システム設計のための
Sパラメタモデリングに関する考察

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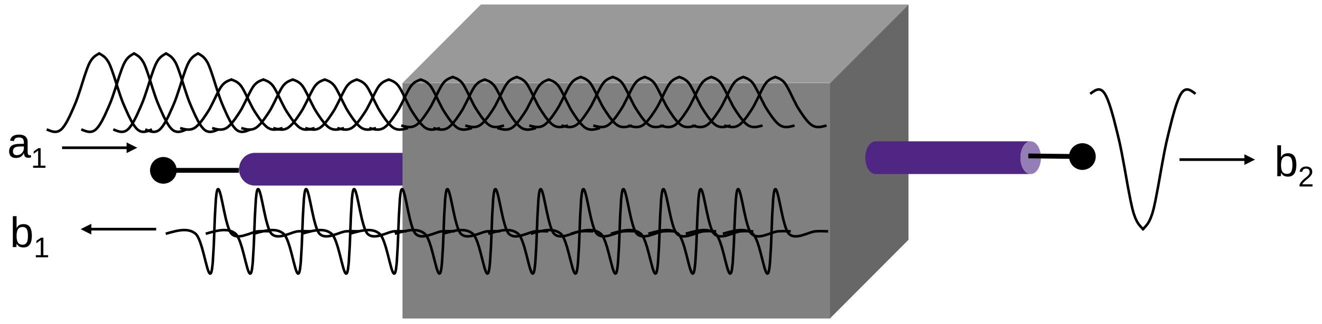
S-parameter definitions and insights

Road to the S-parameters

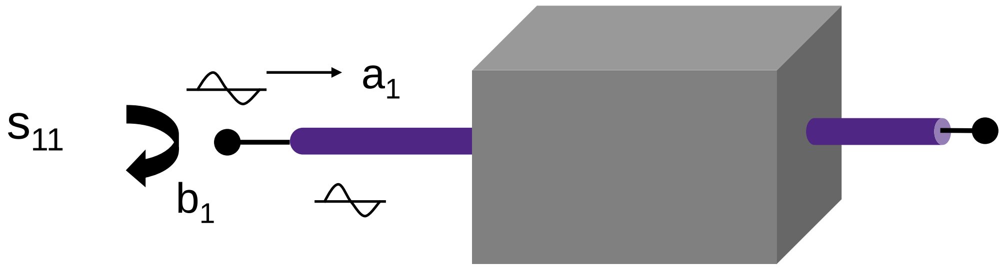


- Simplifying transmission line (EM wave propagation) theory
  - Values for voltage $v(x,t)$ and current $i(x,t)$ along the line can vary dramatically, so they are hard to deal with.
  - A more useful approach is to consider the RF signal as a sum of incident ("*a*") and reflected ("*b*") traveling voltage waves.

$$a_1 \sim V_{inc} e^{j(\omega t - \beta x)}$$

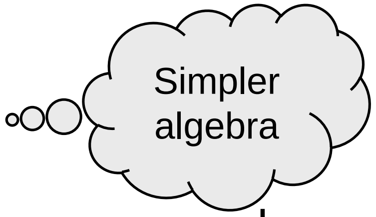
$$b_1 \sim V_{ref} e^{j(\omega t + \beta x)}$$

Scattering Parameters



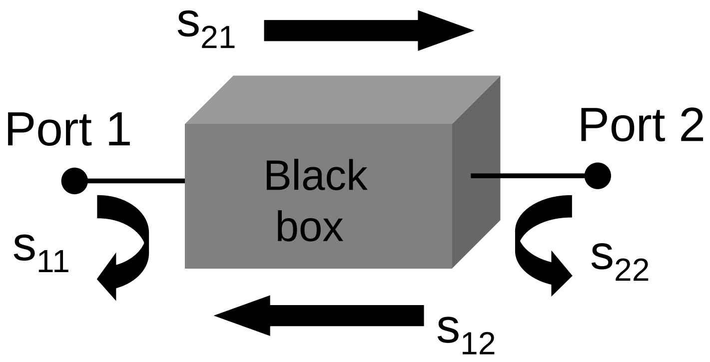
- *S-parameters* represent the complex ratios of these incident and reflected (scattered) voltage waves at a given frequency, e.g.

$$s_{11} = \frac{b_1}{a_1}$$



  - S-parameters are complex numbers: we can make useful calculations using complex arithmetic.
  - S-parameters are easily measured by injecting power and measuring reflected & transmitted signals.

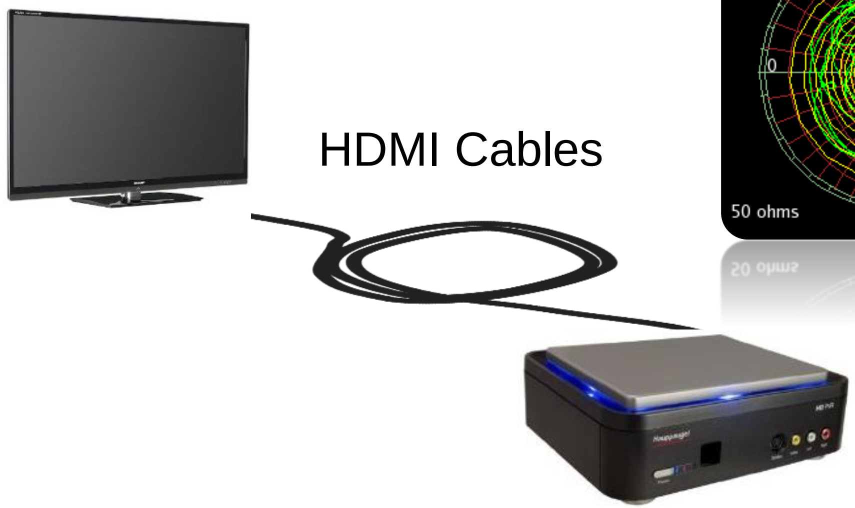
Two-Port Scattering Parameters



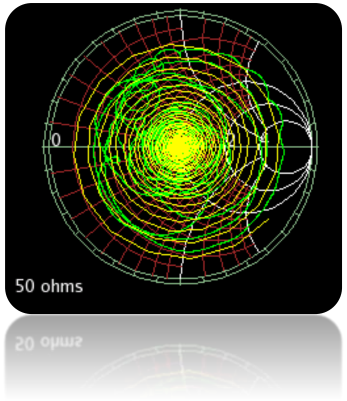
- S11 = input reflection coefficient (return loss)
- S21 = forward transmission coefficient (gain, Insertion loss)
- S12 = reverse transmission coefficient (isolation)
- S22 = output reflection coefficient
- *S-parameter* matrix:

$$\mathbf{S} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}$$

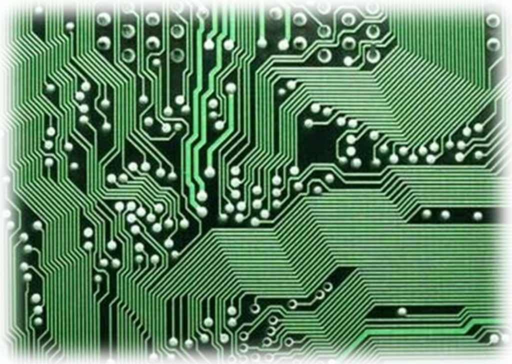
S-Parameter Varieties

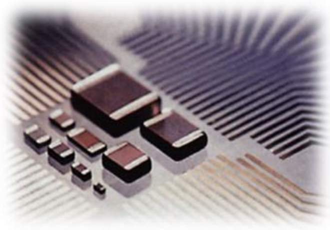


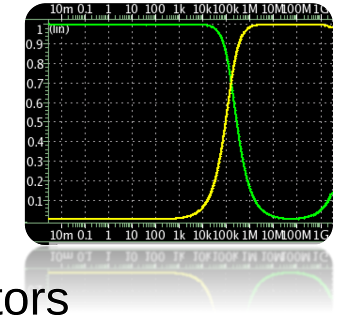
HDMI Cables



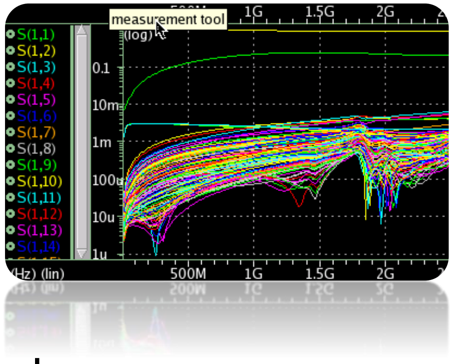
PCB Wires







Ceramic Capacitors



IC Packages

S-parameters Advantages & Challenges

Designers

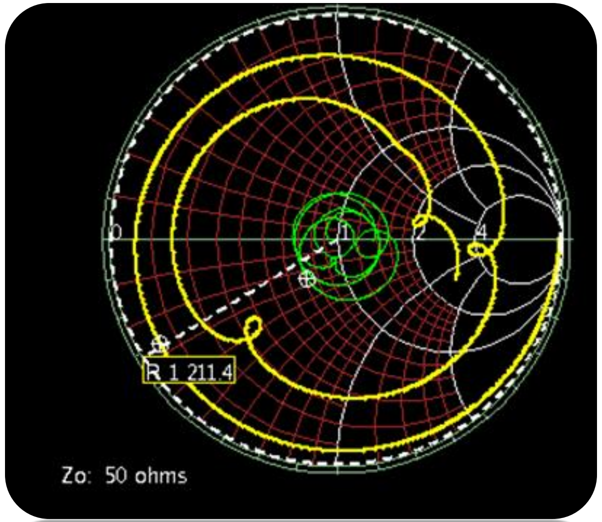
- Useful in system evaluations
  - ☺ Measurable
    - Linear(ized) n-port
    - High frequency coverage
  - ☺ Smith Chart Display
    - Passive : $|S_{ij}| \leq 1$
    - Impedance matching

