Wyatt Technical Services, LLC

EMC Seminars & Design

Characterizing, Troubleshooting & Mitigating Wireless and IoT Self-Generated EMI

Presented by: Kenneth Wyatt

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Presenter Bio

Kenneth Wyatt is principal consultant of Wyatt Technical Services LLC and served three years as the senior technical editor for *Interference Technology Magazine* from 2016 through 2018. He has worked in the field of EMC engineering for over 30 years with a specialty is EMI troubleshooting and pre-compliance testing. He is a co-author of the popular *EMC Pocket Guide* and *RFI Radio Frequency Interference Pocket Guide*. He also coauthored the book with Patrick André, *EMI Troubleshooting Cookbook for Product Designers*, with foreword by Henry Ott. Recently, he published the first of three affordable volumes on EMC troubleshooting; *Creating Your Own EMC Troubleshooting Kit (Volume 1)*.

He is widely published and authors *The EMC Blog* hosted by EDN.com and continues to blog for *Interference Technology*. Ken is a senior member of the IEEE and a longtime member of the EMC Society. To contact Ken or for more information on technical articles, training schedules and links, check out his web site: http://www.emc-seminars.com.

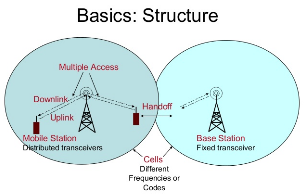
Why do we have self-generated EMI?

Platform interference – self-interference to on-board wireless devices from on-board narrowband and broadband energy sources:

- DC-DC converters
- Clocks
- Bus noise

DC-DC converters have become a dominant EMI source contaminating sensitive cellular LTE, GPS and other wireless devices using frequencies below 1.5 GHz.

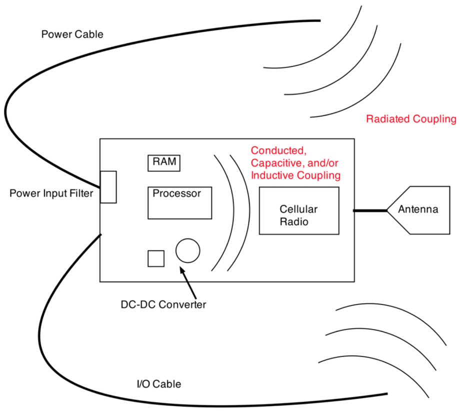
Total isotropic sensitivity (TIS)



Cellular and wireless providers require a certain receiver sensitivity (Total Isotropic Sensitivity) before a device may be used on their system.

On-board, or self-generated EMI can ”desense” receivers in the cellular module to the point where the TIS test fails. *Minimum TIS is generally about -99 dBm*, which also depends on antenna efficiency and whether the device operating in hand or near head.

Common coupling paths for IoT devices

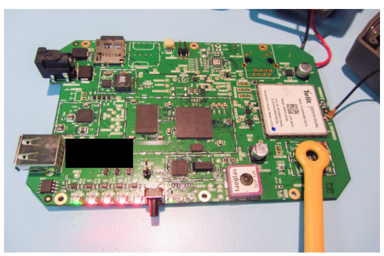


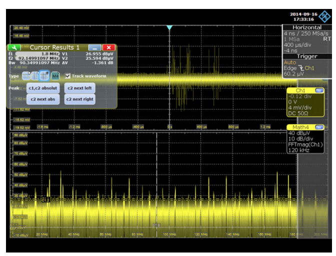
Characterizing self-generated EMI

Ken's three-step process

1. Use near field probes to identify energy sources and harmonics
2. Use current probes to identify harmonic currents on cables
3. Set up a nearby antenna to identify actual emissions from EUT

STEP 1 - Use near field probes to identify energy sources

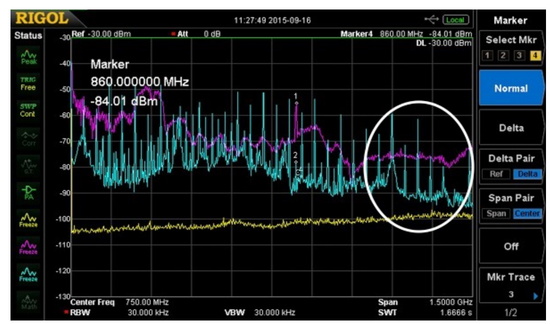




Identify and characterize the emission profile for each source (DC-DC converters, processors, memory, clocks).

http://www.edn.com/electronics-blogs/the-emc-blog/4414975/Identifying-emission-sources-and-propagating-structures

Step 1 - Start with a wide frequency span

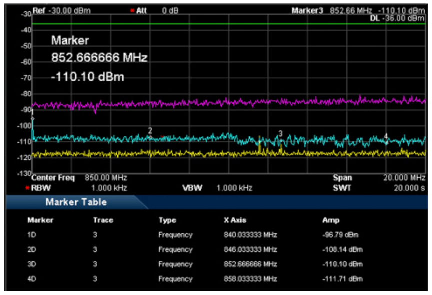


Broadband from DC-DC converter (violet)

Narrow band from Ethernet clock (aqua)

This will help characterize the overall EMI spectrum. Does the energy source being measured produce EMI up into the wireless bands?

