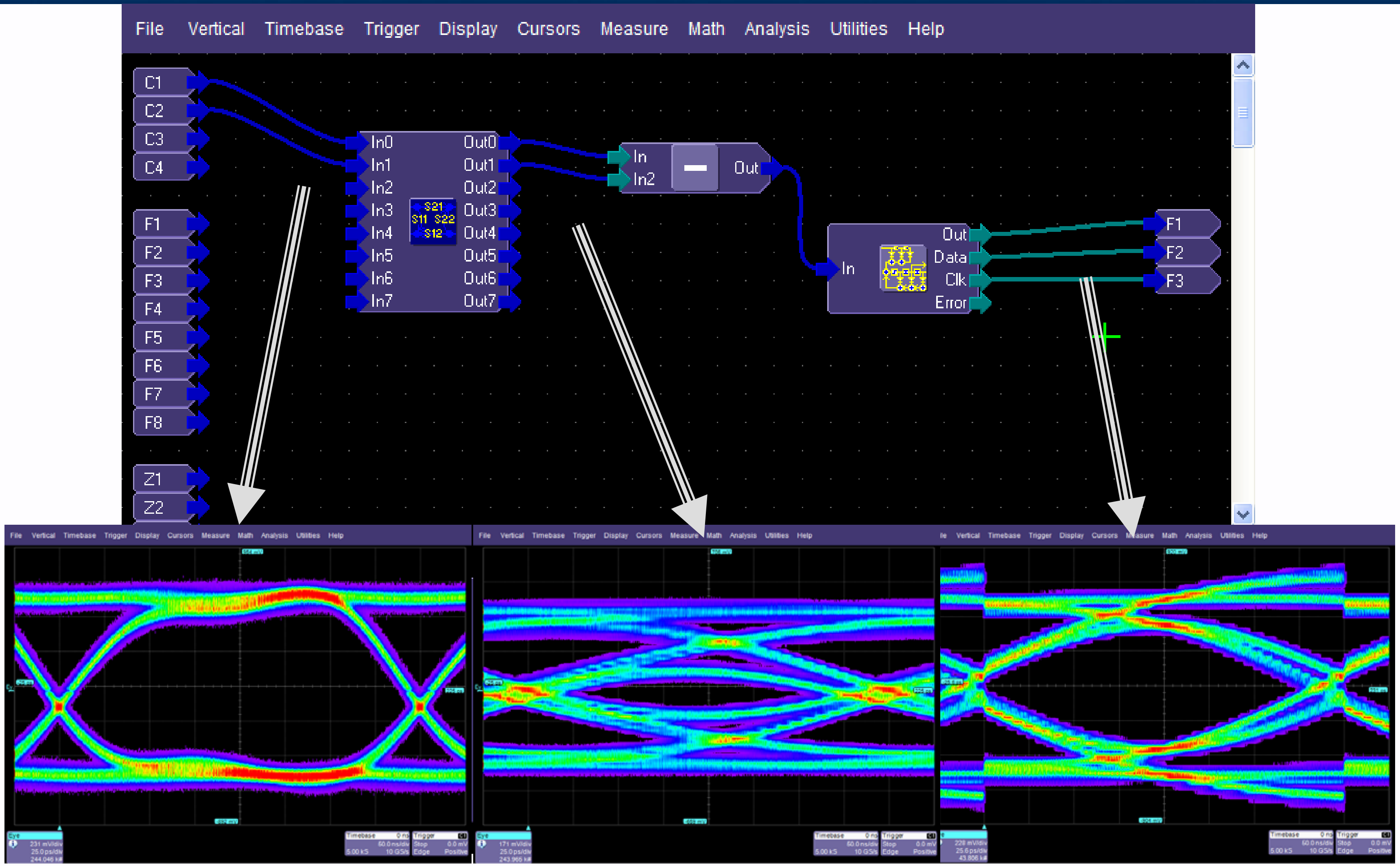
SAS-2 Virtual Probing And Equalizer Emulation

Peter J. Pupalaikis

Michael Schnecker

LeCroy Corp.

The Eye Doctor Solution



Measured Signal at Transmitter | Virtually Probed Signal at Receiver | Equalized Signal

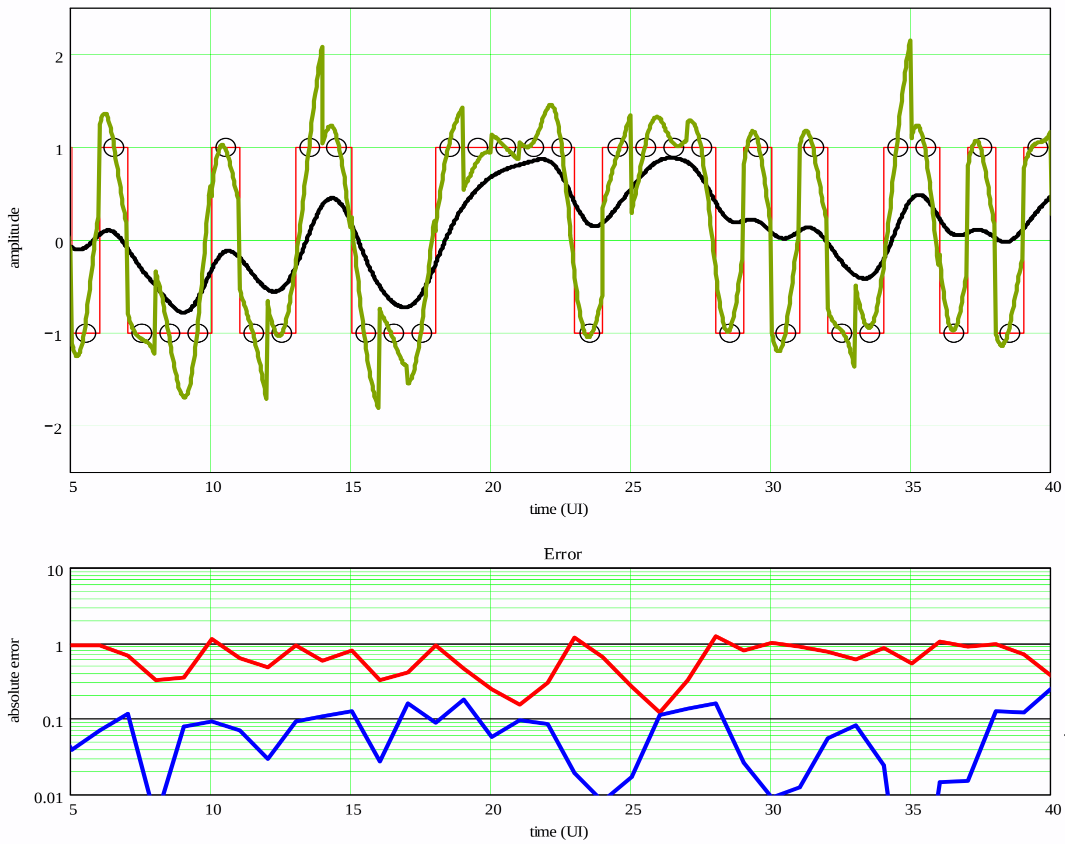
Equalizer overview

- Linear
  - Unsampled
    - Continuous-time (CTLE)
    - Transversal FIR
  - Sampled
    - Rx FIR
    - Tx FIR
- Non-linear
  - Decision Feedback Equalization (DFE)