Designers

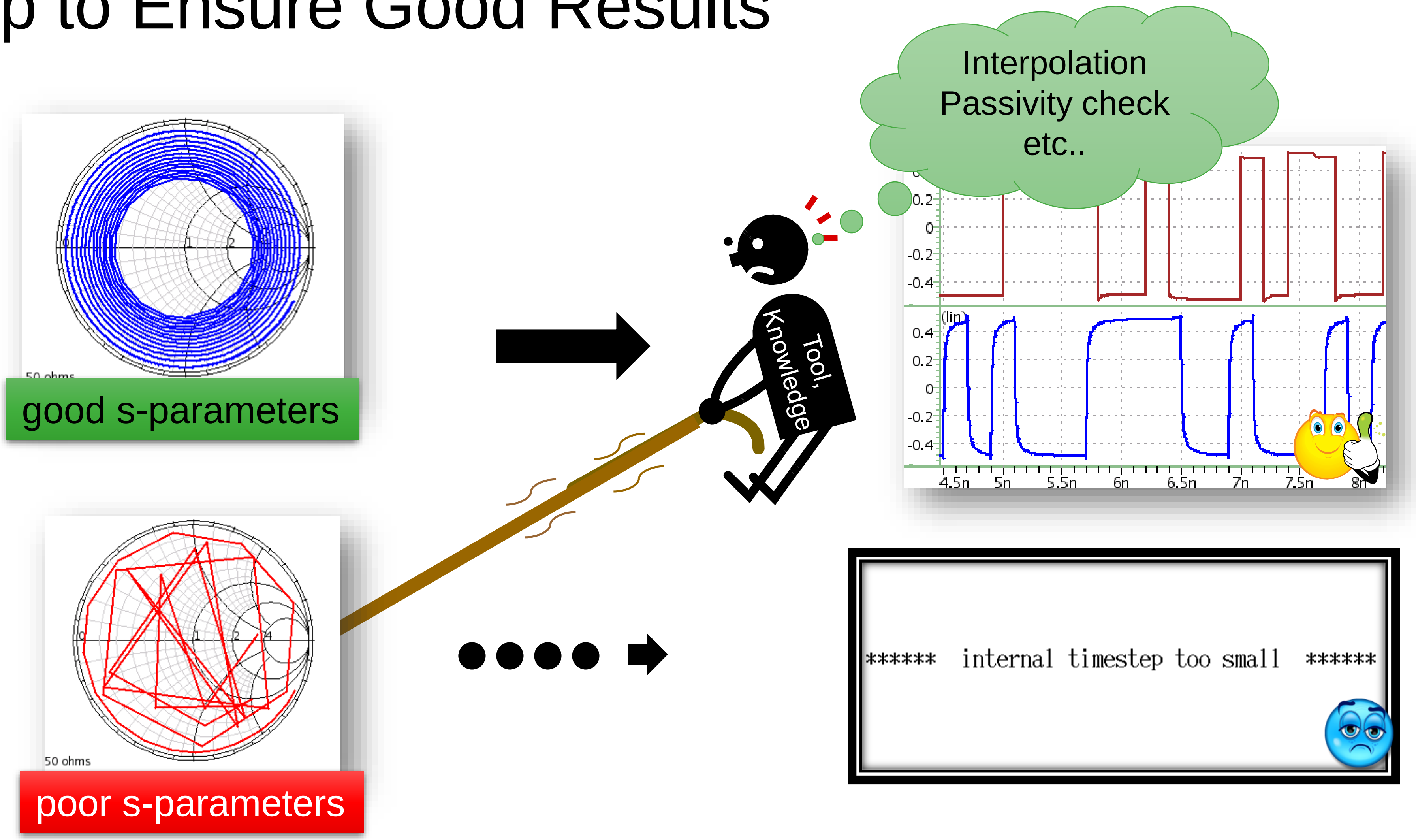
- Useful in IP distribution
  - ☺ Black box
  - ☺ Distributed network

Tools

- Challenges in Simulations
  - ☹ Discrete sampling, limited bandwidth
  - ☹ Passivity violations, bad terminations
  - ☹ $S(f)$ in time domain
  - ☹ Black boxed

