Essential Rules of Thumb

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

TELEDYNE LECROY
Everywhereyoulook™

Dr. Eric Bogatin
Signal Integrity Evangelist
Teledyne LeCroy
www.beTheSignal.com

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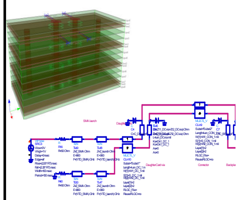
Outline

- 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

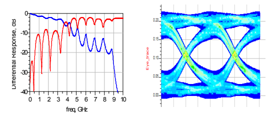


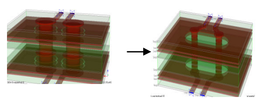
Measure
(validate- anchor to reality, characterize)

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)



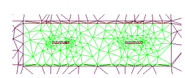


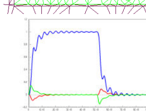
Analyze
(is it reasonable?, extract useful information → make decisions)

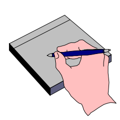
Rules of Thumb:

"sometimes an ok answer NOW! is better than a good answer late"

Numerical simulation: field solver, circuit simulations,





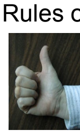


Approximations:
Analytic approximations, useful for quick estimates and early design tradeoffs

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

Accuracy

Rules of thumb



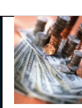
$v = 6 \, in/nsec$

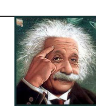
$L = 8 \, nH/in$

$BW = 5 \times F_{clock}$

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

Effort:





Bogatin's 10 Rules: (PCD&F Magazine, Aug 10 , 2010 or www.beTheSignal.com, BTS218))

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

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:

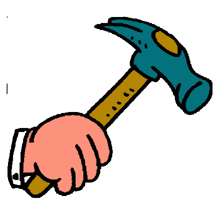
There are so many ways of screwing up a measurement or simulation, you can never do too many consistency checks

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 uA 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

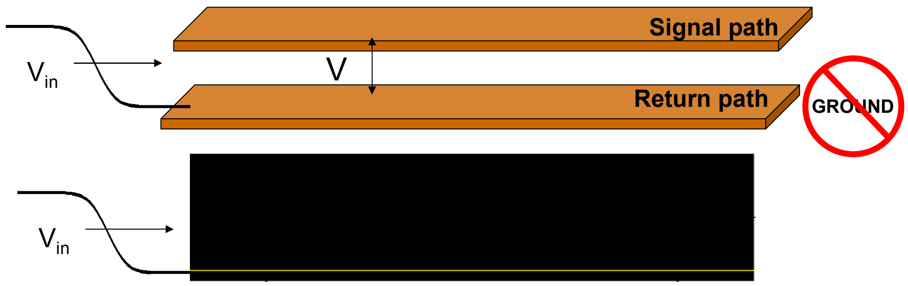
- Always start every problem with a rule of thumb
- Never sign off on a design based on a rule of thumb
- They help "calibrate" your engineering intuition: help establish "what is reasonable?"
- Not designed to be accurate- designed to be easy to use, easy to remember
- Usually have their origin in a 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 ~ 6 inches/nsec
2. Bandwidth of a signal is related to the rise time of the signal: BW = 0.35/RT
3. If all you know is the clock frequency signal: BW = 5 x F_{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_{perLen} ~ 8 nH/inch, C_{perLen} ~ 3.3 pf/in
6. total inductance in a return path: L_{perLen} ~ 10 nH/inch
7. % ground bounce noise = 2% per signal per nH/RT[nsec]
8. skin depth in copper is 2 u @ 1 GHz
9. Attenuation FOM : lossy: 0.2 dB/in/GHz, low loss: 0.1 dB/inch/GHz
10. 3 m far field E ~ 0.4 uV/m/uA/MHz

Rule of Thumb #1:

speed of a signal on a transmission line:
v ~ 6 inches/nsec



$$v = \frac{12\,\frac{\text{inches}}{\text{nsec}}}{\sqrt{Dk}} = \frac{12\,\frac{\text{inches}}{\text{nsec}}}{\sqrt{4}} = \frac{12\,\frac{\text{inches}}{\text{nsec}}}{2} = 6\,\frac{\text{inches}}{\text{nsec}} = 15\,\frac{\text{cm}}{\text{nsec}}$$

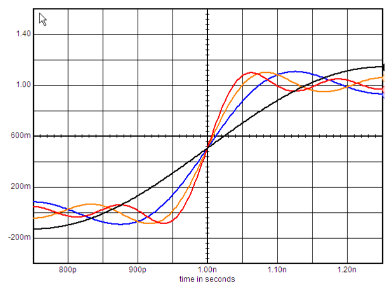
Examples: v ~ 6 inches/nsec

- 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?