Most commonly used equalizers

Implemented in Eye Doctor

Minimum Mean-Squared Error



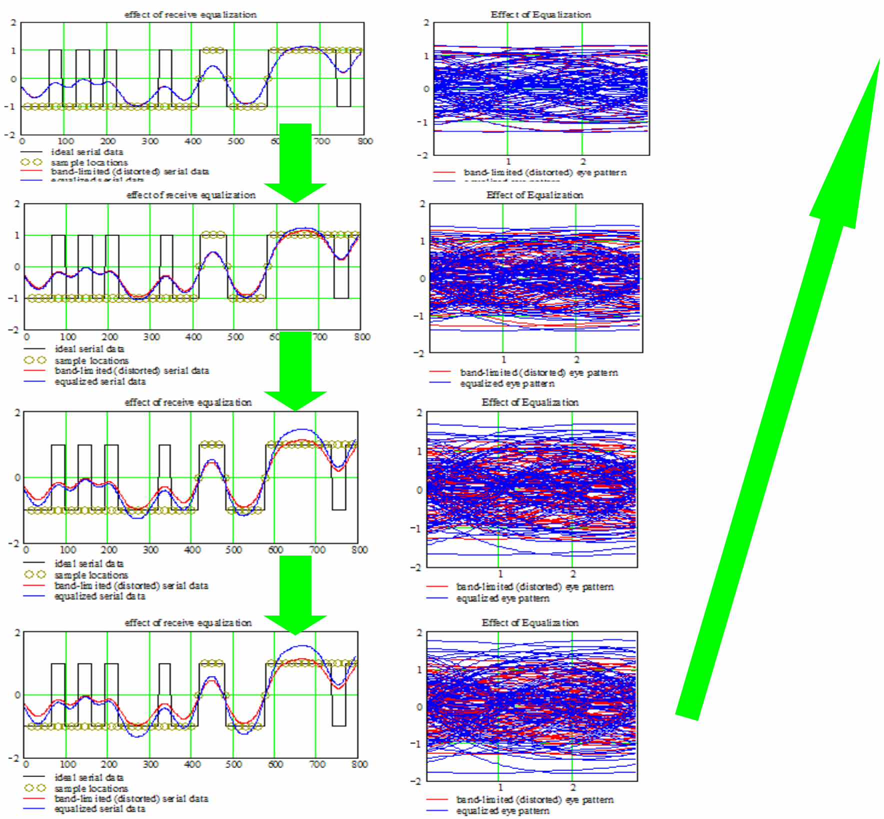
Note: logarithmic scale

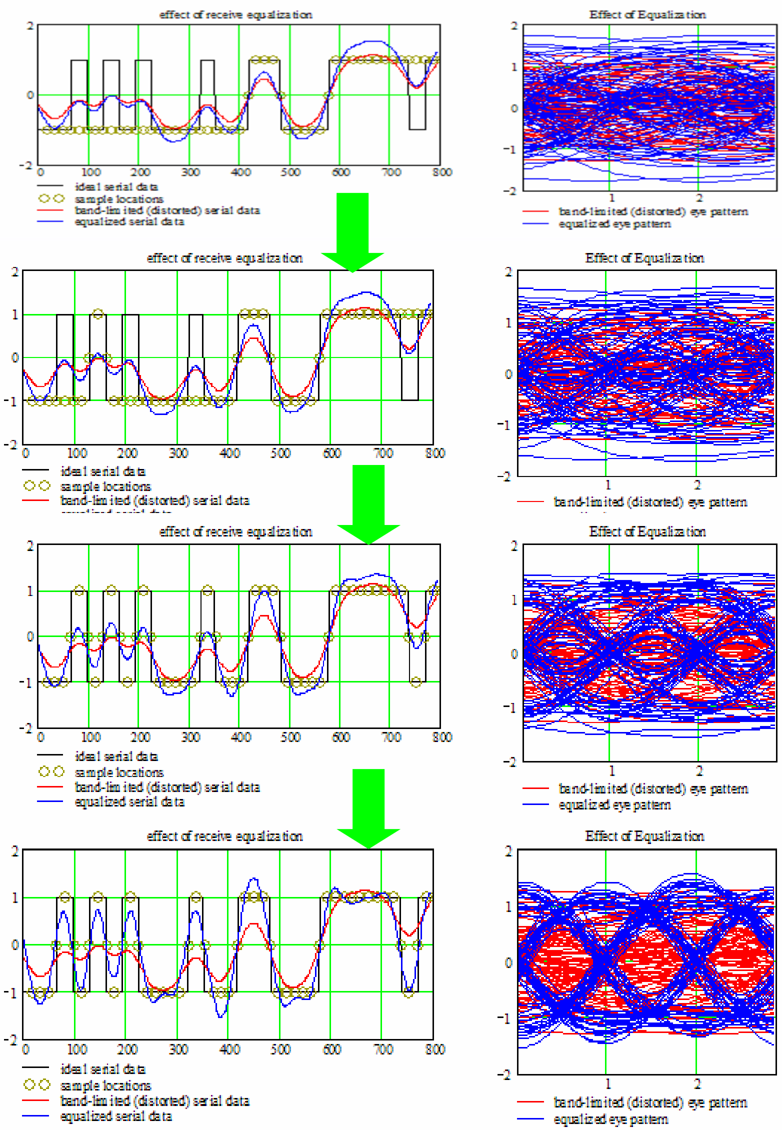
unequalized

equalized

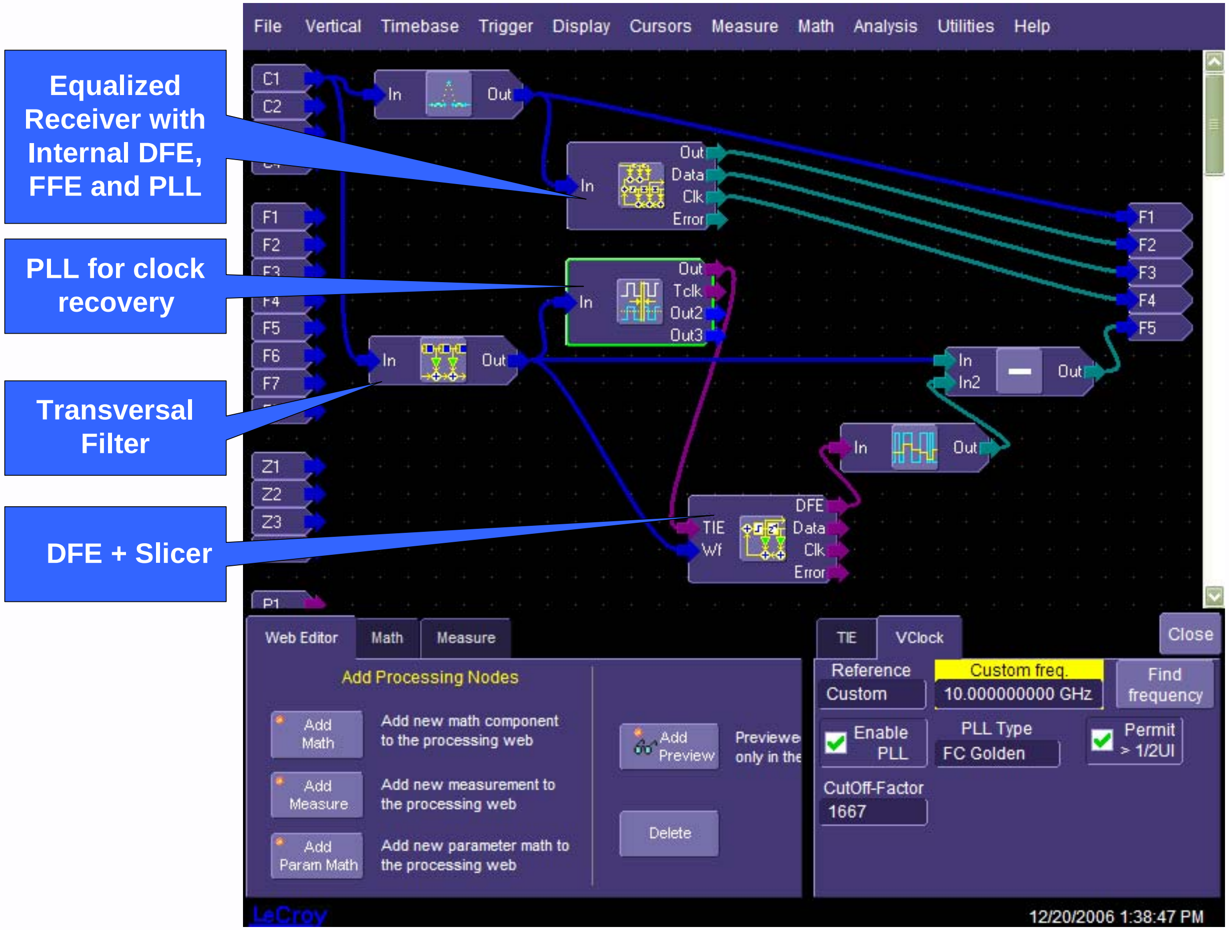
Error signal

Decision Directed Learning (Blind Adaptation)



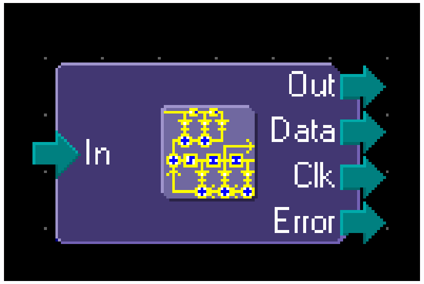


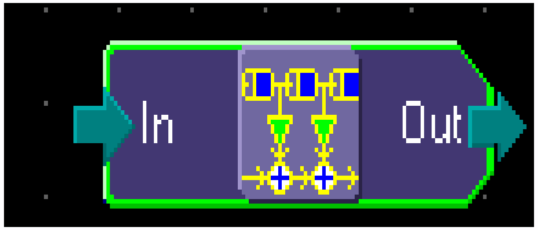
Equalizer Emulation Components



Setting Up Equalization

- DFE
  - Use equalized receiver
  - Set number of taps and train
- FFE
  - Use linear tapped delay line filter
  - Set number taps and train
- De-emphasis
  - Use linear tapped-delay line filter
  - Set taps to 3
  - Set bit time interval (tap delay)
  - Enter weights: -N, 1-N for 1-2N de-emphasis

