



Understanding Radiated EMI

Applications Engineering Group
MCU Division

Agenda

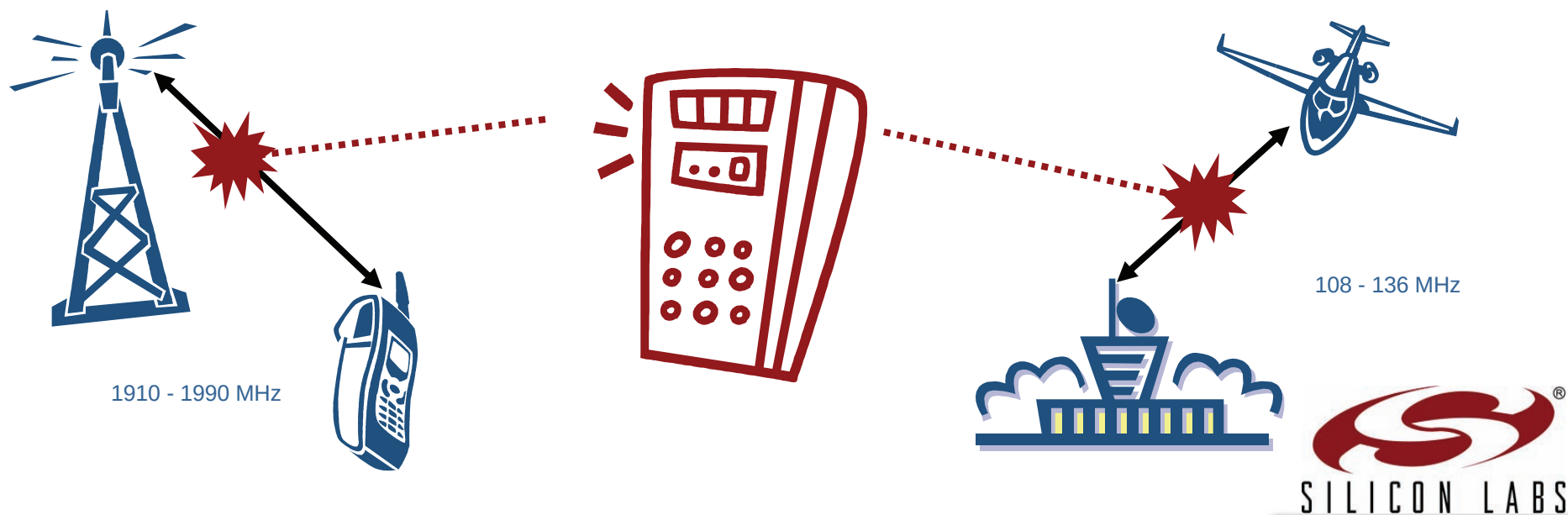
◆ EMI background

- Mechanisms
- Circuit-level causes
- Frequencies
- Measurements
- Shielding

◆ Example problem

What is Radiated EMI?

- ◆ A digital design can become an unintentional transmitter
- ◆ Circuit elements can act as antennas
 - PCB traces
 - Cables and connections
 - IC's and devices
- ◆ This unintentional transmitter can cause problems for other intentional radio systems

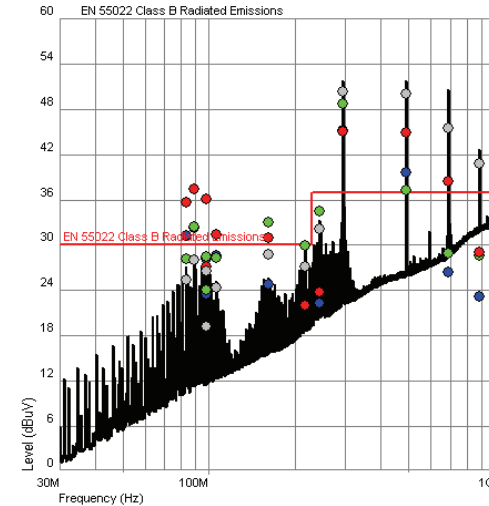


Types of Radiated EMI Issues

◆ Regulatory: Fails a spec limit

➤ Examples

- System clock harmonics violate EN55022 maximum limits
- PWM signal harmonics in an automotive display exceed maximum level allowed by auto maker



◆ Functional: Interferes with itself

➤ Examples

- Radio scanner: System clock frequency may jam the receiver
- GPS blocking: 16th harmonic of system clock may block GPS reception



Agenda

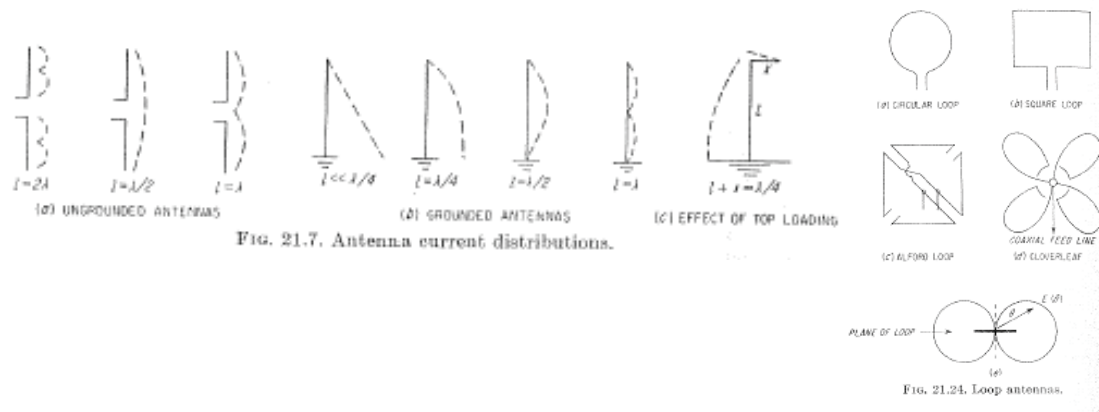
◆ EMI background

- Mechanisms
- Circuit-level causes
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- Shielding

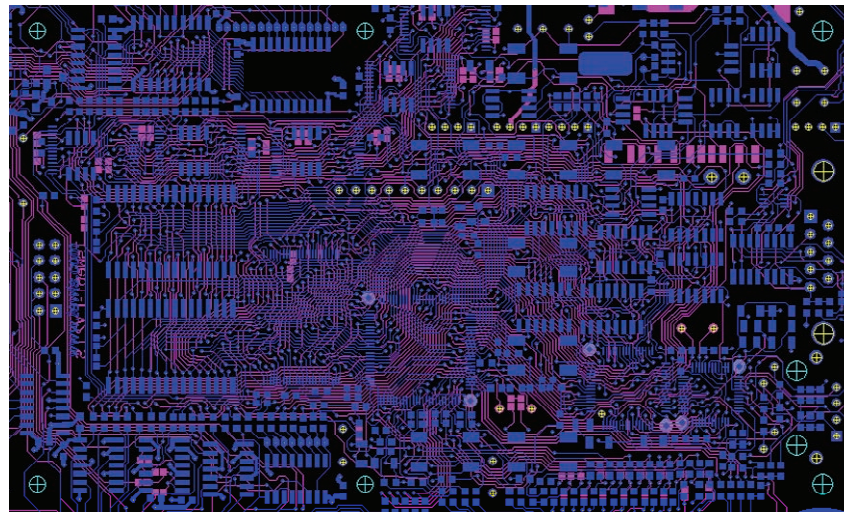
◆ Example problem

Radiation Mechanism: Antennas

- ◆ Intentional antennas—designed to radiate



- ◆ Unintentional antennas—not designed to radiate (but do!)



Reducing EMI

- ◆ To eliminate EMI, the engineer must
 - Reduce the currents or voltages exciting the antennas
 - Eliminate the transmitting antennas
 - Block the radiated fields
- ◆ In practical terms, this is done by
 - Understanding and minimizing high-frequency sources
 - Clean PCB layout
 - Using shielding

Agenda

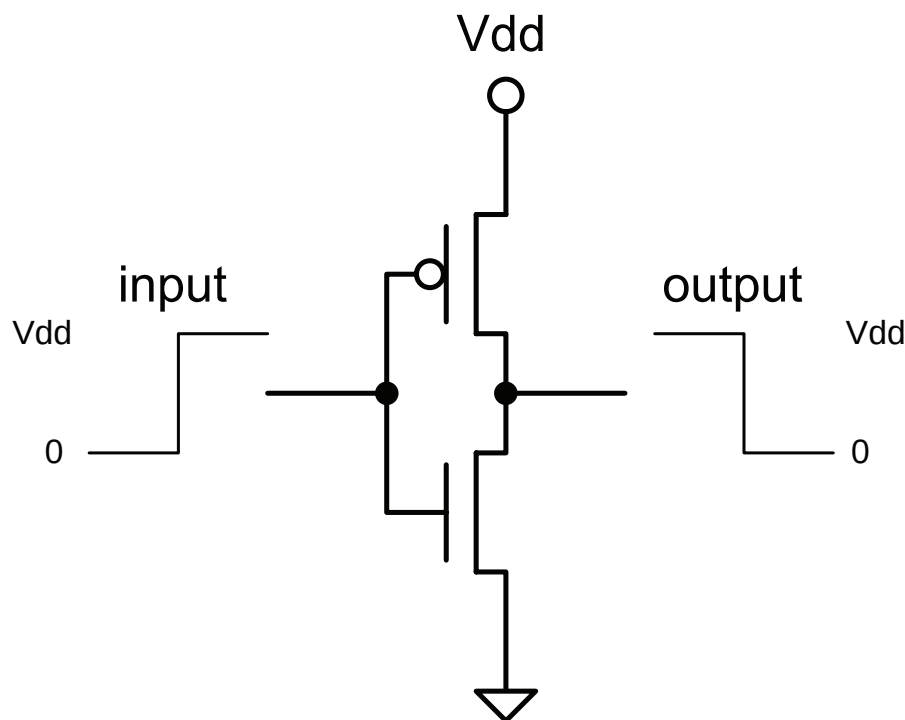
◆ EMI background

- Mechanisms
- Circuit-level causes
- Frequencies
- Measurements
- Shielding

◆ Example problem

What is the Source of EMI?

- ◆ CMOS digital devices are made of thousands of gates
- ◆ For simplicity, consider each gate as a CMOS inverter:



V_{DD} Current

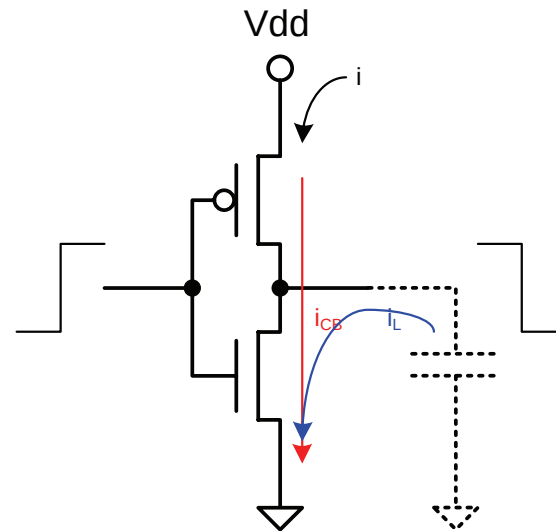
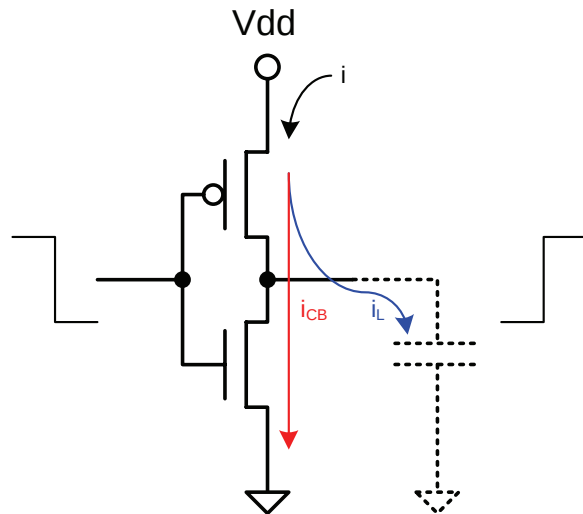
◆ In dynamic operation, transitions consume current

➤ i_{CB} : Crowbar current

- Both gates are momentarily on at the same time, conducting current from Vdd to ground

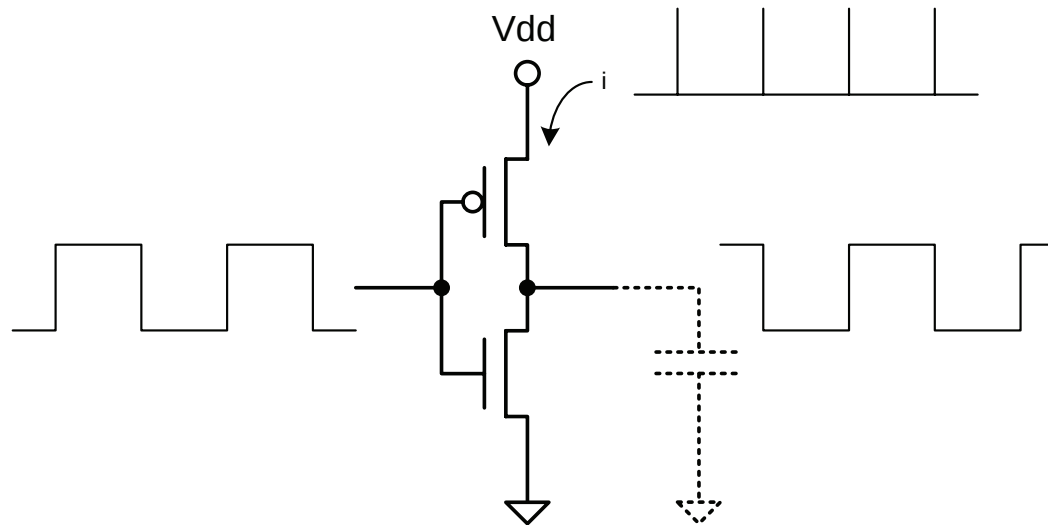
➤ i_L : Load current

- Output of the gate is likely connected to input of another gate
- Gate inputs are capacitive



V_{DD} current

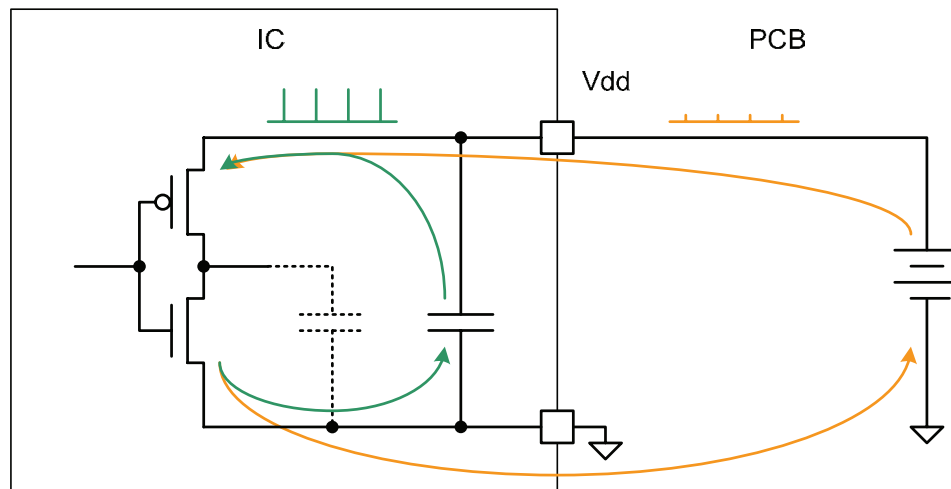
- ◆ Periodic signals through gates cause current impulses



- ◆ Average current depends on switching frequency
- ◆ Spectrum depends on switching frequency
 - Usually system clock
 - Sometimes a subharmonic ($\text{sysclk}/2$, 3, 4, etc)
 - Peripherals often use $\text{sysclk}/2$

V_{DD} Current: DC and AC Components

- ◆ Think in terms of both AC and DC power supplies
 - Where does the AC current come from?
- ◆ Ideal case
 - Most AC current comes from **on-chip sources**
 - Little or no AC current comes from **off-chip sources**
 - Small current loop, small antenna

