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#### Subcircuits, S-Parameters, and T-line Models: Why and How We Set References

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# Subcircuit as a Multi-Terminal Object



- N+1-terminal subcircuit has N+1 terminal potentials and N+1 terminal currents
- Among them, only *N* terminal currents and *N* inter-terminal voltages are independent (because of Kirchhoff CL and VL relations).
- One of the terminals is usually chosen as a reference. Then, terminal voltages can be measured with respect to this reference
- A linear subcircuit can be described by equations in terminal voltages/terminal currents using NxN conductance or impedance matrix, such as: I=YV, V=ZI. Those can be transformed into S-parameters: B = SA.
- A subcircuit may internally provide conductive connection between all its terminals

# S-parameter model (object used in circuit simulators)



Consider S-parameter model, the way it is implemented in circuit simulators

- Suppose, that it is described by the same equations: I=YV,
   V=ZI, or B = SA. Is it equivalent to the subcircuit? Not entirely
- Inside the simulator, S-parameter model is implemented as *N*-port or (2x*N*)-terminal model. Currents, voltages, and scattered parameters are all port-, not terminal variables
- Each port has two terminals, whose currents are *always* equal (by design). This feature is called port "regularity".
- Unlike subcircuits, S-parameter model creates "direct connection" only between its terminals (due to: I'<sub>n</sub>=I<sub>n</sub>)
- Ports are electrically isolated, like coils in transformers. Interport relations are established by controlled sources

# S-parameter model (object used in circuit simulators)



 $\begin{array}{c}
 p_{2} \\
 p_{$ 

 $p_{1} \qquad P_{2} \qquad P_{2$ 

- S-parameter model by itself doesn't establish/define voltages between terminals that belong to different ports
- Difference in potentials could be very large, even if ports "show" nearly ideal connection
- Inter-port voltages make sense again if we add external interport connections
- Here, all terminals are electrically connected

- Connecting together reference terminals of ports (grounding them) is another way to make them all electrically connected
- The resulted model becomes equivalent to *N+1* terminal subcircuit

# W-element model (object used in circuit simulators)



(a) "Physical perception"



(b) Implementation in the simulator

- W-element has two "multi-terminal" ports, A and B. We can think of them as ports whose voltages and currents are vectors
- Each port has *K*+1 terminals (pins), where *K* is # of conductors
- The "ports" or "sides" are coupled by the line's equations, but conductively isolated (similar to S-parameter ports)
- Conductive connection exists between terminals of one port
- Difference in potentials on both sides could be very large, even for loss-less lines. Depends on external connections
- If reference terminals A<sub>ref</sub> and B<sub>ref</sub> are connected to the same node, then (a) and (b) become equivalent
- S-parameter and W-element are based on similar principles, differ only in component relationships

KCL equations can be written separately for side A and side B:

$$I_{A,ref} = \sum_{k=1}^{K} I_{A,k}$$
  $I_{B,ref} = \sum_{k=1}^{K} I_{B,k}$ 

# Do S-parameters properly represent subcircuits?

- It depends on how they are created and used in schematic. The way ports were defined should be consistent with their usage
- Port's KCL equations should be enforced by external connections
- Subcircuits and S-parameters created from them may behave differently if ports' regularity not enforced
- They are always equivalent if N+1-terminal subcircuit is represented by N-port Sparameters, and all ports' reference terminals are connected together

Four different subcircuits represented by identical 2-port S-parameters:



Proper usage: in this topology all subcircuits and S-parameters behave similarly: port regularity enforced by external topology:



Improper usage: all subcircuits give different solutions. S-parameters behave similarly to case "D", because S and D enforce port regularity by their structure



This current is always zero if using S-parameters or subcircuit D, but not for A, B, and C

# Four-terminal subcircuit is transparent for common mode, but not four-terminal (2-port) S-parameters

For subcircuits A, B, and C the common-mode current is not zero. For case D and S-param:  $I_1 = I'_1$ ,  $I_{com} = 0$ ,  $V_2 = 0$ .



A two-port S-parameter model (not the subcircuit) blocks common-mode propagation through the chain of the 4-port components (S-parameters or subcircuits).

Example: differential-only component of the differential via model.



# Connecting nodes to "ground" when working with S-parameters

• Sometimes, we have to do this to avoid "No [DC] path to ground" error



- Adding (more than one) ground connections is wrong for T-line sections, but right and necessary for Sparameters, why?
  - Needed because S-parameter ports are electrically isolated, hence we have sets of connected nodes which don't have a path to ground (shown red)
  - Safe thing to do because the current from this area into global ground is always zero (due to port regularity)

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As implied by cascading connection: I_1 = I_2
From ports' regularity, we have: I'_1 = I_1 I'_2 = I_2
Therefore, I'_1 = I'_2 and I_{gnd} \equiv 0.
Hence, adding connection to ground doesn't change
ports' currents and voltages. It may only affect
absolute potential.
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Both methods work equally well!

