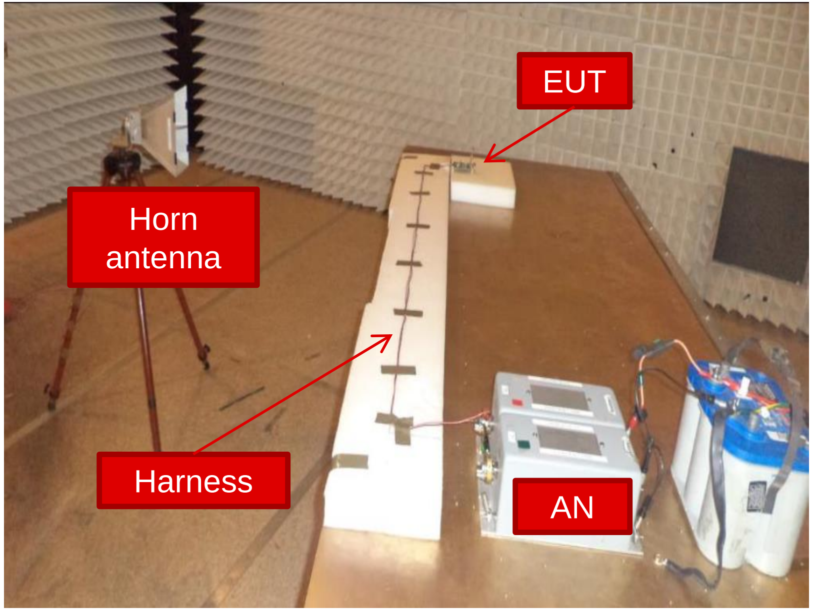
8 = High-quality coaxial cable, e.g. double-shielded 50Ω

11 = 50Ω load

12 = Bulkhead connector

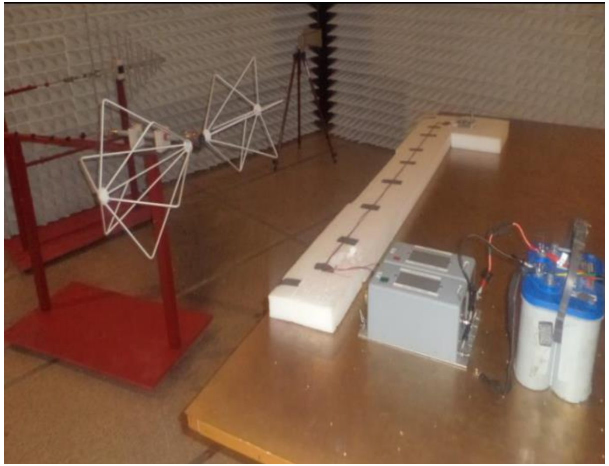
Radiated EMI test setup

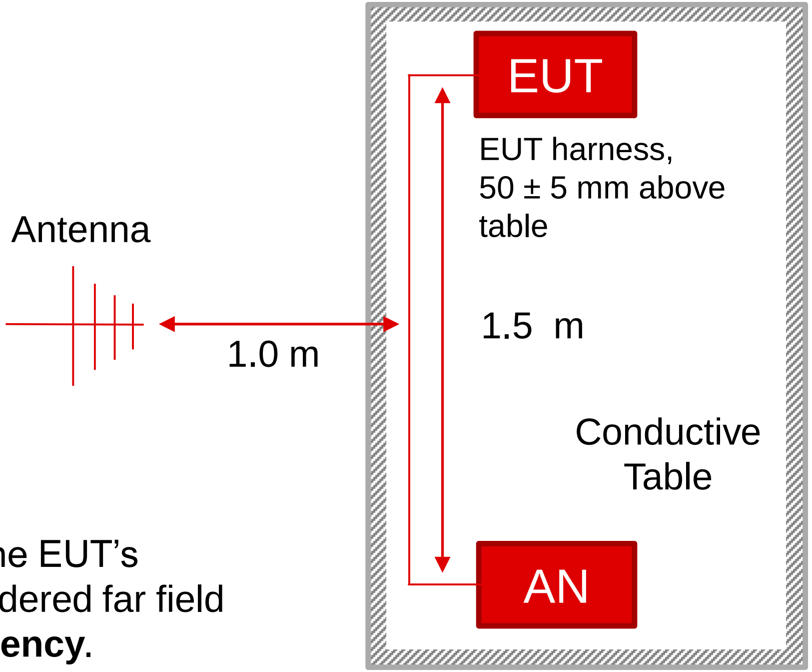




1. LM53601-Q1 set up for radiated emissions using biconical and horn antennas (UL, with permission)
2. Monopole, log and biconical antennas are centred on input cable, not the EUT
3. Horn antennas (for high frequencies) are aimed directly at the EUT
4. Input harness makes excellent antenna for common mode noise

Why conducted EMI is important for radiated EMI



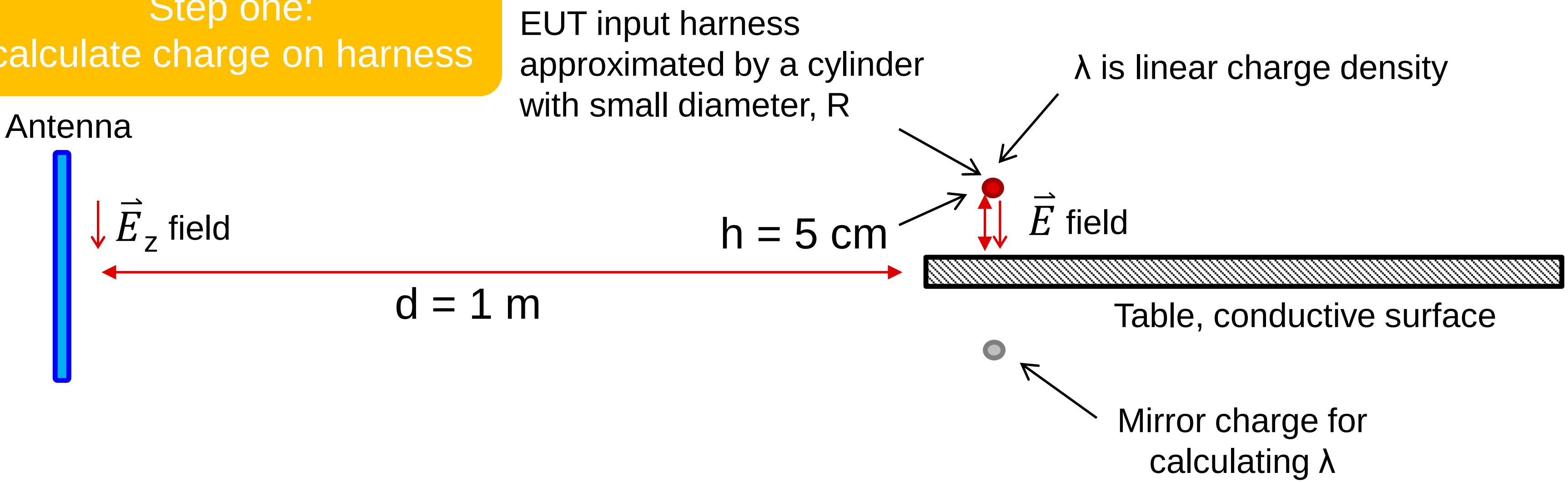


In addition to being pointed at the center of the EUT's harness, the antenna is too close to be considered far field below approximately 600 MHz → **high frequency**.

The length of the harness allows it to be considered a lumped element and the entire system to be considered a near field system below approximately 20 MHz → **low frequency**.
In the TV and lower FM bands, near field interaction still dominates → **intermediate frequency**.

1. A rough estimate of low frequency "radiated" emissions

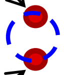
Step one:
calculate charge on harness



1. **λ can be approximated by assuming that the harness is a small diameter cylinder above an infinite conducting surface giving capacitance** $C_l = \frac{2 \cdot \pi \cdot \epsilon_o}{\ln \frac{2 \cdot h}{R}}$

   With a 22 gauge wire, the linear charge density, λ, is approximately $\lambda \approx 10 \frac{pC}{V \cdot m}$

2. A rough estimate of low frequency “radiated” emissions

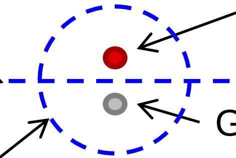


Equivalent diameter –
≈ 1.2 x for wires in contact to
≈ 1.6 x for large separations

Equivalent radius must take into account fields between wires limiting equivalent radius to 2.7 x R for charge calculation

Cable geometric factor for common mode shown

Step two: adjust charge

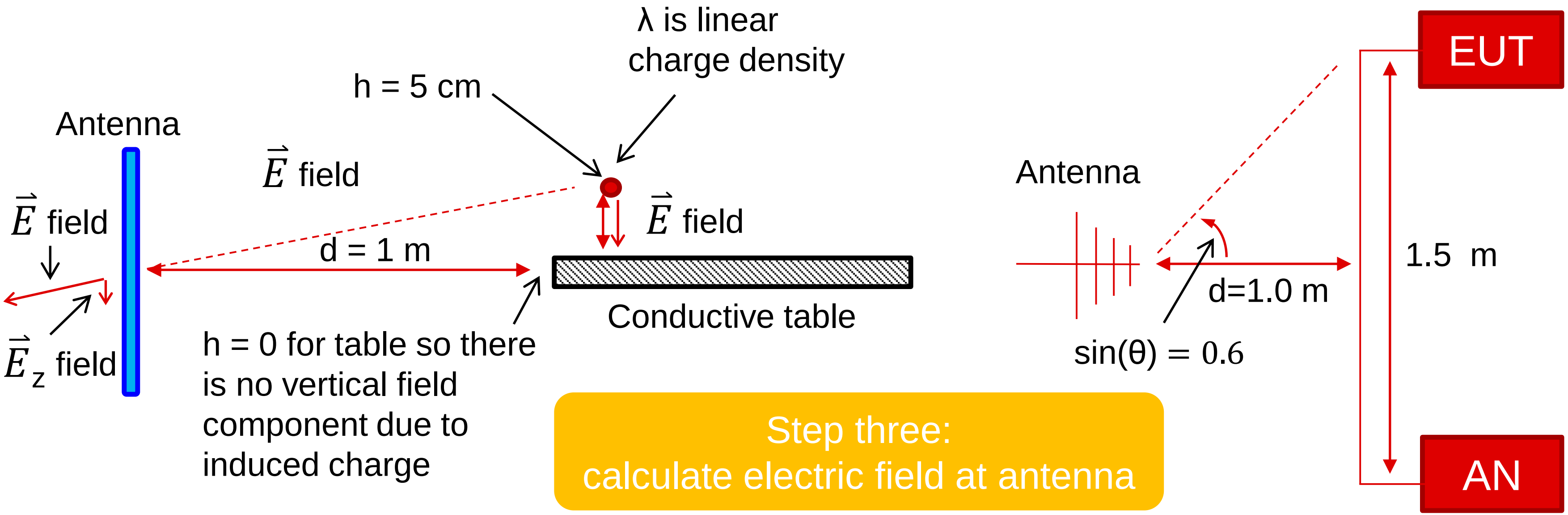


Dipole and higher order components of the field drop off very rapidly with distance

Why is unbalanced mode factor 0.5 for 2 wires?

