Matrix Parameters in Touchstone (Updated)

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Agenda

- Goals
- Touchstone V1.0, V1.1, V2.0, V2.1 differences
- Reference Impedances (resistances)
- n-Port matrices (S, Y, Z)
  - Conversions and mathematics
- 2-port matrices (H, G)
  - Conversions (updated)
- Conclusion

Goals

- Show features for an upcoming Touchstone Version 2.1 document
- Show conversion mathematics for different per-port reference impedances (resistances) for TSCHK2.1.0 parser development

- Note, reference impedance will be designated as reference resistance since complex references are not supported

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Touchstone Version 2.1 Document

- Touchstone V1.0 and V1.1 formats in the Version 2.1 Document
  - No keywords, content based on strict formatting rules
  - V1.0 supports a single port reference resistance in the option line beginning with # … R <r value> …
  - V1.1 supports per-port reference resistances at the end of the option line with # … R <r_1> <r_2>… <r_n> syntax
  - S-parameter matrices are defined based on the option line resistance entries
  - All other matrices are NORMALIZED regardless of option line entries. For example, if R = 50.0 Ω and $z_{1,1}$ = 1.0 in V1.0, then the actual measured value of $z_{1,1}$ is 50.0 Ω in V2.0
  - Per-port reference resistances are already supported by several EDA tools (but they may have different formats)

Touchstone Version 2.1 Document

- Touchstone V2.0 and V2.1 rules in the Version 2.1 Document
    - Keywords and [Version] 2.0 or [Version] 2.1 are required
    - V2.0 and V2.1 have identical matrix data
    - S-parameter matrices remain unchanged from V1.0 or V1.1 and are based on the reference resistance entries
    - Y-, Z-, H-, G-parameter matrices are UN-NORMALIZED (sensitive to reference resistor values) – as if measured directly in ohms or siemens (mhos)
    - [Reference] keyword lists the reference resistors
        - Values can wrap (unlike in V1.1 where all values are on a single option line)

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TSCHK2.0 Conversion Syntax Between V1.0 and V2.0

tschk2 –canonical

```
tschk2 -canonical    <options> FILE  Shortcut for -canonical-v2.
```

tschk2 –canonical –v2

```
tschk2 -canonical-v2 <options> FILE  Checks the file, sending error and warning
                                       information to stderr, and writes a valid file
                                       to stdout in Touchstone v2 format.
```

tschk2 –canonical –v1

```
tschk2 -canonical-v1 <options> FILE  Checks the file, sending error and warning
                                       information to stderr, and writes a valid file
                                       to stdout in Touchstone v1 format, if possible.
```

<u>A tschk2.1.0 parser will support the V1.1 and V2.1 conversions</u>

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Notation

- Z (normalized), Z^U (un-normalized)
- Y (normalized), Y^U (un-normalized)
- H (normalized), H^U (un-normalized), 2-port only
- G (normalized), G^U (un-normalized), 2-port only

- R <r_1> <r_2>… <r_n> per-port reference resistors
- R <r> for a single reference resistance

General N-Port Z Matrix Conversion

- José Schutt-Ainé, ECE 546, Lecture 13, *Scattering Parameters*, Slides 28-29, Spring 2022, http://emlab.illinois.edu/ece546/Lect_13.pdf
- Formulas are restated using the notation in this presentation
- k = diagonal $[\sqrt{r_1},\ \sqrt{r_2},\ \ldots\ ,\ \sqrt{r_n}\ ]$ are based on power wave per-port normalization between incident and reflected waves (b = Sa)
- $Z = (I + S)(I - S)^{-1}$ (normalized to r = 1; *I* = unit matrix)
- $Z^U = k\,(I + S)(I - S)^{-1}\,k = k\,Z\,k$
- Multiplication by the diagonal matrix k produces the terms $z^u{}_{i,j} = z_{i,j}\sqrt{r_i r_j}$

Illustrating $z^u{}_{i,j}$ Term Calculation

$$z^u{}_{i,j} = \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_i & 0 \\ 0 & 0 & k_n \end{bmatrix} \begin{bmatrix} z_{1,1} & z_{1,j} & z_{1,n} \\ z_{i,1} & z_{i,j} & z_{i,n} \\ z_{n,1} & z_{n,j} & z_{n,n} \end{bmatrix} \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_j & 0 \\ 0 & 0 & k_n \end{bmatrix} =$$

$$\begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_i & 0 \\ 0 & 0 & k_n \end{bmatrix} \quad \mathrm{X} \quad \begin{bmatrix} z_{1,1}k_1 & z_{1,j}k_j & z_{1,n}k_n \\ z_{i,1}k_1 & z_{i,j}k_j & z_{i,n}k_n \\ z_{n,1}k_1 & z_{n,j}k_j & z_{n,n}k_n \end{bmatrix} =$$

$$\begin{bmatrix} k_1 z_{1,1} k_1 & k_1 z_{1,j} k_j & k_1 z_{1,n} k_n \\ k_i z_{i,1} k_1 & k_i z_{i,j} k_j & k_i z_{i,n} k_n \\ k_n z_{n,1} k_1 & k_n z_{n,j} k_j & k_n z_{n,n} k_n \end{bmatrix} = z_{i,j}\sqrt{r_i r_j}$$