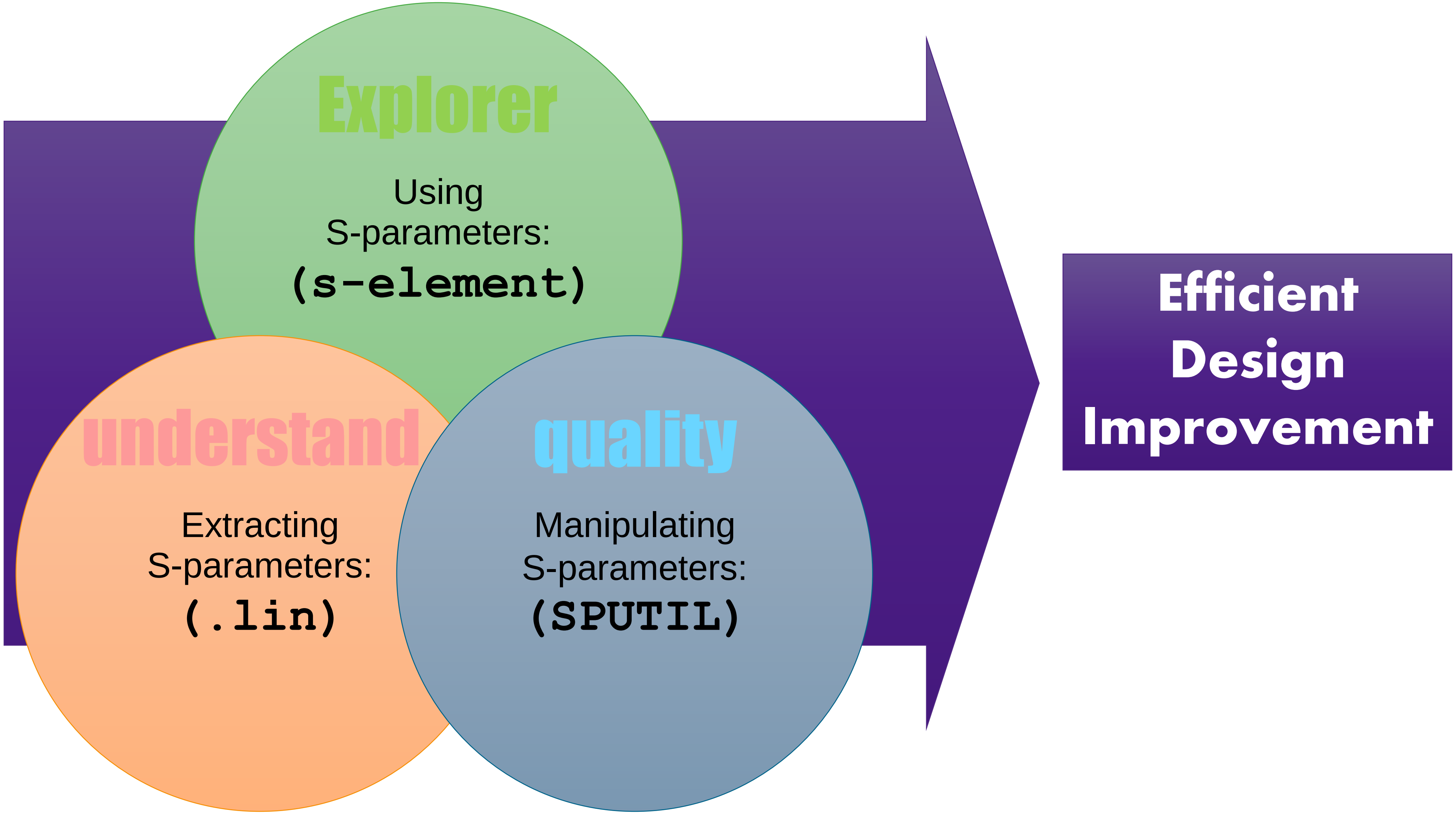


1st Step to Ensure Good Results



Best practice: Please look at your s-parameters before using them

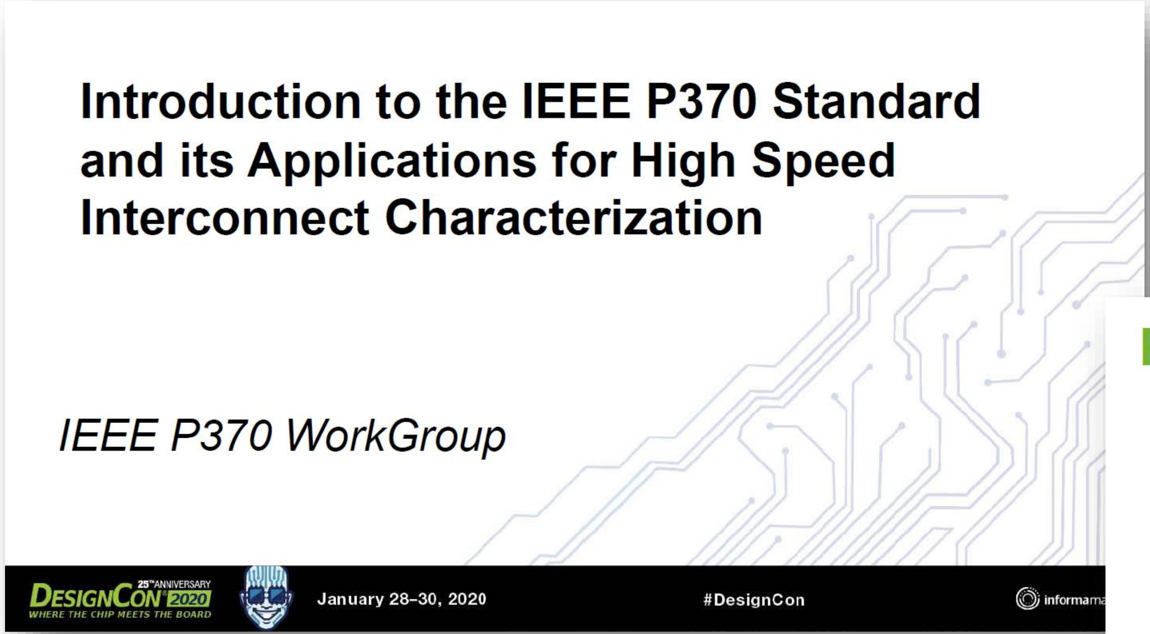
Essentials in Designs with S-parameters

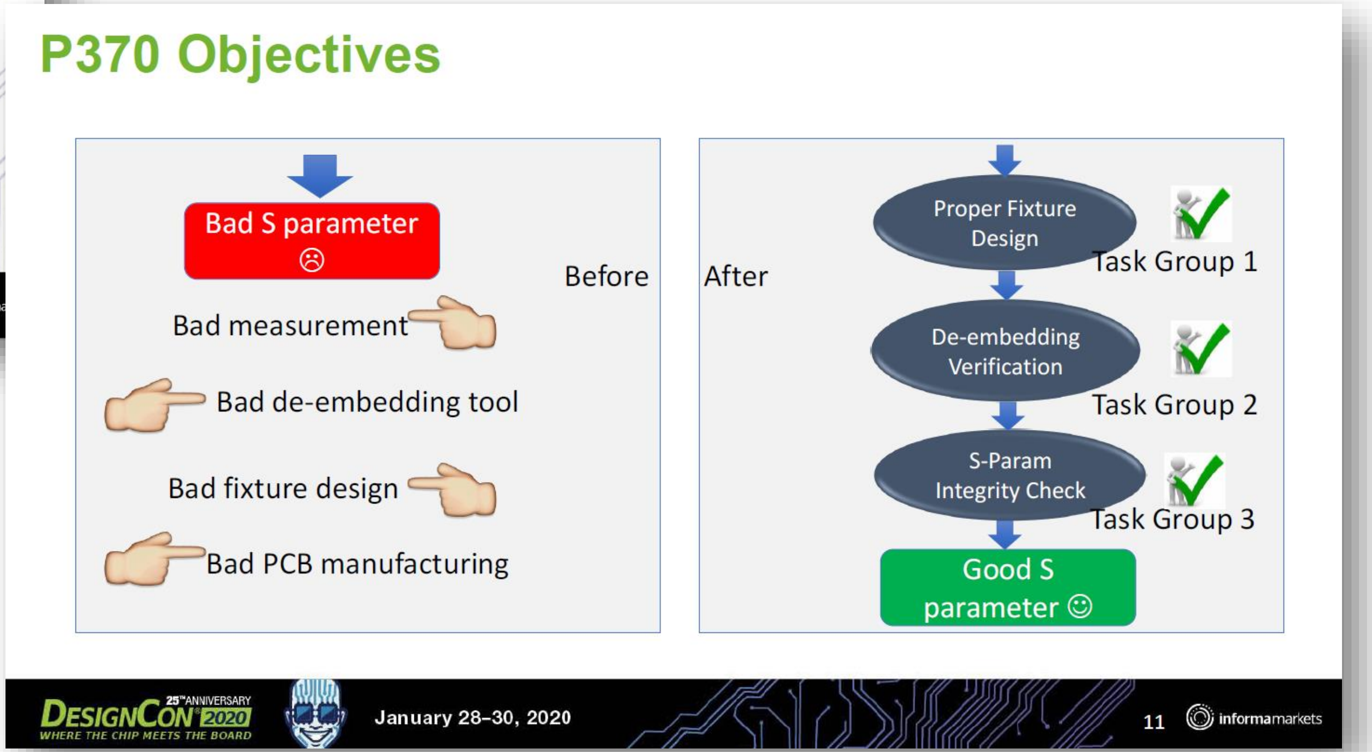


S-parameter Quality Assessments

Passivity, reciprocity, causality and more…

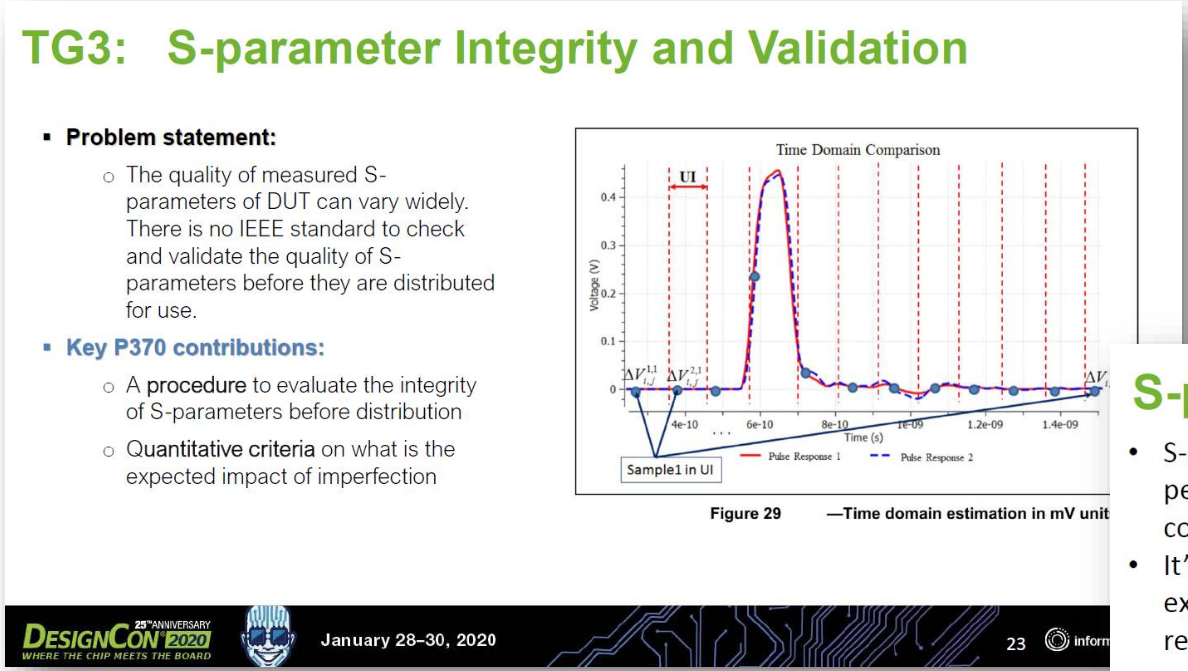
S-parameter Quality Assessment in IEEE P370[1]

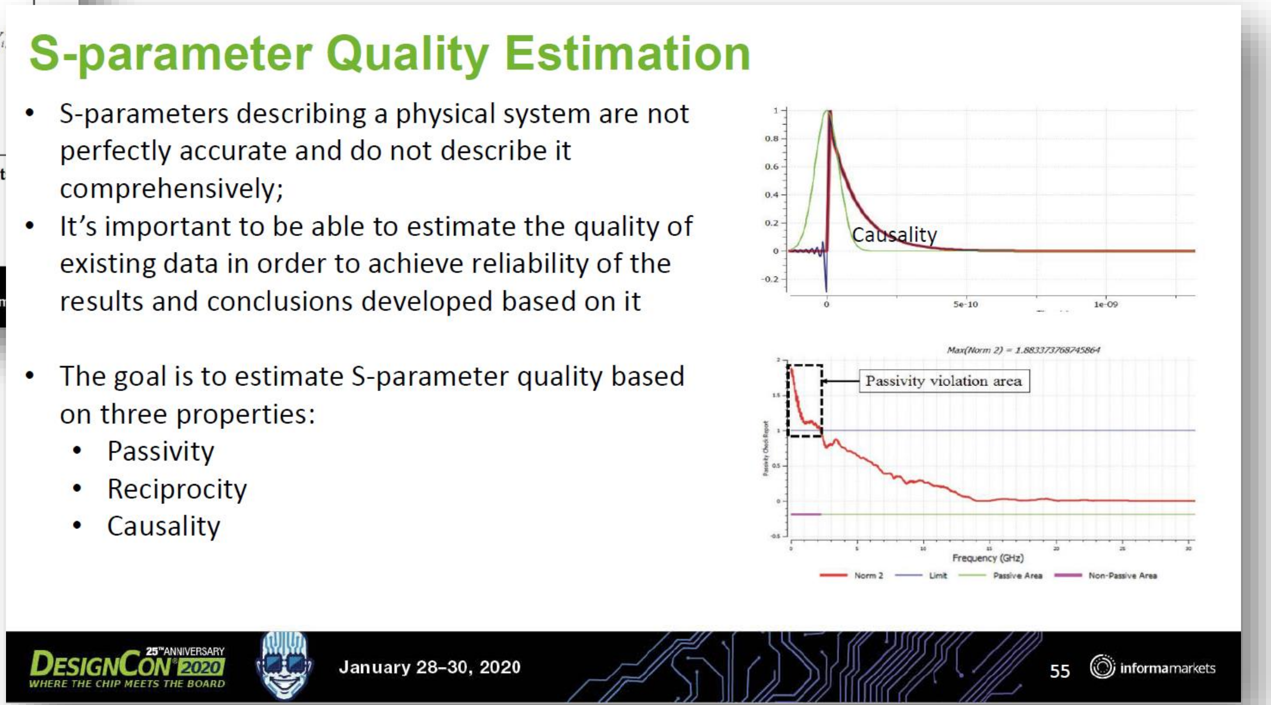




[1] IEEE P370 Work Group,
“Introduction to the IEEE P370 Standard and its Applications for High Speed Interconnect Characterization,” DesignCon 2020

S-parameter Quality Assessment in IEEE P370[1]





[1] IEEE P370 Work Group,
"Introduction to the IEEE P370 Standard and its Applications for High Speed Interconnect Characterization," DesignCon 2020

Causality

“consequence should not happen before a cause”