1. **Since the harness has a power and a ground wire, multiply by 1.2 (wires separated by < 1 wire diameter) – 1.6 (wires separated by 5x wire diameter). After multiplying, divide by 2 if unbalanced noise and leave as is for common mode noise. This number is different if the harness is not two wires of equal gauge. Note that at frequencies above >10 MHz, common mode noise typically dominates for small Buck converters with filter.**

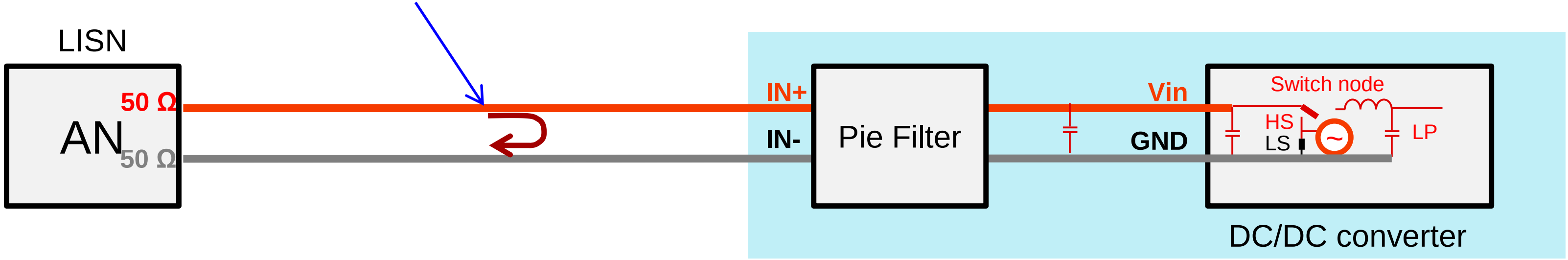
3. A rough estimate of low frequency “radiated” emissions



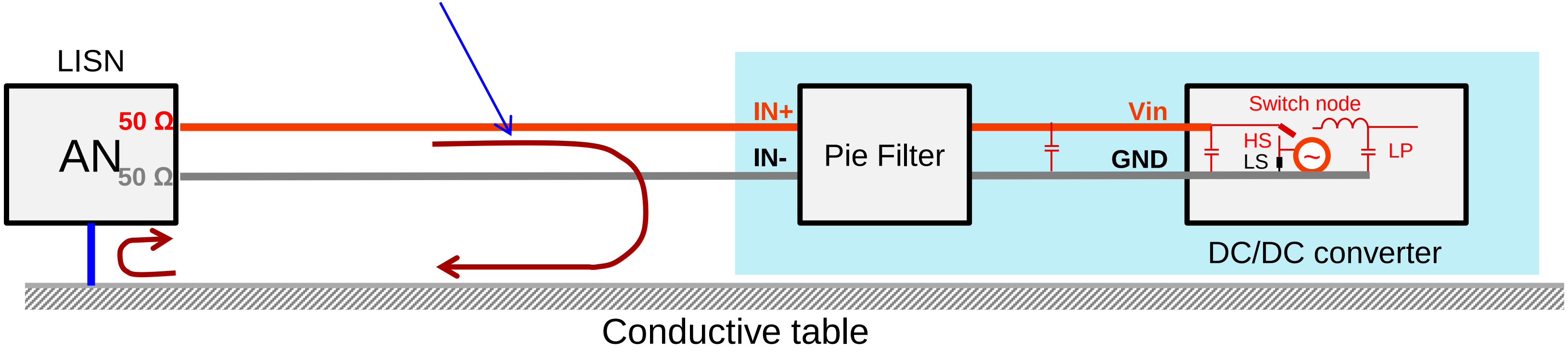
1. **Integrating the vertical component field produced by λ and ignoring its mirror charge and using h = 5 cm, d = 1 m, harness length = 1.5 m closely spaced wires with common mode noise and antenna vertically oriented electric field in V/m is ≈ 35 to 50 dB below conducted voltage in V.**
2. **mV level input ripple should be avoided since in most bands, radiated will fail as well as conducted EMI testing**

Two types of conducted noise

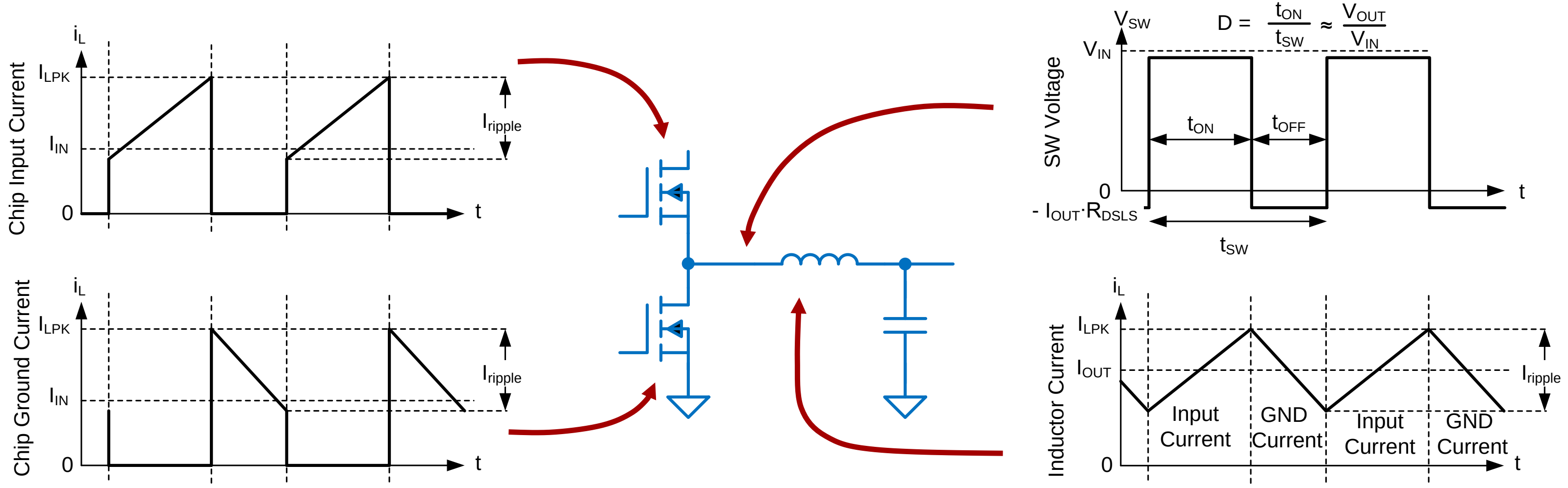
1. **Differential mode noise, typically the result of line noise from the input of a buck. The return path of this input noise is the ground wire.**



2. **Common mode noise, typically the result of noise coupled off the SW node of a Buck. The return path of this input noise is over the conductive table.**



Source of input differential noise for Bucks



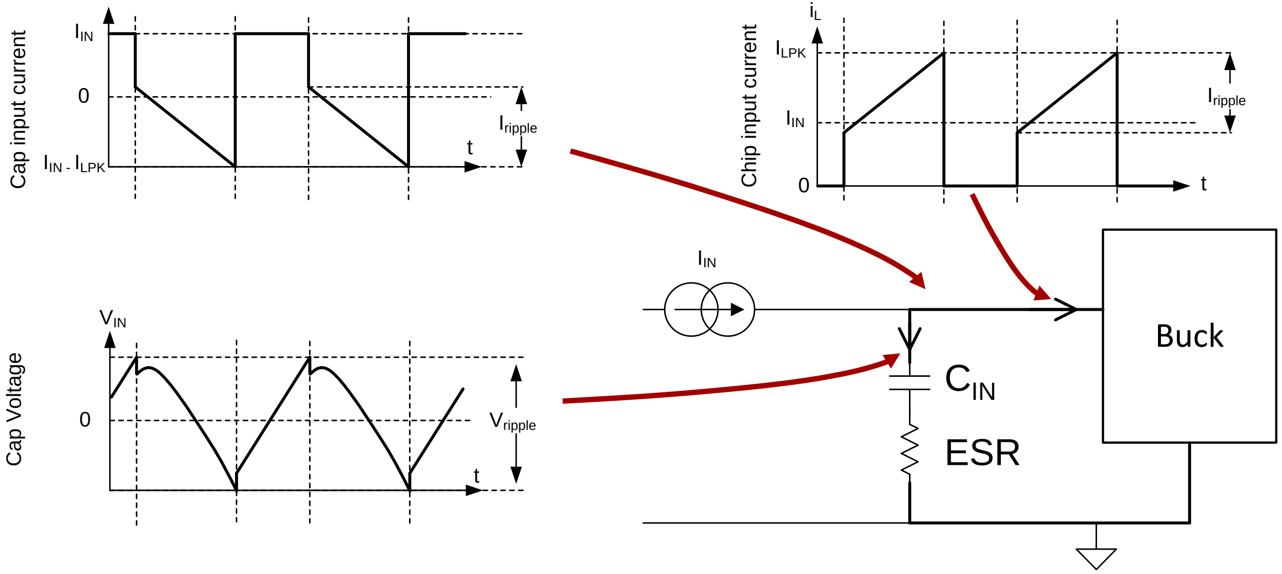
1. **The only assumption for this model is that the converter is a Buck**
2. **Note: High frequency details covered in section "waveform shaping"**
3. **Chip input can be seen as a current waveform source**
   a. **Inductor has high impedance at relevant frequencies**
   b. **SW node voltage swing is much larger, typically approximately factor of 1000x, than input or output ripple. As a result, input and output ripple have little effect on input current.**

The buck converter can be modelled as a current waveform source.

Source of input differential noise for Bucks

Input ripple, ignoring spikes, is typically is typically 10 mV to 100 mV.