Step 1 - Then, narrow the span to the downlink

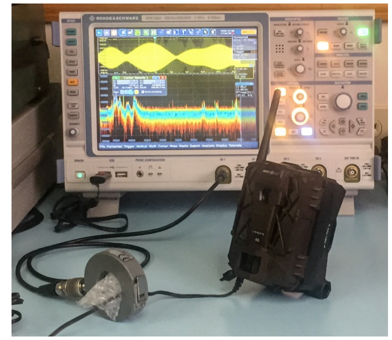


25 dB above the noise floor!

Example: AT&T's Band 5 downlink EMI (840 – 860 MHz)

The spectral plot of AT&T's cellular LTE Band 5 downlink from 840 to 860 MHz. The violet and aqua traces are from two different DC-DC converters running at 3 MHz. The yellow trace is the ambient noise floor. There's enough potential noise coupling to the wireless module to fail the TIS compliance test.

STEP 2 – Use current probes to characterize cables



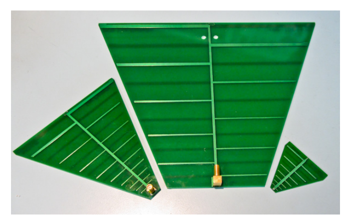
Use a current probe to measure common mode currents on cables.

More info: http://www.interferencetechnology.com/the-hf-current-probe-theory-and-application/

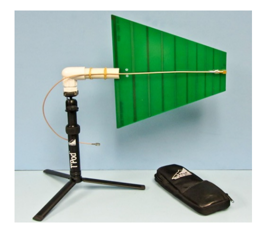
STEP 3 – Use simple antennas to check emissions

Test setup in a conference room. If there is too much cellular interference from outside sources, you may need to move into a shielded room. You may need to move the antenna closer to the EUT.

PC board antennas from Kent Electronics



PC board log periodic antennas (ranging from 400 MHz to 11 GHz shown). Approximate gain is 6 dB and AF ranges from 18 to 25 dB. Available from www.wa5vjb.com/. Cost ranges from \$8 to \$30.



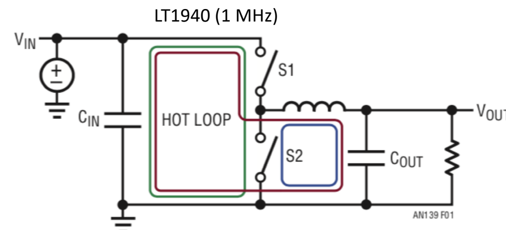
400 to 1000 MHz LP antenna on DIY mount and table-top tripod (\$40).

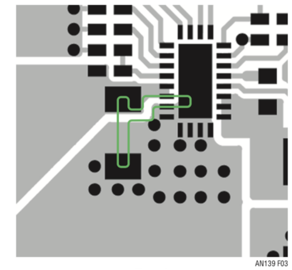
http://www.edn.com/electronics-blogs/the-emc-blog/4403451/PC-board-log-periodic-antennas

Why do DC-DC converters "suck" for EMI?

- The new on-board DC-DC converters are switching at 1 to 3 MHz and use very fast edge speeds for best efficiency.
- This can create a very broadband EMI up past 1.5 GHz, which tends to couple into wireless, cellular and GPS receivers, decreasing their sensitivity.

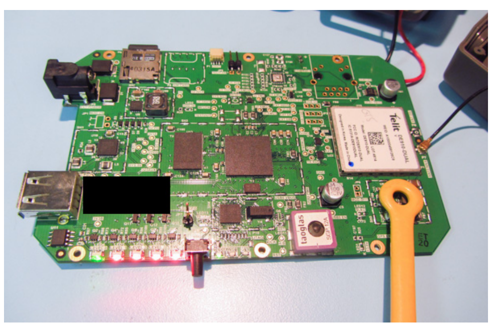
Example: DC-DC buck converter





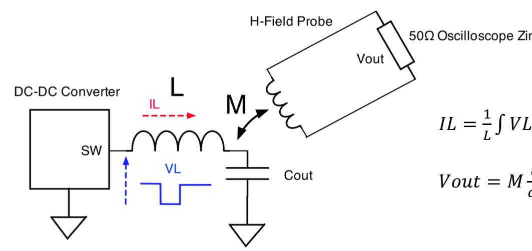
- On cycle: S1 closed, S2 open. AC current flows in the red loop.
- Off cycle: S1 open, S2 closed. AC current flows in the blue loop.
- Fully-switched AC current is the green loop ("hot" loop). Need to minimize the loop areas.