Non-Causality Creates Uncertainty in Transient Sim

- A system is causal if the result (output) comes after the cause (input)
- When system is non-causal, transient (marching in time) analysis cannot identify valid results

$$I_{out}(\omega) = Y(\omega) \cdot V_{in}(\omega)$$

$$\downarrow$$

$$out(t) = \int_{-\infty}^{\infty} h(t-\tau) \cdot in(\tau) d\tau$$

Convolution Integral

$out(t)$: output

$in(t)$: input

$h(t)$: transfer function

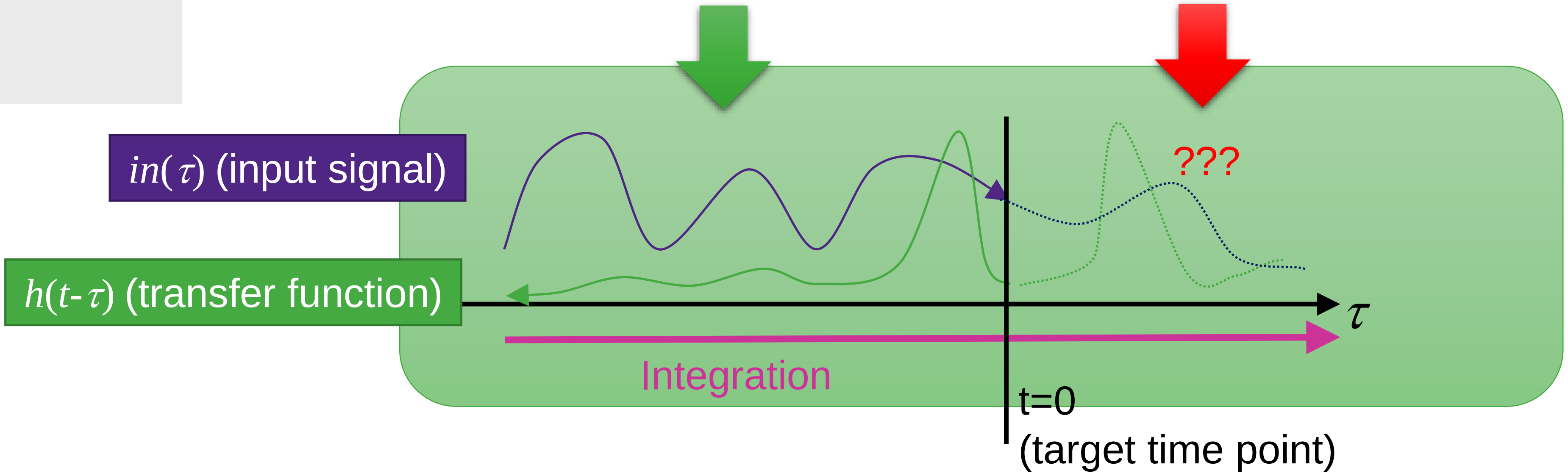
Look at the output at t=0 (for example)

$$out(t=0) = \int_{-\infty}^{\infty} h(-\tau) \cdot in(\tau) d\tau$$

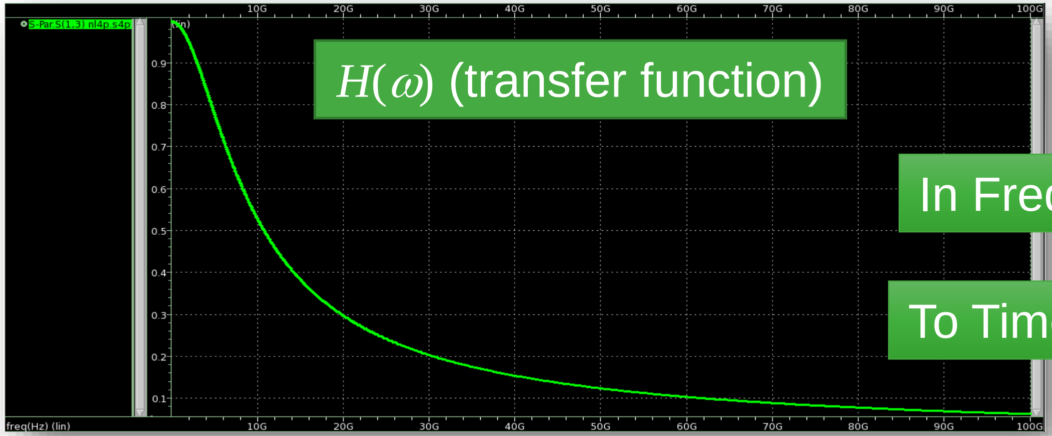
$$= \int_{-\infty}^{0} h(-\tau) \cdot in(\tau) d\tau + \int_{0}^{\infty} h(-\tau) \cdot in(\tau) d\tau$$

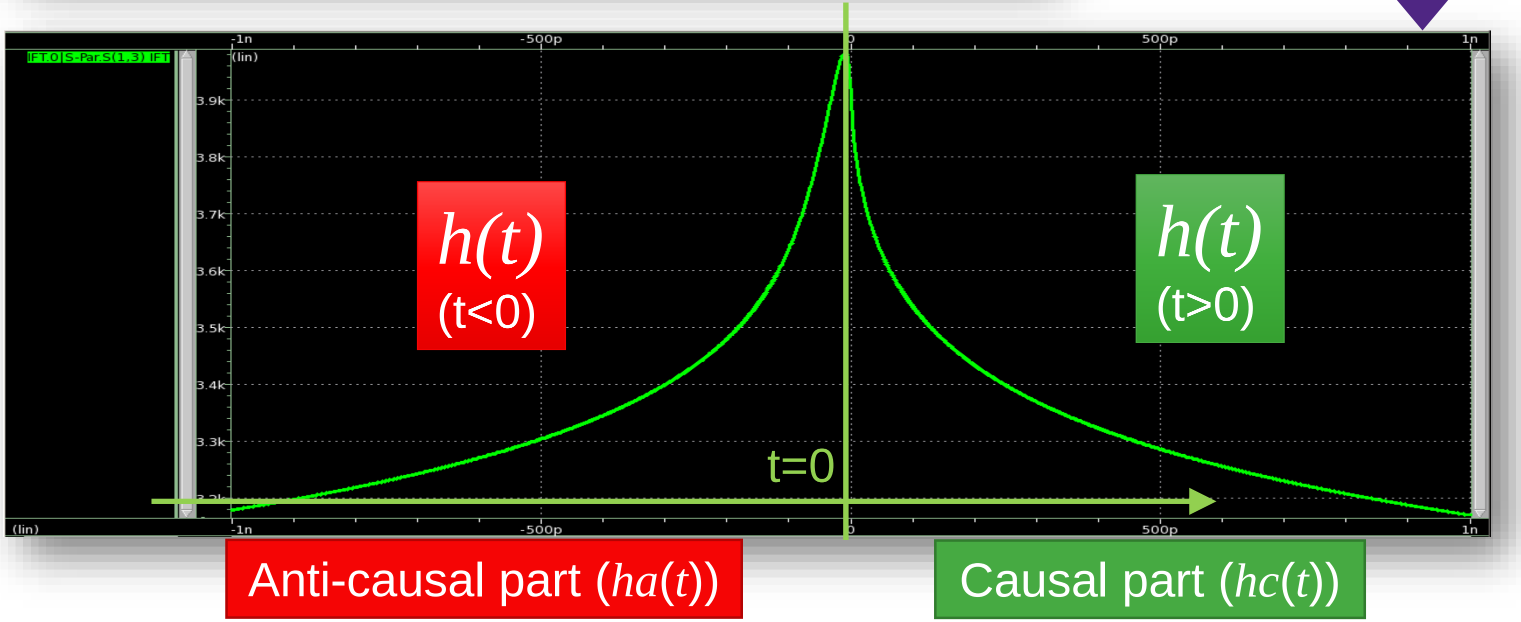
Dependency on the past

Dependency on the future!!



Observing Causality Issue





Causal function (Rc: real, Ic: imag) satisfies Kramers-Kronig relations (in Frequency domain)

- $Rc(j\omega) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{Ic(j\omega')}{(\omega-\omega')} \cdot d\omega' = H\{Ic(j\omega)\}$
- $Ic(j\omega) = -\frac{1}{\pi}\int_{-\infty}^{\infty} \frac{Rc(j\omega')}{(\omega-\omega')} \cdot d\omega' = -H\{Rc(j\omega)\}$
- Where $H\{\cdot\}$ is the Hilbert Transform.

Typical Causes of non-causal S-Parameters

- Incorrect calibration in measurement
  - E.g. over de-embedding fixture (propagation delay)
- Incorrect physical constant in EM extraction
  - E.g. real-only frequency dependent parameters (skin effect, dielectric loss)
- Insufficient frequency sampling

many
more

Tools to Ensure S-parameter Quality (e.g. SPUTIL)

- Format conversion (S/Y/Z Touchstone-v1,v2,CITIfile)
- Merge multiple data files
- Change reference impedance
- Arbitrary re-sampling (w/ inter-/extrapolation, windowing)
- Passivity checker/enforcement
- Causality checker
- Partial view, zero padding (e.g. S_{dd} ←→ S_{mixed})
- Port swap/reorder/pick
- more…

Causality Checker in SPUTIL

SPUTIL

```
TSTONEFILE my_sparam.s2p
CAUSAL check
```

- SPUTIL automatically decomposes given system s-parameters into causal and anti-causal part using discrete Hilbert transform in frequency domain
- Feature Selected Validation (FSV) to judge if given data set is causal enough, resulting in the Global Difference Measure (GDM)
- eGDM is a gaussian mapping of average GDM.

eGDM roughly tells :

$$0.20 >= eGDM : poor.$$
$$0.65 >= eGDM > 0.2 : fair.$$
$$1.0 >= eGDM > 0.65 : good.$$

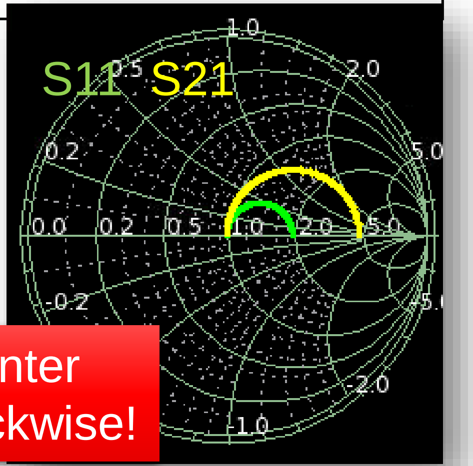
Causality Checker Example

```
P1 1 0 port=1
P2 2 0 port=2

R1 1 2 50
C1 2 0 -1n

.lin format=touchstone
.ac sweepblock=my_swp
.sweepblock my_swp
+ POI 1 0.0
+ DEC 100 1e3 1e9
```