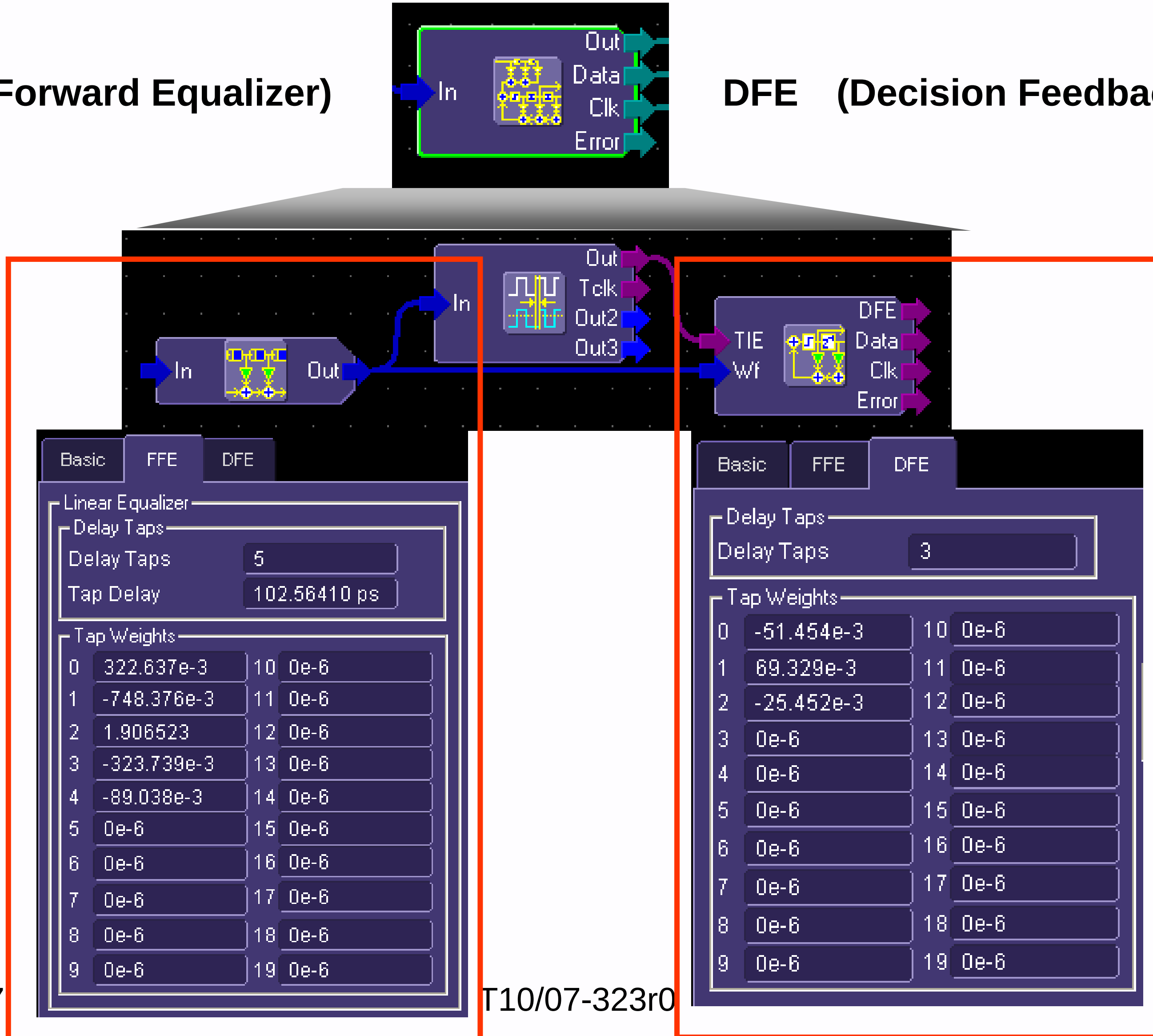




Configuration of the equalizer emulator

FFE (Feed Forward Equalizer)

DFE (Decision Feedback Equalizer)

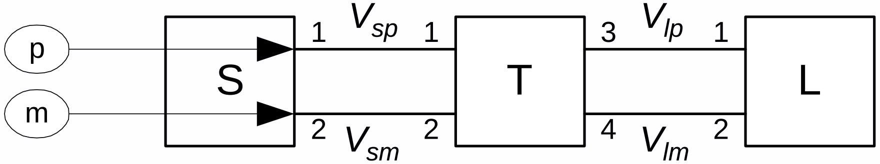


Up to 20 Taps

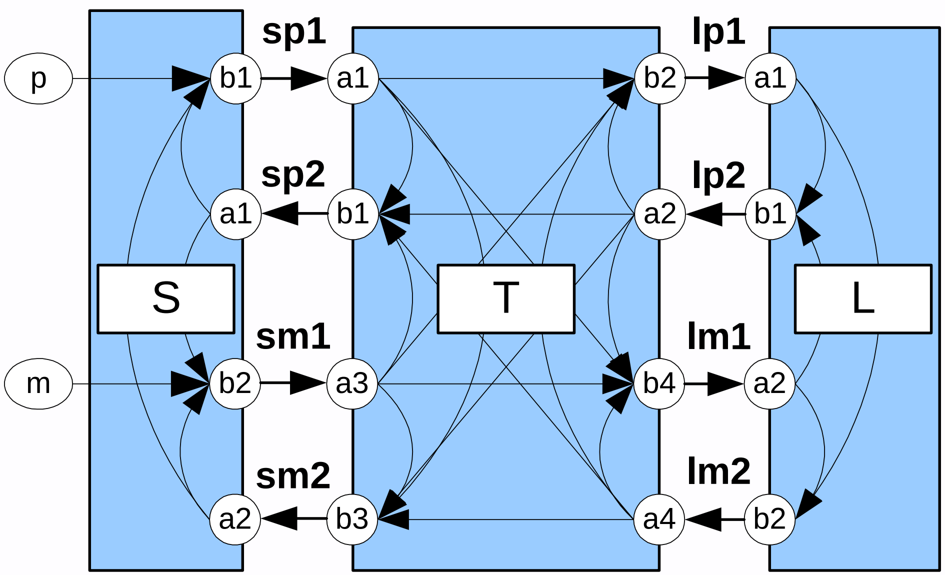
Up to 20 Taps

Virtual Probing Theory of Operation

Network Diagram



Signal Flow Diagram



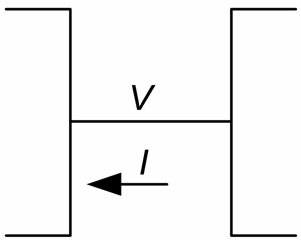
System Description File

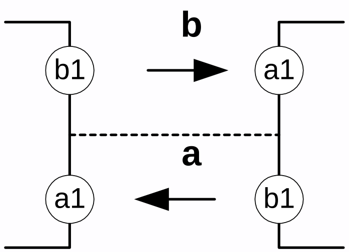
```
.device S 2 file "s.s2p"
.device T 4 file "t.s4p"
.device L 2 file "l.s2p"
.node vsp S 1 T 1
.node vsm S 2 T 2
.node vlp T 3 L 1
.node vlm T 4 L 2
.stim p S 1
.stim m S 2
.meas vsp
.meas vsm
.output vlp
.output vlm
```

Power Wave Relationship

$$a = \frac{V + I \cdot Z0}{2 \cdot \sqrt{Z0}} \qquad b = \frac{V - I \cdot Z0}{2 \cdot \sqrt{Z0}}$$

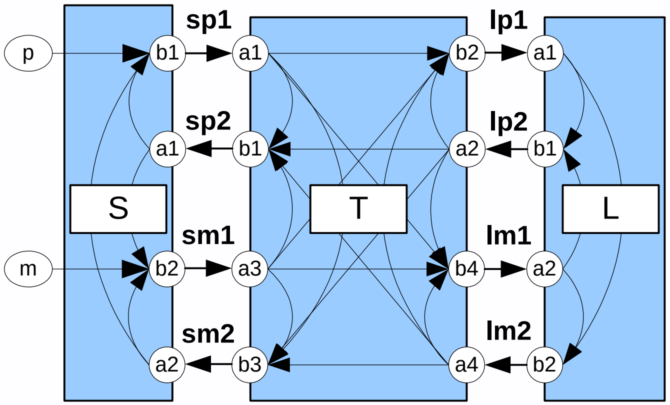
$$V = (a + b) \cdot \sqrt{Z0} \qquad I = (a - b) \cdot \frac{\sqrt{Z0}}{Z0}$$





- Voltage is voltage at node
- Current is into leftmost port
- A is incident wave on leftmost port
- B is reflected wave from leftmost port