Non-invasive probing of DC-DC converters



The characteristics of the DC-DC converter switching can be measured non-invasively by coupling the H-field probe to the switched inductor.

Non-invasive probing of DC-DC converters



$$IL = \frac{1}{L}\int VL * dt$$

$$Vout = M\frac{d}{dt}\frac{1}{L}\int VL * dt = \frac{M}{L}VL$$

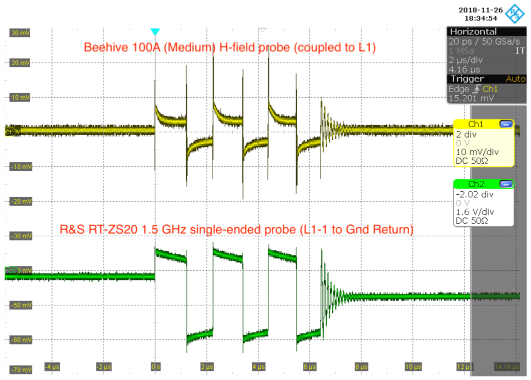
$$Vout \propto VL$$

Vout from the probe is proportional to VL across the switch inductor.

Non-invasive probing of DC-DC converters

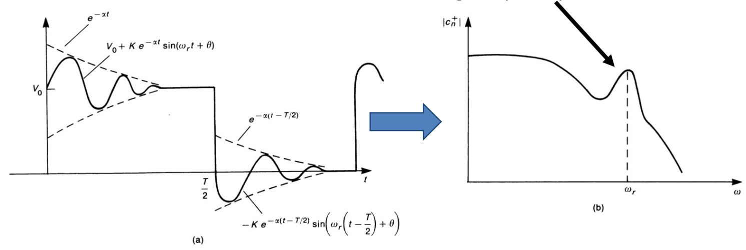
Near field probe

Oscilloscope probe



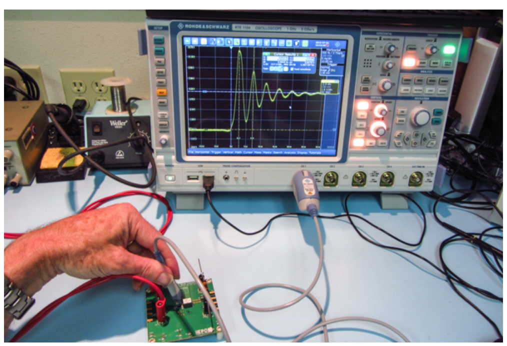
Effect of ringing

Ring frequency



Ringing on a switched waveform will cause a resonance in the spectral emissions.

Measuring SMPS ringing

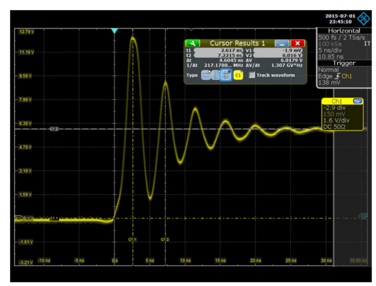


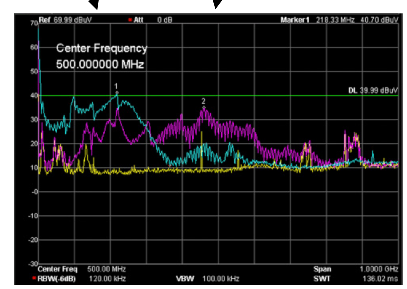
A Rohde & Schwarz RTE 1104 oscilloscope and RT-ZS20 (1.5 GHz) HF probe was used. An H-field probe held close to the switching inductor may also be used.

Effect of ringing

Ring frequency

Second harmonic





1 MHz GaN switcher with 300-500 ps rise time and a 217 MHz ring frequency creates broadband EMI as high as 800 MHz with peaks at 217 and 434 MHz as measured with Fischer F-33-1 current probe.

Yellow = ambient measurement, Aqua=input current, Violet=load current.

Ten Tips for reducing DC-DC converter EMI

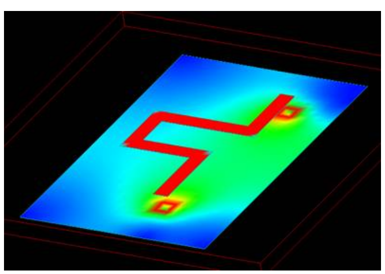
Tip 1 - Above all else, get the PC board LAYOUT and STACK-UP correct!