1. **Note: Current spikes during switching combined with input ESL greatly increase high frequency noise in a typical system.**



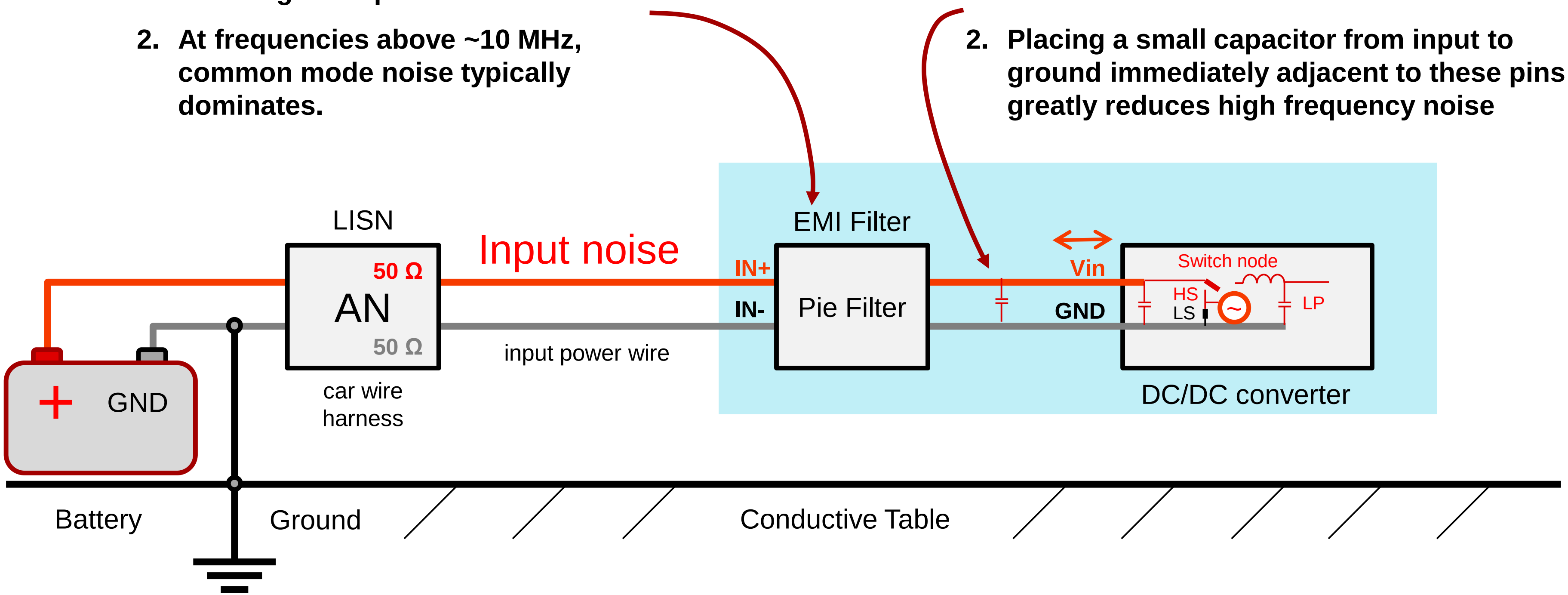
$$V_{ripple} = I_{LPK} \cdot ESR + \cdot \frac{I_{IN}}{C_{IN}} \cdot \frac{1-D}{f_{SW}} \; if \; I_{IN} > 2 \cdot I_{ripple}$$

2. **For a 2.1 MHz Buck converting 13.5 V to 5 V producing 3 A and having 0.75 A of inductor ripple while using input 10 µF capacitor with 4 mΩ ESR will have 48 mV of input ripple. This ripple will cause this Buck to fail EMI without filter.**

Reduction of conducted input differential noise

1. A filter such as a pie filter can prevent DC/DC input ripple from reaching the input cable
2. At frequencies above ~10 MHz, common mode noise typically dominates.

1. More bypassing of the input of the power supply reduces disturbances originating in the DC/DC
2. Placing a small capacitor from input to ground immediately adjacent to these pins greatly reduces high frequency noise



2. Calculating needed filter performance

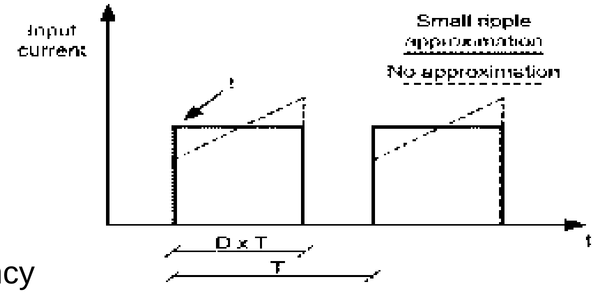
- **Method 1 – Estimation using oscilloscope measurement**
  - Measure the input ripple voltage using a wide bandwidth scope and calculate the attenuation.

$$|Att|_{dB} = 20 \times \log\left(\frac{VinRipple_{pk-pk}}{1\mu V}\right) - V_{MAX}$$

  - V_{MAX} is the allowed dBµV noise level for the particular EMI standard.

- **Method 2 – Estimation using the first harmonic = fundamental of input current**
  - Assume the input current is a square wave (small ripple approximation)

$$|Att|_{dB} = 20\log\left(\frac{\frac{I}{\pi^2 f_s C_{IN}}\sin(\pi D)}{1\,\mu V}\right) - V_{max}$$

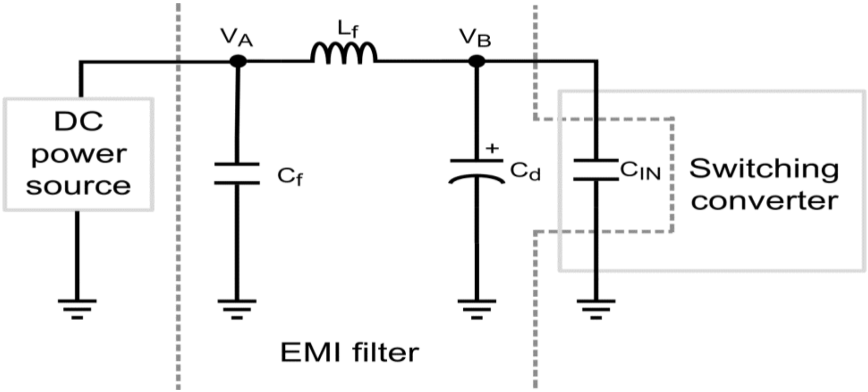


  - V_{max} is the allowed dBµV noise level for the particular EMI standard.
  - C_{IN} is the existing input capacitor of the Buck converter.
  - D is the duty cycle , I is the output current, f_s is the switching frequency

2. Filter design

Follow the design steps described in AN-2162.

- Calculate the required attenuation.
  Use method 1 or method 2.
- Capacitor $\mathbf{C_{IN}}$ represents the existing capacitor at the input of the switching converter.
- Inductor $\mathbf{L_f}$ is usually between 1μH and 10μH, but can be smaller to reduce losses if this is a high current design.



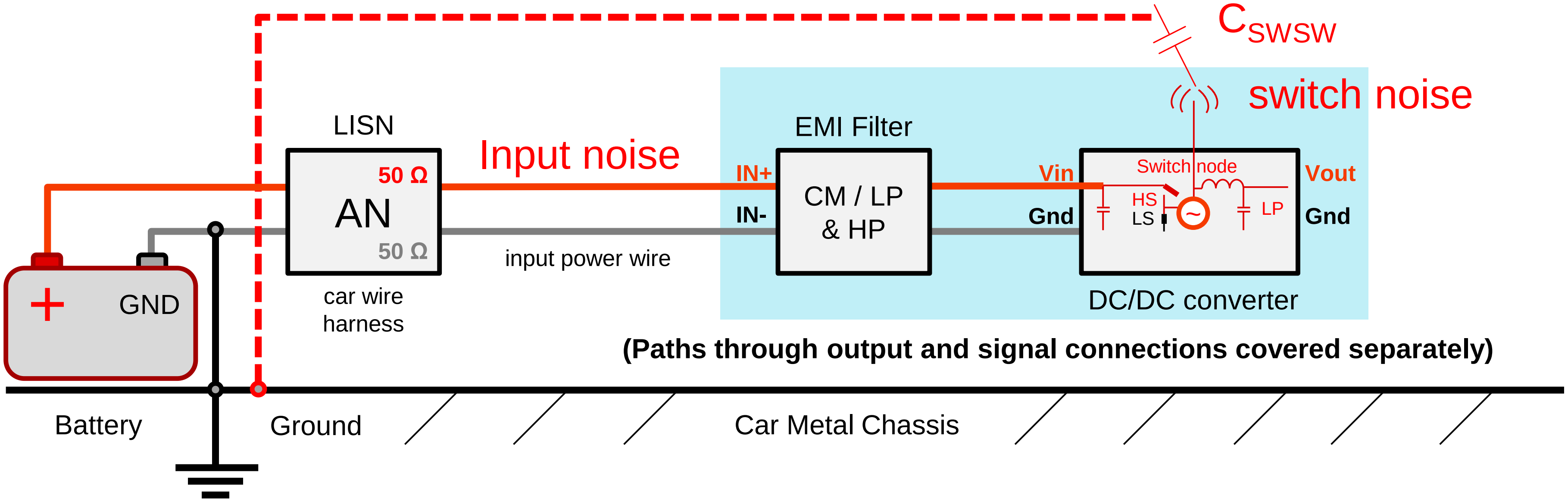
- Calculate capacitor **Cf**. Use the larger of the two values (C_{fa} and C_{fb}) below:

$$C_{fa} = \frac{C_{IN}}{C_{IN}L_f(2\pi f_s/10)^2 - 1} \qquad C_{fb} = \frac{1}{L_f}\left(\frac{10^{|Att|_{dB}/40}}{2\pi f_s}\right)^2$$

- Capacitor **Cd** and its ESR provides damping so that the Lf Cf filter does not affect the stability of the switching converter.