DUT



counter clockwise!

```
S[2,1] avg eGDM is: 1.23e-07
S[1,1] avg eGDM is: 1.23e-07
```

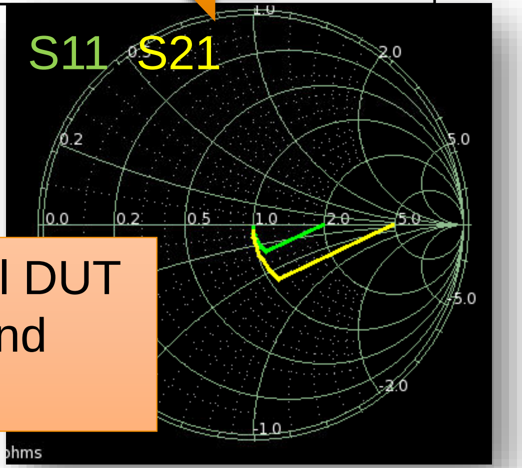
```
P1 1 0 port=1
P2 2 0 port=2

R1 1 2 50
C1 2 0 1n

.lin format=touchstone
.ac sweepblock=my_swp
.sweepblock my_swp
+ POI 1 0.0
+ DEC 20 1e7 1e8
```

corrected

DUT



Causal DUT but band limited

```
S[1,1] avg eGDM is: 0.653
S[2,1] avg eGDM is: 0.653
```

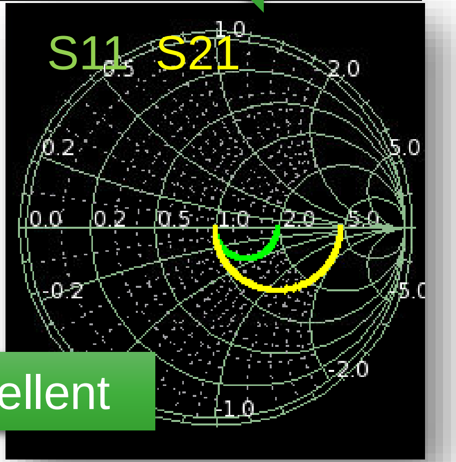
```
P1 1 0 port=1
P2 2 0 port=2

R1 1 2 50
C1 2 0 1n

.lin format=touchstone
.ac sweepblock=my_swp
.sweepblock my_swp
+ POI 1 0.0
+ DEC 200 1e3 20e9
```

DUT

widened



Excellent

```
S[1,1] avg eGDM is: 0.977
S[2,1] avg eGDM is: 0.977
```

Tips in S-parameter Modeling

For High Speed System Designs

[background]
Time Domain Analysis with S-parameters

Time-Domain Simulation with Scattering Parameters

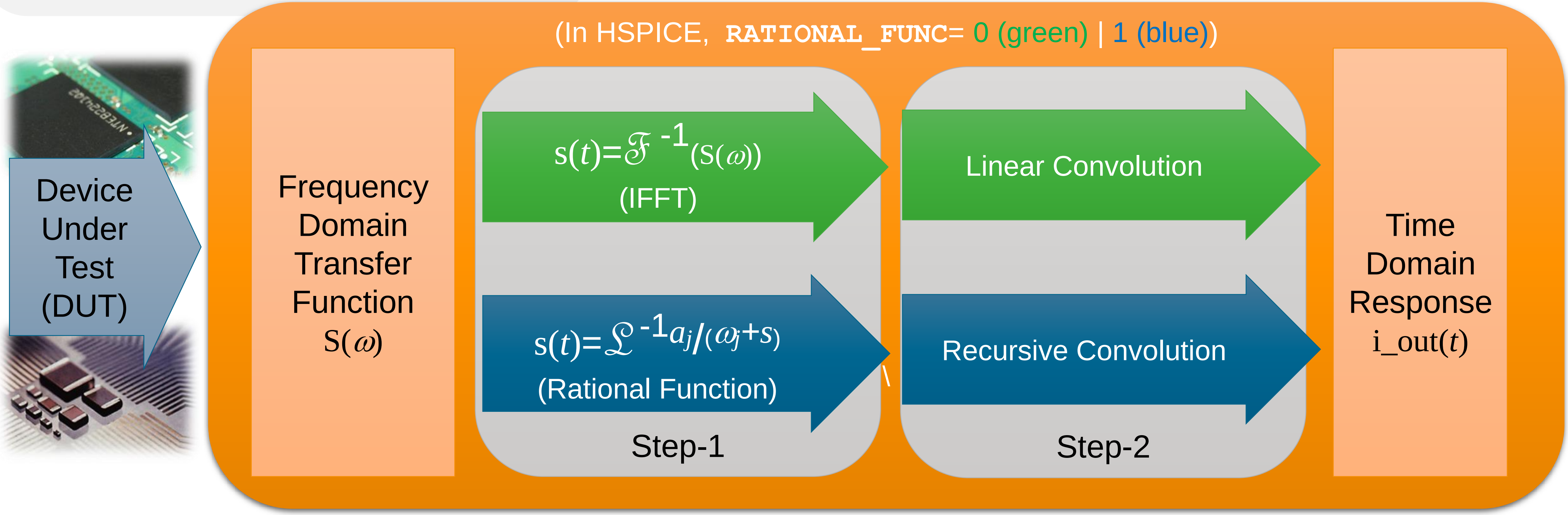
$$I_{out}(\omega) = Y(\omega) \cdot V_{in}(\omega) \qquad \text{(Eq. 1)}$$

↓ convolution

$$i_{out}(t) = v_{in}(t) * y(t)$$

$$= \int_{-\infty}^{t} y(t-\tau) \cdot v_{in}(\tau) d\tau \qquad \text{(Eq. 2)}$$

- Requires two step analysis
  - Step-1 : prepare transfer function in time domain
  - Step-2 : perform convolution integral to get time domain output



Rational Function Modeling

output ... input

$$y(t_n) = \int_{t_0}^{t_n} h(t_n - \tau) \cdot x(\tau) d\tau$$

Linear Convolution (Eq. 2)

$$H(\omega) \cong \frac{1}{\omega_o + s}$$

$$h(t) = e^{-\omega_o t}$$

Rational Function

(Eq. 3)

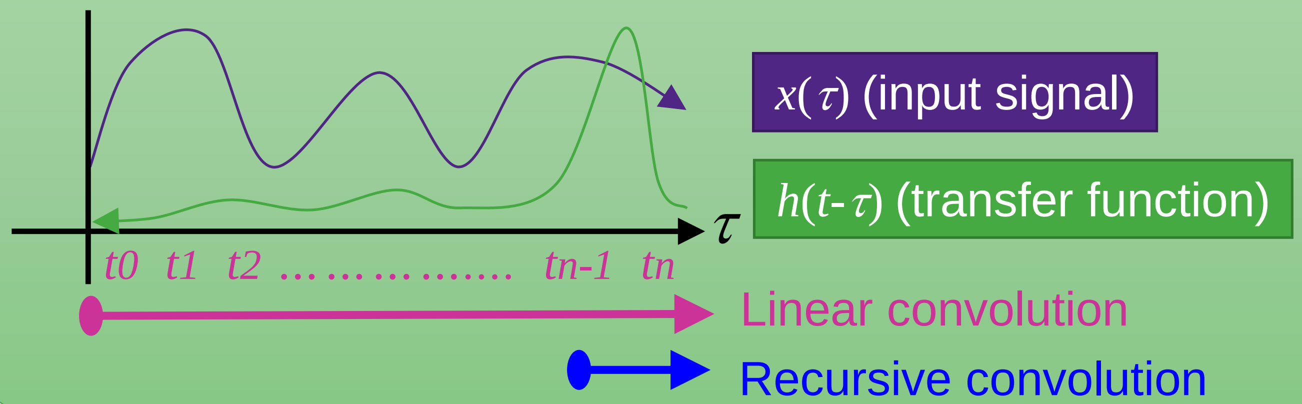
$$y(t_n) = e^{-\omega_o \Delta t} \cdot y(t_{n-1}) + \int_{t_{n-1}}^{t_n} h(t_n - \tau) \cdot x(\tau) d\tau$$

state variable

latest response

(Eq. 4)

Recursive convolution



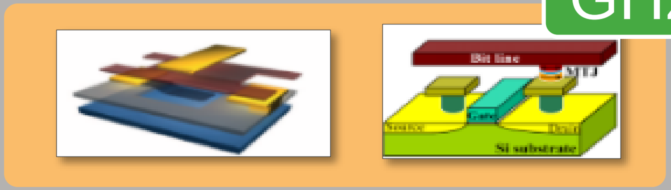
Rational function modeling is ideal for SI/PI simulations

Transient Simulations for SI/PI Analyses

Modeling Challenges

Parasitic Capacitance

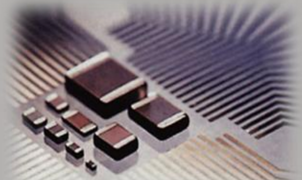
GHz



- Determines [psec] responses

Decoupling Capacitors

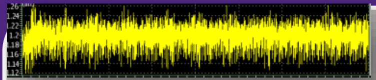
kHz



- Determines [msec] stability

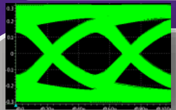
High Speed System

Simulation Challenges



Power Integrity

- SSO analysis to capture both spikes[psec] & drifts[msec] on supply line with deCap



Signal Integrity

- Million bit PRBS analysis to capture extremely low BER

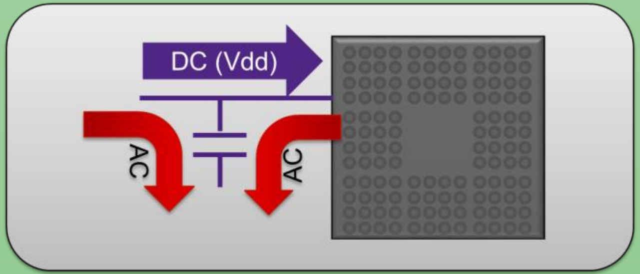
PRBS transient sim runtime	Linear Convolution (*)	Recursive Convolution (*)
500 bits	32 sec	1 sec
5,000 bits	6.4 min	22 sec
50,000 bits	3.5 hr	195 sec