1. Every signal trace needs an adjacent return plane (or trace)
2. Every power trace (or plane) needs an adjacent return path
3. This includes return paths up/down through layers
    - Ground vias
    - Stitching capacitors

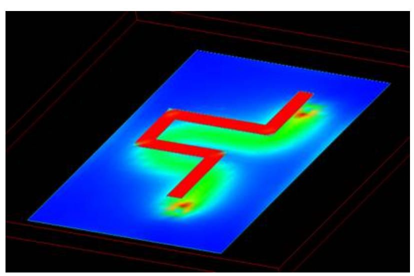
This will dictate the stack-up design!

PCB Design Series for low EMI: https://www.edn.com/design-pcbs-for-emi-part-1-how-signals-move/

Tip 1 – Return current simulation



Frequency = 1 kHz



Frequency = 1 MHz

Source: Keysight Technologies

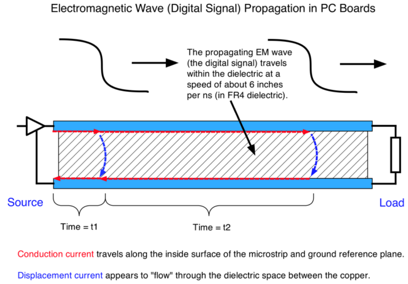
Tip 1 – Circuits versus fields point of view

Circuits point of view:
Signals and power require a *Return Path* back to source.

Fields point of view:
Signal and power transients propagate as *Fields* and travel in the *Dielectric* at near light speed, while the conduction/displacement currents simultaneously flow back to the source at ~1 cm/s.

The signal energy is in the fields, not the copper!

Tip 1 – How signals propagate

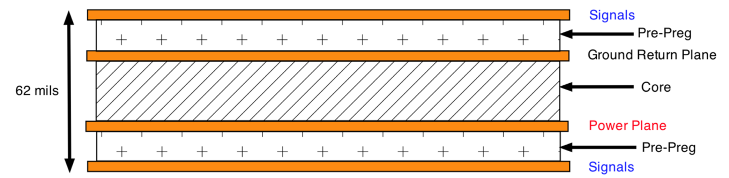


Signal propagation is NOT through the flow of electrons in copper!

The conduction and displacement current is electron flow, but at ~1 cm/s.

The wave-front moves through the dielectric at about 6 in/ns in FR4.

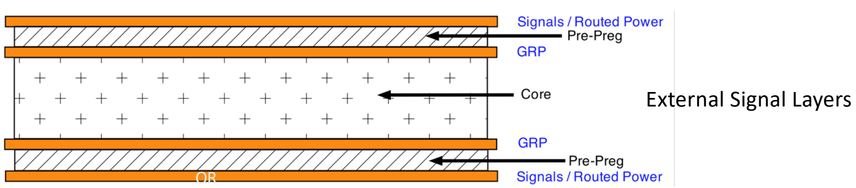
Tip 1 – "Classic" four-layer board stack-up



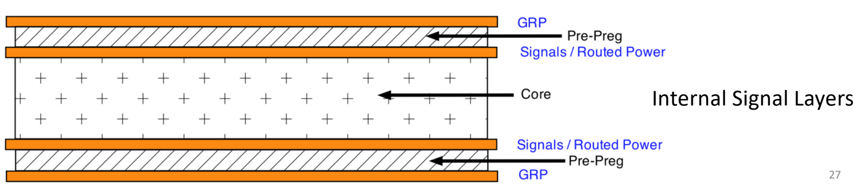
This common stack-up is a VERY HIGH EMI RISK for wireless products!

- Power and ground return plane are too far separated for good high frequency decoupling (typ. 30 – 40 mils). Needs to be 2-3 mils, max, for wireless applications.
- Signals on layer 4 are referenced to power, rather than signal return. This is OK, <u>if and only if</u>, the power and return planes are <u>tightly-coupled</u> together and with adequate decoupling capacitors. I still don't recommend it for wireless applications!

Tip 1 – Examples of good four-layer stack-ups

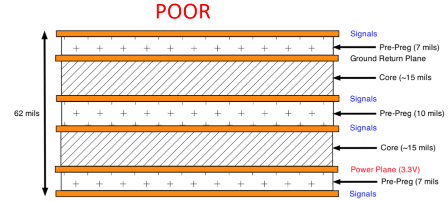


OR



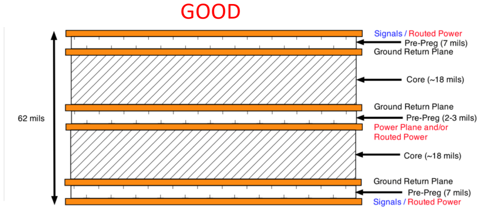
Tip 1 – Six-layer stack-ups

POOR



- *Very common* stack-up
- Signal referenced to power!
- Power and return plane too far separated!
- Power transients couple to inner signal layers!