Voltage Relationships

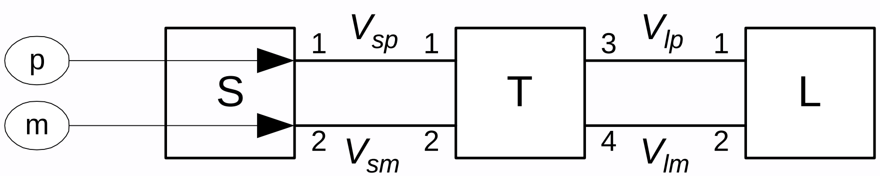


$$V_{sp} = (sp1 + sp2) \cdot \sqrt{Z0}$$

$$V_{sm} = (sm1 + sm2) \cdot \sqrt{Z0}$$

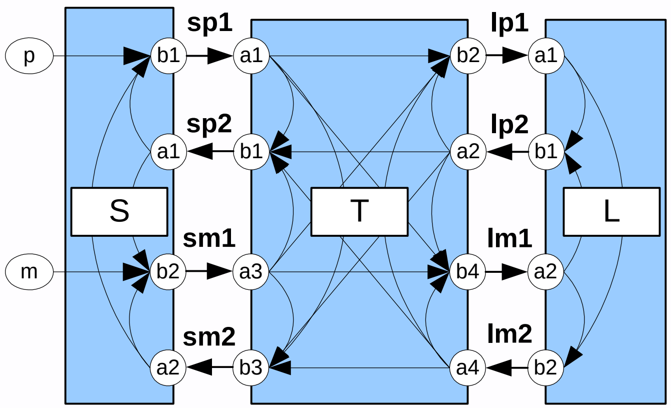
$$V_{lp} = (lp1 + lp2) \cdot \sqrt{Z0}$$

$$V_{lm} = (lm1 + lm2) \cdot \sqrt{Z0}$$



$$V = \begin{bmatrix} V_{sp} \\ V_{sm} \\ V_{lp} \\ V_{lm} \end{bmatrix} = \sqrt{Z0} \cdot \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} sp_1 \\ sm_1 \\ sp_2 \\ sm_2 \\ lp_1 \\ lm_1 \\ lp_2 \\ lm_2 \end{bmatrix}$$

Systems of Equations



$$sp1 = p + sS_{12} \cdot sm2 + sS_{11} \cdot sp2$$
$$sp2 = sT_{11} \cdot sp1 + sT_{13} \cdot sm1 + sT_{12} \cdot lp2 + sT_{14} \cdot lm2$$
$$sm1 = m + sS_{21} \cdot sp2 + sS_{22} \cdot sm2$$
$$sm2 = sT_{33} \cdot sm1 + sT_{31} \cdot sp1 + sT_{32} \cdot lp2 + sT_{34} \cdot lm2$$
$$lp1 = sT_{21} \cdot sp1 + sT_{23} \cdot sm1 + sT_{24} \cdot lm2 + sT_{22} \cdot lp2$$
$$lp2 = sL_{11} \cdot lp1 + sL_{12} \cdot lm1$$
$$lm1 = sT_{42} \cdot lp2 + sT_{41} \cdot sp1 + sT_{43} \cdot sm1 + sT_{44} \cdot lm2$$
$$lm2 = sL_{22} \cdot lm1 + sL_{21} \cdot lp1$$

$$\begin{bmatrix} 1 & 0 & -sS_{11} & -sS_{12} & 0 & 0 & 0 & 0 \\ 0 & 1 & -sS_{21} & -sS_{22} & 0 & 0 & 0 & 0 \\ -sT_{11} & -sT_{12} & 1 & 0 & 0 & 0 & -sT_{13} & -sT_{14} \\ -sT_{21} & -sT_{22} & 0 & 1 & 0 & 0 & -sT_{23} & -sT_{24} \\ -sT_{31} & -sT_{32} & 0 & 0 & 1 & 0 & -sT_{33} & -sT_{34} \\ -sT_{41} & -sT_{42} & 0 & 0 & 0 & 1 & -sT_{43} & -sT_{44} \\ 0 & 0 & 0 & 0 & -sL_{11} & -sL_{12} & 1 & 0 \\ 0 & 0 & 0 & 0 & -sL_{21} & -sL_{22} & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} sp_1 \\ sm_1 \\ sp_2 \\ sm_2 \\ lp_1 \\ lm_1 \\ lp_2 \\ lm_2 \end{bmatrix} = \begin{bmatrix} p \\ m \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The Simulator Solution

$$\begin{bmatrix} 1 & 0 & -sS_{11} & -sS_{12} & 0 & 0 & 0 & 0 \\ 0 & 1 & -sS_{21} & -sS_{22} & 0 & 0 & 0 & 0 \\ -sT_{11} & -sT_{12} & 1 & 0 & 0 & 0 & -sT_{13} & -sT_{14} \\ -sT_{21} & -sT_{22} & 0 & 1 & 0 & 0 & -sT_{23} & -sT_{24} \\ -sT_{31} & -sT_{32} & 0 & 0 & 1 & 0 & -sT_{33} & -sT_{34} \\ -sT_{41} & -sT_{42} & 0 & 0 & 0 & 1 & -sT_{43} & -sT_{44} \\ 0 & 0 & 0 & 0 & -sL_{11} & -sL_{12} & 1 & 0 \\ 0 & 0 & 0 & 0 & -sL_{21} & -sL_{22} & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} sp_1 \\ sm_1 \\ sp_2 \\ sm_2 \\ lp_1 \\ lm_1 \\ lp_2 \\ lm_2 \end{bmatrix} = \begin{bmatrix} p \\ m \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$Si = \begin{bmatrix} 1 & 0 & -sS_{11} & -sS_{12} & 0 & 0 & 0 & 0 \\ 0 & 1 & -sS_{21} & -sS_{22} & 0 & 0 & 0 & 0 \\ -sT_{11} & -sT_{12} & 1 & 0 & 0 & 0 & -sT_{13} & -sT_{14} \\ -sT_{21} & -sT_{22} & 0 & 1 & 0 & 0 & -sT_{23} & -sT_{24} \\ -sT_{31} & -sT_{32} & 0 & 0 & 1 & 0 & -sT_{33} & -sT_{34} \\ -sT_{41} & -sT_{42} & 0 & 0 & 0 & 1 & -sT_{43} & -sT_{44} \\ 0 & 0 & 0 & 0 & -sL_{11} & -sL_{12} & 1 & 0 \\ 0 & 0 & 0 & 0 & -sL_{21} & -sL_{22} & 0 & 1 \end{bmatrix}^{-1}$$