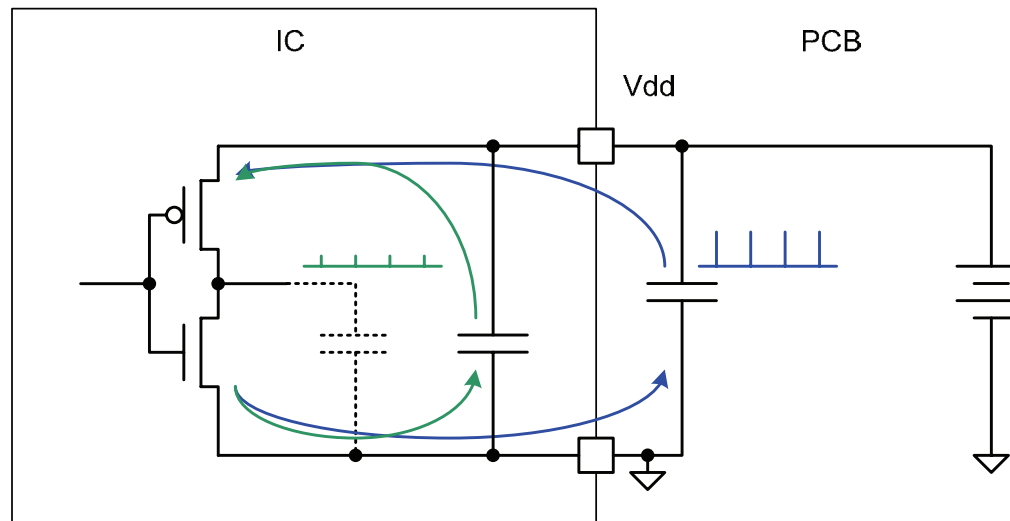


V_{DD} Current: DC and AC Components

◆ Realistic case:

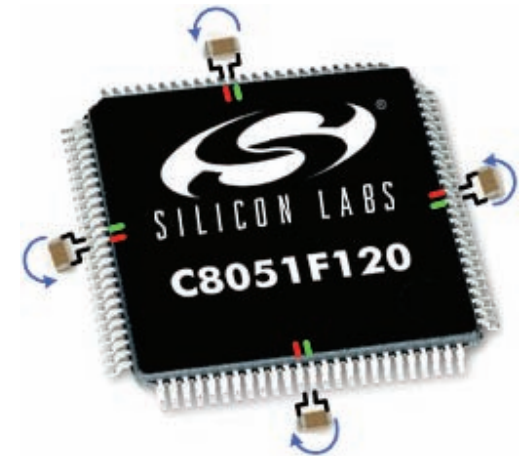
- AC current is sourced from outside the IC
- On-chip capacitors are impractical: silicon area = larger die
- Some on-chip capacitance does exist, but not enough

◆ Engineer must think AC currents when designing PCB



Think Loop Area

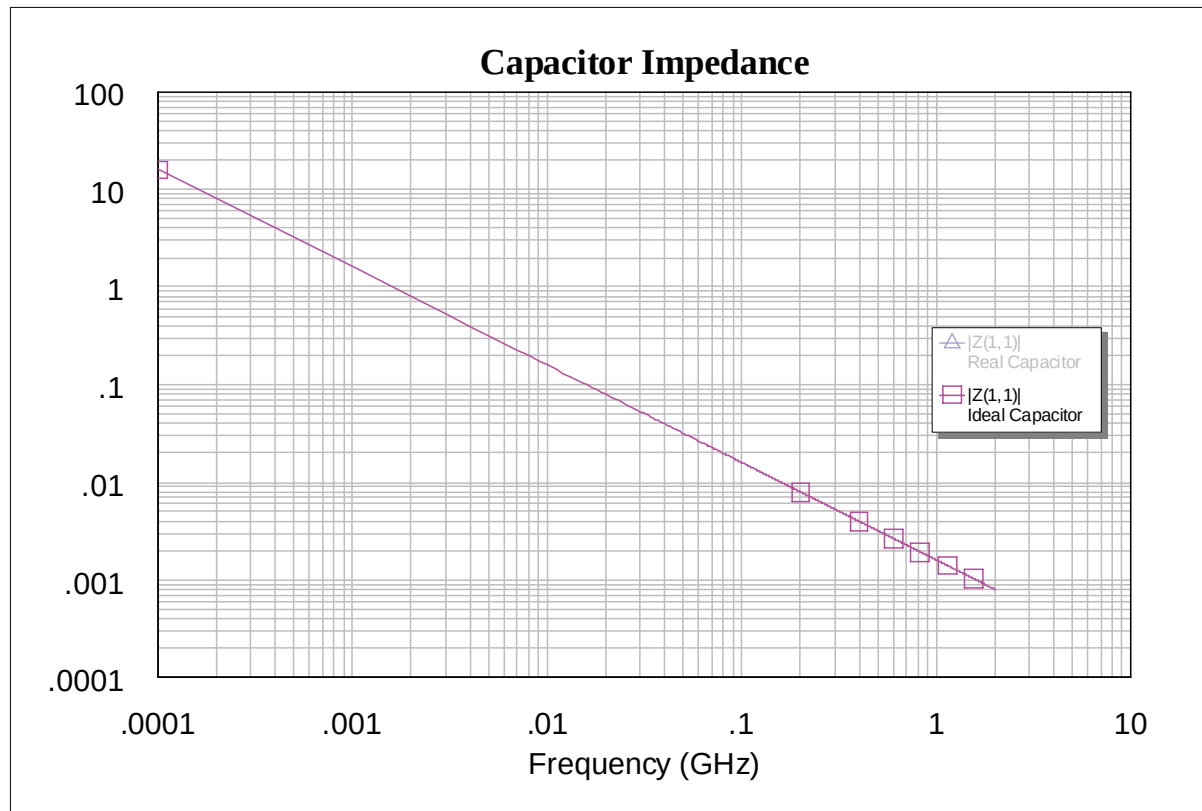
- ◆ Since AC currents need to flow outside the IC, there will be currents in loops
- ◆ Current loops = EMI transmitting antennas
- ◆ Make transmitting loop antennas small !
- ◆ Design a short path for the currents
 - Source currents (from V_{DD})
 - Return currents (through ground)
- ◆ Silicon Labs MCUs designed with adjacent power and ground pins to minimize loop area



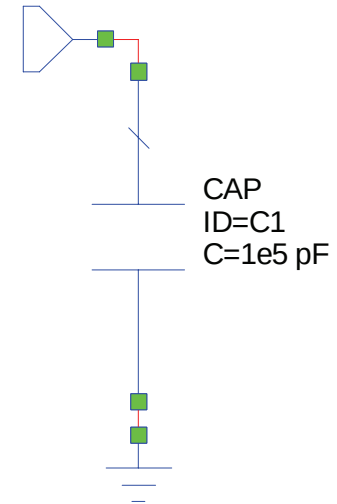
Choosing Capacitors

◆ Ideal capacitor $Z_C = \frac{1}{j\omega C}$ ($Z_C \rightarrow 0$ as frequency $\rightarrow \infty$)

◆ Mag[Z] of an ideal 0.1 uF capacitor:



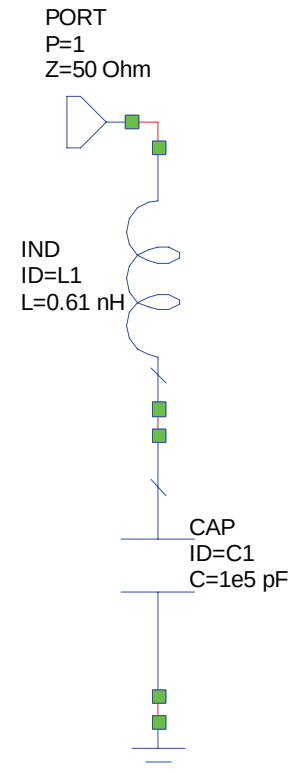
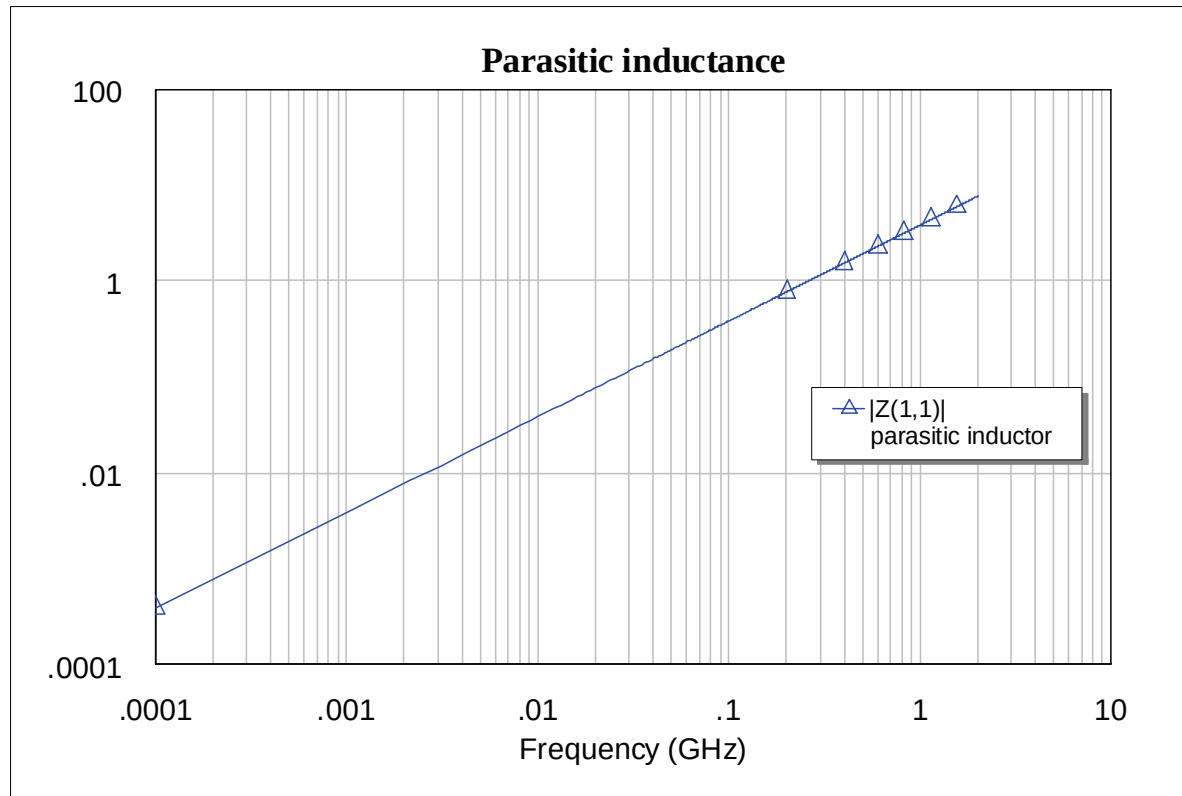
PORT
P=1
Z=50 Ohm



Choosing Capacitors

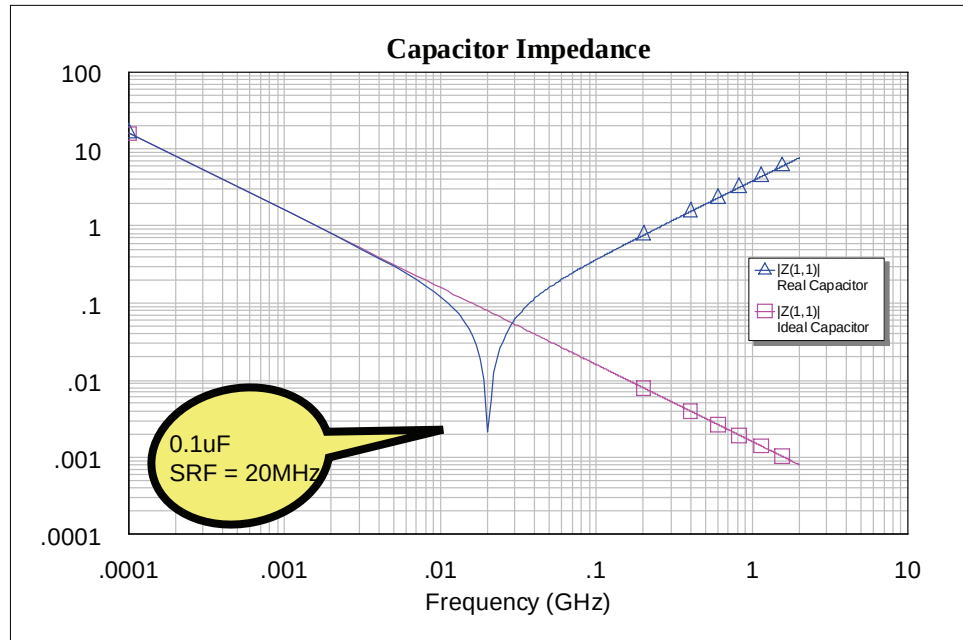
- ◆ Unfortunately there are no ideal capacitors
- ◆ Real capacitor: capacitor in series with parasitic inductor
- ◆ Inductor adds impedance with increasing frequency

$$Z_c = \frac{1}{j\omega C} + j\omega L$$

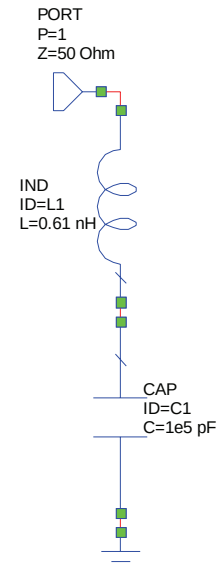


Choosing Capacitors

- ◆ Real capacitor—inductance cancels, dominates impedance



$$Z_C = \frac{-j}{\omega C} + j\omega L$$

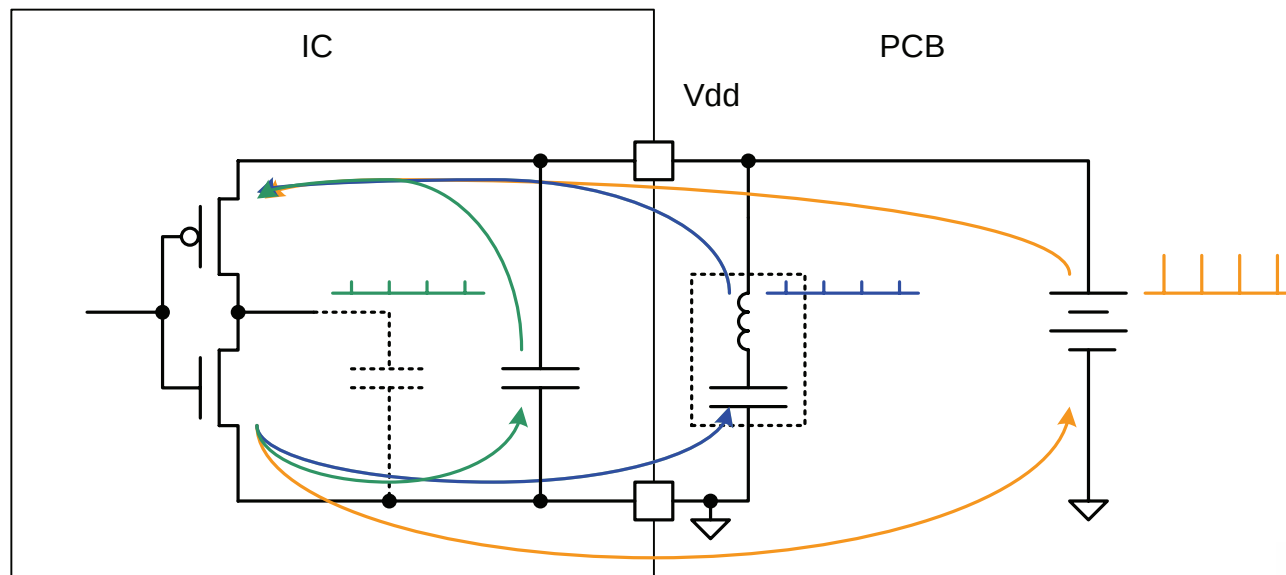


- ◆ A capacitor behaves differently in three frequency bands

1. $f < \text{SRF}$: Capacitor acts like a capacitor ($Z \downarrow$ as $f \uparrow$)
2. $f = \text{SRF}$: Reactive impedances cancel
3. $f > \text{SRF}$: Capacitor behaves like an inductor ($Z \uparrow$ as $f \uparrow$)