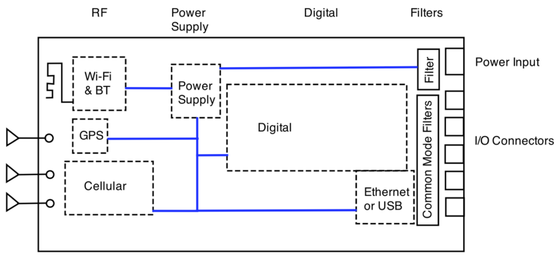
GOOD



- Each signal layer has adjacent return plane
- Power and return plane adjacent
- You lose one signal layer

Tip 1 – Concept of partitioning

Concept of Partitioning Circuit Functions - Important Exceptions



There are times when it makes better sense to locate switch-mode power supplies near what they power. Make sure related circuit loops are minimum.

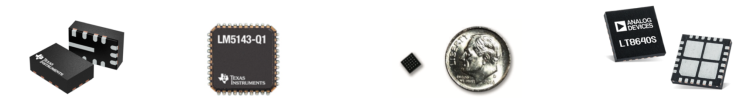
Also, it's important for fast bus I/O, such as Ethernet and USB circuitry to be located nearest their I/O connectors. We don't want their clocks running all over the board.

Power Distribution

Tip 2 – Use low EMI converters

Texas Instruments

Analog Devices/Linear



LMR36015 "HotRod" QFN pkg

LM5143-Q1 Adj. slew rate

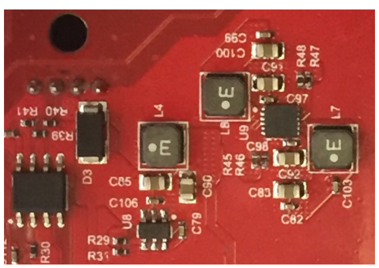
LTM8074 "Silent Switcher"

LT8640S "Silent Switcher 2"

- Both TI and Analog Devices (Linear Technologies) are developing low-EMI DC-DC converters.
- New packaging design allows the output inductor, Cin and Cout to be located very close to the IC package. In the latest designs, Cin, Cout and output L are internal to the package.
- Use devices with optional spread spectrum.

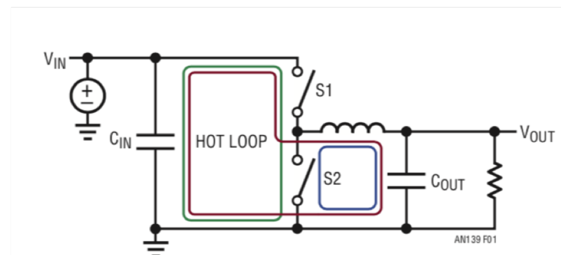
Images, courtesy Texas Instruments and Analog Devices.

Tip 3 – Keep converter circuitry on same layer



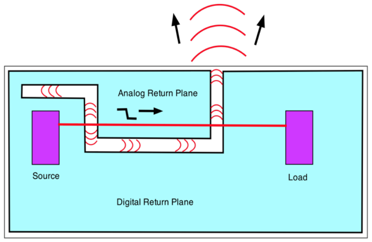
- Keep all DC-DC converter circuitry on the top (or bottom) layer and *over an adjacent ground reference plane.*
- We want to avoid converter currents from traveling from top to bottom of the board – especially the primary and secondary current loops.
- Physically separate input and output loops (no trace overlaps)!

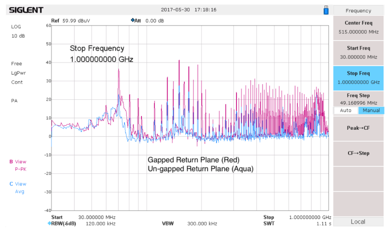
Tip 4 – Keep all converter circuitry close to IC



- Cin, Cout, and the output inductor should be located as close as possible to the DC-DC converter IC.
- Circuit layouts should minimize the input and output current loops.