$$\begin{bmatrix} sp_1 \\ sm_1 \\ sp_2 \\ sm_2 \\ lp_1 \\ lm_1 \\ lp_2 \\ lm_2 \end{bmatrix} = Si \cdot \begin{bmatrix} p \\ m \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} sp_1 \\ sm_1 \\ sp_2 \\ sm_2 \\ lp_1 \\ lm_1 \\ lp_2 \\ lm_2 \end{bmatrix} = \begin{bmatrix} Si_{0,0} & Si_{0,1} \\ Si_{1,0} & Si_{1,1} \\ Si_{2,0} & Si_{2,1} \\ Si_{3,0} & Si_{3,1} \\ Si_{4,0} & Si_{4,1} \\ Si_{5,0} & Si_{5,1} \\ Si_{6,0} & Si_{6,1} \\ Si_{7,0} & Si_{7,1} \end{bmatrix} \cdot \begin{bmatrix} p \\ m \end{bmatrix}$$

$$\begin{bmatrix} V_{sp} \\ V_{sm} \\ V_{lp} \\ V_{lm} \end{bmatrix} = \sqrt{Z0} \cdot \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{0,0} & Si_{0,1} \\ Si_{1,0} & Si_{1,1} \\ Si_{2,0} & Si_{2,1} \\ Si_{3,0} & Si_{3,1} \\ Si_{4,0} & Si_{4,1} \\ Si_{5,0} & Si_{5,1} \\ Si_{6,0} & Si_{6,1} \\ Si_{7,0} & Si_{7,1} \end{bmatrix} \cdot \begin{bmatrix} p \\ m \end{bmatrix}$$

- Simulators need to solve for voltages with respect to stimuli.
- Virtual Probing is not a simulator.

The Transfer Function Solution

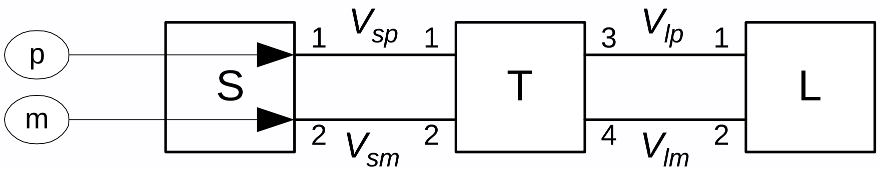
$$\begin{bmatrix} V_{sp} \\ V_{sm} \\ V_{lp} \\ V_{lm} \end{bmatrix} = \sqrt{Z0} \cdot \begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{0,0} & Si_{0,1} \\ Si_{1,0} & Si_{1,1} \\ Si_{2,0} & Si_{2,1} \\ Si_{3,0} & Si_{3,1} \\ Si_{4,0} & Si_{4,1} \\ Si_{5,0} & Si_{5,1} \\ Si_{6,0} & Si_{6,1} \\ Si_{7,0} & Si_{7,1} \end{bmatrix} \cdot \begin{bmatrix} p \\ m \end{bmatrix}$$

$$\begin{bmatrix} V_{sp} \\ V_{sm} \end{bmatrix} = \sqrt{Z0} \cdot \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{0,0} & Si_{0,1} \\ Si_{1,0} & Si_{1,1} \\ Si_{2,0} & Si_{2,1} \\ Si_{3,0} & Si_{3,1} \end{bmatrix} \cdot \begin{bmatrix} p \\ m \end{bmatrix} \qquad \begin{bmatrix} V_{lp} \\ V_{lm} \end{bmatrix} = \sqrt{Z0} \cdot \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{4,0} & Si_{4,1} \\ Si_{5,0} & Si_{5,1} \\ Si_{6,0} & Si_{6,1} \\ Si_{7,0} & Si_{7,1} \end{bmatrix} \cdot \begin{bmatrix} p \\ m \end{bmatrix}$$

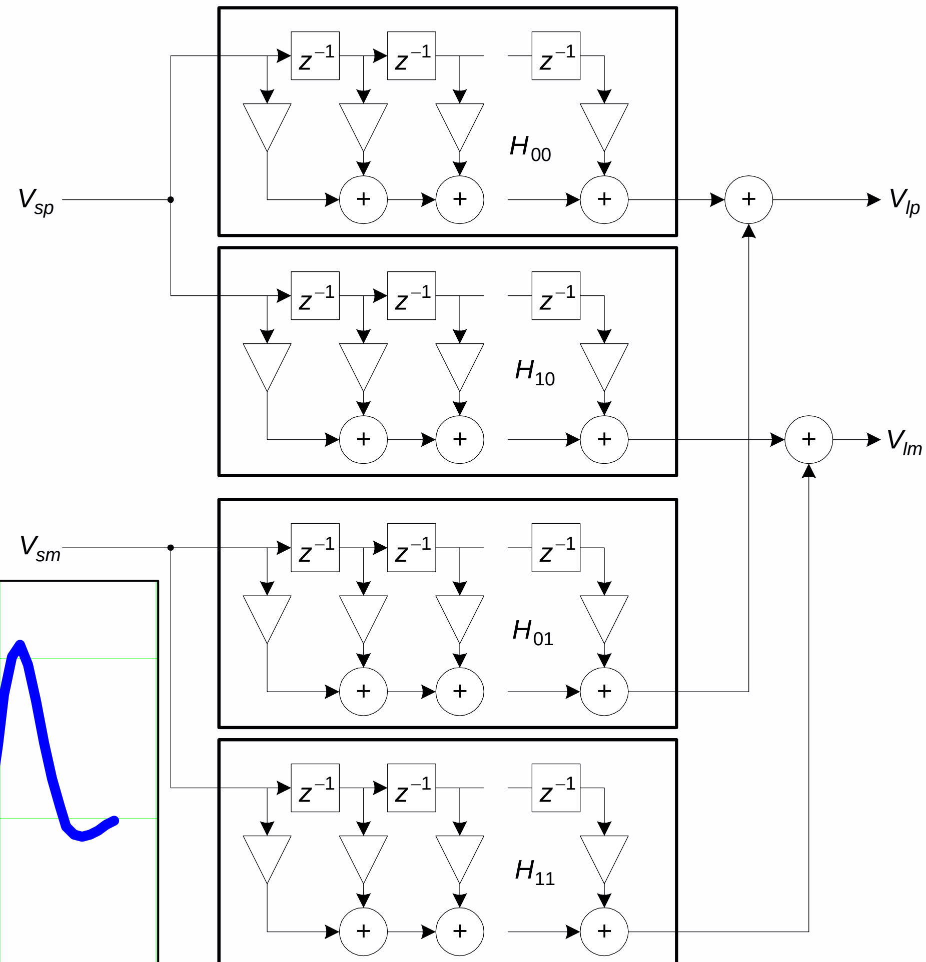
$$\begin{bmatrix} V_{lp} \\ V_{lm} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{4,0} & Si_{4,1} \\ Si_{5,0} & Si_{5,1} \\ Si_{6,0} & Si_{6,1} \\ Si_{7,0} & Si_{7,1} \end{bmatrix} \cdot \left[\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{0,0} & Si_{0,1} \\ Si_{1,0} & Si_{1,1} \\ Si_{2,0} & Si_{2,1} \\ Si_{3,0} & Si_{3,1} \end{bmatrix} \right]^{-1} \cdot \begin{bmatrix} V_{sp} \\ V_{sm} \end{bmatrix}$$