2. Common mode EMI noise

1. **Equivalent circuit for common mode loop is C_{SWSW} in series with 25 Ω**
2. **Both input voltage side and ground side of the LISN are in parallel**
3. **C_{SWSW} is the self capacitance of the SW node = total capacitance less all capacitance between SW and nodes on the system side of the LISN**



(Paths through output and signal connections covered separately)

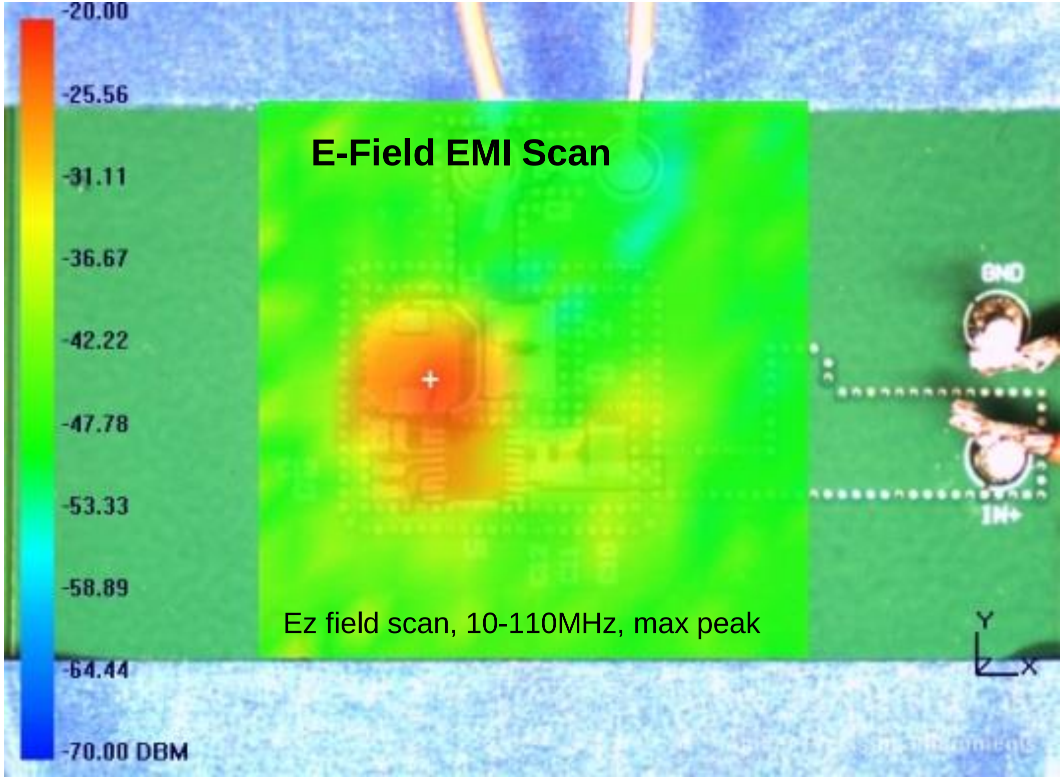
1. E-Field scanning of automotive 2.1MHz 3A Buck

PMP10628: LM53603

XYZ E-Field Scanning:
Shows EMI around the power IC, the external components and PCB traces.

Advantages and Use:

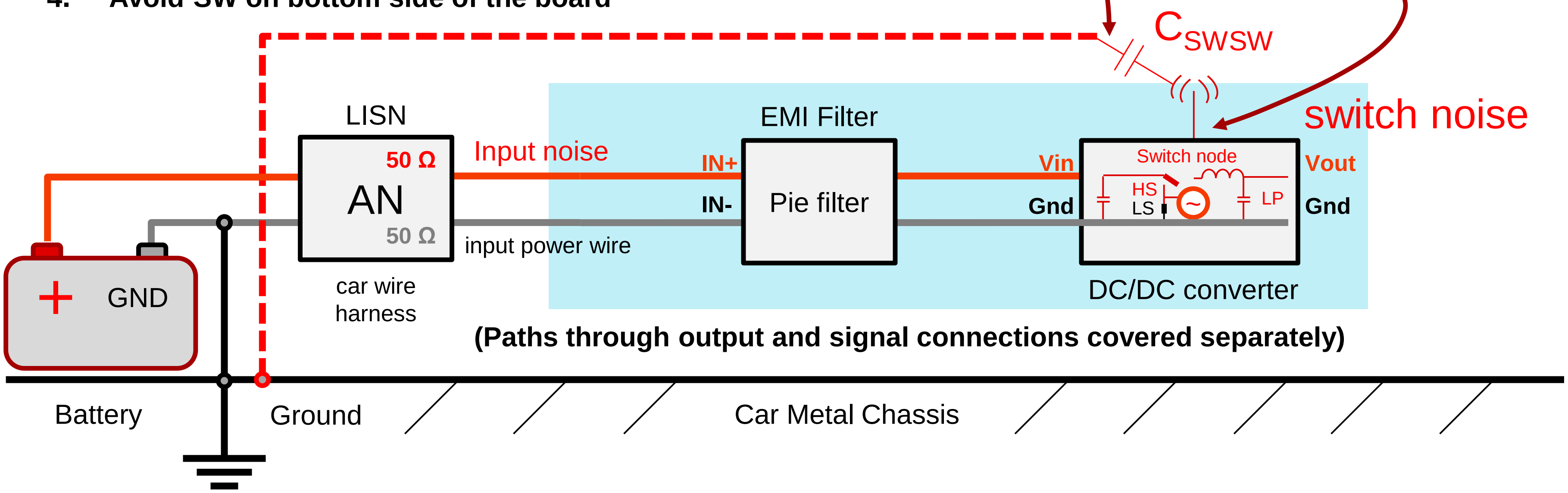
✓ Repeatable xyz Spectrum
1. Shows effect on optimization
2. Identify root causes



2. Reduction of common mode noise

1. Reduce C_{SWSW} by reducing SW node size on PCB
2. Reduce size of inductor and connect pin 1 (side with dot) to SW. Some inductors internally shield electric fields better than others
3. Avoid routing SW node on back of board
4. Avoid SW on bottom side of the board

1. Waveform shaping can reduce SW mode noise at its source
2. Switching frequency selection low frequency = lower RF noise

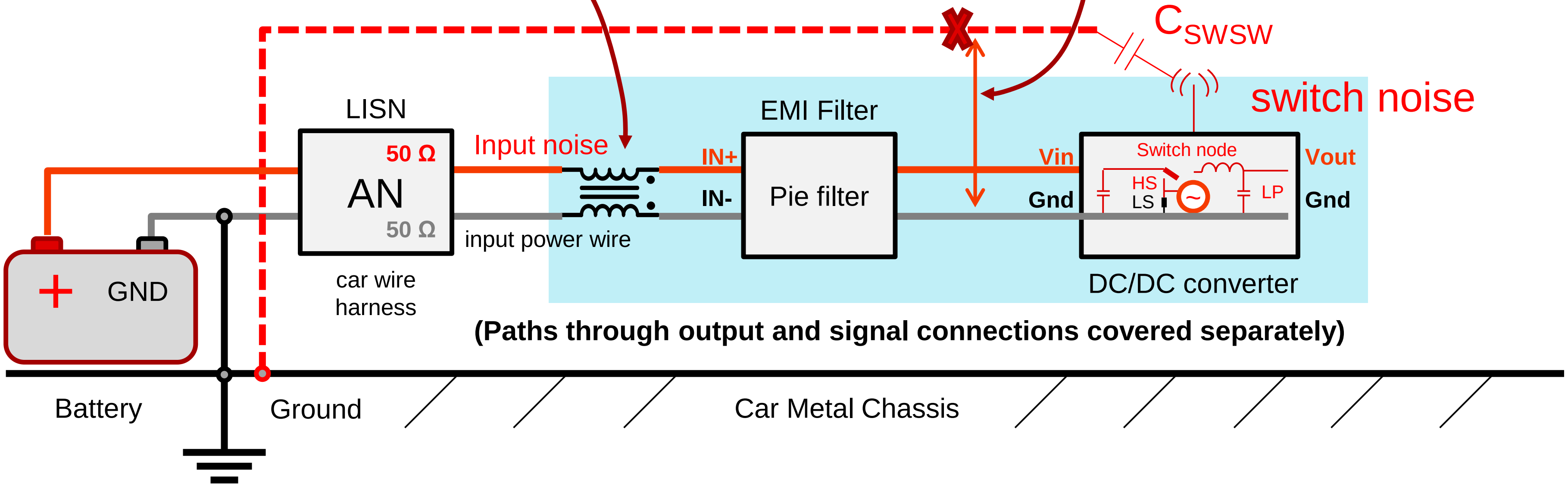


(Paths through output and signal connections covered separately)

2. Reduction of common mode noise

1. **Interrupt circuit by installing a shield connected to ground on system side of the filter**
2. **Tall components near SW can act as a partial shield**

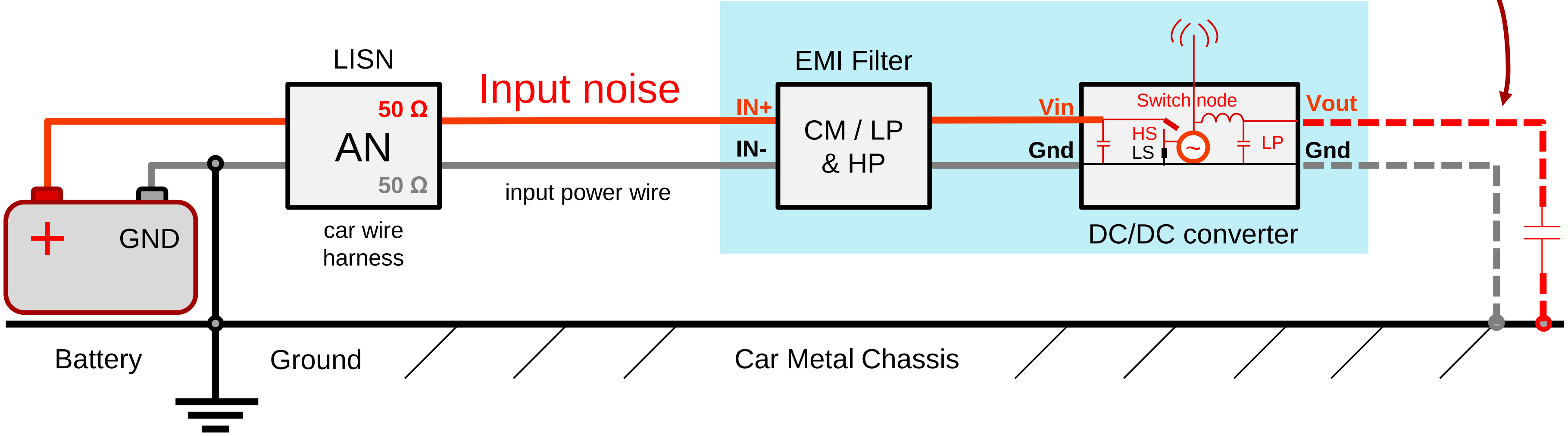
Common mode choke can break common mode circuit



