Essential Rules of Thumb

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Be sure to check out Eric’s Rules of Thumb column on EDN.com

Outline

- What’s a rule of thumb and why do we care
- Ten incredibly useful rules of thumb
- Examples
Five Critically Important Processes for EVERY Engineer

Measure
(validate anchor to reality, characterize)

Model
(turn physical system into mathematical approximation)

Understand
(Essential Principles "...just say know"

Simulate
(use virtual prototype to explore design space: rules of thumb, approximations, numerical simulations)

Analyze
(is it reasonable?, extract useful information → make decisions)

Rules of Thumb:
"sometimes an ok answer NOW! is better than a good answer late"

Approximations:
Analytic approximations, useful for quick estimates and early design tradeoffs

\[ L_{eq} = 5\left[ \ln\left(\frac{2d}{w+t}\right) + \frac{1}{2}\right] H \]

Rule of thumb is:
"better than a guess"
"easier to remember than an equation"
"a lot quicker than a simulation"

Numerical simulation: field solver, circuit simulations,
Bogatin’s 10 Rules: (PCD&F Magazine, Aug 10, 2010 or www.beTheSignal.com, BTS218)

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<th>Rule</th>
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<td>Answer “it depends” questions by “putting in the numbers”</td>
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<td>2</td>
<td>Separate myth from reality by “putting in the numbers”</td>
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<td>3</td>
<td>Watch out for the whack-a-mole effect</td>
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<td>Most important step in solving a problem: find the root cause</td>
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<td>Apply the Youngman Principle to optimize designs</td>
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<td>Sometimes an OK answer now! is better than a good answer late</td>
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<td>Evaluate “bang for the buck” with virtual prototypes</td>
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<td>Watch out for mink holes</td>
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<td>9</td>
<td><strong>Never perform a measurement or simulation without first anticipating what you expect to see</strong></td>
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<td>10</td>
<td>There are two kinds of designers: those who have signal integrity problems and those who will</td>
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**Rule #9:** Never do a measurement or simulation without first anticipating what you expect to see.

If you are wrong, there is a reason—either the set up is wrong or your intuition is wrong. Either way, by exploring the difference, you will learn something.

If you are right, you get a nice warm feeling that you understand what is going on.

**Corollary to rule #9:**

There are so many ways of screwing up a measurement or simulation, you can never do too many consistency checks.
Typical questions to answer with a rule of thumb

- What is the bandwidth of a signal with a rise time of 0.3 nsec, typical of DDR3?

- The fab vendor comes back with a line width of 8 mils and dielectric thickness of 8 mils for a 50 Ohm microstrip. Is this reasonable?

- How much total inductance is in a connector 0.25 inches long? Is this too much for 4 signals lines with 0.3 nsec rise time?

- How much radiated emissions is expected from 10 µA of common current in a 1 m long cable, in a class B test?

Most Important Principle of Applying a Rule of Thumb

“if all you have is a hammer, everything looks like a nail”
Cautions when using Rules of Thumb

- Always start every problem with a rule of thumb
- Never sign off on a design based on a rule of thumb
- They help "calibrate" your engineering intuition: help establish "what is reasonable?"
- Not designed to be accurate- designed to be easy to use, easy to remember
- Usually have their origin in a specific situation: try to be aware of the assumptions
- If you are concerned about the difference between 50 Ohms and 60 Ohms, don’t use a rule of thumb!
- If you have to use a calculator, do not use a rule of thumb
- If you want confidence in the answer, don’t use a rule of thumb!
- If you ask too many questions, don’t use a rule of thumb!

Summary of 10 Rules of Thumb

1. Speed of a signal on a transmission line: \( v \approx 6 \text{ inches/nsec} \)
2. Bandwidth of a signal is related to the rise time of the signal: \( \text{BW} = 0.35/\text{RT} \)
3. If all you know is the clock frequency signal: \( \text{BW} = 5 \times F_{\text{clock}} \)
4. Aspect ratio for 50 Ohm Transmission line in FR4: microstrip: \( w/h = 2 \), stripline: \( w/h = 1 \)
5. \( L \) and \( C \) in a 50 Ohm FR4 transmission line: \( L_{\text{per Len}} \approx 8 \text{ nH/inch}, C_{\text{per Len}} \approx 3.3 \text{ pf/in} \)
6. Total inductance in a return path: \( L_{\text{per Len}} \approx 10 \text{ nH/inch} \)
7. \% ground bounce noise = 2\% per signal per nH/RT[nsec]
8. Skin depth in copper is 2 \( \mu \) at 1 GHz
9. Attenuation FOM: lossy: 0.2 dB/in/GHz, low loss: 0.1 dB/inch/GHz
10. 3 m far field \( E \approx 0.4 \text{ uV/m/uA/MHz} \)
Rule of Thumb #1:

- Speed of a signal on a transmission line: \( v \approx 6 \text{ inches/nsec} \)

Examples: \( v \approx 6 \text{ inches/nsec} \)

- What is the time delay for a 3 foot cable?