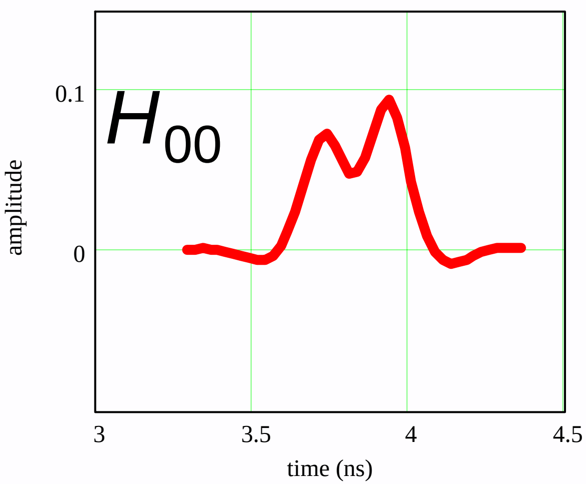
$$\begin{bmatrix} H_{00} & H_{01} \\ H_{10} & H_{11} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{4,0} & Si_{4,1} \\ Si_{5,0} & Si_{5,1} \\ Si_{6,0} & Si_{6,1} \\ Si_{7,0} & Si_{7,1} \end{bmatrix} \cdot \left[\begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} Si_{0,0} & Si_{0,1} \\ Si_{1,0} & Si_{1,1} \\ Si_{2,0} & Si_{2,1} \\ Si_{3,0} & Si_{3,1} \end{bmatrix} \right]^{-1} \qquad \begin{bmatrix} H_{00} & H_{01} \\ H_{10} & H_{11} \end{bmatrix} \cdot \begin{bmatrix} V_{sp} \\ V_{sm} \end{bmatrix} = \begin{bmatrix} V_{lp} \\ V_{lm} \end{bmatrix}$$

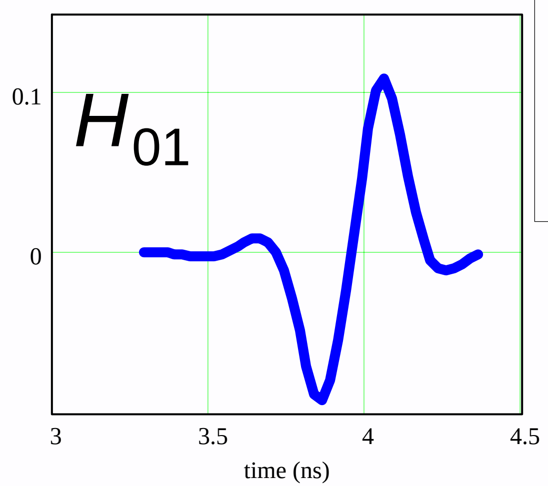
Virtual Probing Filter Structure



Both filters transmit the common mode in the same polarity, and the differential mode in the opposite polarity.

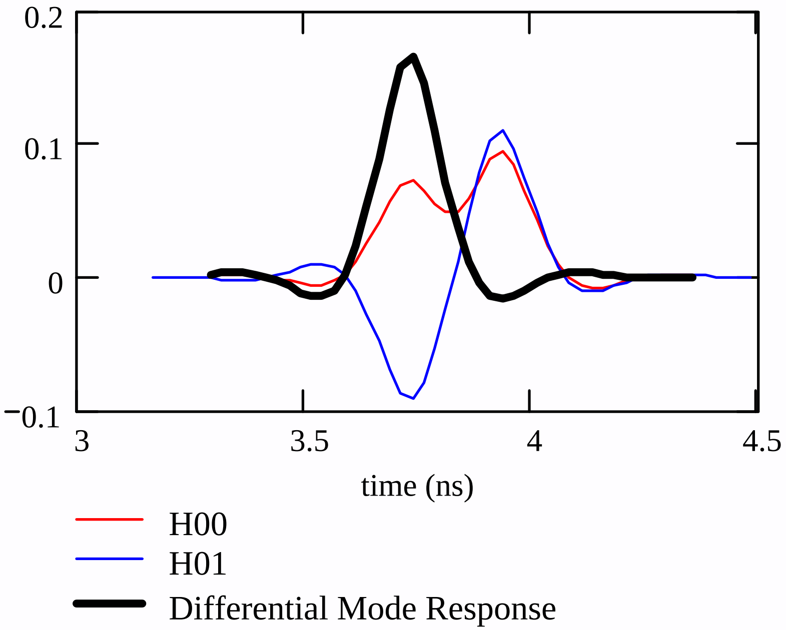


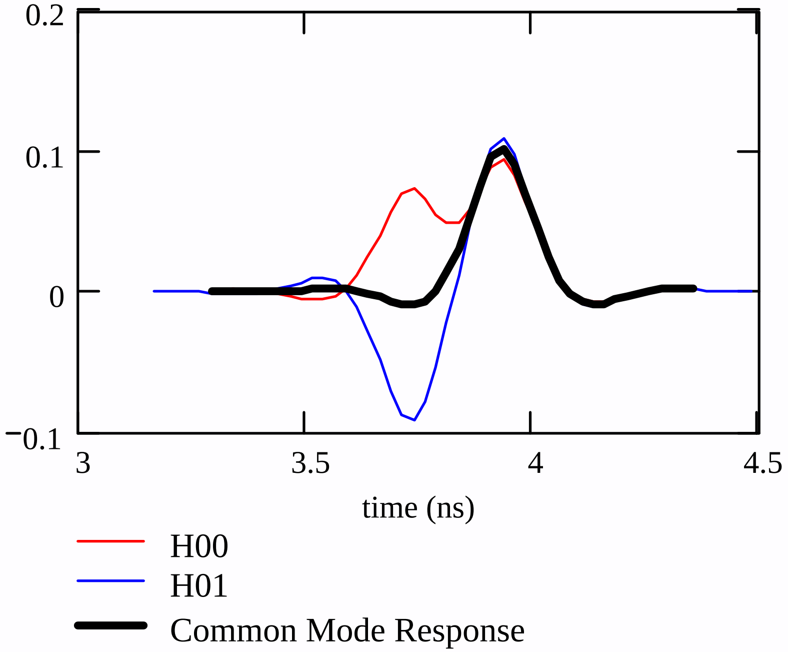




$$\begin{bmatrix} H_{00} & H_{01} \\ H_{10} & H_{11} \end{bmatrix} \cdot \begin{bmatrix} V_{sp} \\ V_{sm} \end{bmatrix} = \begin{bmatrix} V_{lp} \\ V_{lm} \end{bmatrix}$$