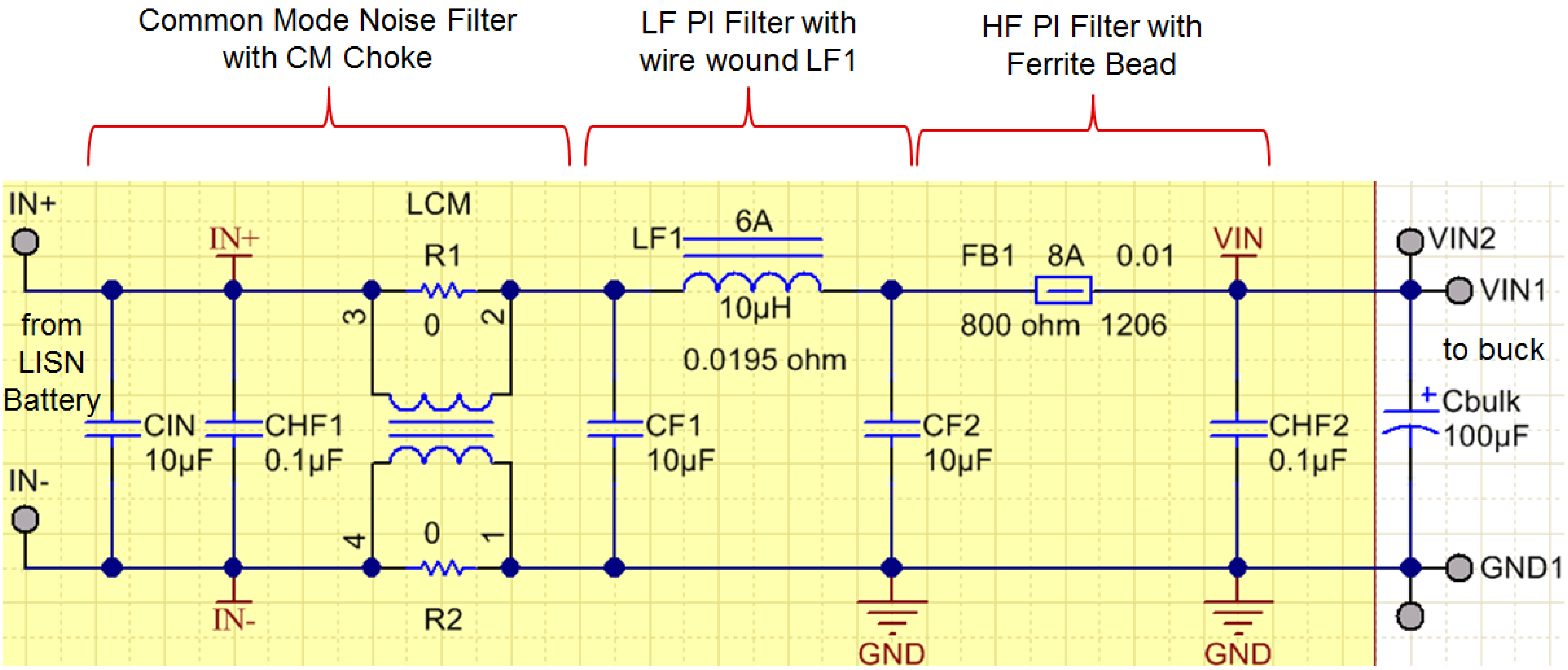
(Paths through output and signal connections covered separately)

2. Common mode EMI noise, other outputs

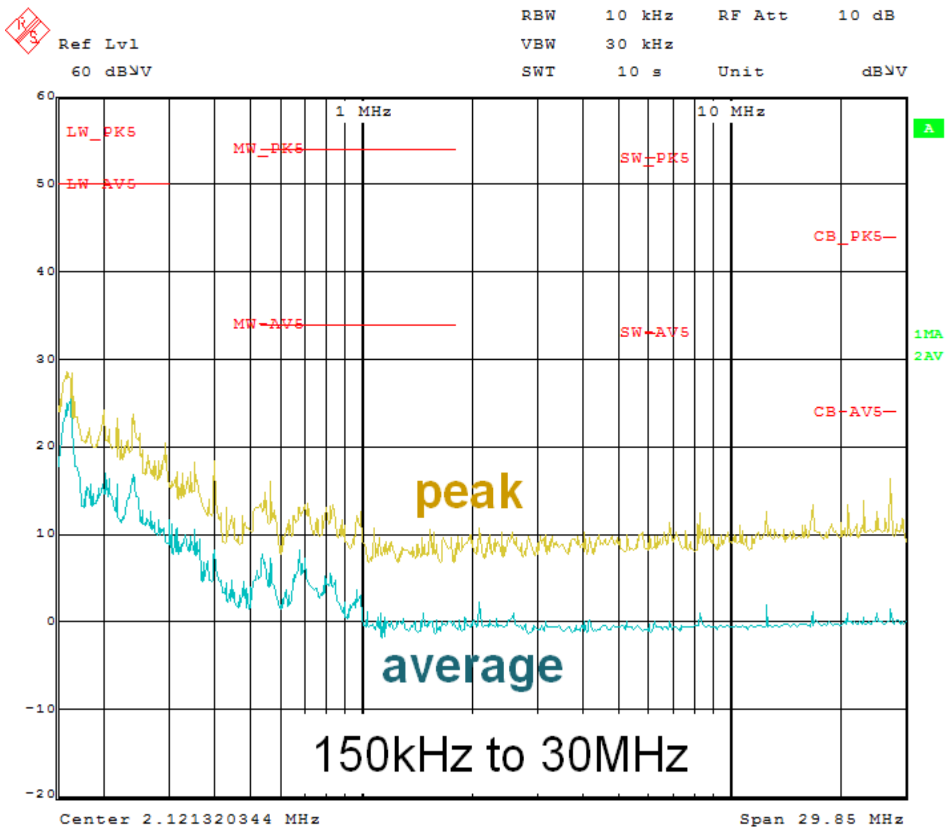
1. **External load capacitance can couple to ground external to the system creating a common mode circuit**
2. **If external load ground connections is not close to input ground, ground plane currents can generate ground noise which is seen as common mode noise on the input**
3. **Signal connections act the same way**

