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
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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
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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

![Diagrams showing current flow](image-url)
**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 (sysclk/2, 3, 4, etc)
    - Peripherals often use sysclk/2
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: \[ Z_C = \frac{1}{j \omega C} \] \( (Z_C \rightarrow 0 \text{ as } \omega \rightarrow \infty) \)

- Mag\([Z]\) of an ideal 0.1 uF capacitor:

![Graph showing capacitor impedance vs frequency](image-url)
Choosing Capacitors

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

\[ Z_C = \frac{1}{j\omega C} + j\omega L \]

<table>
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<tr>
<th>Frequency (GHz)</th>
<th>Parasitic inductance</th>
<th>Parasitic inductor</th>
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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 \( f \uparrow \))

- 0.1\( \mu \)F, SRF = 20MHz

<table>
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<tr>
<th>Frequency (GHz)</th>
<th>Capacitor Impedance</th>
<th>Ideal Capacitor</th>
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</tbody>
</table>
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
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

![Graph showing connecting trace impedance](image-url)
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
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
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
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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)  
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
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
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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
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
Loop antenna test results

- Spectrum analyzer plot
- Amplitude units arbitrary as antenna is not calibrated
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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)
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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 * 98MHz = 1470MHz
  - 16 * 98MHz = 1568MHz (close, but not in GPS RX band)
  - 17 * 98MHz = 1666MHz
Frequencies

- **Nominal case**
  - sysclk = 24.5 * 4

- **From datasheet**
  - sysclk = (24.5 ± 2%) * 4

- **Revisiting 16th harmonic**
  - 16 * (24.0 * 4) = 1536MHz
  - 16 * (25.0 * 4) = 1600MHz

- **Conclusion**
  - 16th harmonic can interfere with GPS reception
Frequencies—Possible Solutions

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

2. Use more accurate sysclk
   - $1568\text{MHz}$ does not interfere, but $1568 \pm 2\%$ does
   - Crystal, typical: $\pm 20$ppm
   - $24.5 \text{ MHz} \pm 20$ppm = $24.500490 \sim 24.499510 \text{ MHz}$
   - $(24.5 \times 4) \text{ MHz} \pm 20$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
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
  ➢ mcuapps@silabs.com