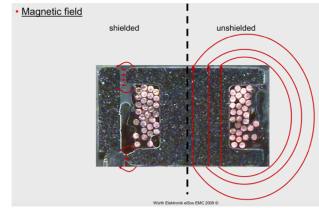
Tip 5 – The ground return plane must be solid

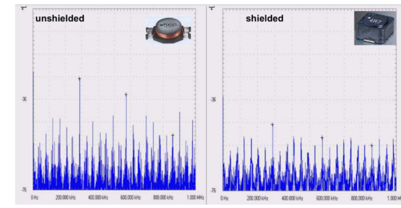




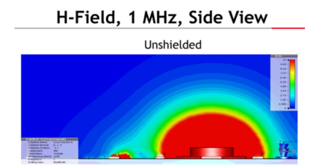
- Many EMI problems can be traced to discontinuous signal return paths. Ideally, a high frequency signal travels out a trace and (due to mutual self-inductance) returns immediately under that trace as the wave propagates along the transmission line.
- a discontinuity, such as a gap or slot in the return plane or power plane
- changing reference planes without a defined return current path

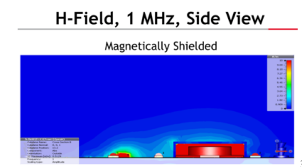
Tip 6 – The output inductor should be shielded





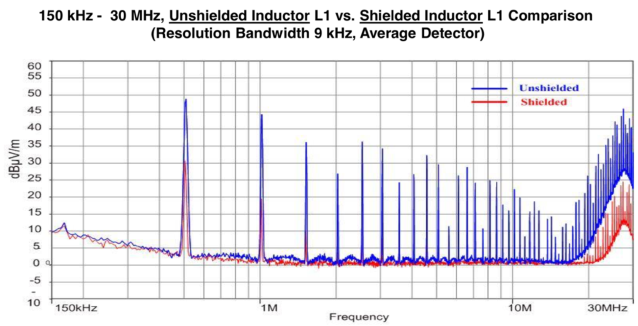
If you can see the windings, the inductor is unshielded!





Courtesy, Patrick DeRoy, CST

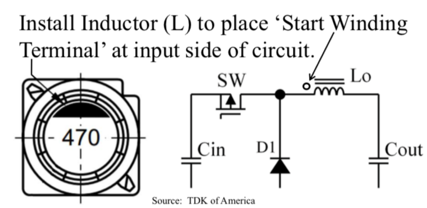
Tip 6 - Use of shielded inductors



Blue = unshielded / Red = shielded

Courtesy, Patrick DeRoy, CST

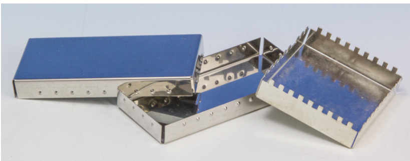
Tip 7 – Orient the output inductor for low EMI

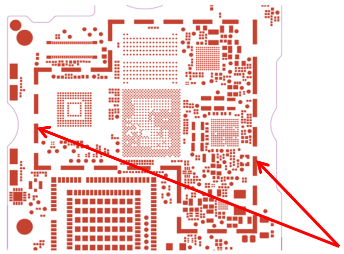


- Orient the output inductor for lowest EMI.
- We want the "start" of the winding to be buried (shielded) by the remaining turns. This can help reduce EMI by 2-3 dB.
- The start of the winding is usually indicated by a "half-moon", dot or line.

Figure, courtesy Rick Hartley Enterprises and TDK of America / photo, courtesy, Würth Elektronik, eiSos

Tip 8 – Use local shields

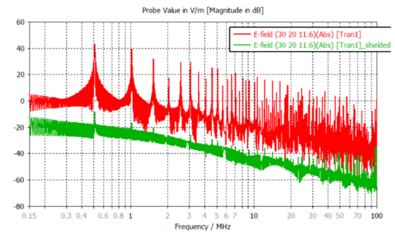




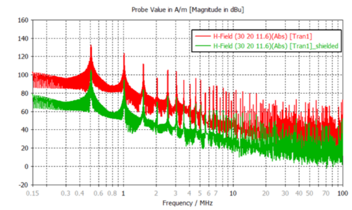
- DC-DC converters will likely require local shields.
- Even a magnetically-shielded inductor is not good enough for wireless applications. We still need a local E-field shield.
- It's best to pre-plan for this by designing in ground "fencing" around critical circuit functional areas, in case needed.

Tip 8 - Use local shields

Adding a long shield above the inductor and the switch node does reduce the E and H field 1 cm above the PCB



E-field



H-field

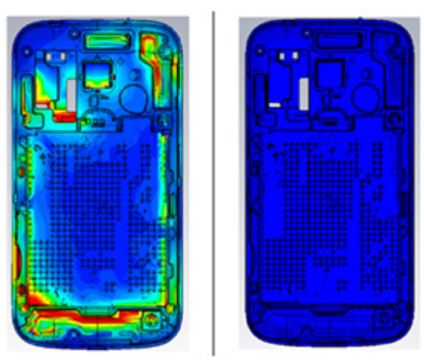
Courtesy, Patrick DeRoy, CST

Tip 8 - Use of a local shield

Near field distribution in a smart phone – with, and without, local shields over most of the circuit functions.

From: RFI and Receiver Sensitivity Analysis in Mobile Electronic Devices (Scogna, et al).