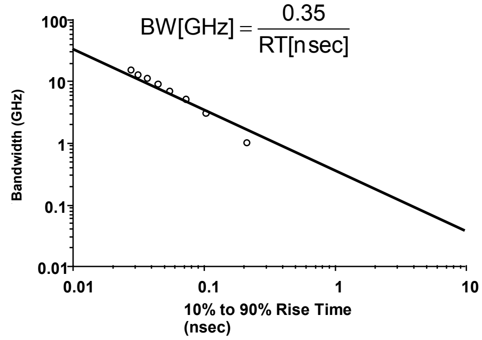
Rule of Thumb #2: Bandwidth of a signal is related to the rise time of the signal: BW = 0.35/RT

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)



$$BW[GHz] = \frac{0.35}{RT[nsec]}$$



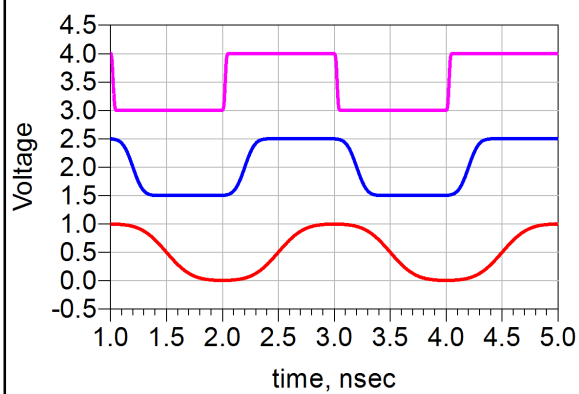
Example

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

- 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 x F_{clock}

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



RT[nsec] = ? x Period[nsec]

Assumption:
RT[nsec] = 7% x Period[nsec]

$$BW = \frac{0.35}{RT} = \frac{0.35}{0.07 \text{ x Period}} = 5 \text{ x } F_{clock}$$

Examples

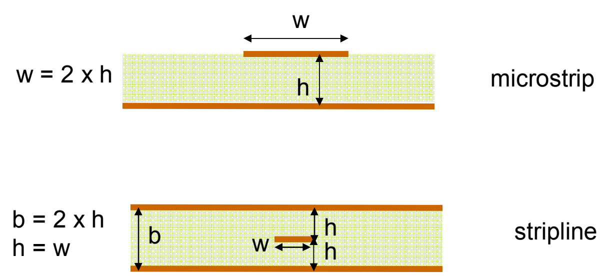
BW = 5 x F_{clock}

- 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



Examples

Aspect ratio for a 50 Ohm Transmission line in FR4:
microstrip: w/h = 2, stripline: w/h = 1

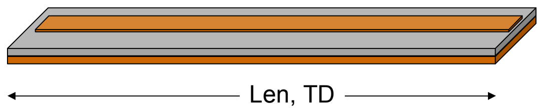
- In microstrip in FR4, what dielectric thickness gives 50 Ohms for a line width of 5 mils?
- In stripline in FR4, what dielectric thickness gives 50 Ohms for a line width of 7 mils?

Rule of Thumb #5:

L and C in a 50 Ohm FR4 transmission line

L_{perLen} ~ 8 nH/inch

C_{perLen} ~ 3.3 pf/in



$$Z_0 = \sqrt{\frac{L_{total}}{C_{total}}} \qquad TD = \sqrt{L_{total} C_{total}} \qquad TD = \frac{Len}{c}\sqrt{Dk}$$

$$C_{total} = \frac{TD}{Z_0} \qquad C_{total} = \frac{\frac{Len}{c}\sqrt{Dk}}{Z_0} = \frac{Len}{6\,{}^{in}/_{nsec} \times 50\Omega} = 3.3\,{}^{pF}/_{in} \times Len$$

$$L_{total} = TD \times Z_0 \qquad L_{total} = \frac{Len}{c}\sqrt{Dk} \times Z_0 = \frac{Len}{6\,{}^{in}/_{nsec}} \times 50\Omega = 8\,{}^{nH}/_{in} \times Len$$

Examples

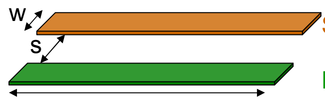
L and C in a 50 Ohm FR4 transmission line