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N-Port Matrix Conversions

$Z^U \leftarrow Z$

$z^u{}_{i,j} = \sqrt{r_i r_j}\, z_{i,j}$

$Z \leftarrow Z^U$

$z_{i,j} = z^u{}_{i,j} / \sqrt{r_i r_j}$

$Y^U \leftarrow Y$

$y^u{}_{i,j} = y_{i,j} / \sqrt{r_i r_j}$

$Y \leftarrow Y^U$

$y_{i,j} = \sqrt{r_i r_j}\, y^u{}_{i,j}$

In V1.0 and V2.0, R <r> is used if $r_i = r_j$

V2.0 cannot be converted to V1.0 if $r_i \neq r_j$

Derivation of 2-Port H Conversions

$$\begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} = \begin{bmatrix} \frac{d_z}{z_{2,2}} & \frac{z_{1,2}}{z_{2,2}} \\ \frac{-z_{2,1}}{z_{2,2}} & \frac{1}{z_{2,2}} \end{bmatrix} \text{ where determinant of } \mathbf{Z} = d_z = z_{1,1}z_{2,2} - z_{1,2}z_{2,1} \qquad (1)$$

$$d_z{}^u = z_{1,1}{}^u z_{2,2}{}^u - z_{1,2}{}^u z_{2,1}{}^u = z_{1,1}z_{2,2}r_1r_2 - z_{1,2}z_{2,1}\sqrt{r_1r_2}\sqrt{r_2r_1} = d_z r_1 r_2$$

Correction

$$\begin{bmatrix} h_{1,1}{}^u & h_{1,2}{}^u \\ h_{2,1}{}^u & h_{2,2}{}^u \end{bmatrix} = \begin{bmatrix} \frac{d_z{}^u}{z_{2,2}{}^u} & \frac{z_{1,2}{}^u}{z_{2,2}{}^u} \\ \frac{-z_{2,1}{}^u}{z_{2,2}{}^u} & \frac{1}{z_{2,2}{}^u} \end{bmatrix} = \begin{bmatrix} \frac{d_z r_1 r_2}{z_{2,2} r_2} & \frac{z_{1,2}\sqrt{r_1 r_2}}{z_{2,2} r_2} \\ \frac{-z_{2,1}\sqrt{r_1 r_2}}{z_{2,2} r_2} & \frac{1}{z_{2,2} r_2} \end{bmatrix} = \begin{bmatrix} h_{1,1} r_1 & h_{1,2}\sqrt{r_1/r_2} \\ h_{2,1}/\sqrt{r_2/r_1} & h_{2,2}/r_2 \end{bmatrix}$$

(1) L. Weinberg, “Fundamentals of Scattering Matrices”, *Electro-Technology*, July 1967, p. 68; Online: S. Jahn, M. Margraf, V. Habchi, R. Jacob, “Two-Port Transformations” section, http://tinyurl.com/yzc2w4vr

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2-Port H-Parameter Conversions

$H^U \leftarrow H$

$$\begin{bmatrix} h^u{}_{1,1} & h^u{}_{1,2} \\ h^u{}_{2,1} & h^u{}_{2,2} \end{bmatrix} = \begin{bmatrix} h_{1,1}\, r_1 & h_{1,2}\sqrt{r_1/r_2} \\ h_{2,1}/\sqrt{r_2/r_1} & h_{2,2}/r_2 \end{bmatrix}$$

$H \leftarrow H^U$

$$\begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{bmatrix} = \begin{bmatrix} h^u{}_{1,1}/r_1 & h^u{}_{1,2}/\sqrt{r_1/r_2} \\ h^u{}_{2,1}\sqrt{r_2/r_1} & h^u{}_{2,2}\, r_2 \end{bmatrix}$$

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2-Port G-Parameter Conversions

$G^U \leftarrow G$

$$\begin{bmatrix} {g^u}_{1,1} & {g^u}_{1,2} \\ {g^u}_{2,1} & {g^u}_{2,2} \end{bmatrix} = \begin{bmatrix} g_{1,1}\,/r_1 & g_{1,2}/\sqrt{r_1/r_2} \\ g_{2,1}\sqrt{r_2/r_1} & g_{2,2}\,r_2 \end{bmatrix}$$

$G \leftarrow G^U$

$$\begin{bmatrix} g_{1,1} & g_{1,2} \\ g_{2,1} & g_{2,2} \end{bmatrix} = \begin{bmatrix} {g^u}_{1,1}\,r_1 & {g^u}_{1,2}\sqrt{r_1/r_2} \\ {g^u}_{2,1}/\sqrt{r_2/r_1} & {g^u}_{2,2}\,/\,r_2 \end{bmatrix}$$

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Conclusion

- Differences in Touchstone V1.0, V1.1, V2.0, V2.1 are shown
- New V1.1 option line syntax is shown
- Transformations between normalized and un-normalized matrix data are given for different per-port reference resistances
- TSCHK2.1 parser developer will add the per-port reference matrix transformation capability

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