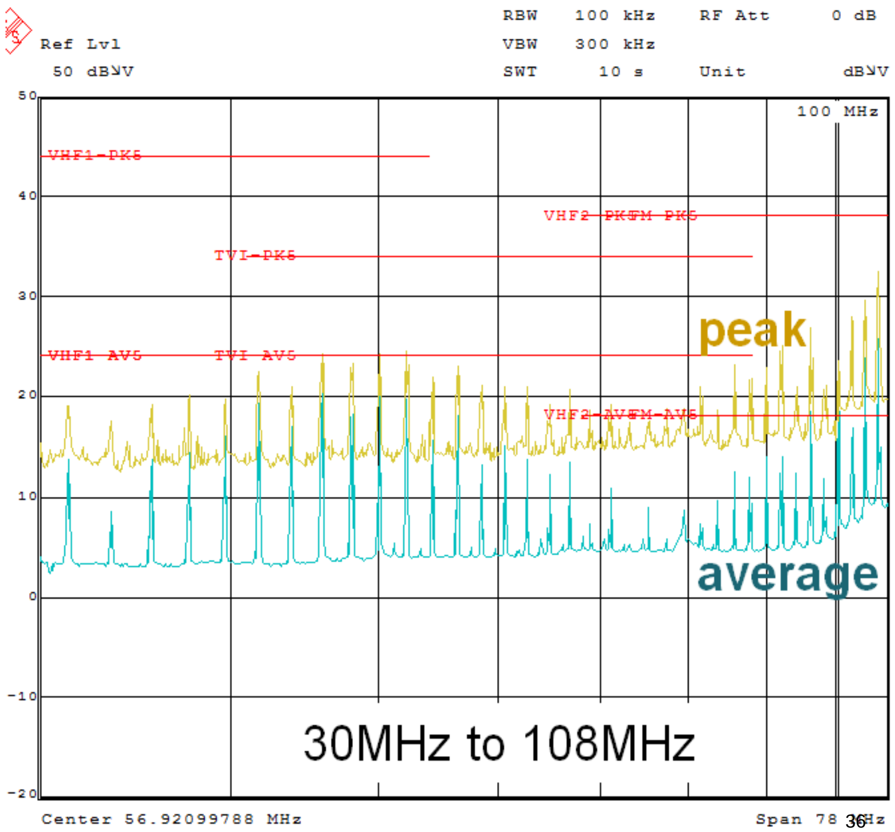


Typical 3-stage EMI filter

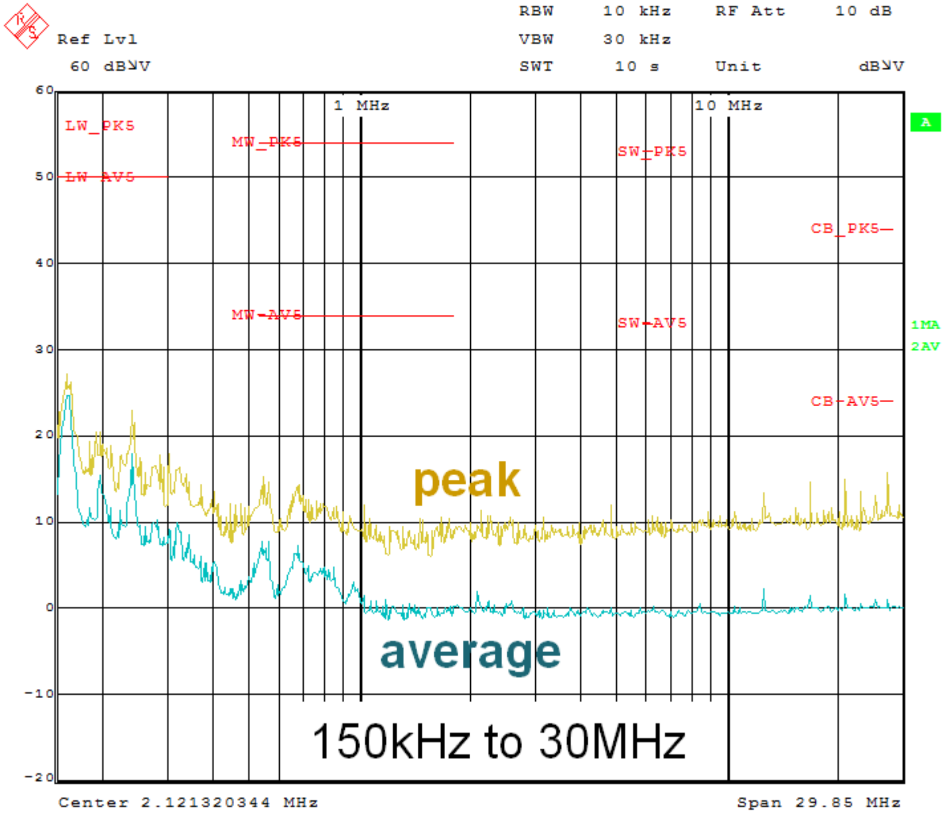


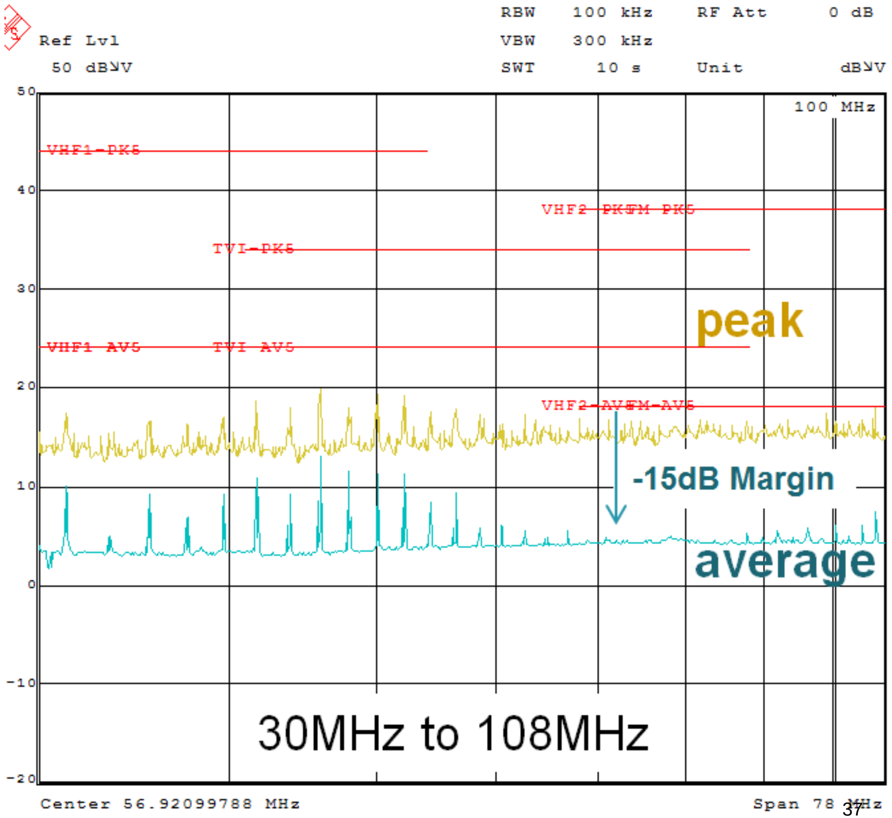
2.1MHz 3A Buck LM53603 – with 2-stage filter



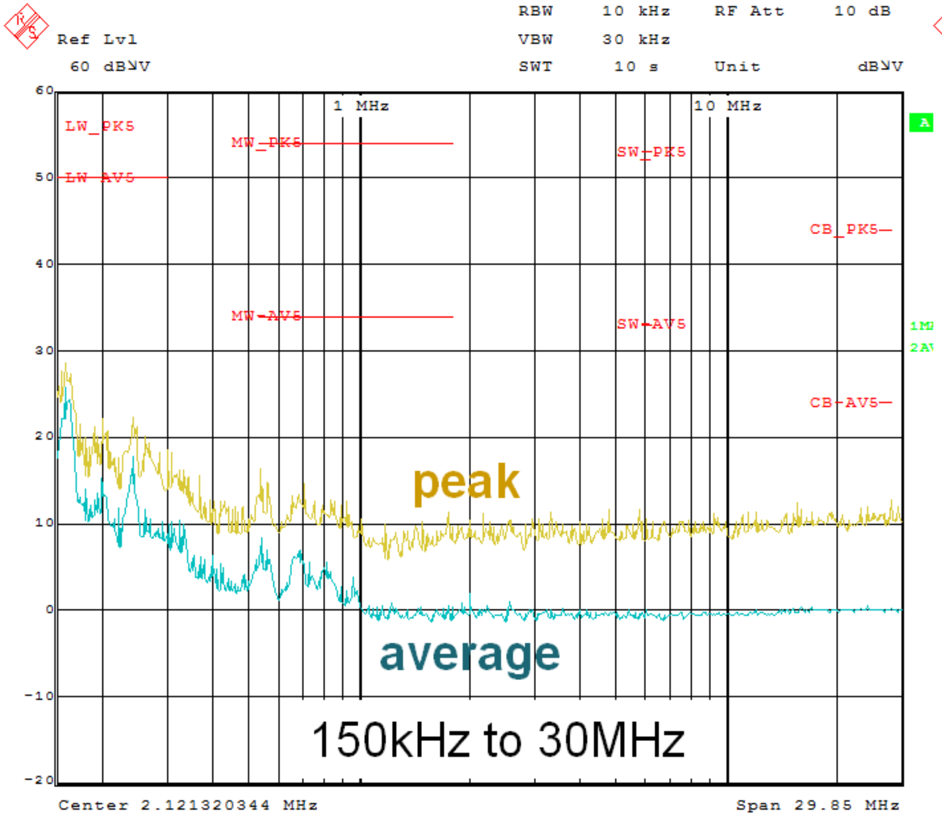


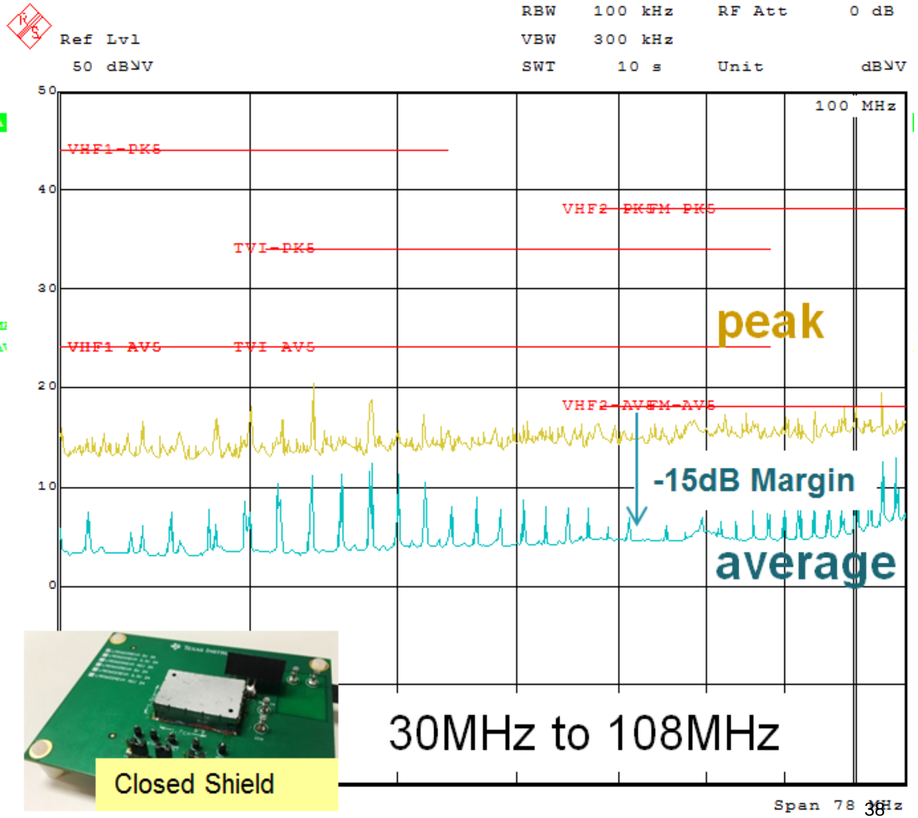
2.1MHz 3A Buck LM53603 – with 3-stage filter CM