Voted Best Paper at DesignCon 2017.



Source: Samsung

Tip 9 – Use of RF absorber

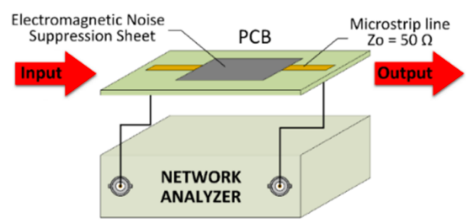


Figure 4: Microstrip Line Measurement System

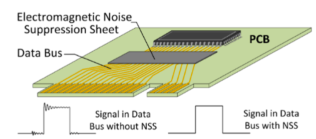


Figure 3: Transmission Line Application

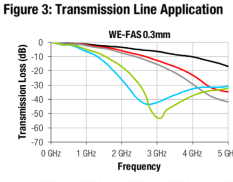
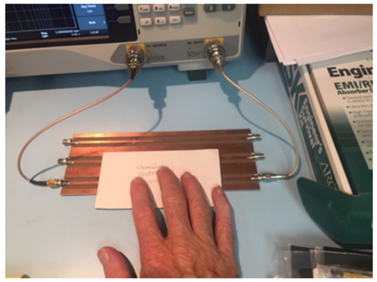


Figure 5: Transmission coefficient as a function of different materials

Ref: Würth Elektronik ap-note ANP059 (FAS material) and ANP022 (FSFS material)

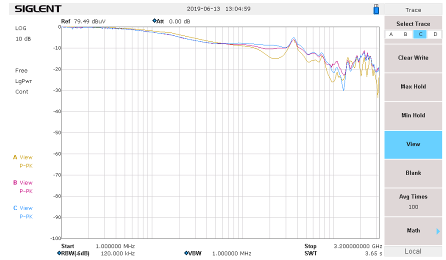
Images, courtesy Würth Elektronik.

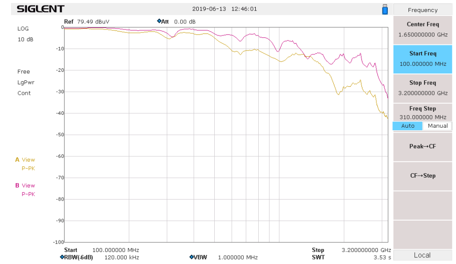
Tip 9 – Use of RF absorber



I'm starting to evaluate EMI absorber sheets for use in reducing leakage fields around known energy sources on boards. For an article on this, see references.

Tip 9 – Use of RF absorber





Parker-Chomerics SS4850 0100 0150 300

I had to extend the frequency range downward in order to capture the desired range, 100 to 1000 MHz.

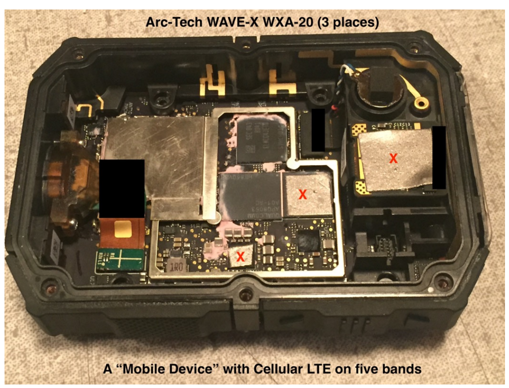
Good results in the LTE cellular bands.

Arc Technologies WAVE-X WXA10 & 20.

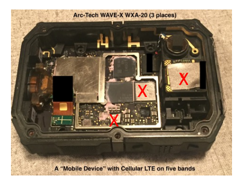
Good results in the LTE cellular bands WAVE-X WXA-20, only).

Tip 9 – Use of RF absorber – case study

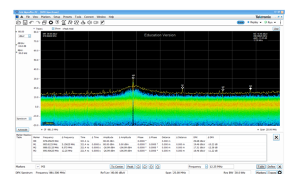
Arc Technologies WAVE-X WXA20 was attached over DDS RAM, internal flex cable and DC-DC converter (as shown by red "X"s).

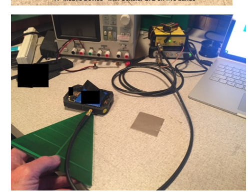


Tip 9 – Use of RF absorber – case study

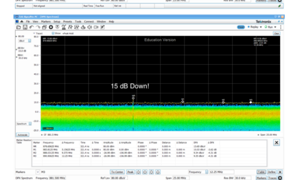


LTE Band 5 - Before





LTE Band 5 - After (15 dB down)

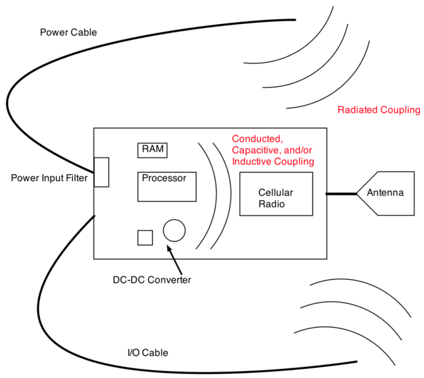


Apply absorber over known energy sources (Arc-Tech "Wave-X WXA-20").