# "Grounding" should not be overdone...

1. This one gives an error "No path to ground"



2. This one simulates without errors, but the results are not as expected. Why?



3. External component makes areas marked red conductively connected



Hence, we need just one connection between this area and the ground: any one of the four would work.

# Some S-parameters may have no grounded terminals...



S1 S2 S4 S4

5. If we are unsure where to connect: add connection to "ground" through 1MOhm resistance: the current should be zero anyway!

# Decoupling capacitor and channel S-parameters (example)

A designer wants to represent channel with 3-port S-parameters, to substitute different DC blocking caps



After series of transformations, we get the design in which DC blocking capacitor appears grounded!



# *N*-port S-parameters made from (*N*+1)-terminal subcircuits may have their individual references connected to any node!

1. We have three 2-port S-parameter models. Each one has common reference for all its ports. Hence, all terminals are conductively connected



2. What if S-parameter models should be connected so that *their references become different nodes*. Is this OK?



3. Yes, this is a legitimate connectivity. Define all ports by listing its +/- terminals. Make sure there is a path to global ground from any node

SA 5 1 3 1 mname = SmodelA \*2-port model
SB 4 3 2 3 mname = SmodelB \*2-port model
SC 1 6 2 6 mname = SmodelC \*2-port model
R1 4 5 50
\*\* To avoid "No path to ground" error
\*\* connect one node to "ground":
.connect 6 0
\*\* Or: .connect 1 0
\*\* Or: .connect 2 0
\*\* Or: etc.

4. The solution(s) should be voltages between terminals of the models, not the potentials of nodes with respect to "global ground".

5. No need to convert (N+1)-terminal subcircuit into Sparameters with more than N ports, no need to add virtual "global grounds" to create S-parameters

# 2N-port S-parameters representing connectors, how many terminals we need for them?

- Connectors are essentially 2-side structures. Ports on either side have their terminals in close proximity, hence a common reference can be used for ports located on each side. Hence need 2\*(N+1) terminals total.
- Conceptually, connector S-parameters are similar to transmission lines: (a) they have two vector ports (on the left and right), (b) KCL equations apply to each side separately thus ensuring conductive connection between all terminals of each side, and (c) the "sides" are coupled by conductively disconnected.
- There is no limitations on how terminals on each side are connected to external devices. No need to connect reference terminals to global ground.
- To make simulator happy, we need to make sure that there exists at least one path to ground from any terminal of each side. If not, can add one, possibly through a large resistor. This doesn't affect currents/voltages of the ports.



Example:

- S1 and S3 are connector models
- All nodes in the encircled area are conductively connected and have a path to ground
- Current through Rg is zero (KCL for side B of S1 and KCL for side A of S3)



### 2N-port S-parameters representing connectors

Nestlisting S-parameters describing connectors: use one reference terminal for each "side":

S1 1 4 2 4 3 4 5 8 6 8 7 8 mname = SmodelS1 \*6-port model with 8 terminals S3 9 12 10 12 11 12 13 16 14 16 15 16 mname = SmodelS3 \*6-port model with 8 terminals

S2 5 6 9 10 mname = SmodelS2 \*2-port model with 4 terminals R1 7 11 20 R2 8 12 10 RG 10 0 1E6

\* Need to continue: define what's to the left of S1 and to the right of S3



### Conclusions

- S-parameters may differ from objects or subcircuits from which they have been created
- In particular, they enforce isolation between ports, and regularity of every single port
- Transmission line models are similar to S-parameters and can be thought as having two vector ports
- In many cases, S-parameters require connection to global reference in places where it didn't exist in the prototyped objects.
- The rules about required connections to ground are very simple and follow from port isolation and regularity: we can safely add exactly one connection to a global ground from every set of connected nodes not having the path to ground
- S-parameters and W-element may not preserve absolute potentials of all nodes. However, they
  remain perfectly valid as long as unknown variables are port variables: voltages, currents, or
  scattered waves
- (N+1)-terminal subcircuits can be represented by N-port S-parameters with all port references connected together. No need to connect port references to "global ground". Such objects could be connected to arbitrary nodes.
- Connector models are similar to Transmission lines, and have a pair of vector ports. No need to connect reference terminals to ground, a path to ground is needed from each side.