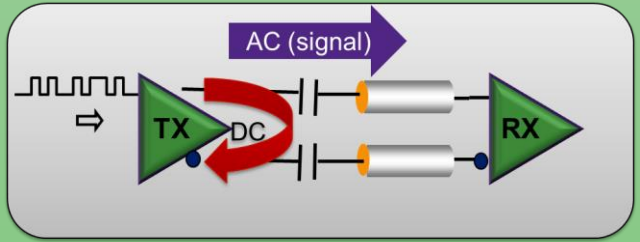
60x

Tip 1 : Decoupling Capacitor

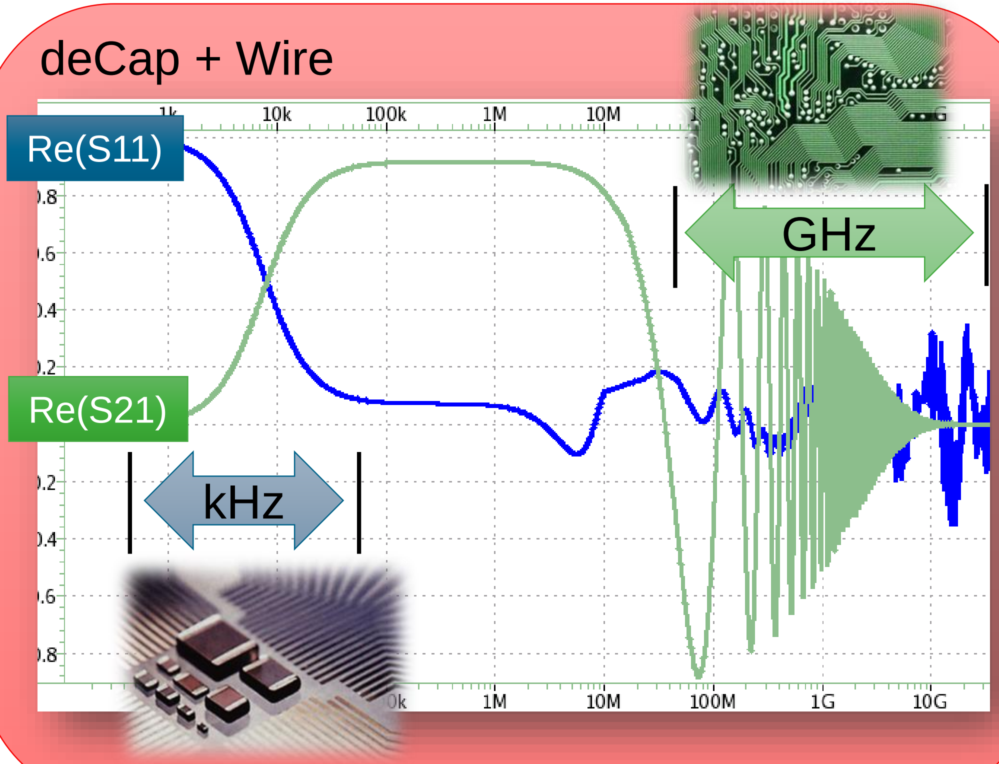
deCap Creates Ultra-Low Frequency Effect

- Decoupling Capacitor :
  a **capacitor** used to **decouple** one part of an electrical network (circuit) from another. (Wikipedia)



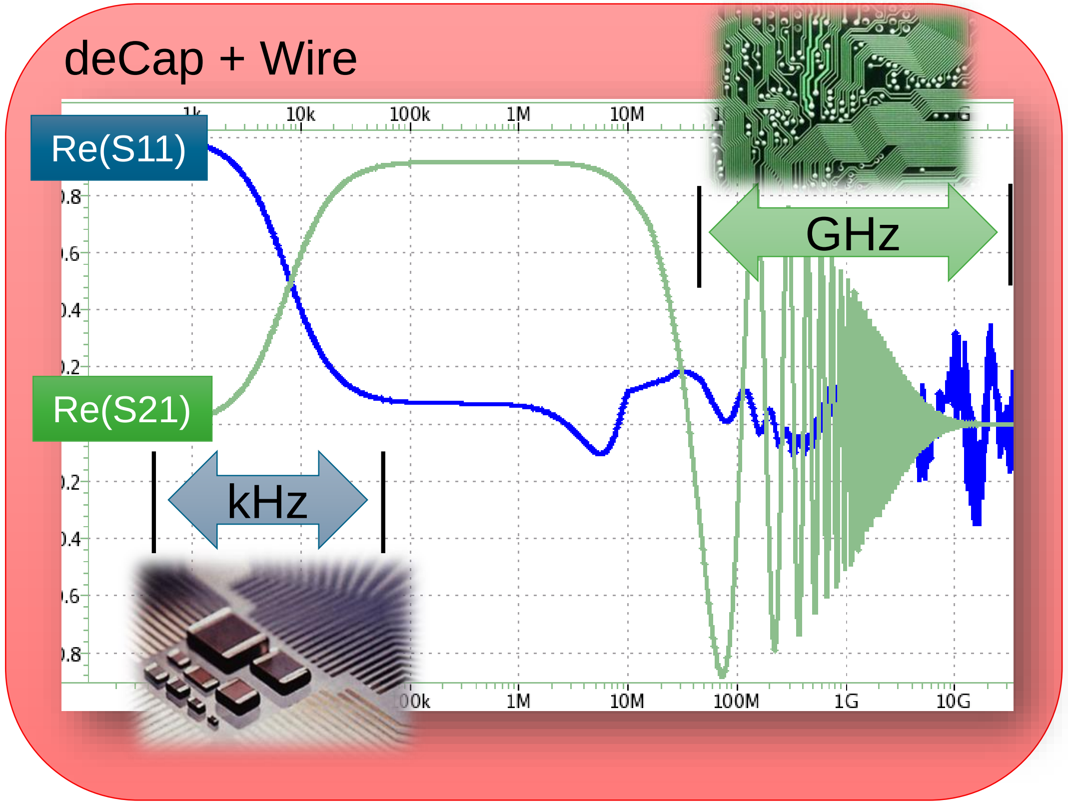


deCap + Wire

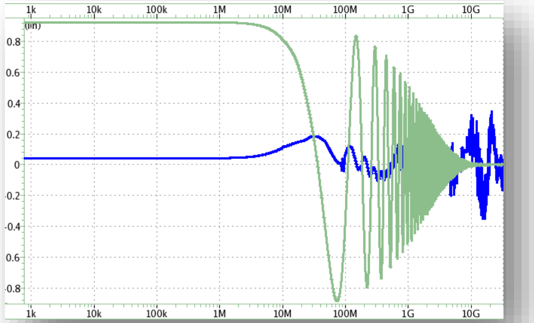


Model separation
→ Accurate sim, convenient for optimization

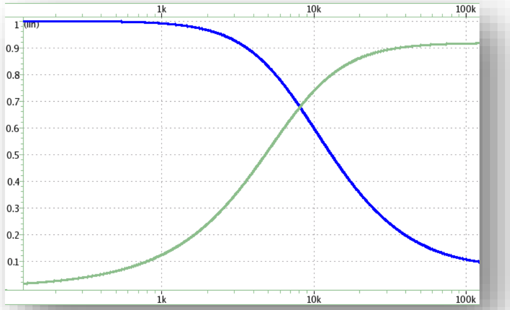
Recommendation: Model Separation



model-1
(wire)



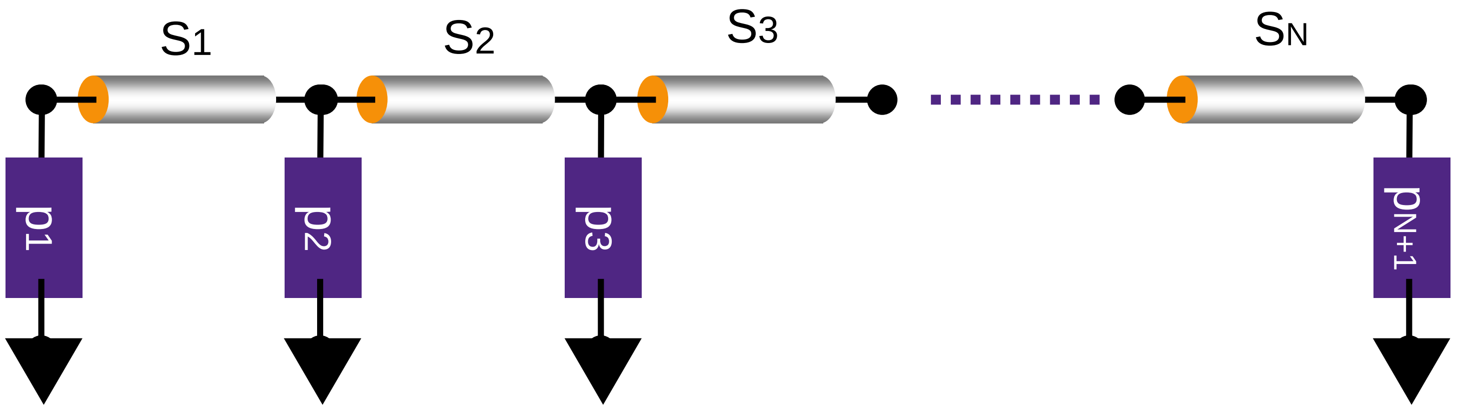
model-2
(deCap)