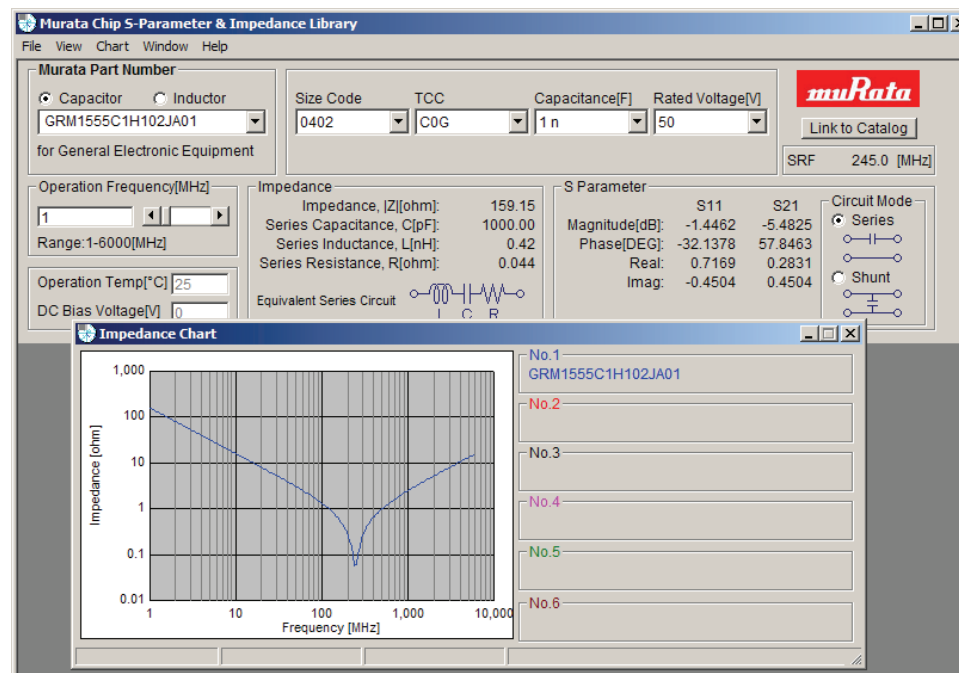
Choosing Capacitors

- ◆ Wrong capacitor may have little or no effect
 - Capacitors are capacitors only below SRF
 - Capacitors are inductors above SRF
 - Increasing inductive impedance will prevent capacitor from sourcing impulse currents



Choosing Capacitors

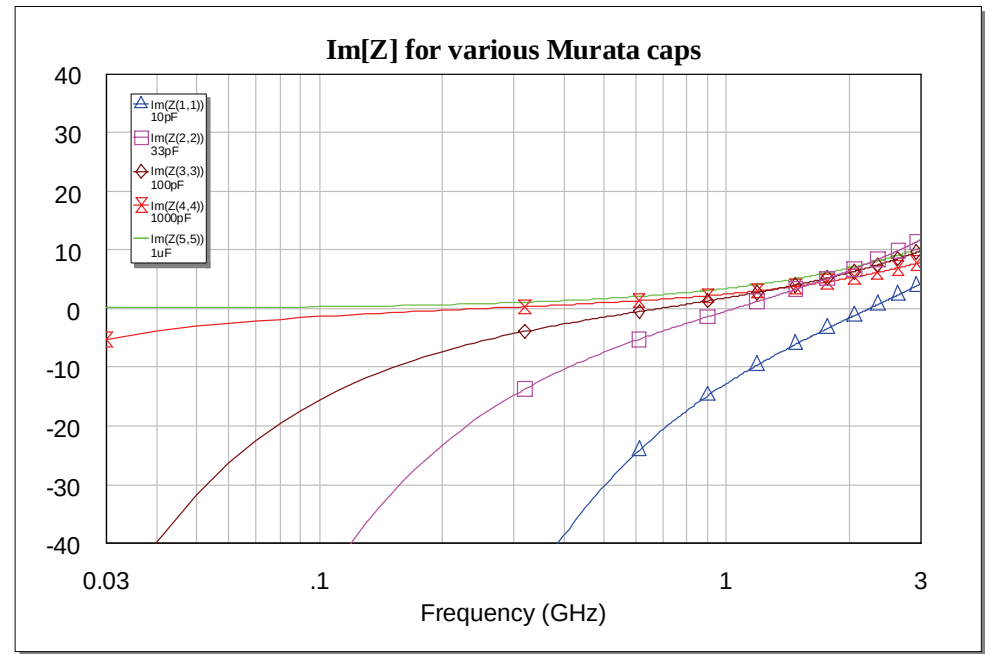
- ◆ Solution: select another capacitor
 - Different capacitor values have different parasitics
 - Choose capacitor for frequency of interest
- ◆ Help available from capacitor manufacturers
 - Murata tool: <http://www.murata.com/designlib/mcsil/index.html>



Capacitor Selection Examples

◆ Compare the imaginary impedance for various Murata capacitors

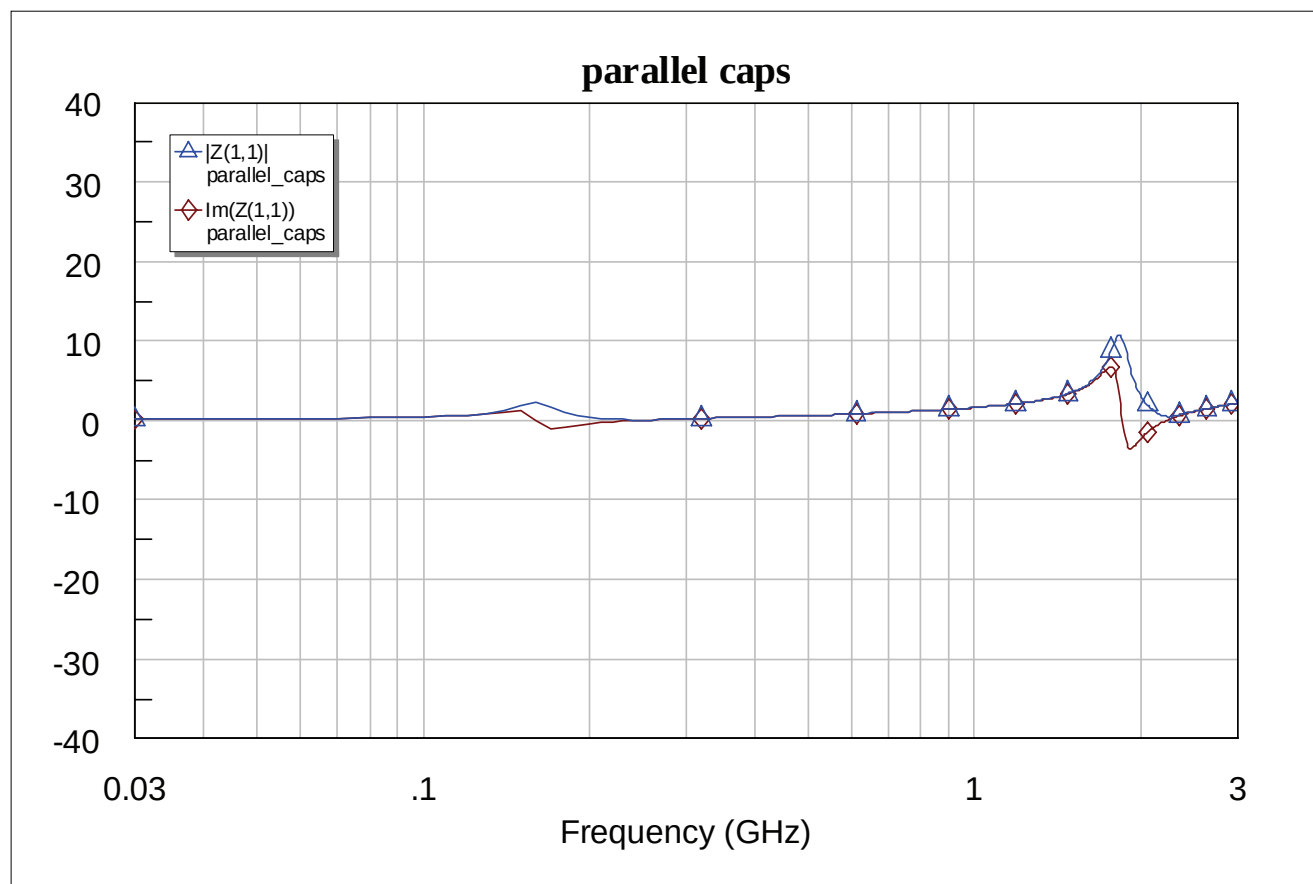
- 10pF
(GRM1555C1H100JZ01)
- 33pF
(GRM1885C1H330JA01)
- 100pF
(GRM1555C1H101JZ01)
- 1000pF
(GRM1555C1H102JA01)
- 1uF
(GRM188F51C105ZA01)



Which Capacitor is Best?

◆ Use multiple capacitors in parallel

➤ Example: 10pF || 1000pF || 1uF

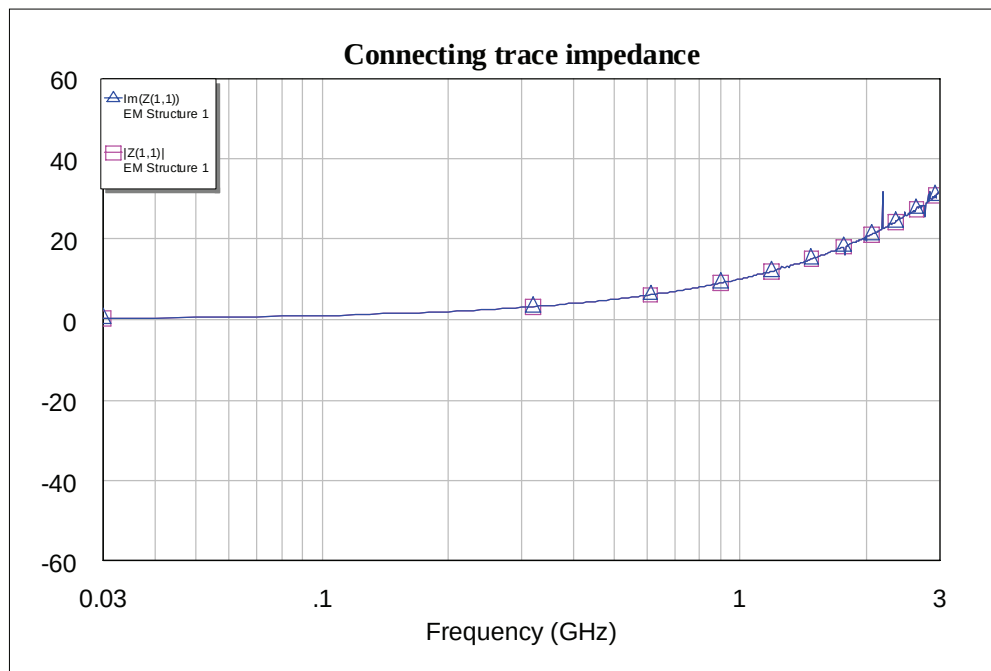
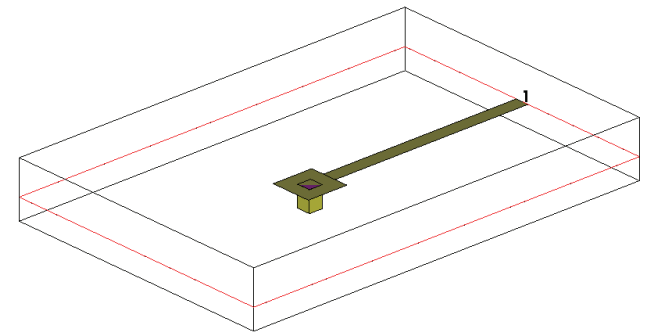


Another Reason to Keep Short Traces

◆ Connecting trace to capacitor adds series inductance

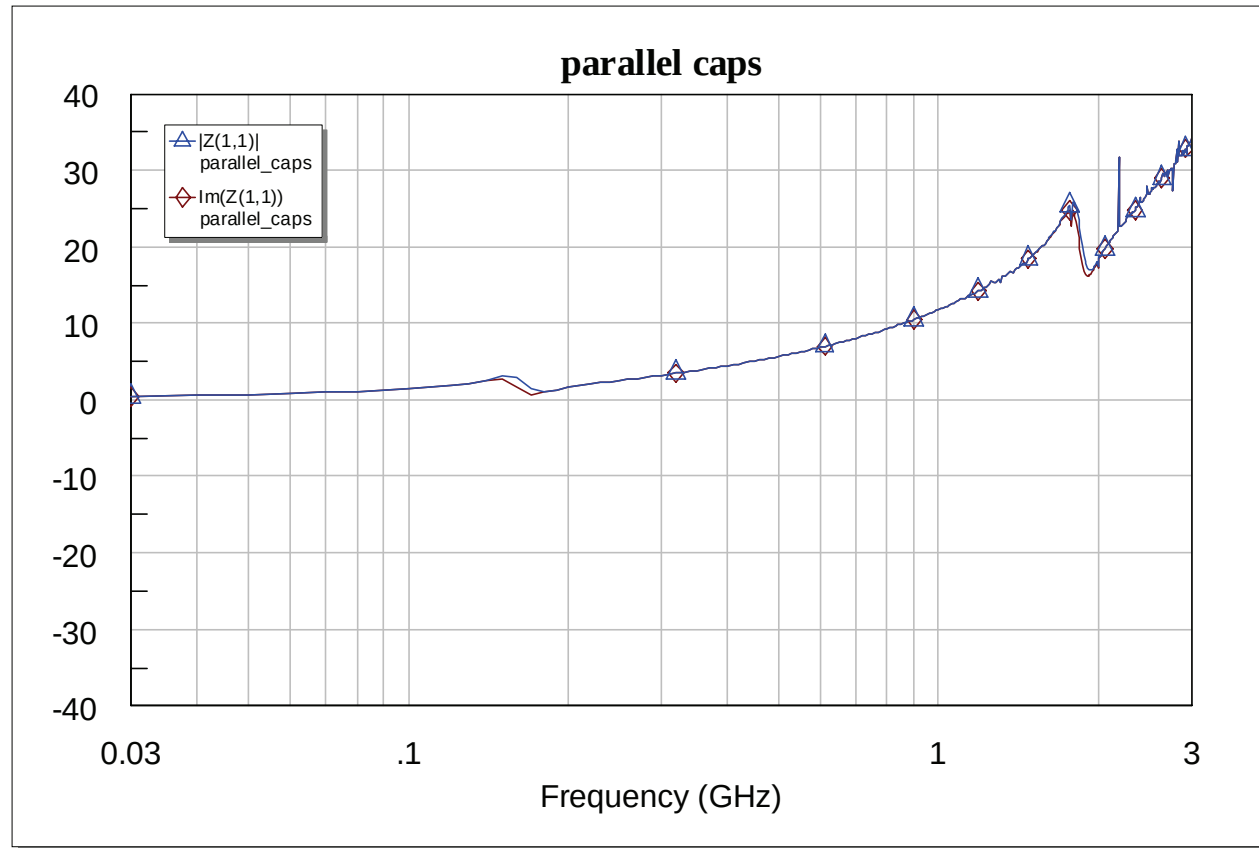
➤ Simulate a 3mm trace with via to ground:

➤ Trace is inductive



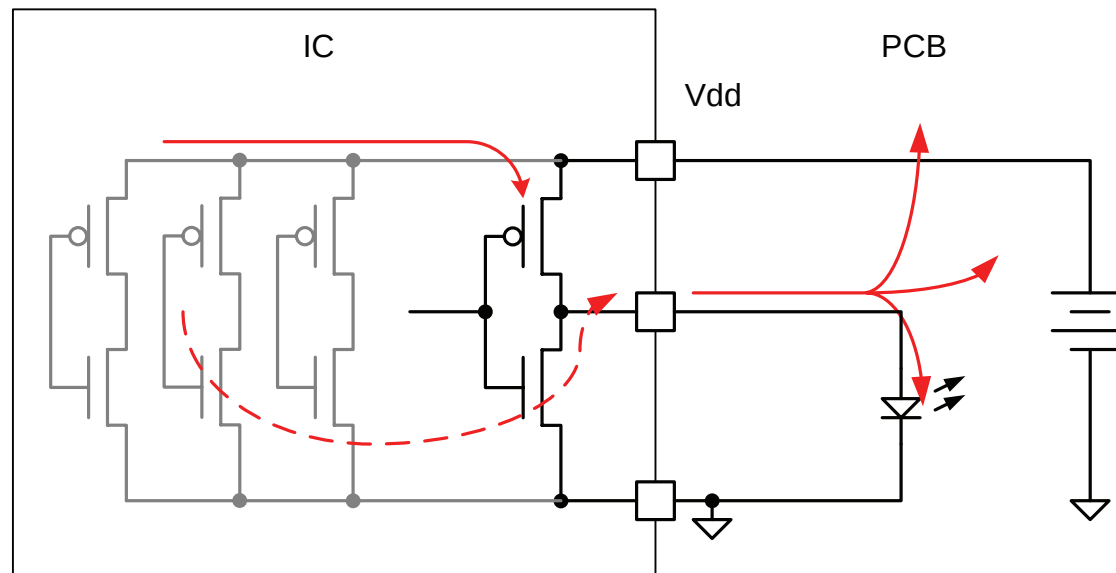
Parallel Caps in Series with Trace

- ◆ Parallel capacitor combination effectiveness is reduced by additional trace inductance