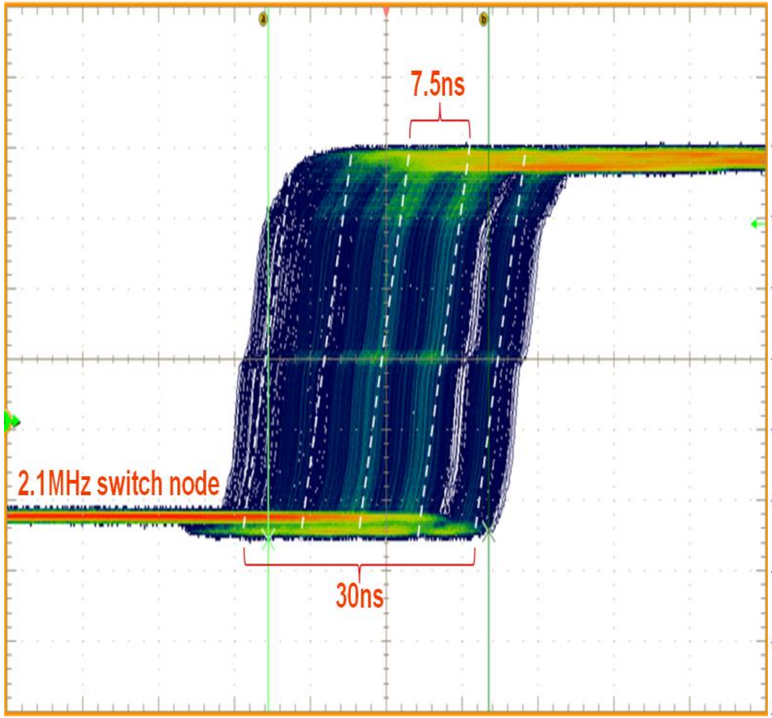


2.1MHz 3A Buck with 2-stage filter + shield

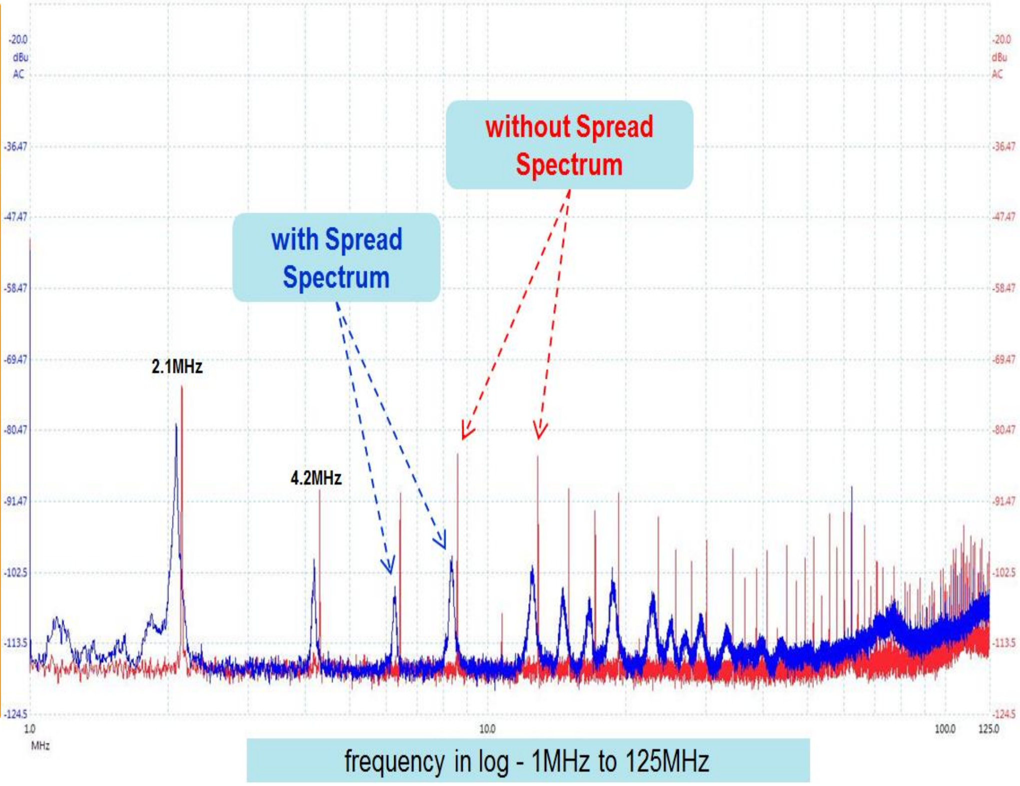




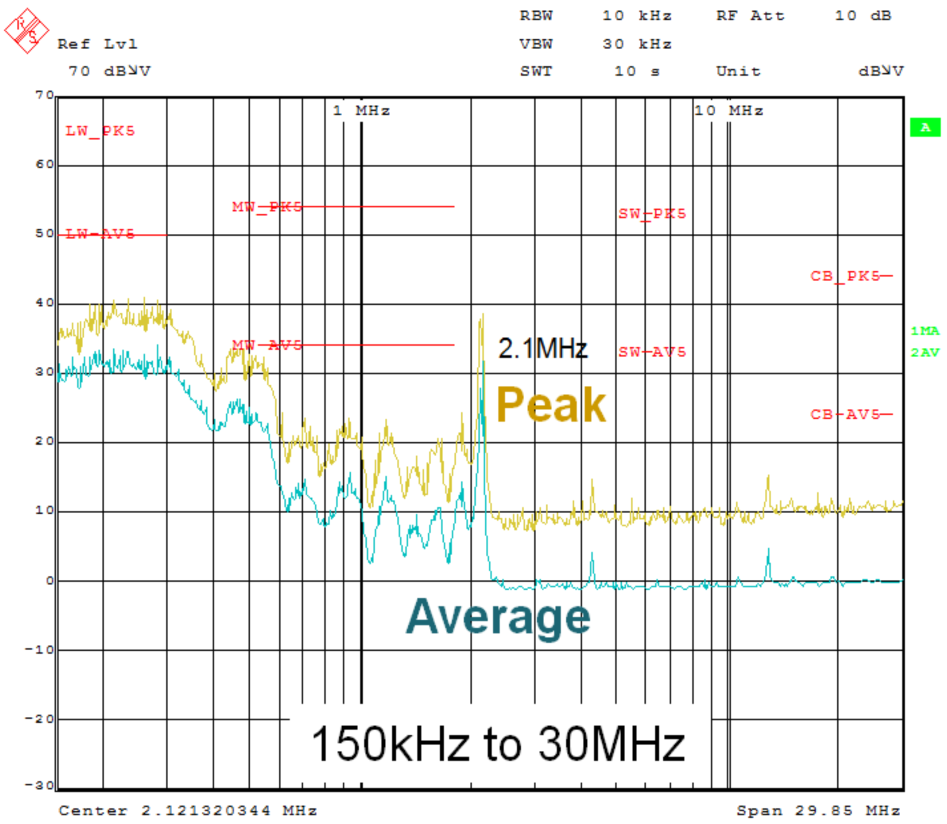
Pseudo random spread spectrum

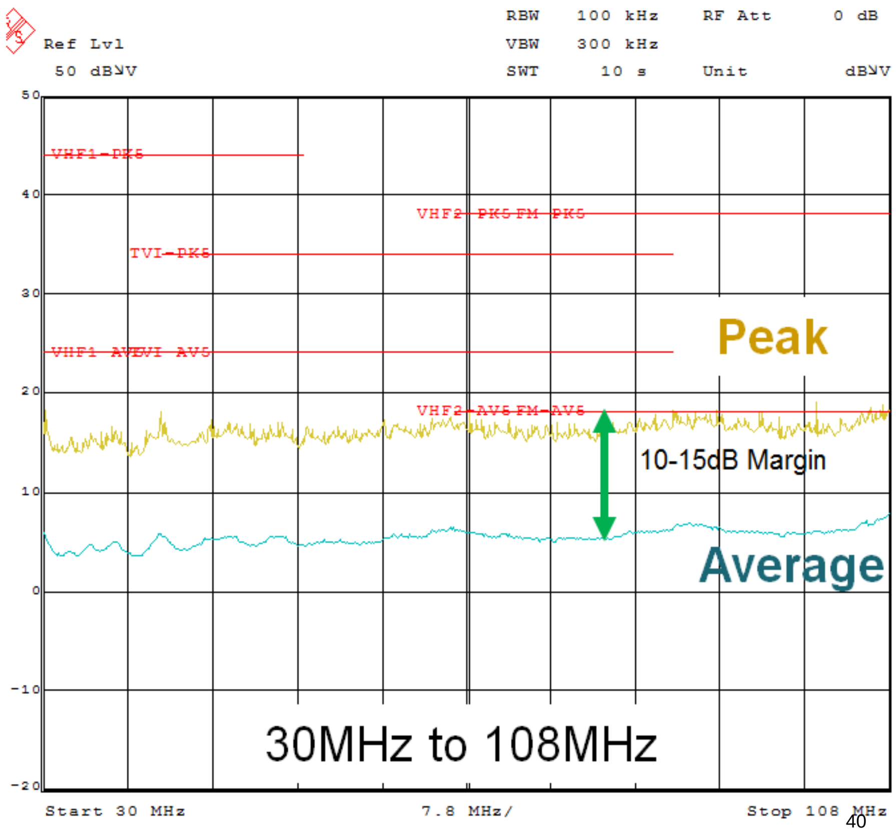


Oscilloscope time domain 10ns per div

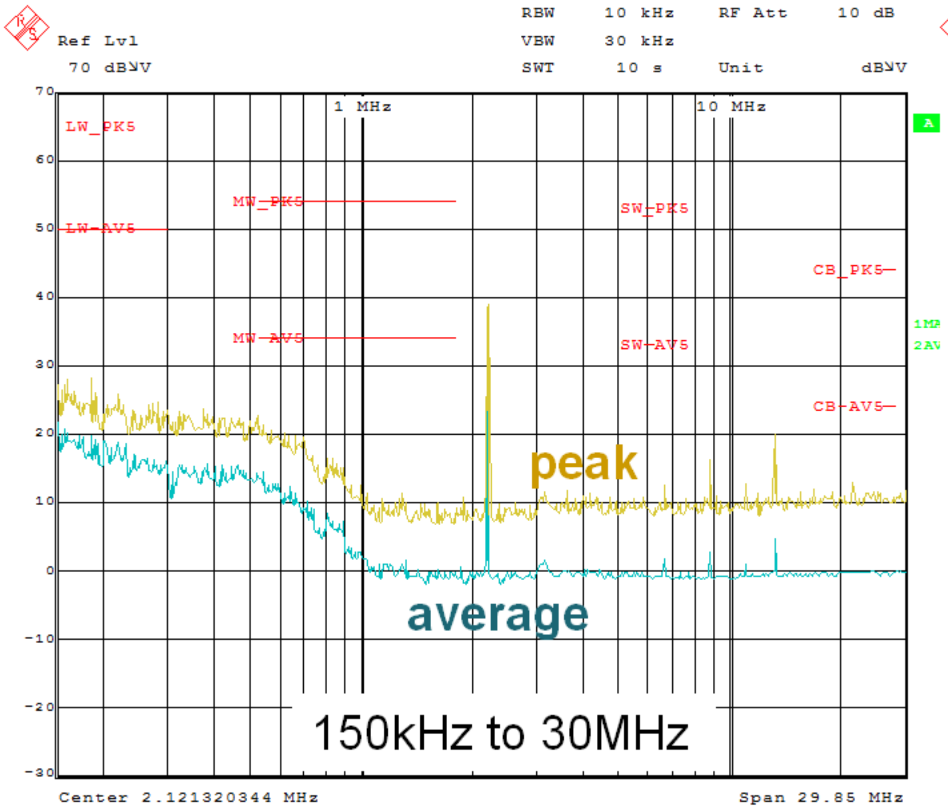


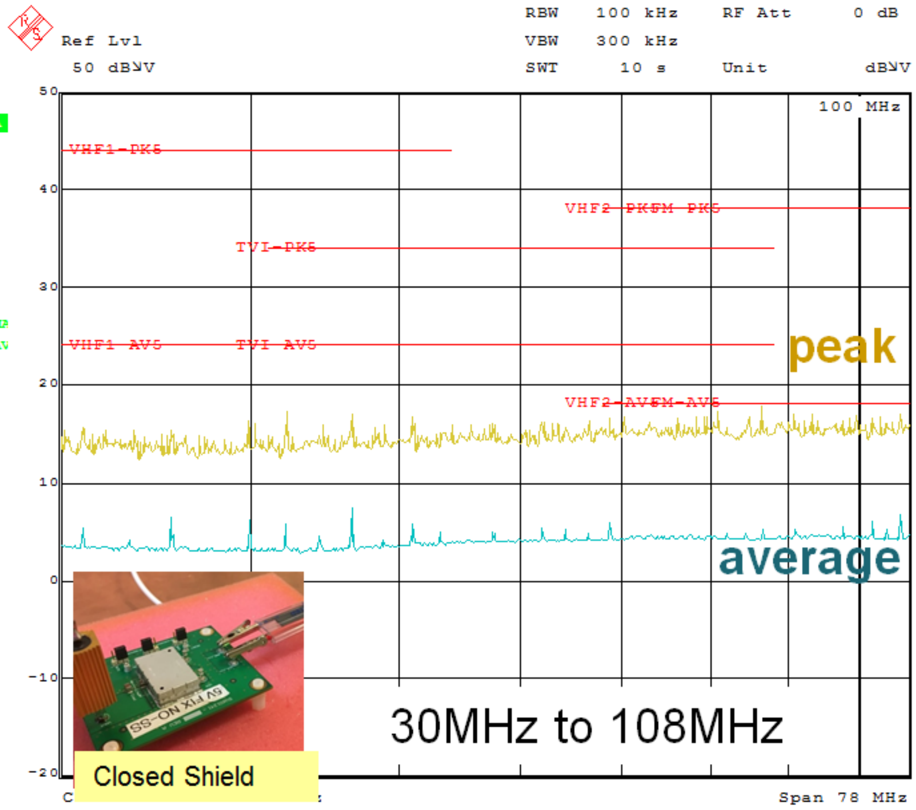
1A 2.1MHz Buck – with spread spectrum + FB filter