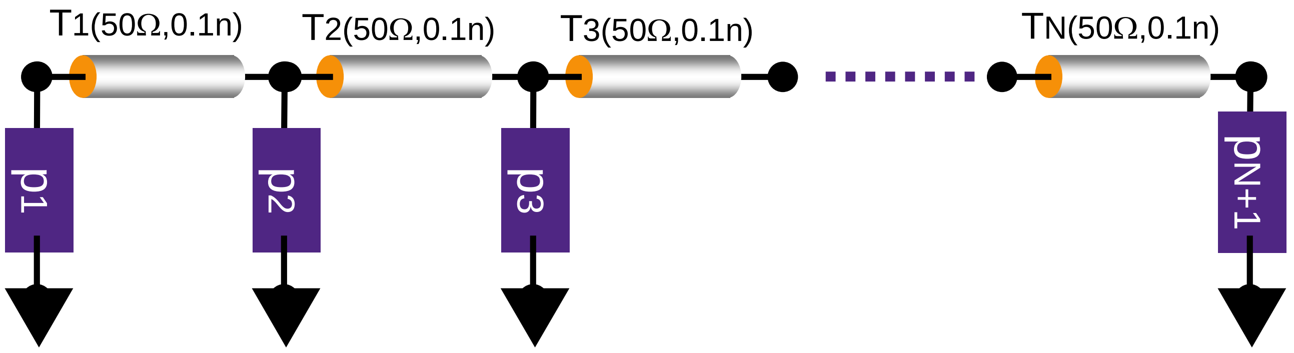
Model separation
→ Fast/Accurate simulation
→ convenient for optimization

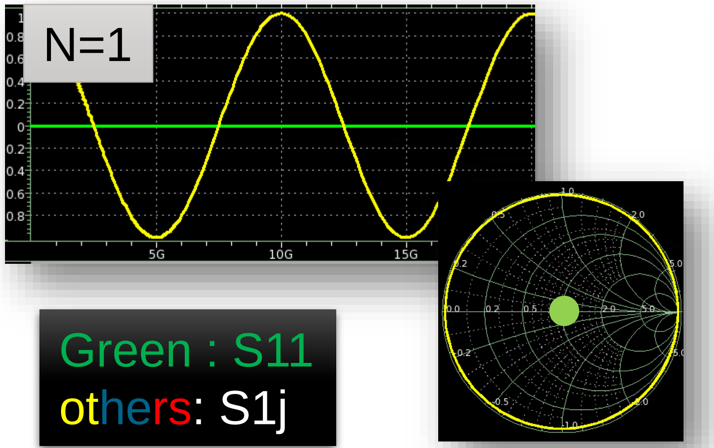
Tip 2 : Multi Segment Transmission Lines

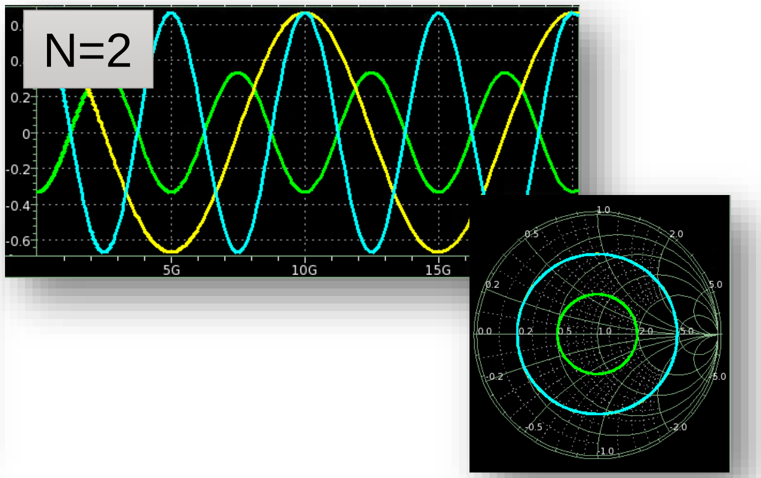
Cascading short transmission line segments drastically increase the s-parameter complexity