Internal Coupling/Leakage

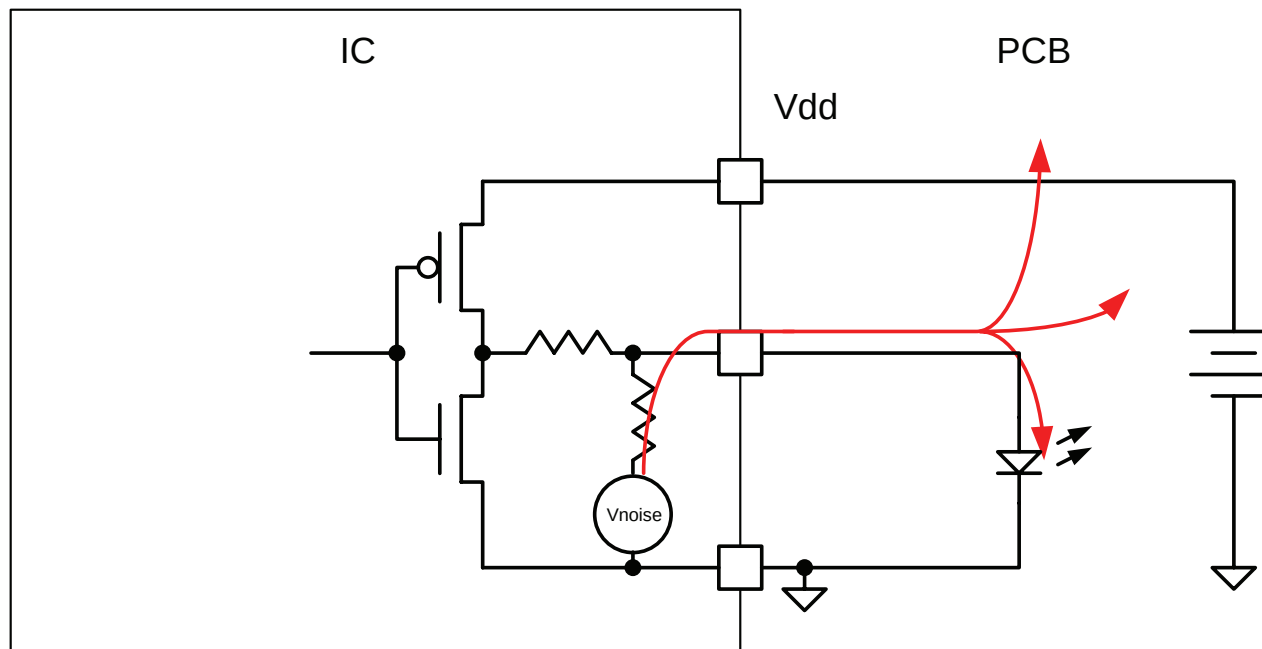
- ◆ EMI can result from AC energy coupling to digital I/O lines inside the IC
- ◆ Static digital I/O's may be a source of EMI
- ◆ Possible causes:
 - Conduction through power supply
 - Capacitive coupling
 - Inductive coupling



Internal Coupling/Leakage

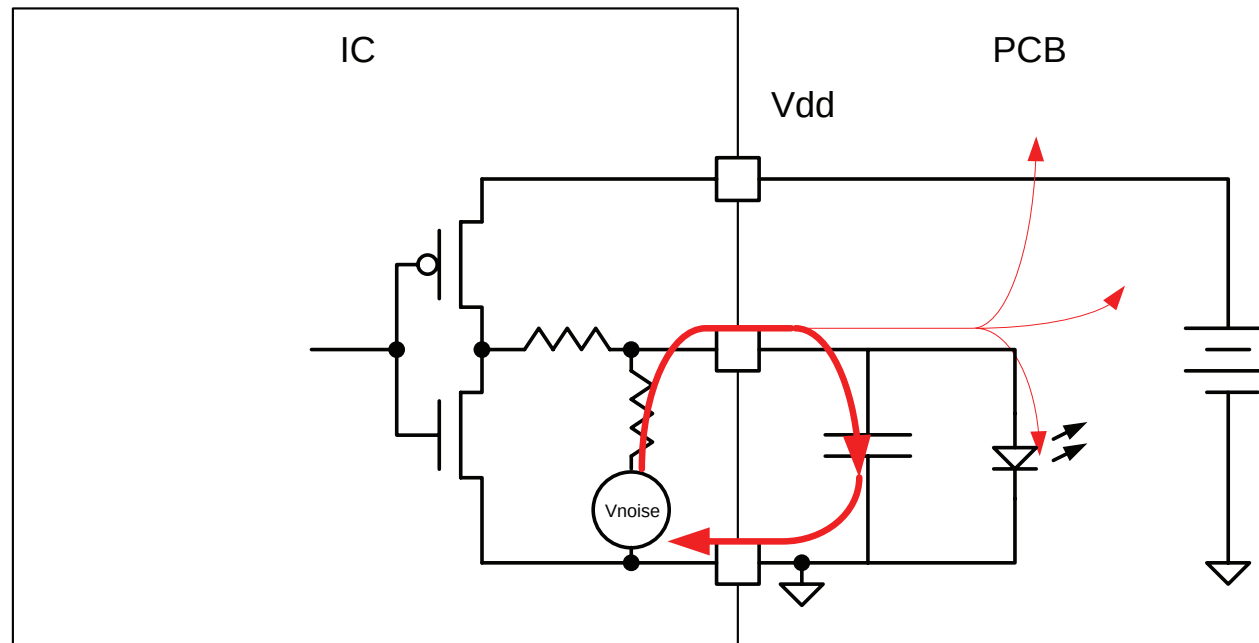
◆ Consider a simplified model

- Think of the EMI as a noise source with some impedance coupling it to a digital I/O
- Current at the digital I/O is from two sources
 - Digital driver (good)
 - EMI (bad)



Internal Coupling/Leakage

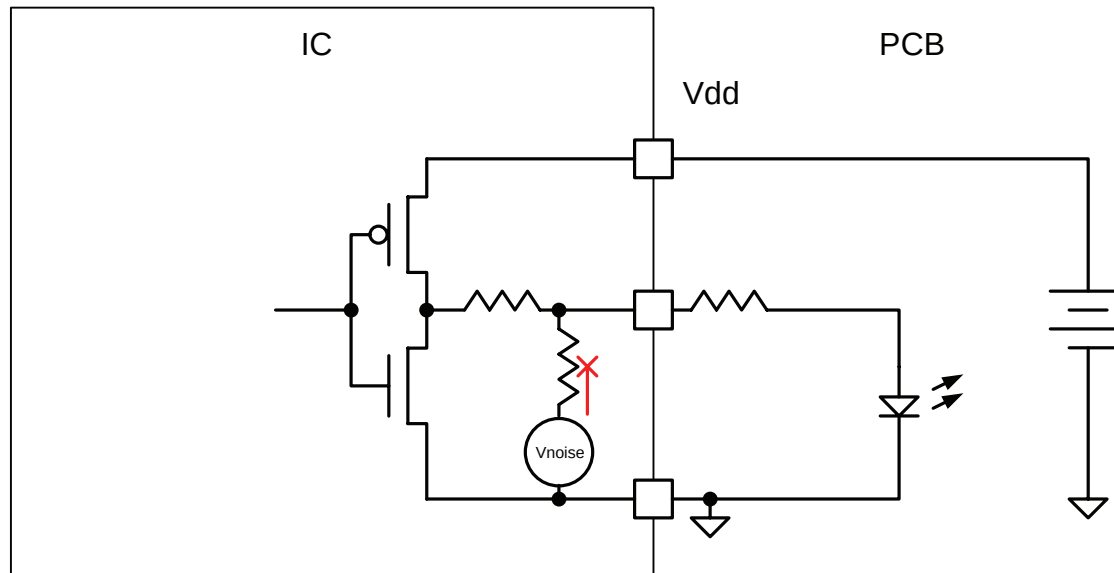
- ◆ How should we block the noise? Add a capacitor?
- ◆ May make EMI worse
 - Capacitor provides a low-impedance path outside the IC
 - The low impedance path may increase current



Internal Coupling/Leakage

◆ Add series resistance? May help

- Less current (good and bad current) flows through high impedance
- May reduce EMI by reducing currents flowing outside IC



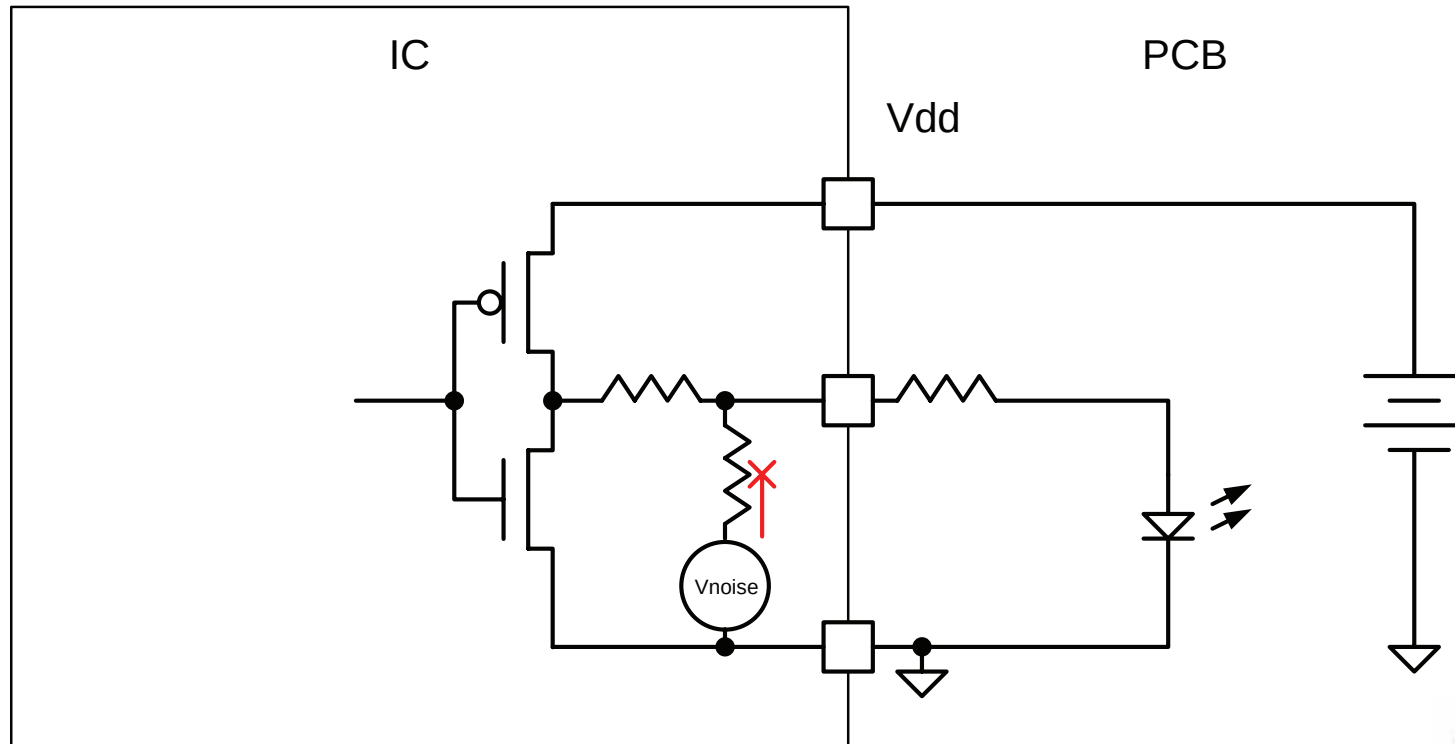
◆ Disadvantage

- Adding resistance may attenuate or distort the wanted signal
For example, it may not provide enough LED current, or may slow a signal's slew rate

Internal Coupling/Leakage

◆ Troubleshooting experiment

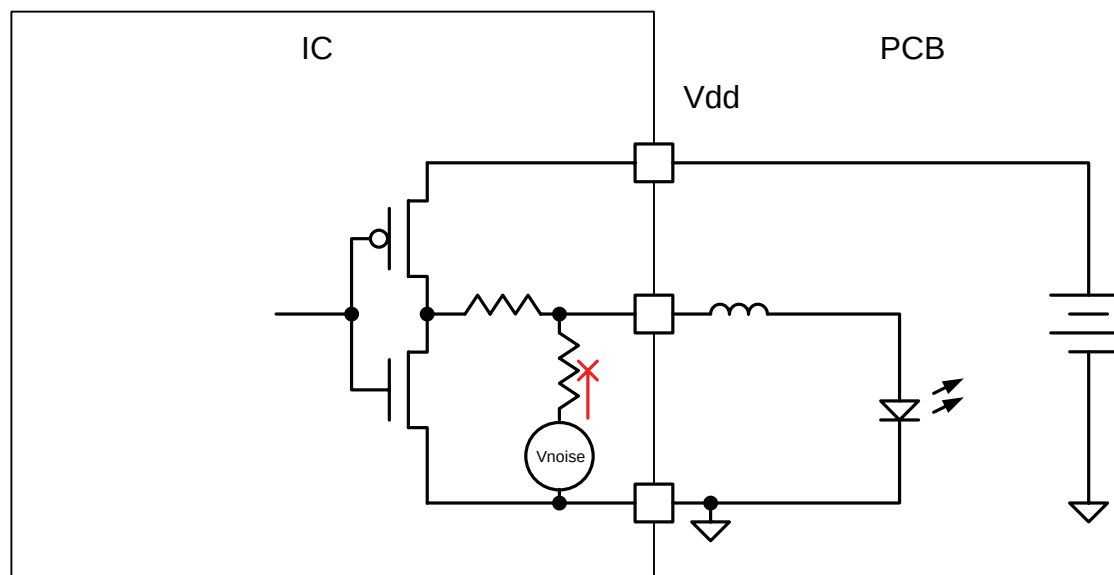
- Set $R = \infty$ by lifting pin
- Reduced EMI means that this pin is contributing



Internal Coupling/Leakage

◆ Add an external inductor or choke?

- Provides high impedance for high frequencies, low impedance for low frequencies



◆ Disadvantages

- Inductor may actually create and radiate EMI (inductors turn electric currents into magnetic fields)
- Inductors cost more than resistors and capacitors

Agenda

◆ EMI background

- Mechanisms
- Circuit-level causes
- Frequencies
- Measurements
- Shielding

◆ Example problem

Time and Frequency Domains

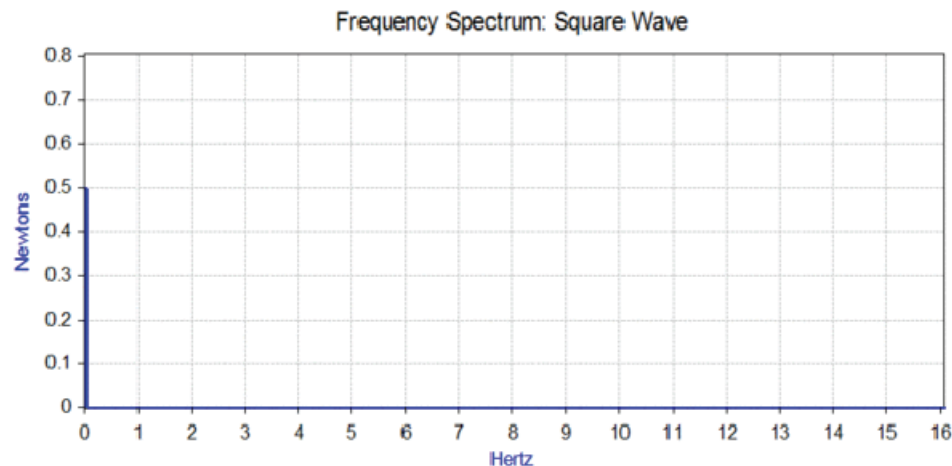
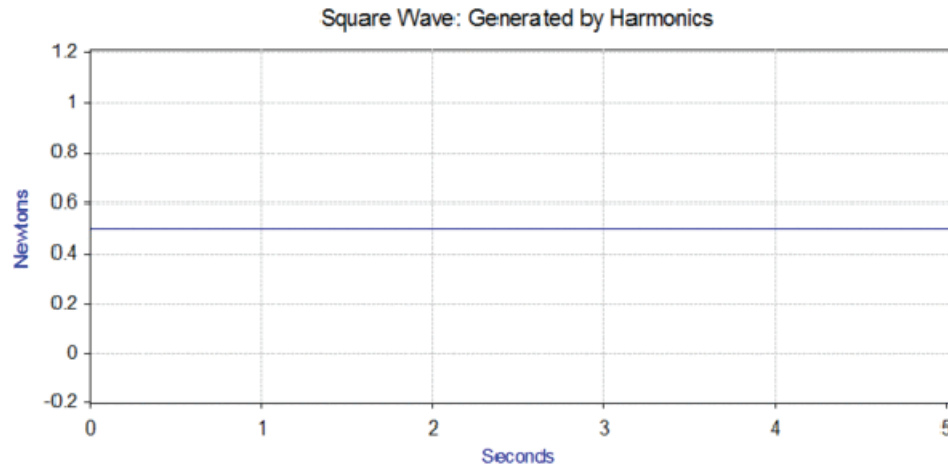
- ◆ Signals can be represented in time or frequency domains
 - Fourier transform $\mathcal{F}$: Transform between time and frequency domains
 - Digital designers think in time domain
 - EMI measurements are in the frequency domain