L_{perLen} ~ 8 nH/inch

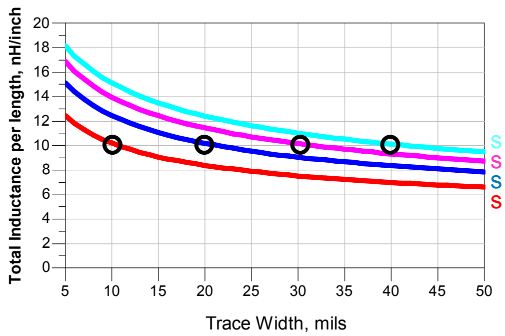
C_{perLen} ~ 3.3 pf/in

- 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_{perLen} ~ 10 nH/inch



Total inductance of return path

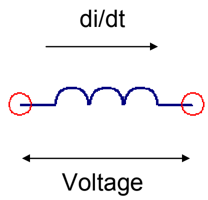


For w = s
L_{total} ~ 10 nH/inch x Len

Examples total inductance in a return path: L_{perLen} ~ 10 nH/inch

- 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]



$$V = L\frac{dI}{dt}$$

When the L is the return path, V is "ground bounce"

$$V_{gndBnc} = L_{return}\frac{dI}{dt}$$

$$V_{gndBnc} = L_{return}\frac{dI}{dt} = L_{return}\frac{V_{signal}}{Z_0 RT} = L_{return}\, n\frac{V_{signal}}{Z_0 RT}$$

$$dI = \frac{V_{signal}}{Z_0}$$

$$dt = RT$$

$$\%noise = \frac{V_{gndBnc}}{V_{signal}} = L_{return}\, n\frac{V_{signal}}{Z_0 RT} = n\frac{L_{return}}{50\Omega\, RT} = 2\%\frac{n\, L_{return}}{RT}$$

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

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

- 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?

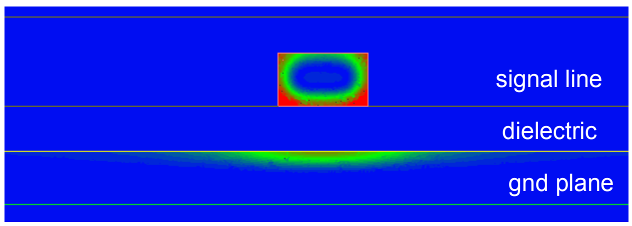
Rule of Thumb #8: skin depth in copper is 2 u @ 1 GHz

$$\text{Skin depth, } \delta = \sqrt{\frac{1}{\pi \sigma \mu_0 \mu_r f}} \qquad = 2\mu\sqrt{\frac{1}{f[GHz]}}$$

For copper:

d = 2µ @ 1 GHz

d = 20µ @ 10 MHz



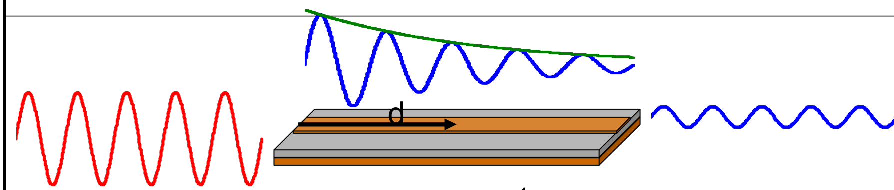
Examples

skin depth in copper is 2 u @ 1 GHz

- Above what frequency is the current frequency dependent in ½ oz copper, t = 17u?
- Surface roughness of VLP (very low profile) copper is about 2 u rms. Above what freq is most of the current seeing the surface roughness and increasing the resistance over smooth copper?

Rule of Thumb #9:

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



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

FR4 Example: @ 4 GHz, (8 Gbps) w = 5 mil, Dk = 4.3, Df = 0.02

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

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

Figure of Merit (FOM) ~ 0.22 dB/in/GHz

Megtron6 Example: @ 4 GHz, (8 Gbps) w = 5 mil, Dk = 3.7, Df = 0.002

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

$$0.4\text{dB / in} + 0.035\text{dB / in} = 0.43\text{dB / in}$$

Figure of Merit (FOM) ~ 0.1 dB/in/GHz

Very expensive material wasted by conductor loss

Examples

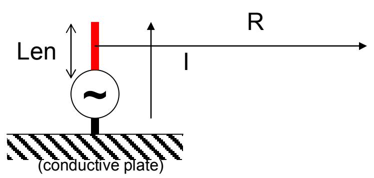
Attenuation FOM :
lossy: 0.2 dB/in/GHz, low loss: 0.1 dB/inch/GHz

- 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:

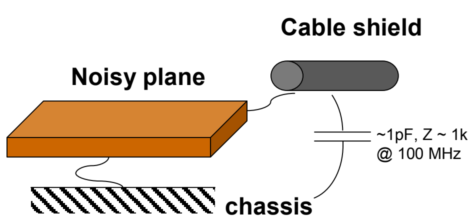
3 m far field is E ~ 0.4 uV/m/uA/MHz



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

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

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



$$I_{comm} = \frac{V_{comm}}{Z_{comm}} \sim \frac{0.1v}{1k\Omega} = 100uA$$

FCC part 15, class B limits
30 MHz – 88 MHz ~ 100 uV/m

$$E[uV/m] = 0.4[uV/m/uA/MHz]$$
$$\times 100uA \times 100MHz = 4{,}000uV/m!!!!$$

Examples

E ~ 0.4 uV/m/uA/MHz

- 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