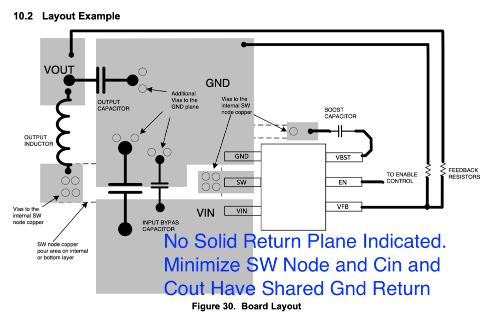
https://www.edn.com/insertion-loss-measurements-of-ferrite-absorber-sheets/

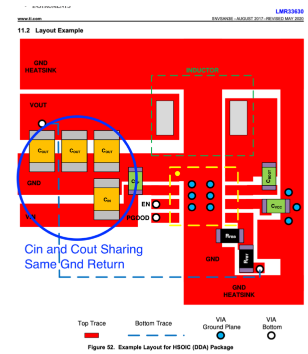
Tip 10 – Locate antennas and coax away from DC-DC converters & processors

Locate antennas and coax cables far from DC-DC converter circuitry.



Tip 11 (Bonus) – Don't trust manufacturer's data sheets



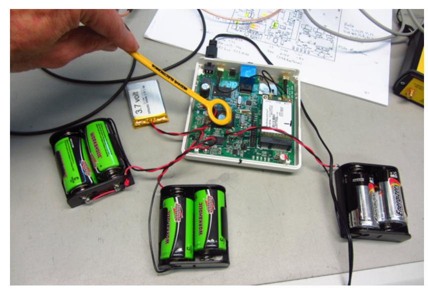


Assume EMC information and PC board layout is wrong, until proven accurate. This occurs among ALL IC manufacturers, not just TI.

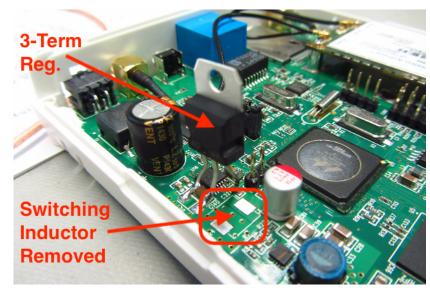
Mitigation experiments

- Relocate antenna(s)
- Try a different antenna type
- Extend antenna(s) with 1-2 foot coax (ferrite choke?)
- Reroute internal cables away from high energy sources
- Replace unshielded inductors with shielded
- Orient inductors so conv. SW-node at pin 1
- Replace DC-DC converters with batteries
- Replace DC-DC converters with linear regulators
- Add local shields (usually tough to accomplish)
- Add EMI absorber material over high energy sources
- Try shielding board with aluminum foil

Mitigation experiments



Remove switching inductors and replace with batteries (use series Schottky diodes to drop voltage as required)



Instead of external batteries, use 3-terminal voltage regulators

Mitigation checklist - summary

To mitigate platform interference, the product design must be developed with EMC in mind and no corners should be cut. This will consist of:

- A near perfect PC board layout
- Specify low-EMI DC-DC converters
- Keep DC-DC converters & circuitry on top side
- Keep Cin and Cout very close to converter IC
- Add filtering at the radio module
- Add local shielding around high noise areas
- Add RF absorber to known energy sources
- Proper antenna placement

Suggested references

- CTIA, Test Plan for Wireless Device Over-The-Air Performance, https://api.ctia.org/docs/default-source/certification/ctia-test-plan-for-wireless-device-over-the-air-performance-ver-3-6-2.pdf
- AT&T, Basics of IoT Compliance, https://iotdevices.att.com/basics.aspx
- Cellular LTE Bands (U.S.), https://en.wikipedia.org/wiki/LTE_frequency_bands
- Wyatt, Design PCBs for Low EMI (Part 1), EDN, https://www.edn.com/design-pcbs-for-emi-part-1-how-signals-move/
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- Wyatt, Characterizing DC-DC Converters with Near Field Probes (EDN), https://www.edn.com/characterize-dc-dc-converter-emi-with-near-field-probes/
- Todd Hubing, https://learnemc.com
- Slattery and Skinner, Platform Interference in Wireless Systems - Models, Measurement, and Mitigation, Newness Press, 2008.

Questions?