- ◆ Periodic events in a circuit create distinct EMI frequencies
 - Frequencies often harmonics of the system clock
 - Frequencies may be harmonics of system clock subharmonics
 - Example: Flash memory read every third sysclock period
 - Digital waveforms will create harmonics
 - Square wave creates odd harmonics
 - Impulse train creates even and odd harmonics

Fourier Transform Review

◆ Square wave

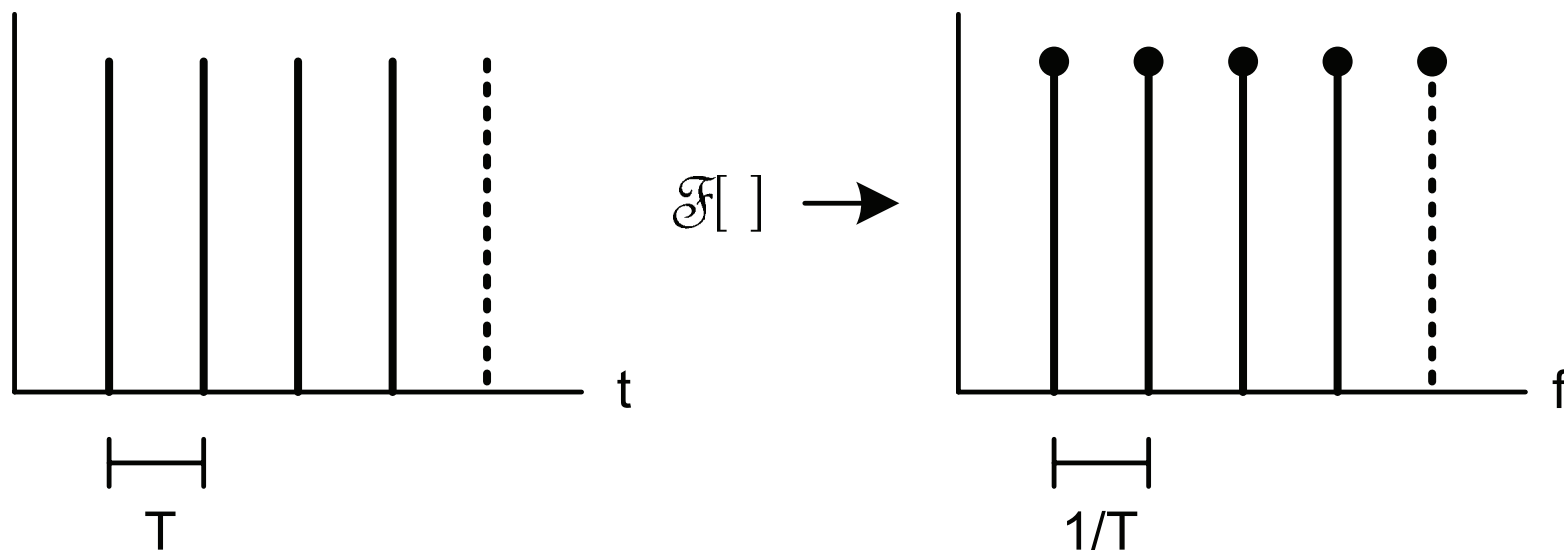
- Square wave is composed of several odd harmonics



Fourier Transform Review

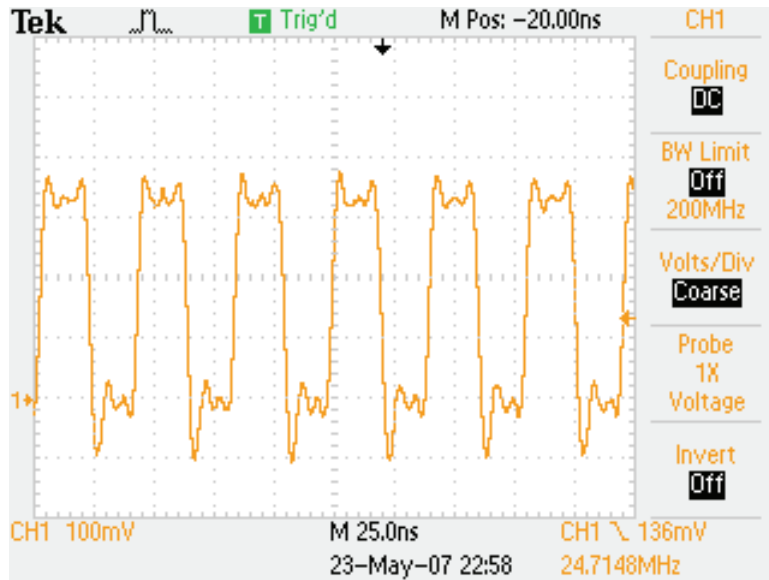
◆ Impulse train

➤ A series of pulses in time is a series of tones in frequency

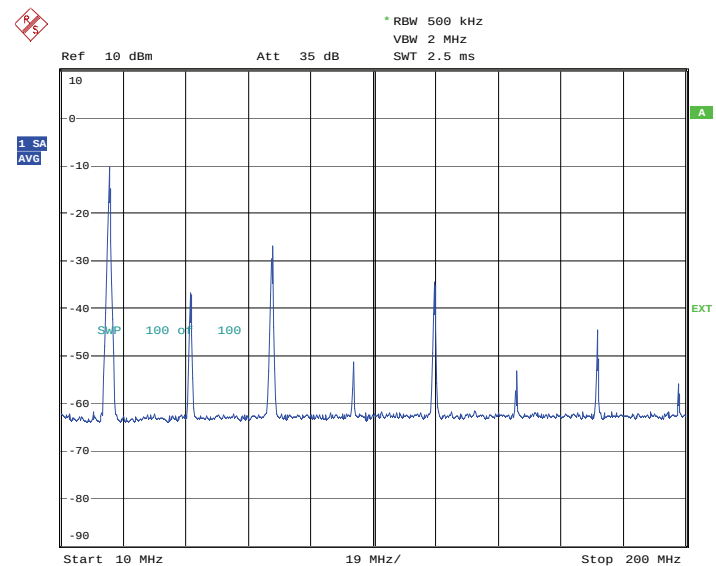


Example—Spectrum of a Square Wave

- ◆ F120 24.5MHz sysclock from a port pin



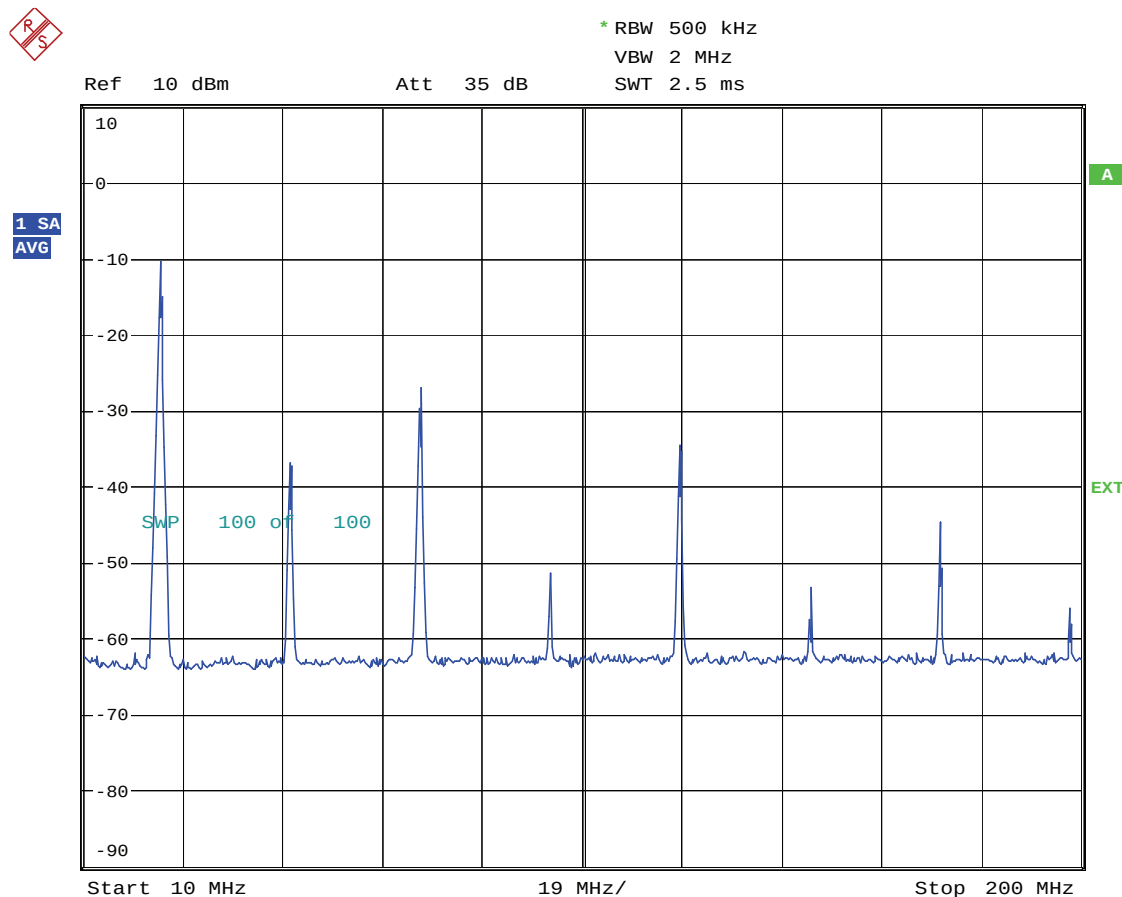
Oscilloscope (time)



Date: 23.MAY.2007 10:11:54

Spectrum Analyzer (frequency)

System Clock Design Tradeoffs



◆ Difficult to change waveform

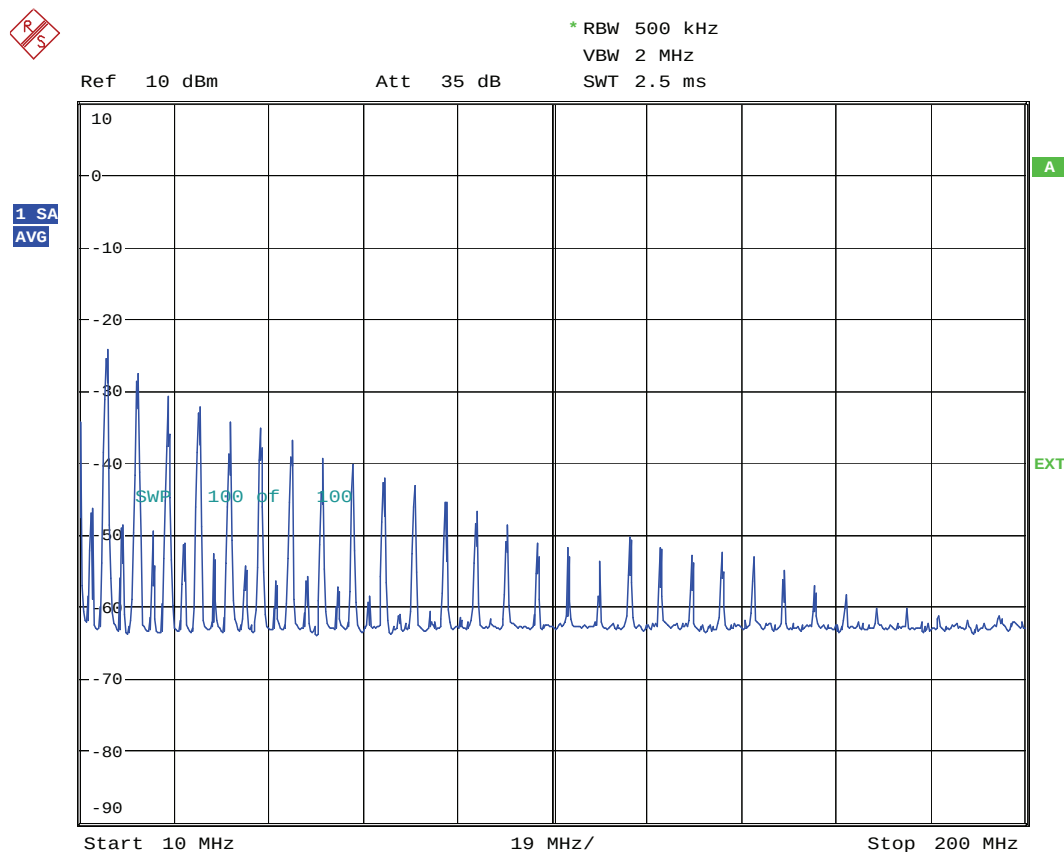
◆ Easy to change system clock

➤ Example—C8051F120

- reduce sysclk using clock dividers
- increase sysclk using clock multiplier
- 24.5MHz shown here