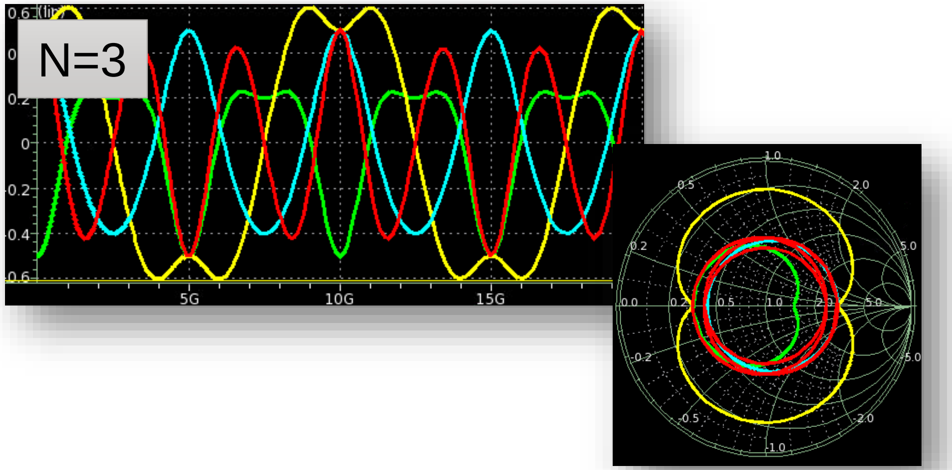


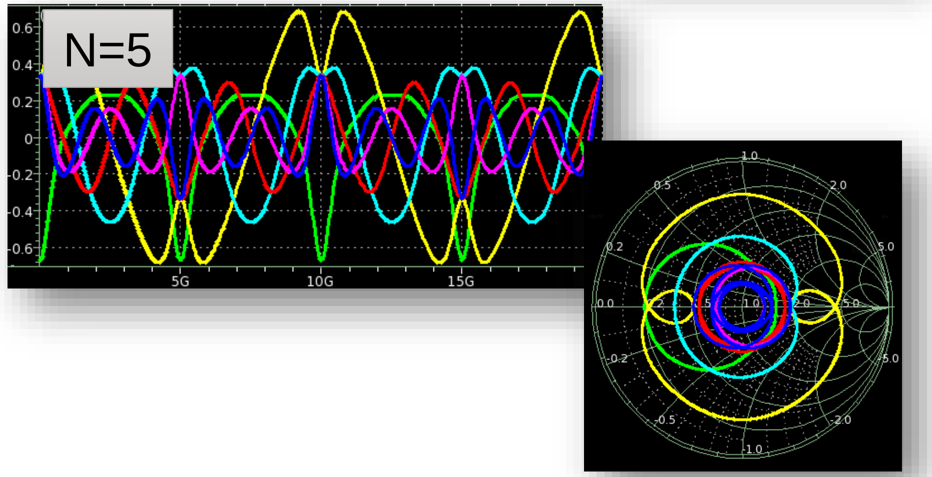
Understanding Multi-Drop S-parameters









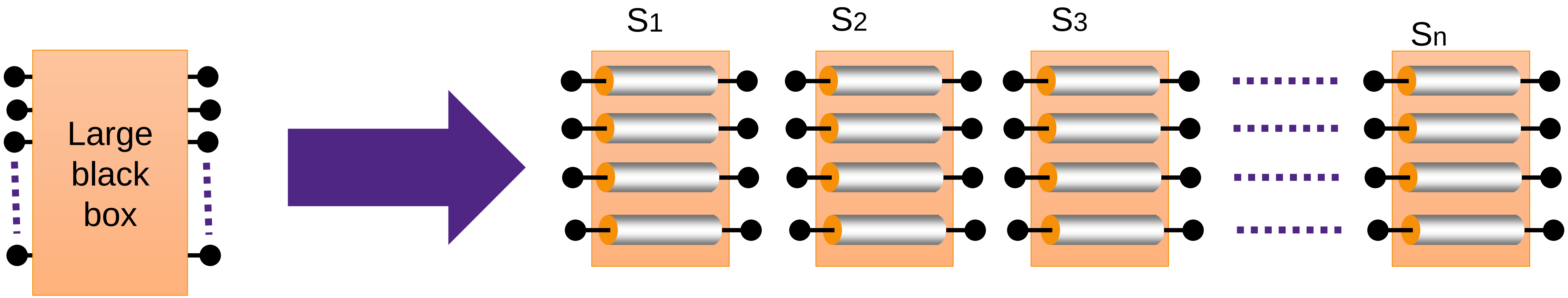


Green : S11
others: S1j

# segment	1	2	3	4	20	n
S(*i*,*i*)	0	-0.33	-0.5	-0.6	-0.91	-(n-1)/(n+1)
S(*i*,*x*)	1	0.66	0.5	0.33	0.095	2/(n+1)

Recommendation: Model Separation

When possible, separate s-parameter for each bus segment is recommended

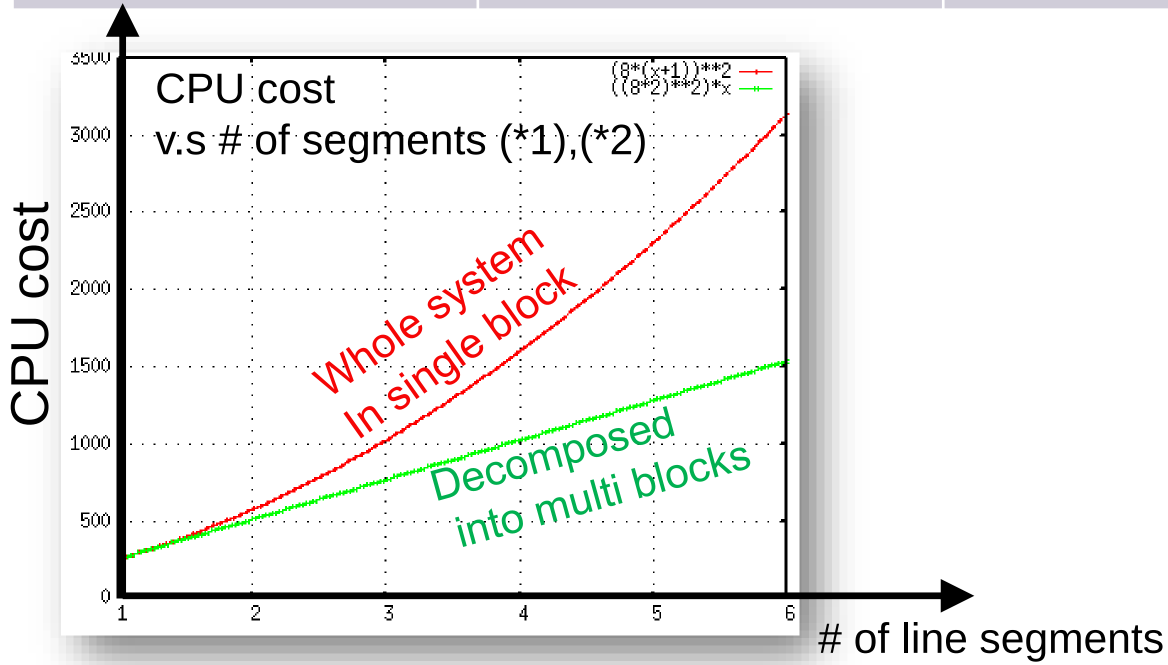


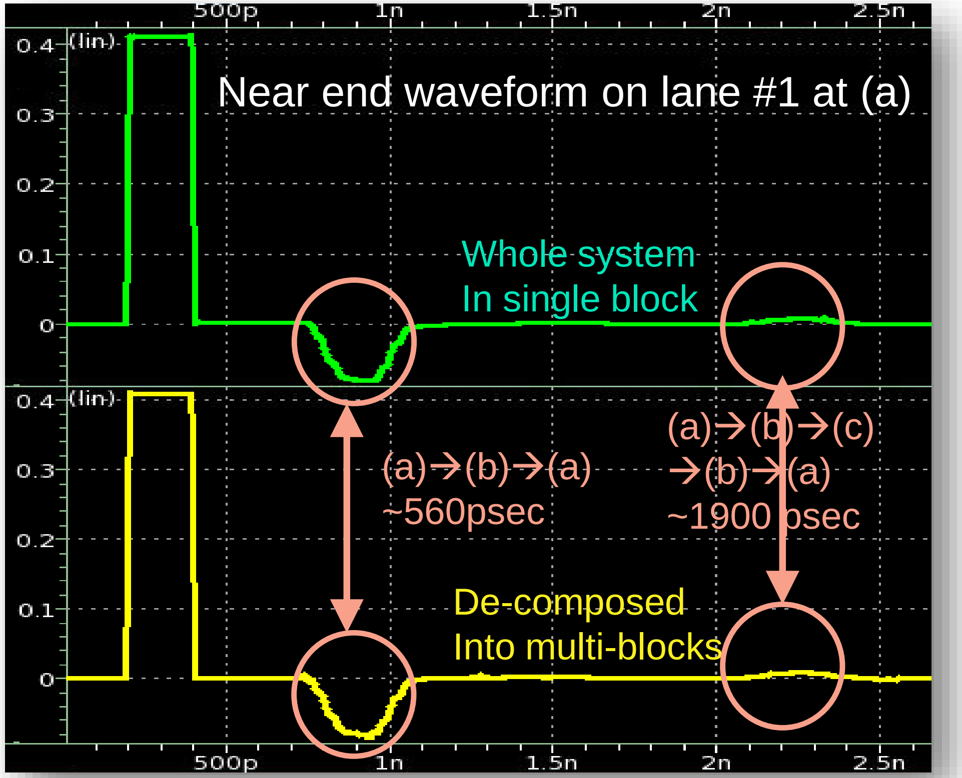
Simulation Performance with Model Separation

Performance and Accuracy

- Performance benefit w/ model separation
- Accuracy preserved

	one 12 port s-parameter block	two 8 port s-parameter blocks
1000 bit transient runtime (sec)	69.1	41.51



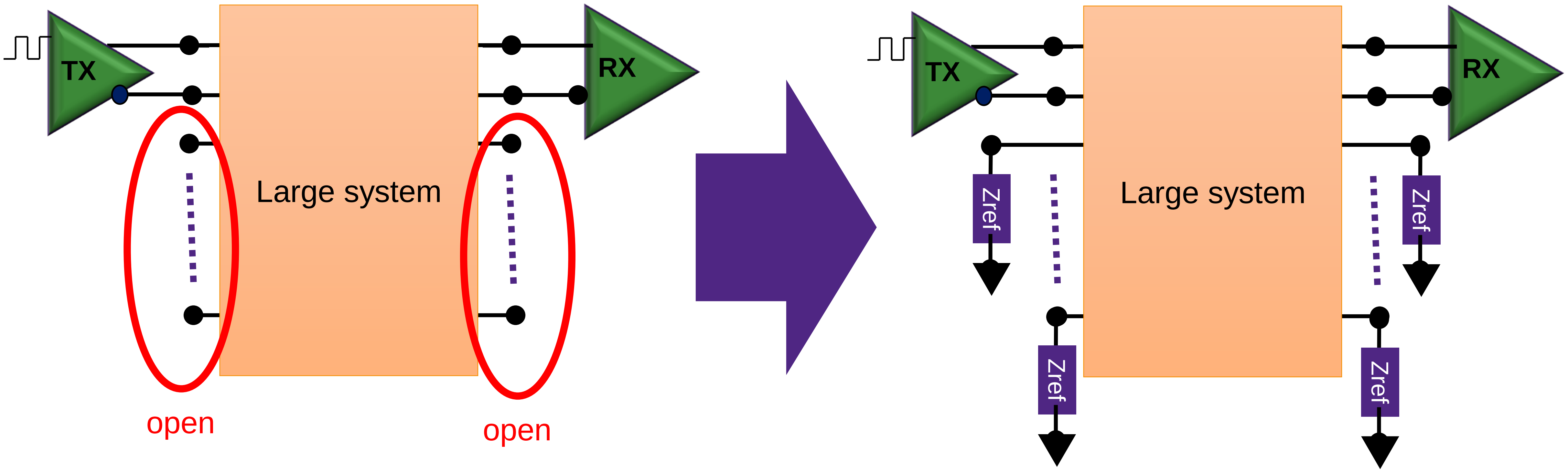


(*1) These plots assume the same waveform complexity
(*2) Difference may further increase because of high complexity of multi-drop system in single block

Tip 3 : Focusing on Partial Network in Large Systems

Approach 1: Terminating Unused Ports

- In testing a subset of a big system, many unused s-parameter ports tend to be left open
- Adding proper termination would help simulation stability
  - Add terminations manually
  - Let tools to handle them (*)



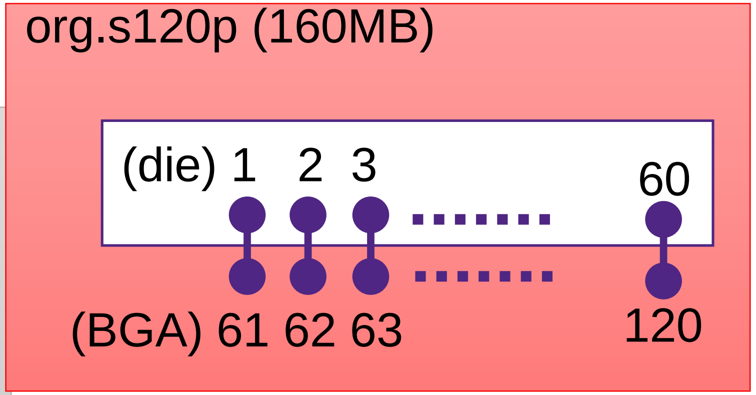
(*) .option TERM_S_OPEN_END=1

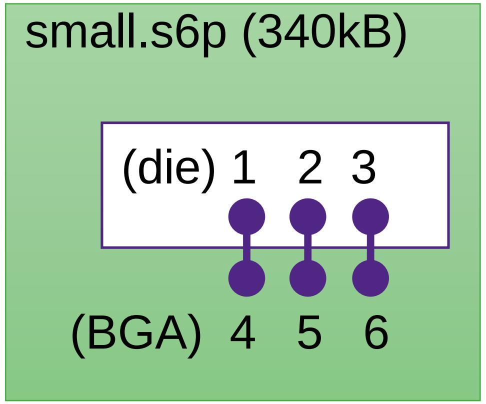
Approach 2: Partial Use of Large Systems

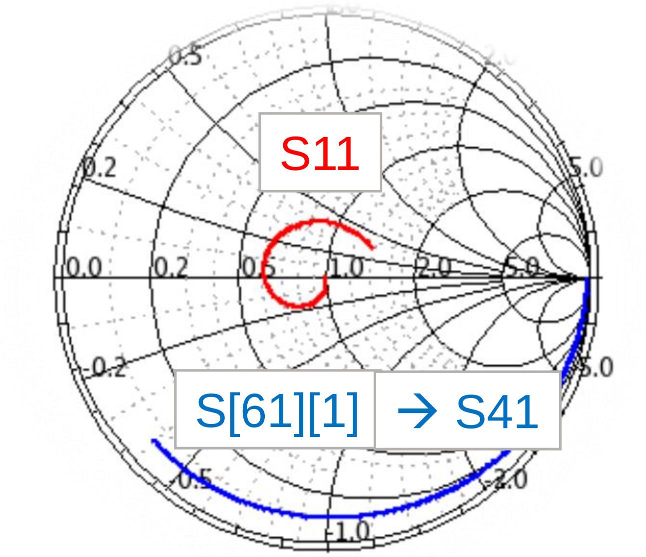
- Efficient way for preliminary test
  - Smaller data size, fewer pins → quicker simulation setup & run

SPUTIL example

```
TSTONEFILE org.s120p
PICK_PORT 1 2 3 61 62 63
TSTONE_OUT small.s6p
```







Optionally choose termination condition (Zref(default)/open/short) of port to be removed by
REDUCE_W_OPEN *indices*
REDUCE_W_SHORT *indices*

Summary

- Introduction
  - Increasing Variation and Complexity in S-parameter modeling
- S-parameter Quality Assessments
  - Passivity, Causality and Reciprocity
- Tips in s-parameter modeling
  - Decoupling Capacitor
  - Multi-segment Transmission Lines
  - Focusing on Partial Network in Large System

Design Success:
- Good Designers
- Good Tools
- Good Understandings

Thank You