- For how long will a driver see a 50 Ohm load, when the transmission line it is connected to is 6 inches long?
Rule of Thumb #2: Bandwidth of a signal is related to the rise time of the signal: $BW = \frac{0.35}{RT}$

Bandwidth: the highest sine wave frequency that is “significant”

The edge of a re-created square wave built from a limited number of harmonics (known bandwidth)

![Graph showing bandwidth vs. rise time](image)

Example

- What is the bandwidth of a signal with a rise time of 1 nsec?

- A scope has a bandwidth of 30 GHz. What is the shortest rise time it can record?

$\text{Example} \quad BW[\text{GHz}] = \frac{0.35}{RT[\text{nsec}]} \quad \text{and} \quad RT[\text{nsec}] = \frac{0.35}{BW[\text{GHz}]}

- What is the bandwidth of a signal with a rise time of 1 nsec?

- A scope has a bandwidth of 30 GHz. What is the shortest rise time it can record?
Rule of Thumb #3: If all you know is the clock frequency signal: \( BW = 5 \times F_{\text{clock}} \)

What is the BW for these signals, each with exactly the same \( F_{\text{clock}} \)?

\[
\text{RT}[\text{nsec}] = ? \times \text{Period}[\text{nsec}]
\]

Assumption:
\[
\text{RT}[\text{nsec}] = 7\% \times \text{Period}[\text{nsec}]
\]

\[
\frac{BW}{RT} = \frac{0.35}{0.07 \times \text{Period}} = 5 \times F_{\text{clock}}
\]

Examples

- What is the bandwidth of a 600 MHz clock?
- What is the bandwidth (@ the TX) of a 5 Gbps PCIe II signal?
Rule of Thumb #4:

Aspect ratio for a 50 Ohm Transmission line in FR4:

- microstrip: Line width/dielectric thickness = 2
- stripline: Line width/dielectric thickness = 1

- $w = 2 \times h$
- $b = 2 \times h$
- $h = w$

Examples

- In microstrip in FR4, what dielectric thickness gives 50 Ohms for a line width of 5 mils?
- In stripline in FR4, what dielectric thickness gives 50 Ohms for a line width of 7 mils?
Rule of Thumb #5:

L and C in a 50 Ohm FR4 transmission line
\[ L_{\text{perLen}} \approx 8 \text{ nH/inch} \]
\[ C_{\text{perLen}} \approx 3.3 \text{ pf/in} \]

\[ Z_0 = \sqrt{\frac{L_{\text{total}}}{C_{\text{total}}}} \]
\[ TD = \sqrt{\frac{L_{\text{total}}}{C_{\text{total}}}} \frac{TD}{Z_0} \]
\[ TD = \frac{Len}{c} \sqrt{Dk} \]
\[ C_{\text{total}} = \frac{Len}{c} \sqrt{Dk} \frac{Z_0}{6 \text{ nsec} / \text{in}} \times 50\Omega = 3.3 \text{ pf/in} \times Len \]
\[ L_{\text{total}} = TD \times Z_0 \]
\[ L_{\text{total}} = \frac{Len}{c} \sqrt{Dk} \times Z_0 = \frac{Len}{6 \text{ nsec} / \text{in}} \times 50\Omega = 8 \text{ nH/in} \times Len \]

Examples

L and C in a 50 Ohm FR4 transmission line
\[ L_{\text{perLen}} \approx 8 \text{ nH/inch} \]
\[ C_{\text{perLen}} \approx 3.3 \text{ pf/in} \]

- How much capacitance is there in a package lead about 0.25 inches long?

- How much loop inductance is there in a surface trace from a capacitor to a via that is 0.2 inches long?
Rule of Thumb #6: total inductance in a return path: \( L_{\text{perLen}} \approx 10 \text{nH/inch} \)

For \( w = s \)

\[ L_{\text{total}} \approx 10 \text{nH/inch} \times \text{Len} \]

Examples

- How much total inductance is in a connector that is 0.5 inches long?