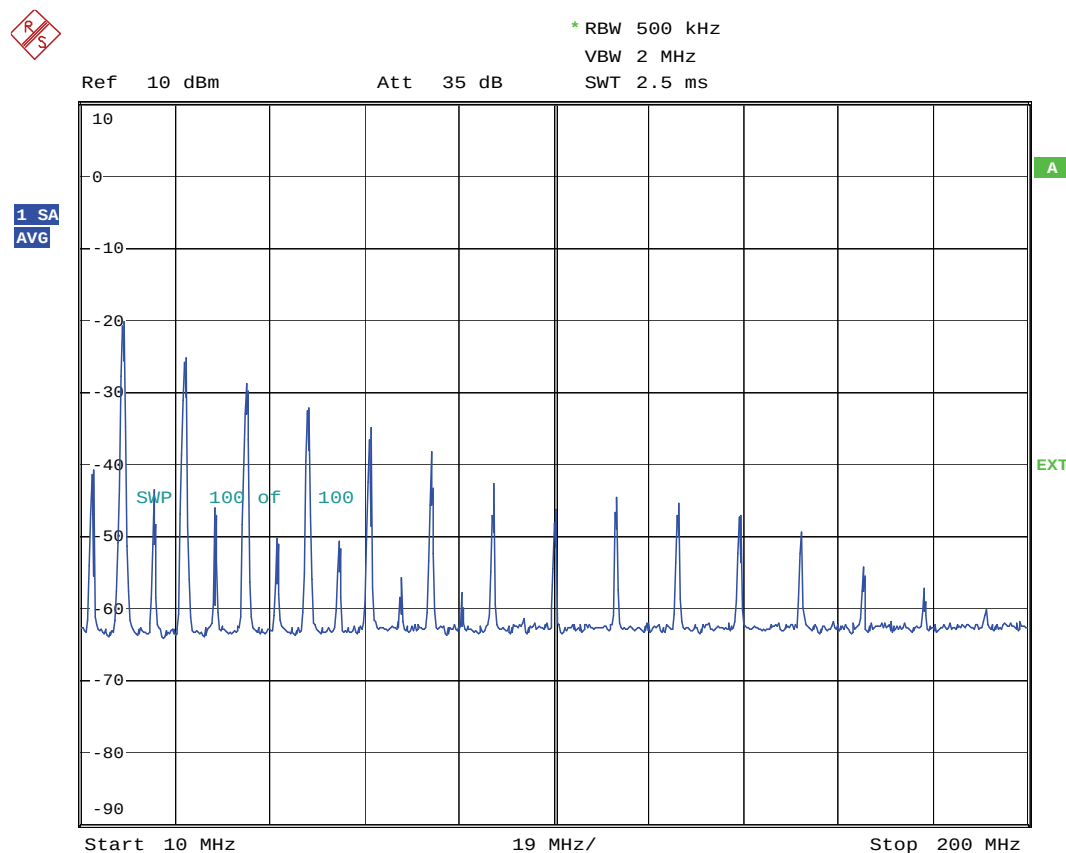
Date: 23.MAY.2007 10:11:54

Spectrum of 3.0625 MHz System Clock



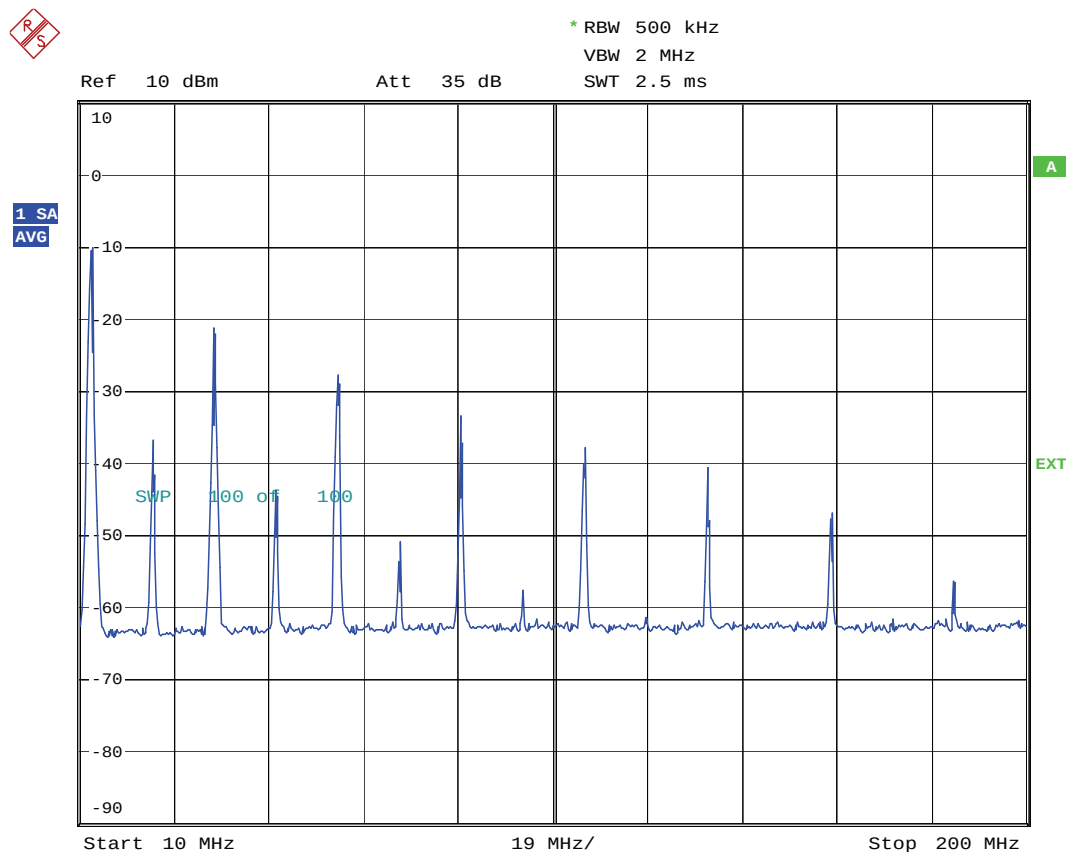
Date: 23.MAY.2007 10:09:28

Spectrum of 6.025 MHz System Clock



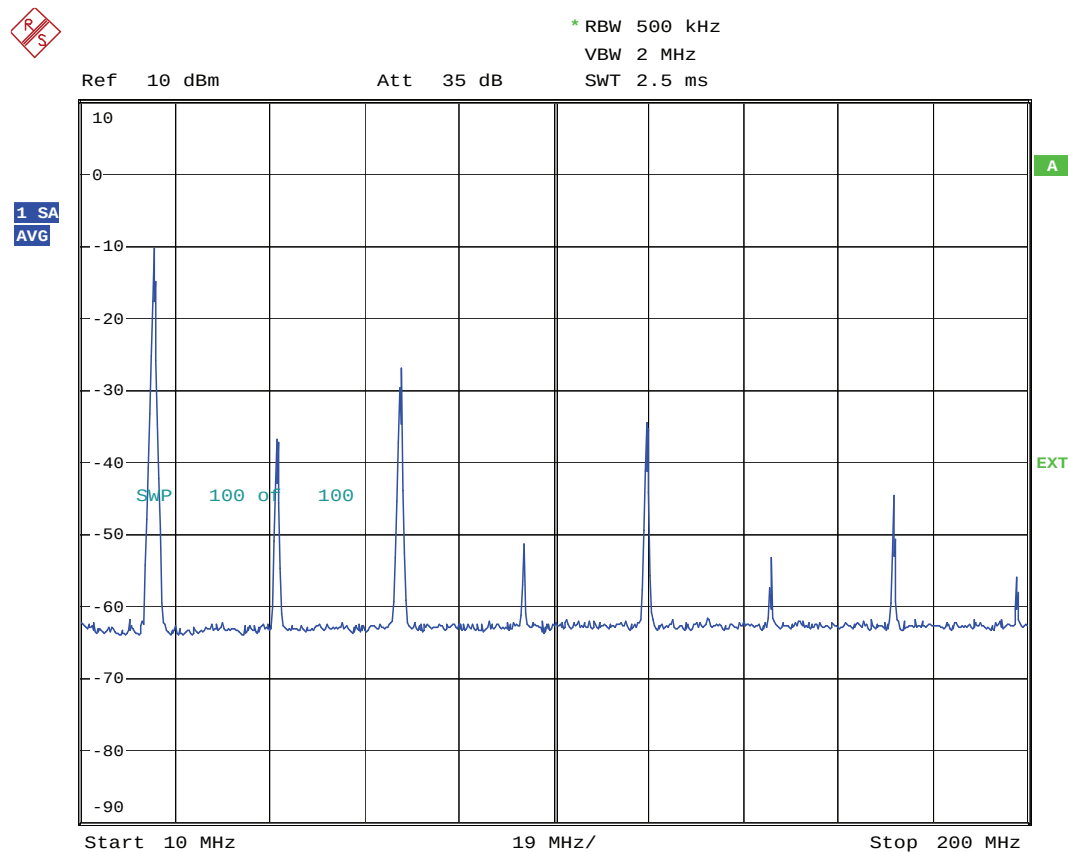
Date: 23.MAY.2007 10:10:09

Spectrum of 12.25 MHz System Clock



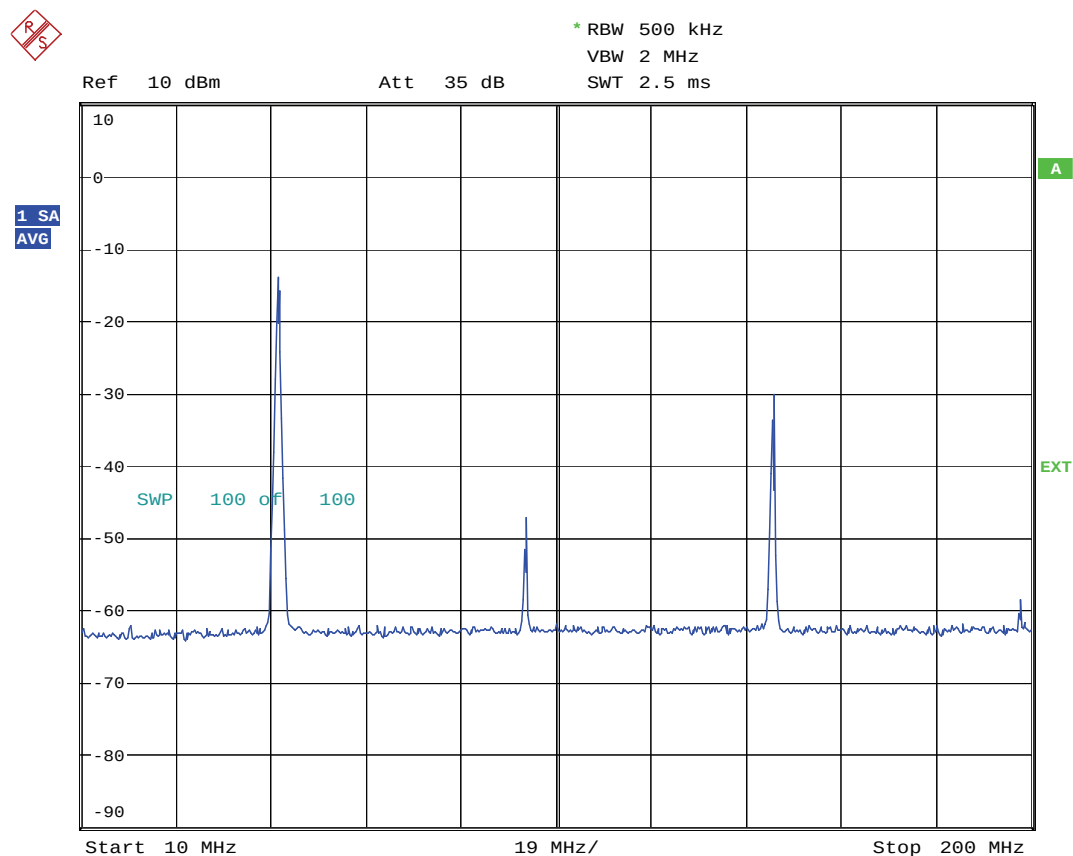
Date: 23.MAY.2007 10:10:44

Spectrum of 24.5 MHz System Clock



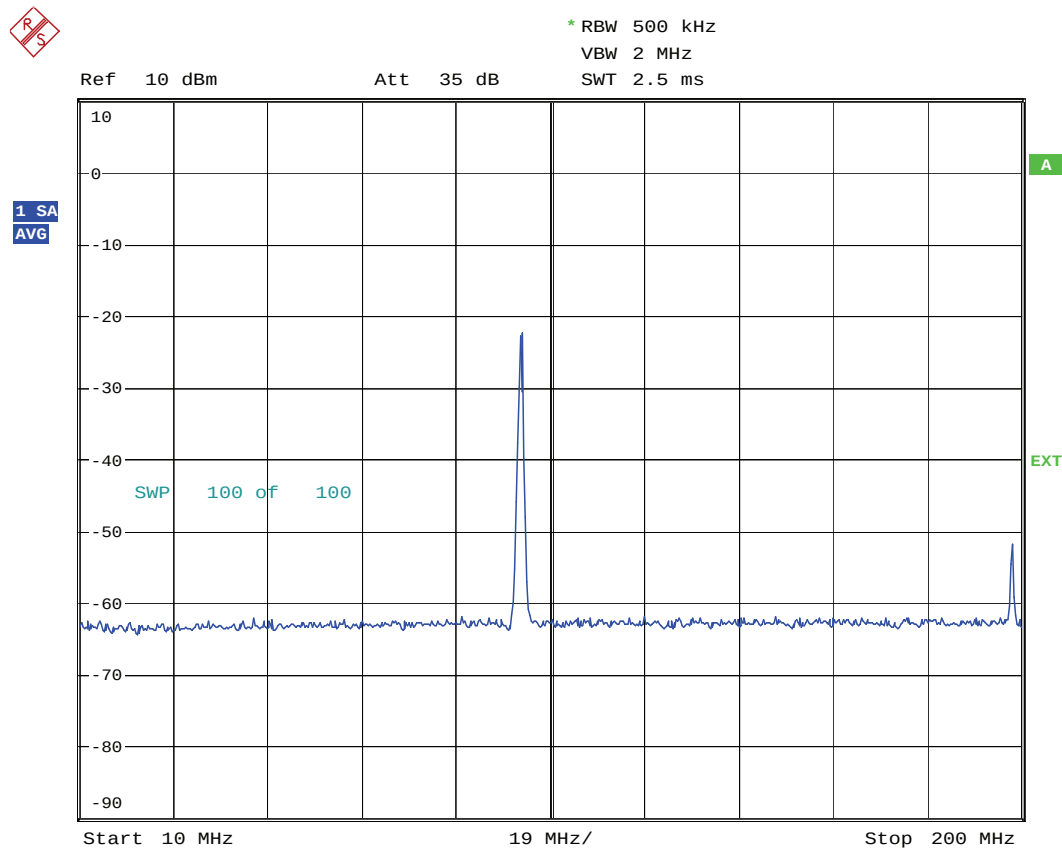
Date: 23.MAY.2007 10:11:54

Spectrum of 49 MHz System Clock



Date: 23.MAY.2007 10:14:42

Spectrum of 98 MHz System Clock



Date: 23.MAY.2007 10:14:02

Agenda

◆ EMI background

- Mechanisms
- Circuit-level causes
- Frequencies
- **Measurements**
- Shielding

◆ Example problem

Measuring EMI

- ◆ Measured by an accredited EMI test facility
 - Open-Air Test Site (OATS)
 - Device placed 3 or 10 meters from measurement antenna
 - Quiet, reflection-free environment
 - Outdoors or anechoic chamber



Measuring EMI—Accredited Test Facility

◆ OATS test results

- Listed in a table
- Includes all frequencies found
- Shows both passing/failing frequencies
- Data for horizontal and vertical receiving antenna polarization

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Note Tool Text Edits Show

Nemko

& EN61000-6-3: 2001
EN61000-6-1: 2001
REPORT NO.: 6L0253EEU1
EQUIPMENT: C8051F340DK, CP2201EK, USB FM RADIO, SINGLE PHASE POL, and TOOLSTICKSK

Test Data -Radiated Emissions, Electric Field, Test# REHE-02

Radiated Emissions Data

Complete: X Job #: 6L0253EEU1 Test #: REHE-02
Preliminary: Page 1 of 1

Client Name: SILICON LABORATORIES INC
EUT Name: MCU DEVELOPMENT KITS
EUT Model #: C8051F340DK
EUT Part #: C8051F340-TB
EUT Serial #: None
EUT Config.: Run BLINK_EXE

Specification: EN 61000-6-3 Reference: CISPR 11
Rod. Ant. #: Temp (deg C): 25 Date: 08/30/06
Bloon Ant. #: 1306 Humidity (%): 24 Time: 14:34
Log Ant. #: 759 EUT Voltage: 230VAC Staff: Brian Boyes
Bilog Ant. #: EUT Frequency: 60Hz Photo ID: 6L0253EEU1-REHE-02
Dipole Ant. #: Phase: Single Peak Bandwidth: 100 KHz
Cable #: 1522 Location: D Gals Video Bandwidth: 100 KHz
Preamp #: 762 Distance: 10m QP Bandwidth: 120 KHz
Limits: na Barometric pressure: 1016
Attenu #: 1264

Meas. Freq. (MHz)	Ant. Pol. (H/V)	Anten. Reading (dB)	Antenna Factor (dB)	Path Loss (dB)	RF Gain (dB)	Corrected Reading (dBuV/m)	Spec. Limit (dBuV/m)	C/N/L (dB)	Pass/Fail	QP readings
30.8	V	0	36.4	13.7	2.2	25.5	23.8	30.0	-6.2	Pass
60	V	0	35.3	9	3.0	27.5	19.5	30.0	-10.5	Pass
62	V	0	35.6	9	3.0	27.5	19.9	30.0	-10.2	Pass
87.7	V	0	37.8	9.5	3.5	27.4	23.5	30.0	-6.5	Pass
150	V	0	28.7	13.6	4.7	27.5	19.2	30.0	-10.8	Pass
290	V	0	33	20.1	6.4	27.5	31.7	37.0	-6.3	Pass
30	H	0	29.1	13.7	2.2	26.5	16.5	30.0	-13.5	Pass
62	H	0	37.6	9	3.0	27.5	21.8	30.0	-8.2	Pass
72	H	0	31.5	8.9	3.1	27.5	16.0	30.0	-14.0	Pass
89	H	0	32.7	9.5	3.5	27.4	12.4	30.0	-17.6	Pass
116	H	0	39	11.7	6.8	27.5	25.9	30.0	-4.1	Pass
137.7	H	0	35	11.7	3.8	27.6	22.9	30.0	-7.1	Pass
137.7	H	0	34.7	12.7	4.2	27.7	23.9	30.0	-6.1	Pass
310	V	0	26.7	19.5	6.8	27.9	25.1	37.0	-11.9	Pass
610	V	0	27	18.8	9.7	27.9	27.6	37.0	-9.4	Pass
310	H	0	26.8	19.5	6.8	27.9	25.2	37.0	-11.8	Pass
610	H	0	27.1	18.8	9.7	27.9	27.7	37.0	-9.3	Pass
310	V	0	26.7	19.5	6.8	27.9	25.1	37.0	-11.9	Pass
610	V	0	27	18.8	9.7	27.9	27.6	37.0	-9.4	Pass
310	H	0	26.8	19.5	6.8	27.9	25.2	37.0	-11.8	Pass
610	H	0	27.1	18.8	9.7	27.9	27.7	37.0	-9.3	Pass