1A 2.1MHz Buck LM53601 – with E-Field shielding





EMI shielding of 42Vin/3A Buck module LMZ14203

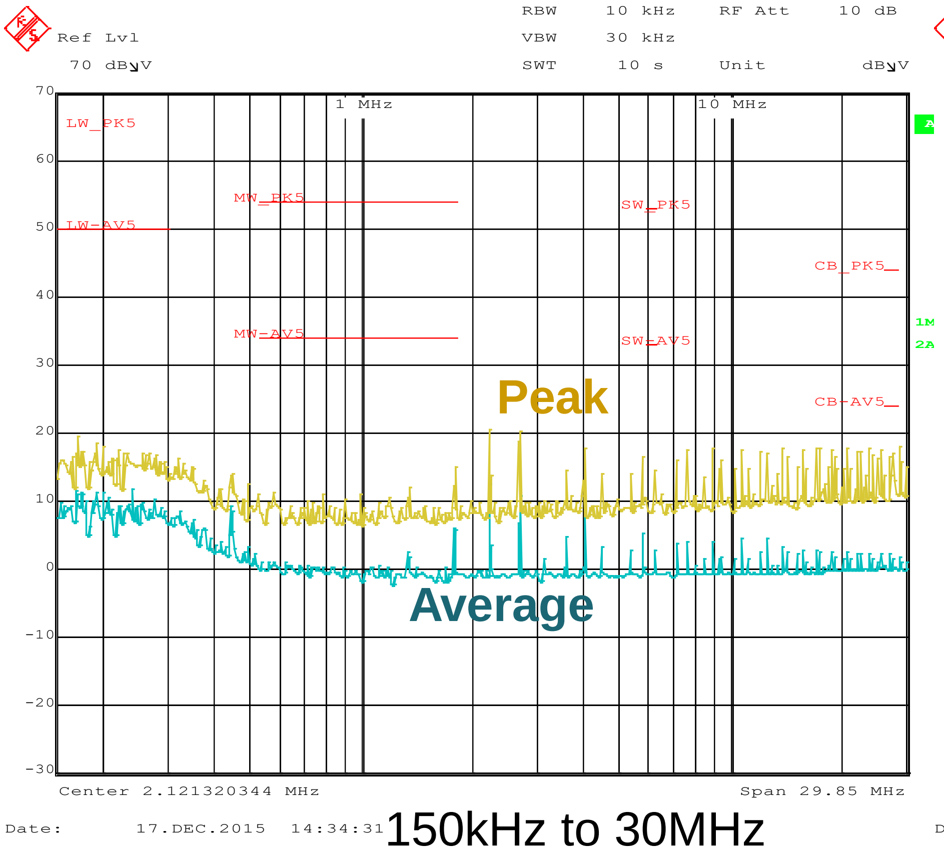
Pi-EMI Filter

LMZ14203TZ with EMI Filter

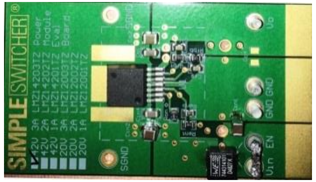
+ Metal Frame soldered to GND

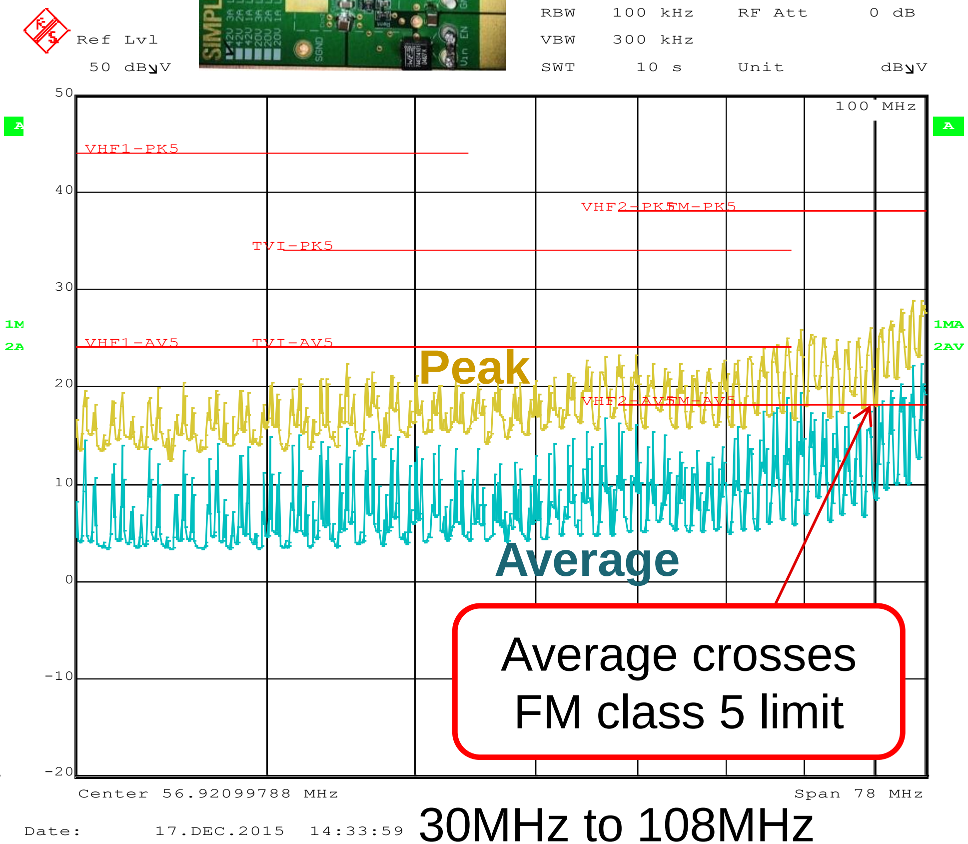
+ closed Metal Lid for full shielding

LMZ14203TZ – off the shelf



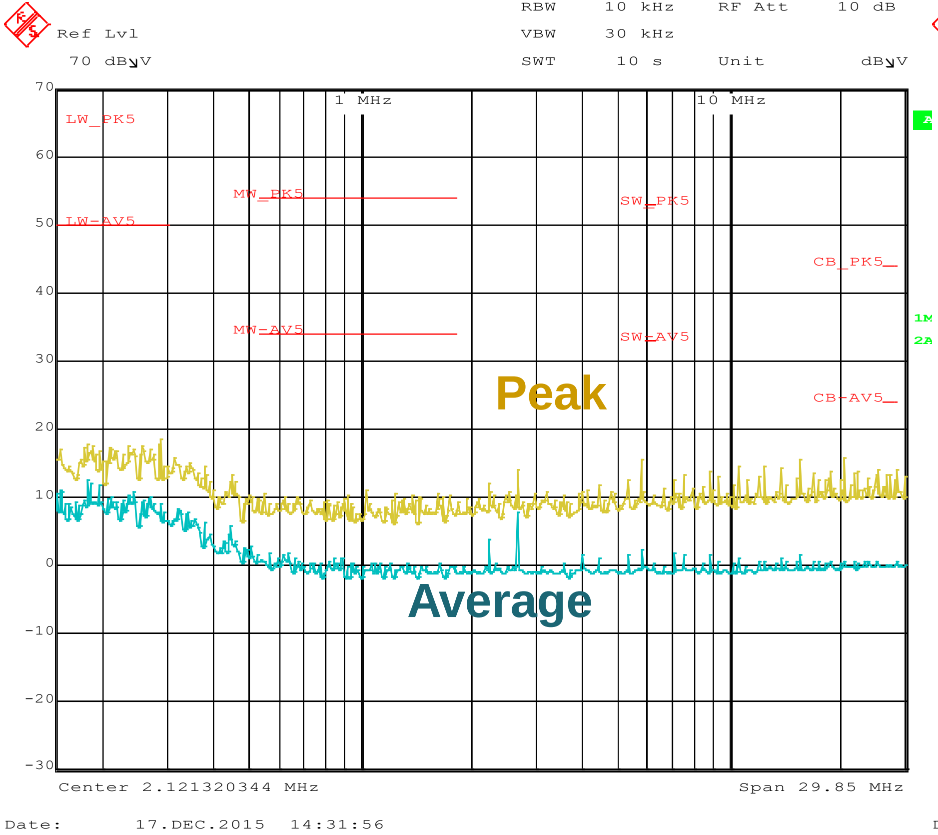
150kHz to 30MHz

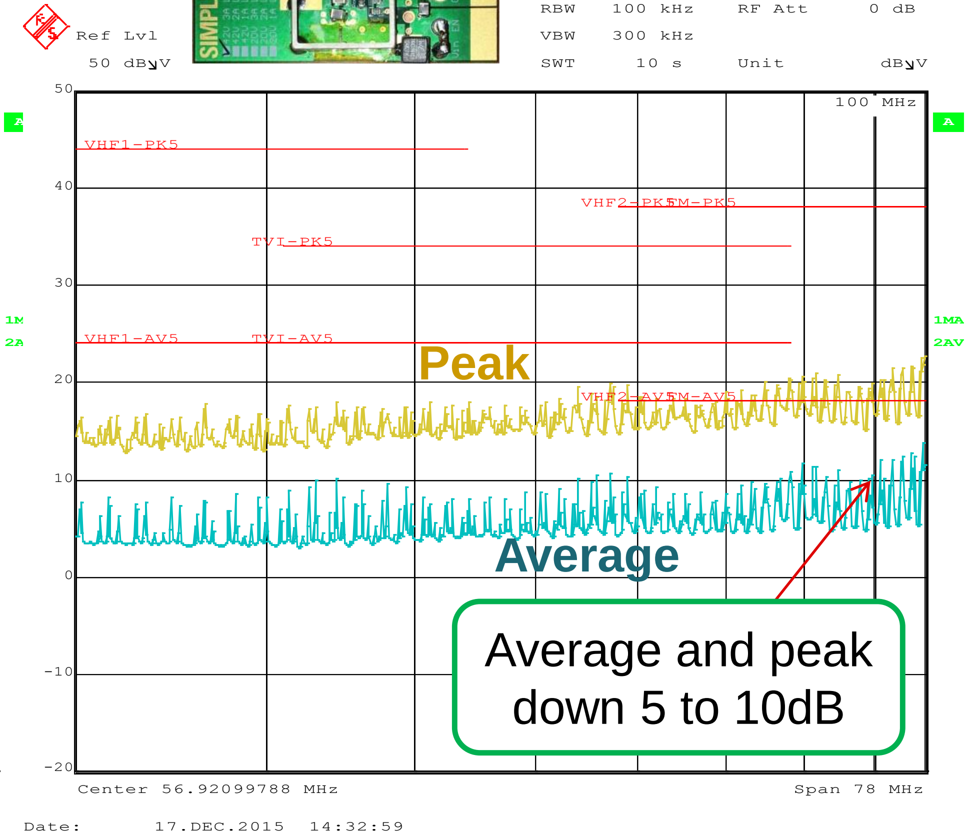




30MHz to 108MHz

LMZ14203TZ + metal frame





LMZ14203TZ + closed lid