- How much total inductance is there in a via that is 0.064 inches long?
### Rule of Thumb #7: % ground bounce noise = 2% per signal per nH/RT[nsec]

\[
V_{\text{ground bounce}} = L_{\text{return}} \frac{\text{di}}{\text{dt}} = V = \frac{L}{Z_0} \frac{\text{di}}{\text{dt}} = L_{\text{return}} V_{\text{signal}} = n \cdot \frac{V_{\text{signal}}}{Z_{0\text{RT}}} = L_{\text{return}} V_{\text{signal}} = n \cdot \frac{V_{\text{signal}}}{Z_{0\text{RT}}} = L_{\text{return}} \frac{V_{\text{signal}}}{Z_{0\text{RT}}} = n \cdot \frac{V_{\text{signal}}}{Z_{0\text{RT}}} = 2\% \quad \frac{n L_{\text{return}}}{Z_{0\text{RT}}}
\]

% noise = 2% per signal per nH/RT[nsec]

### Examples

- A package lead has a total inductance in the return path of 5 nH. 3 signals share the return path. If the rise time is 1 nsec, how much ground bounce noise is expected?

- A connector lead is 0.25 inches long. How much ground bounce will there be if 5 signals share it with a rise time of 0.5 nsec?
Rule of Thumb #8: skin depth in copper is 2 \( \mu \) @ 1 GHz

Skin depth, \( \delta = \frac{1}{\sqrt{\pi \sigma \mu_f}} = 2\mu \sqrt{\frac{1}{f[GHz]}} \)

For copper:
- \( d = 2\mu \) @ 1 GHz
- \( d = 20\mu \) @ 10 MHz

Examples

- Above what frequency is the current frequency dependent in ½ oz copper, \( t = 17\mu \)?

- Surface roughness of VLP (very low profile) copper is about 2 \( \mu \) rms. Above what freq is most of the current seeing the surface roughness and increasing the resistance over smooth copper?
Rule of Thumb #9: \[ \text{Attenuation FOM} : \]  
lossy: 0.2 dB/in/GHz, low loss: 0.1 dB/inch/GHz

![Graph showing attenuation](image)

\[ \text{atten[dB/in]} \sim \frac{1}{w[\text{mils}]} \sqrt{f[\text{GHz}]} \times 2.3 \times f[\text{GHz}] \times Df \times \sqrt{Dk} \]

**FR4 Example:** @ 4 GHz, (8 Gbps) \( w = 5 \text{ mils}, Dk = 4.3, Df = 0.02 \)

\[ \text{atten[dB/in]} \sim \frac{1}{5} \sqrt{4} \times 2.3 \times 4 \times 0.02 \times \sqrt{4.3} = \]

**Figure of Merit (FOM) \sim 0.22 dB/in/GHz**

\[ 0.4 \text{dB/in} + 0.5 \text{dB/in} = 0.9 \text{dB/in} \]

**Megtron6 Example:** @ 4 GHz, (8 Gbps) \( w = 5 \text{ mils}, Dk = 3.7, Df = 0.002 \)

\[ \text{atten[dB/in]} \sim \frac{1}{5} \sqrt{4} \times 2.3 \times 4 \times 0.002 \times \sqrt{3.7} = \]

**Figure of Merit (FOM) \sim 0.1 dB/in/GHz**

Very expensive material wasted by conductor loss

\[ 0.4 \text{dB/in} + 0.035 \text{dB/in} = 0.435 \text{dB/in} \]

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**Examples**

**Attenuation FOM**:  
lossy: 0.2 dB/in/GHz, low loss: 0.1 dB/inch/GHz

- How much attenuation is expected at the Nyquist in a 20 inch FR4 channel for PCIe III? Is this a lot or a little?

- How much attenuation is expected at the Nyquist for a 20 Gbps channel in Megtron6 that is 40 inches long? Is this a lot or a little?
Rule of Thumb #10:

3 m far field is $E \sim 0.4 \text{ uV/m/uA/MHz}$

$$E[V/m] = 4\pi \times 10^{-7} \frac{f[Hz] \times I[A] \times Len}{R}$$

For specific case: Len = 1 m, R = 3 m (Class B)

$E[uV/m/uA/MHz] = 0.4$

Examples

- What is the 3 m electric field strength for 10 uA of common current in 1 m of peripheral cable at 10 MHz? Is this good or bad?

- How much common current at ~ 100 MHz in a 1 m cable will fail FCC part 15 class B? (100 uV/m will fail)
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*Use them wisely*