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Measuring EMI

◆ GTEM cell

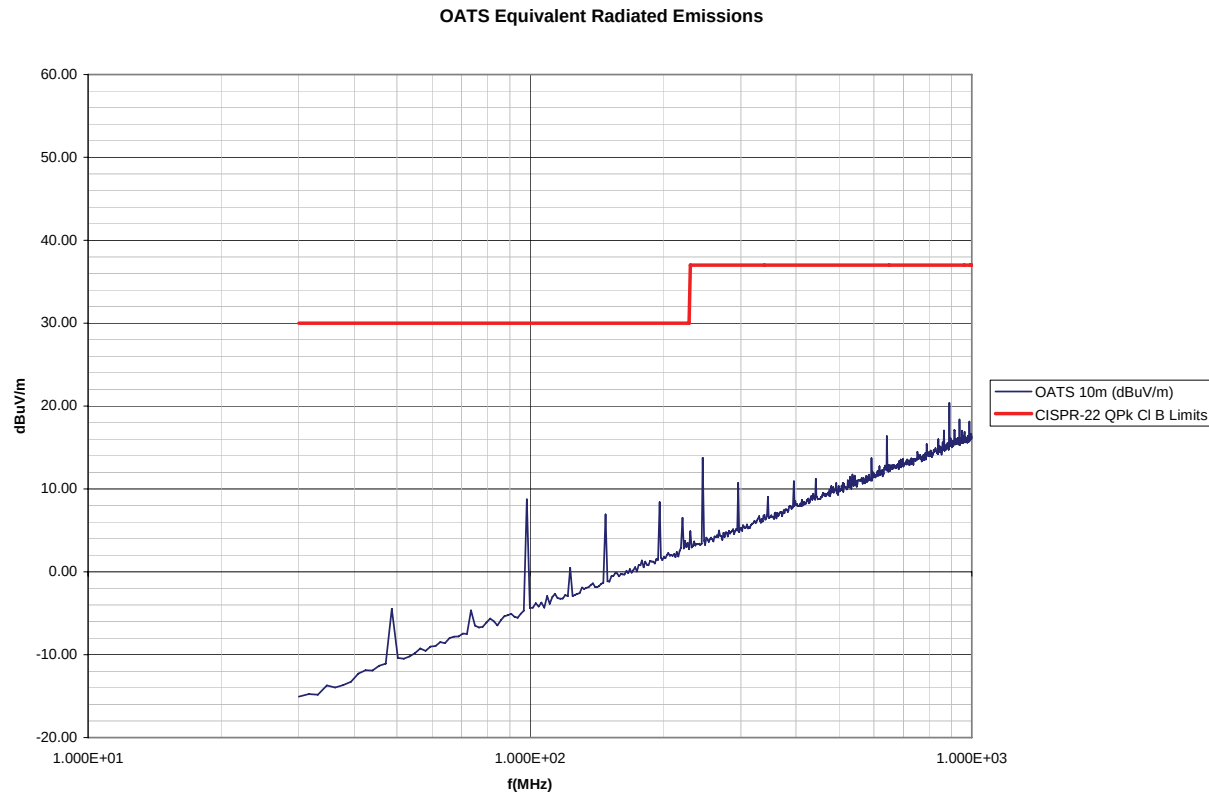
- GTEM cell is an enclosure and antenna in one unit
- Used with a spectrum analyzer and correlation software
- Many digital design companies have one for pre-compliance testing
- Silicon Laboratories has one
- Not normally certified



Measuring EMI—GTEM

◆ GTEM test results

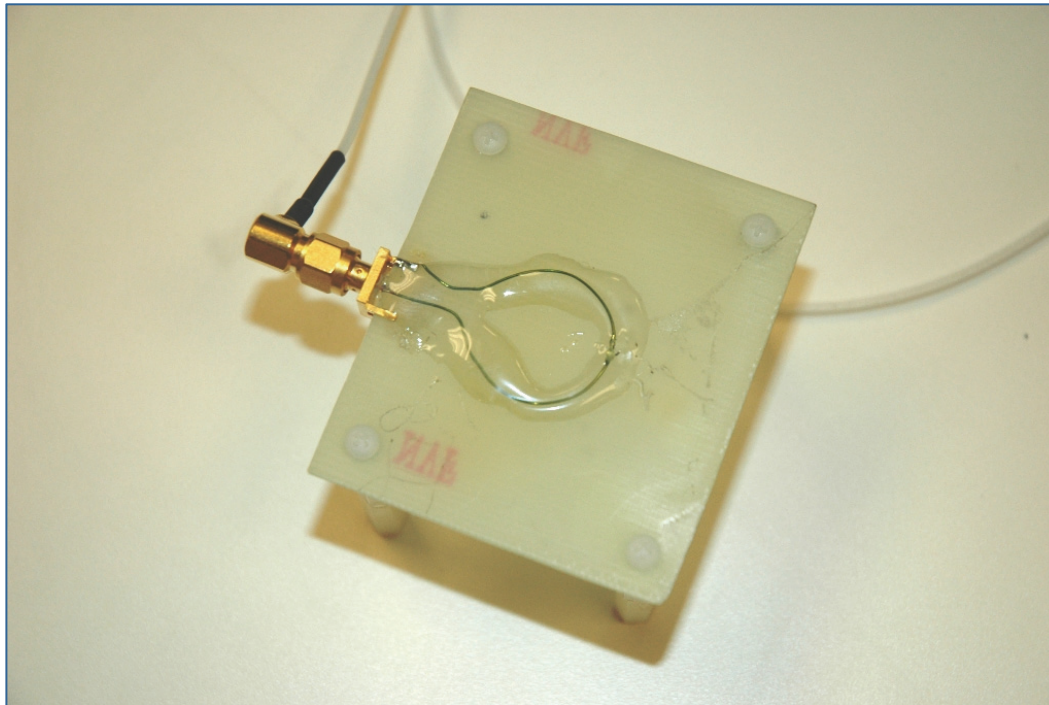
- Continuous test data vs. tabular
- Measurement shows computed OATS equivalent
- Data shows worst-case antenna orientation



Measuring EMI

◆ Loop antenna

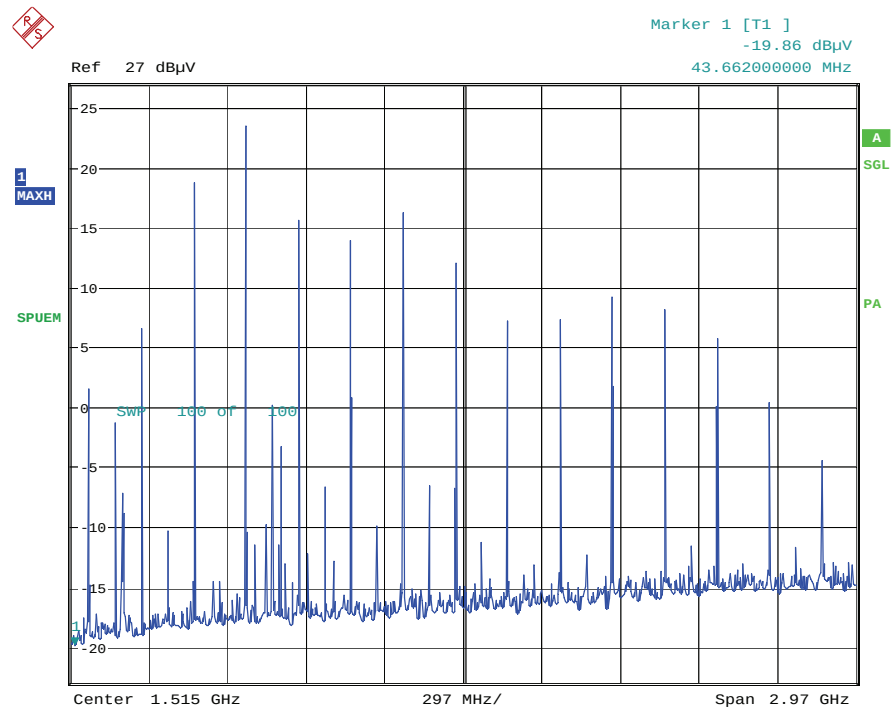
- Simple and inexpensive
- Can make one yourself
- Used with a spectrum analyzer
- Good only for relative measurements



Measuring EMI—Loop Antenna

◆ Loop antenna test results

- Spectrum analyzer plot
- Amplitude units arbitrary as antenna is not calibrated



Date: 3.APR.2007 13:47:56

Agenda

◆ EMI background

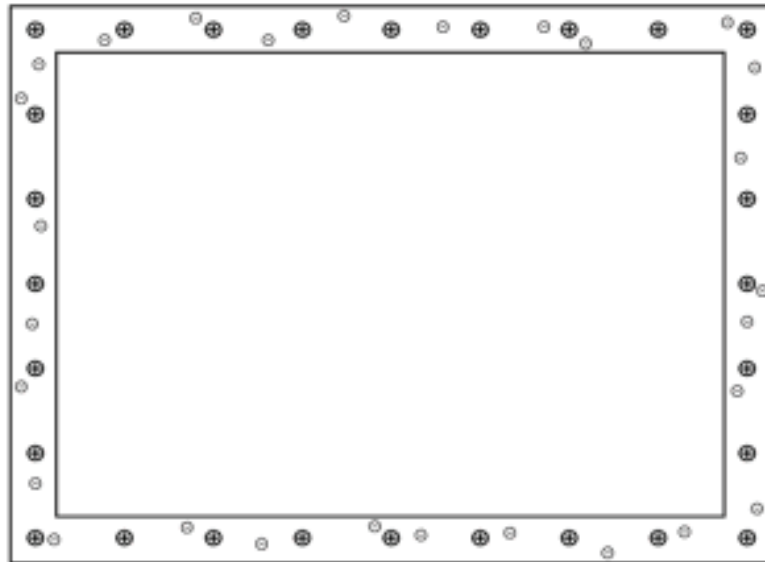
- Mechanisms
- Circuit-level causes
- Frequencies
- Measurements
- Shielding

◆ Example problem

Shielding—Theory

◆ Faraday cage

- Made of conductive material
- Charges in conductor move to cancel electric field
- Faraday cage can keep fields out or in



Shielding—Troubleshooting

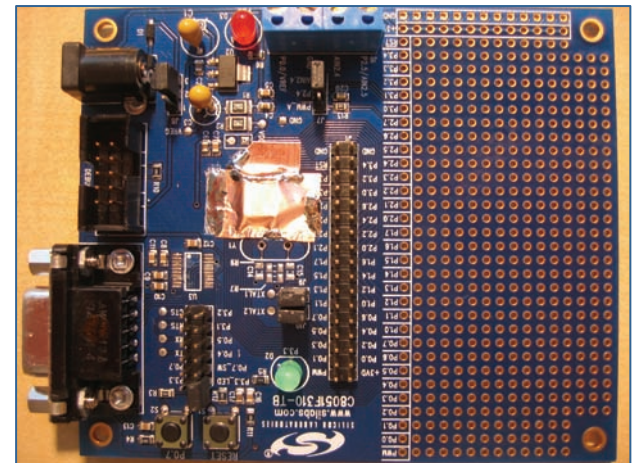
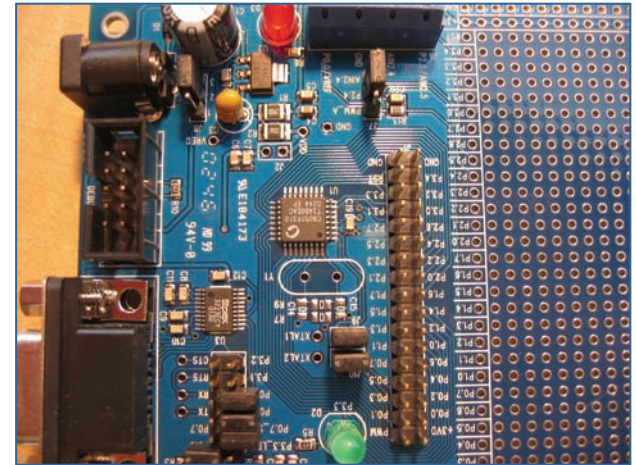
◆ Copper Foil Tape

- Available from 3M (www.3m.com, search for '1125')



◆ Tips and Tricks

- Make good ground connection
 - Leave no gaps
 - Solder to ground in many places
- Start by shielding small areas
 - Shield a device or specific traces rather than a large area: helps pinpoint EMI source
- Adhesive is not conductive
 - (Even if manufacturer says it is)
 - Use solder for good connection
- Use Kapton tape beneath copper
 - Keeps copper tape from shorting out IC pins



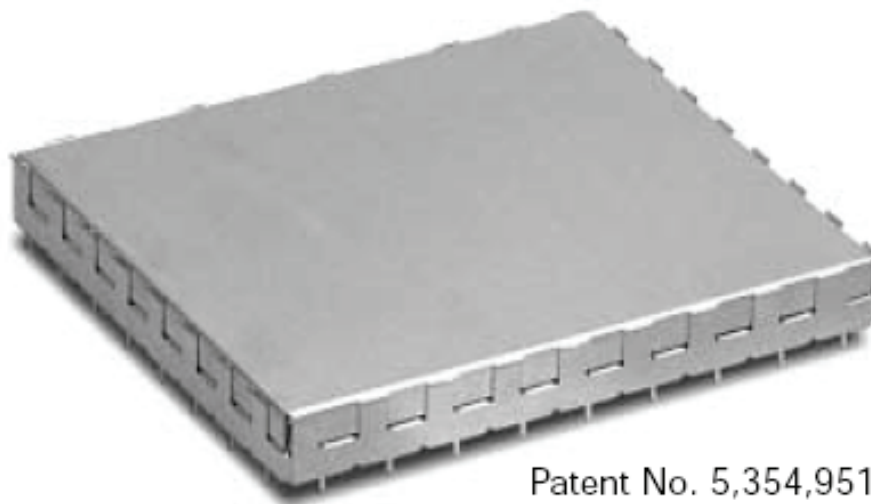
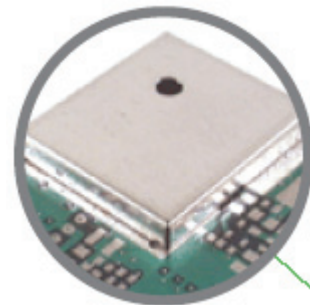
Shielding—Production PCB

◆ Production: Shields

- Commonly used in wireless, computational products
- Effective, but adds cost
- Good source for off-the-shelf shields:

Leader-Tech

(www.leadertechinc.com)



Patent No. 5,354,951

Shielding—Troubleshooting

◆ Conductive paint

- Use to convert non-conductive plastic enclosures to conductive, EMI-shielded enclosures
- Use in troubleshooting or production
- Conductive plastics commonly used in laptop PC's, mobile phones, PDA's, etc
- Available from MG chemicals:
(<http://www.mgchemicals.com/products/shielding.html>)



Agenda

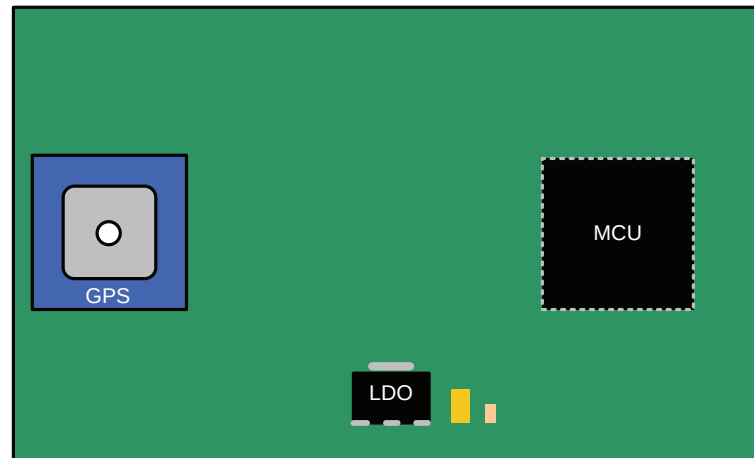
◆ EMI background

- Mechanisms
- Circuit-level causes
- Frequencies
- Measurements
- Shielding

◆ Example problem

Example Problem

- ◆ Product is a GPS data logger using a C8051F120 MCU
- ◆ Problem—GPS receiver sometimes loses satellite reception



- ◆ Hypothesis
 - EMI may be radiating from the micro in to the GPS antenna
 - EMI may be conducted from the micro to the power supply or control lines of the GPS

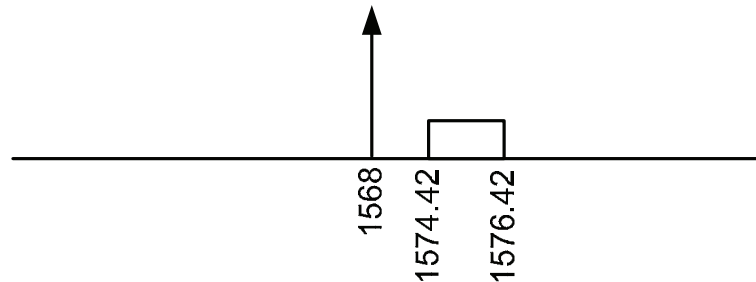
Frequencies

◆ Known

- F120 sysclk: 98MHz (internal 24.5MHz * 4)
- GPS receive band: 1575.42 +/- 1MHz

◆ Are any harmonics close?

- $15 * 98\text{MHz} = 1470\text{MHz}$
- $16 * 98\text{MHz} = 1568\text{MHz}$ (close, but not in GPS RX band)
- $17 * 98\text{MHz} = 1666\text{MHz}$



Frequencies

◆ Nominal case

➤ $\text{sysclk} = 24.5 * 4$

◆ From datasheet

➤ $\text{sysclk} = (24.5 \pm 2\%) * 4$

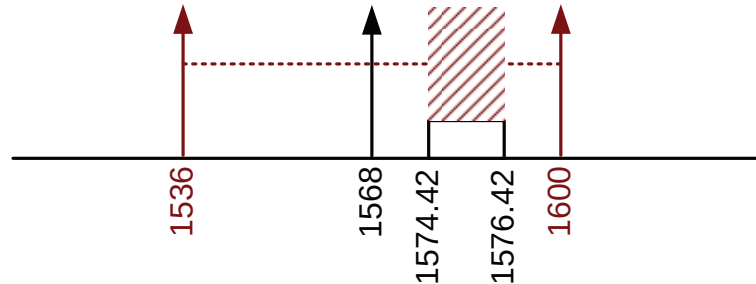
Table 14.1. Oscillator Electrical Characteristics
-40°C to +85°C unless otherwise specified

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
Calibrated Internal Oscillator Frequency		24	24.5	25	MHz
Internal Oscillator Supply					

◆ Revisiting 16th harmonic

➤ $16 * (24.0 * 4) = 1536\text{MHz}$

➤ $16 * (25.0 * 4) = 1600\text{MHz}$



◆ Conclusion

➤ 16th harmonic can interfere with GPS reception

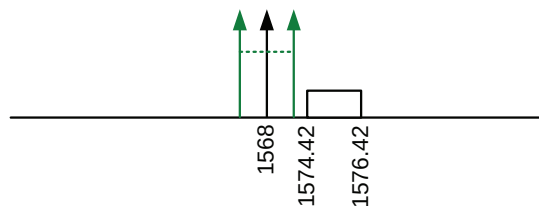
Frequencies—Possible Solutions

1. Use lower sysclk

- Higher-order harmonic at 1568MHz
 - $1568\text{MHz} = 16 * (24.5 * 4) \text{ MHz}$
 - $1568\text{MHz} = 32 * (24.5 * 2) \text{ MHz}$
 - $1568\text{MHz} = 512 * (24.5 / 8) \text{ MHz}$
- Higher order: lower in amplitude

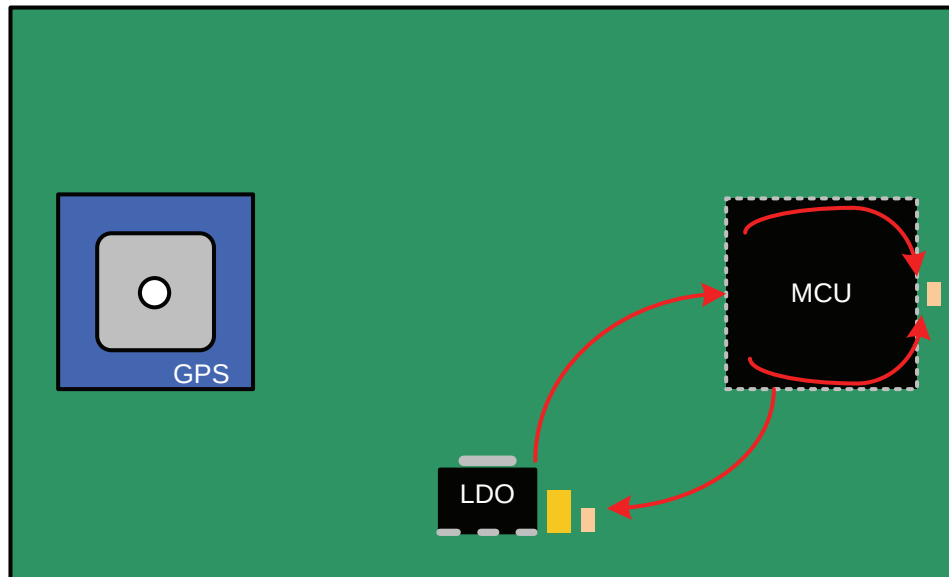
2. Use more accurate sysclk

- 1568MHz does not interfere, but $1568 \pm 2\%$ does
- Crystal, typical: $\pm 20\text{ppm}$
- $24.5 \text{ MHz} \pm 20\text{ppm} = 24.500490 \sim 24.499510 \text{ MHz}$
- $(24.5 * 4) \text{ MHz} \pm 20\text{ppm} = 1567.969 \sim 1568.031 \text{ MHz}$
- Harmonics remain out of GPS RX band



Power Supply Bypass Capacitors

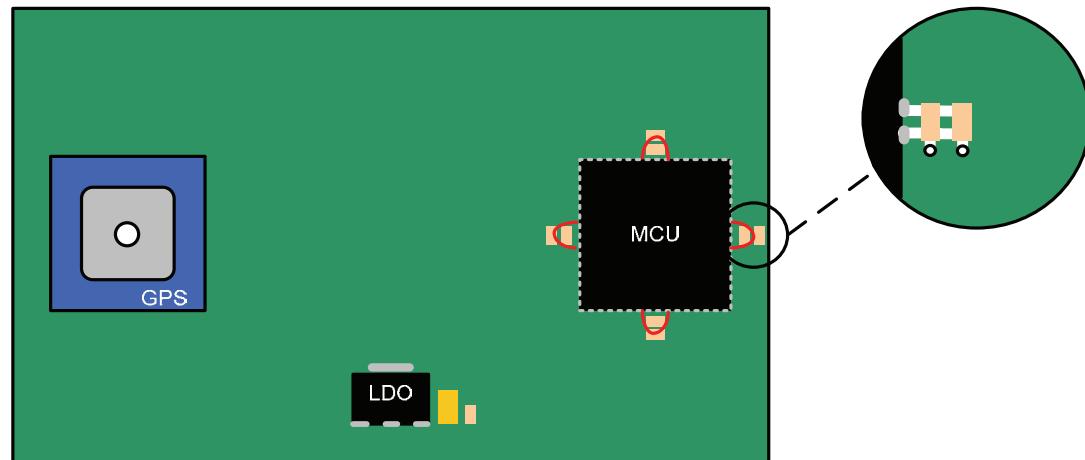
- ◆ Insufficient power supply bypassing
 - C8051F120 has four power supply/ground pin pairs: each should have capacitors
 - Lack of local capacitors may cause larger **current loops**
 - Single value of capacitor may not be effective for all frequencies



Power Supply Bypass Capacitors

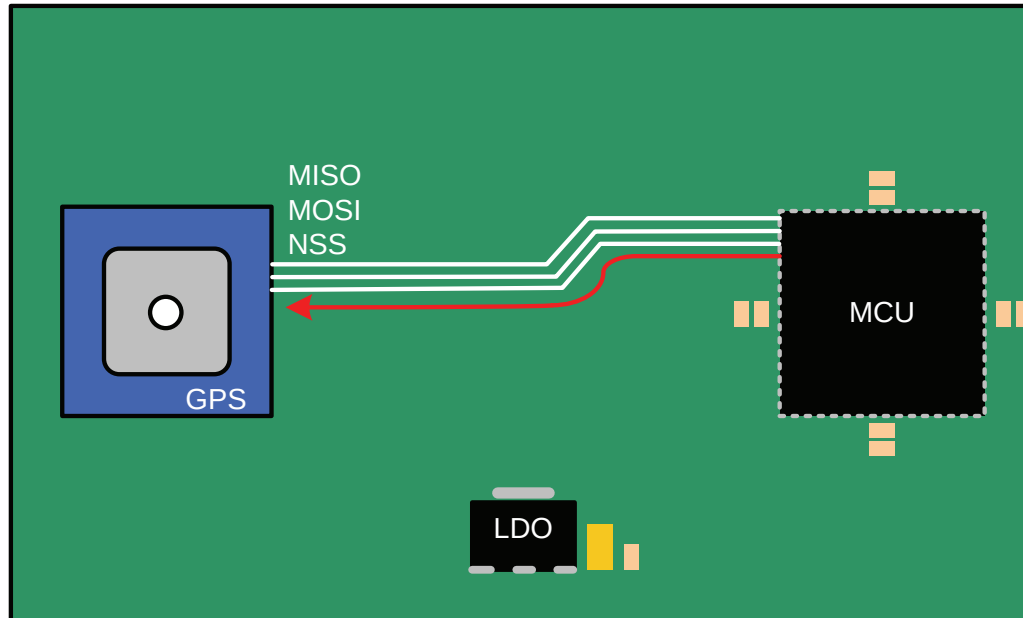
◆ Solution

- Place bypass capacitors at each V_{DD} pin pair (analog and digital)
- Use short connecting traces
- Connect to ground with vias placed close
- Use appropriate capacitance values
 - 22nF: SRF = 50.6 MHz (little help at GPS frequencies)
 - 10pF: SRF = 2240 MHz



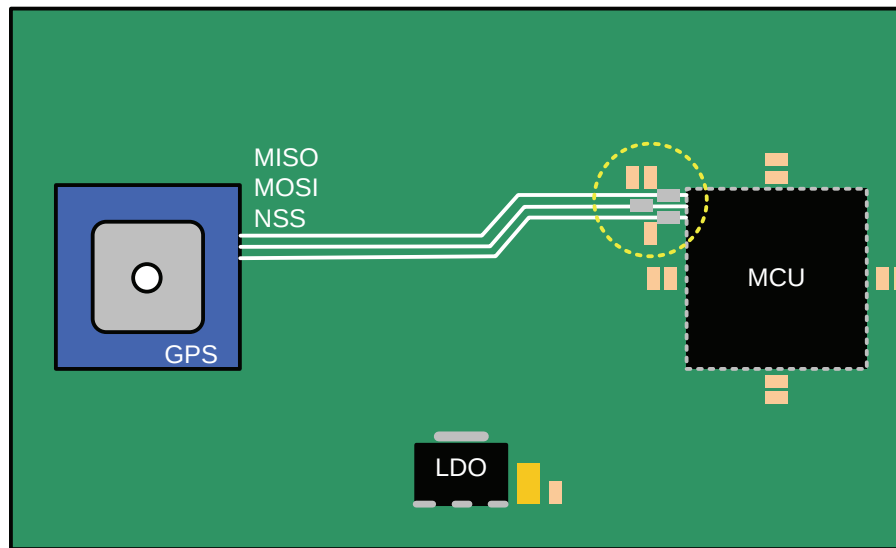
Data Connections

- ◆ EMI may conduct through data lines between MCU and GPS



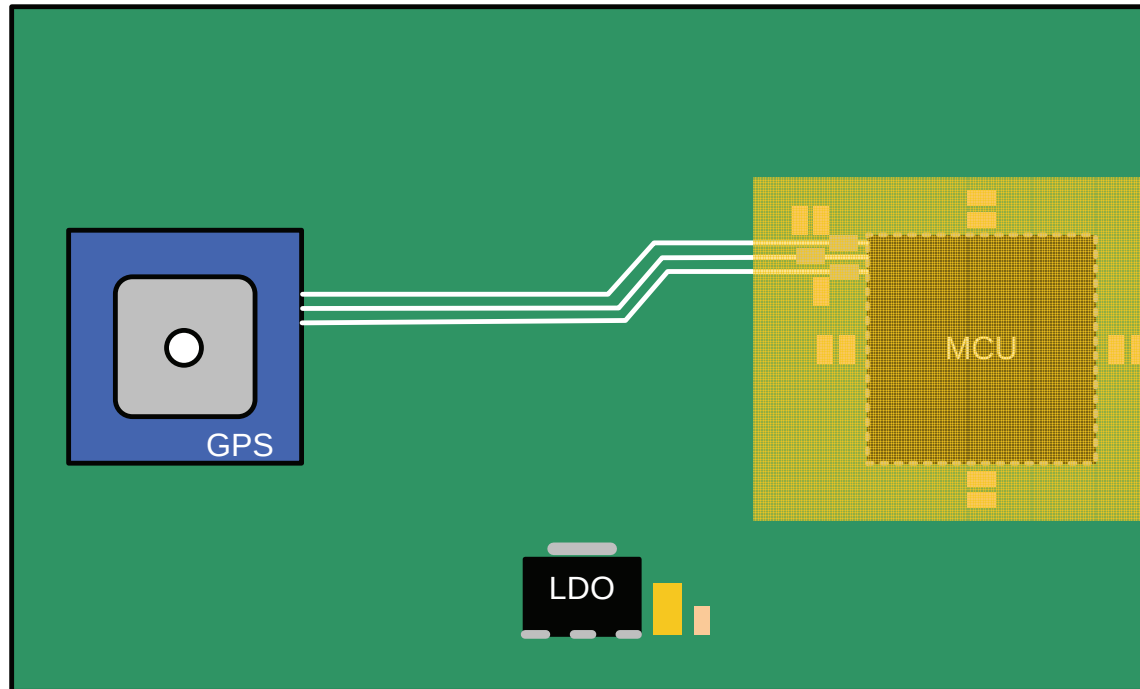
Data Connections

- ◆ Solution—try series resistance/shunt capacitance on data lines
 - Try different combinations
 - Series resistance only
 - Shunt capacitance only
 - Both resistance and capacitance
 - Recall that capacitance may make problem worse



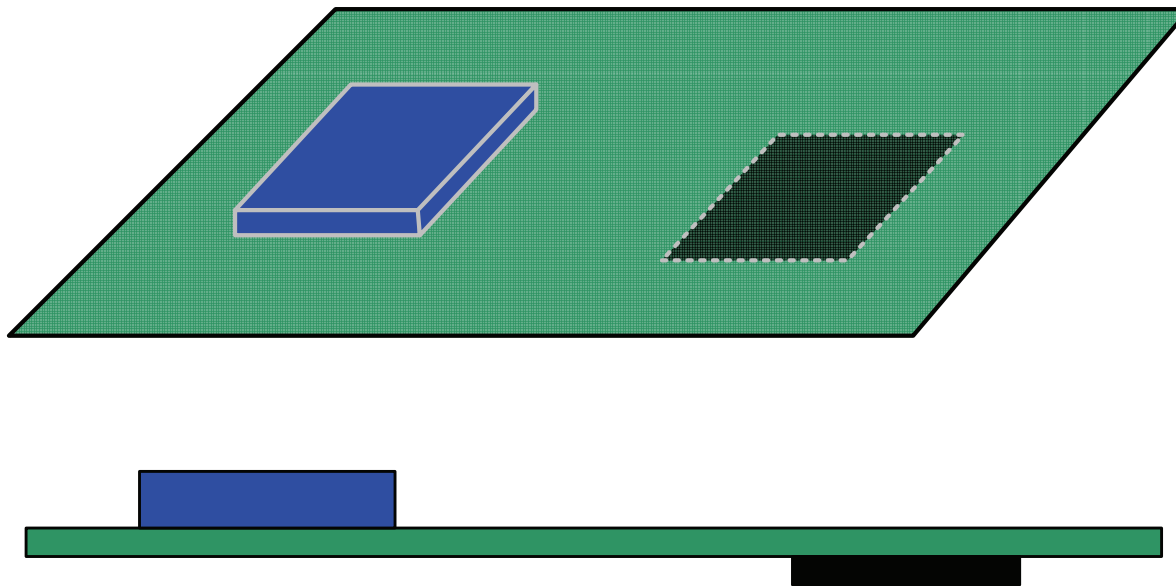
Shielding

- ◆ Add a shield over the MCU area



Shielding

- ◆ Use ground plane as shield
 - Mount MCU and GPS on opposite sides of PCB



Summary

- ◆ To effectively understand EMI problems
 - Understand the frequencies involved and their relation to the system clock
 - Expect high frequency harmonics
 - Consider every node and trace as a potential radiating antenna
- ◆ To effectively troubleshoot EMI problems
 - Think about minimizing the power supply path for high frequencies
 - Select the correct capacitors
 - Design the PCB to minimize loop areas
 - Filter signal lines
 - Use shielding if necessary
- ◆ There is no single EMI fix for all problems
 - Don't be afraid to experiment!

Contact Information

- ◆ MCU Applications Team

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S I L I C O N L A B S

www.silabs.com/MCU