Filter Responses Explained





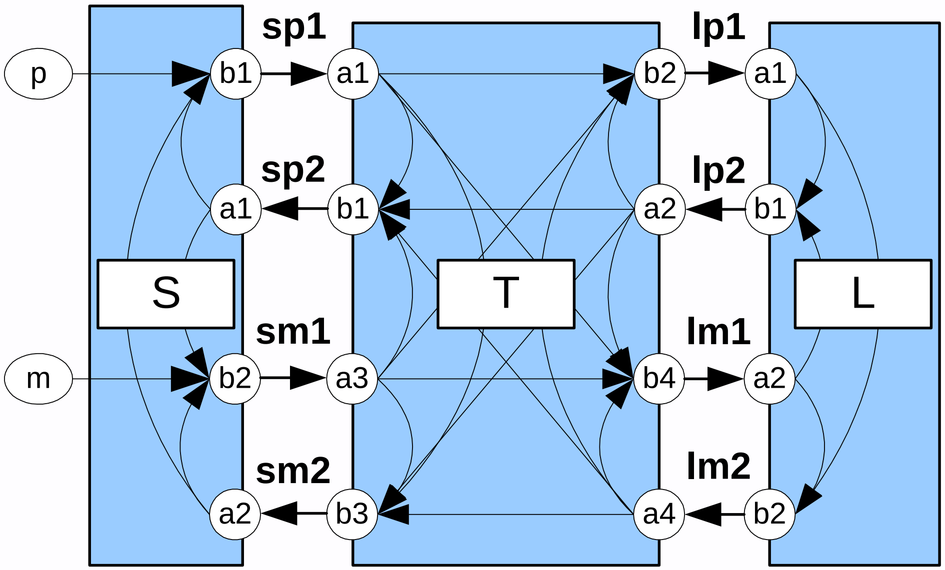
Virtual Probing Agenda

- Setting up Virtual Probing
- System Description Files and Diagrams
- S-parameters and S-parameter files
- Virtual Probing Theory of Operation
- ***How it Works Internally***
- Matching Problems to Diagrams
- TinyCAD
- Summary

Internal Steps

- Set up a ***System Description*** which is an array of devices, each device having S-parameters and an array of ports, each port containing a stimuli, an A node and a B node.
- Set up the equations corresponding to the system description and solve them.
- Convert the solutions into transfer functions and then into filters.

Table Equivalent of System Description



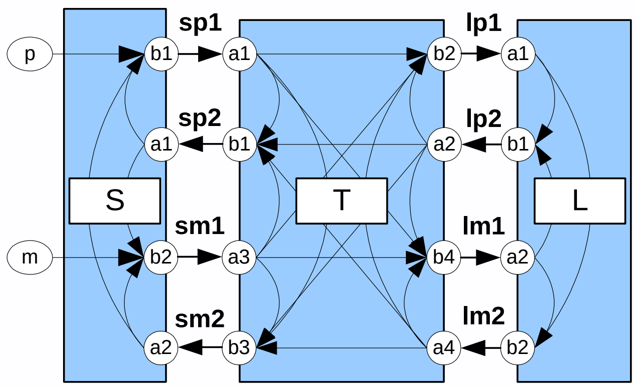
0 S	0	A	sp2
		B	sp1
		S	p
	1	A	sm2
		B	sm1
		S	m
1 T	0	A	sp1
		B	sp2
		S	
	1	A	sm1
		B	sm2
		S	
	2	A	lp2
		B	lp1
		S	
	3	A	lm2
		B	lm1
		S	
2 L	0	A	lp1
		B	lp2
		S	
	1	A	lm1
		B	lm2
		S	

Compact, but Time Consuming Code

```
Array < ComplexMatrix > Sinv(spsd[0].S().Elements());
// build S (and actually Sinv)
for (int n=0; n < spsd[0].S().Elements(); ++n)
{ // for each frequency element
    ComplexMatrix S(ports,ports,COMPLEX(0.0));
    for (int d=0; d < spsd.Elements(); ++d)
    { // for each device...
        for (int p=0; p < spsd[d].Elements(); ++p)
        { // for each port in the device...
            // calculate the row in S based on the B node connection
            int r=Index(spsd[d][p].BNodeName(),N);
            S[r][r] = 1.0;
            //M[r] = Devices[d][p].StimName());
            for (int c=0; c < spsd[d].Elements(); ++c)
            {
                S[r][Index(spsd[d][c].ANodeName(),N)] = -spsd[d].S()[n][p][c];
            }
        }
    }

    Sinv[n] = ComplexMatrix::Inverse(S);
}
```

How System Equations are Generated



$$
\begin{bmatrix}
1 & 0 & -sS_{11} & -sS_{12} & 0 & 0 & 0 & 0 \\
0 & 1 & -sS_{21} & -sS_{22} & 0 & 0 & 0 & 0 \\
-sT_{11} & -sT_{12} & 1 & 0 & 0 & 0 & -sT_{13} & -sT_{14} \\
-sT_{21} & -sT_{22} & 0 & 1 & 0 & 0 & -sT_{23} & -sT_{24} \\
-sT_{31} & -sT_{32} & 0 & 0 & 1 & 0 & -sT_{33} & -sT_{34} \\
-sT_{41} & -sT_{42} & 0 & 0 & 0 & 1 & -sT_{43} & -sT_{44} \\
0 & 0 & 0 & 0 & -sL_{11} & -sL_{12} & 1 & 0 \\
0 & 0 & 0 & 0 & -sL_{21} & -sL_{22} & 0 & 1
\end{bmatrix}
\cdot
\begin{bmatrix}
sp_1 \\ sm_1 \\ sp_2 \\ sm_2 \\ lp_1 \\ lm_1 \\ lp_2 \\ lm_2
\end{bmatrix}
=
\begin{bmatrix}
p \\ m \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{bmatrix}
$$

0 S	0	A	sp2
		B	sp1
		S	p
	1	A	sm2
		B	sm1
		S	m
1 T	0	A	sp1
		B	sp2
		S	
	1	A	sm1
		B	sm2
		S	
	2	A	lp2
		B	lp1
		S	
	3	A	lm2
		B	lm1
		S	
2 L	0	A	lp1
		B	lp2
		S	
	1	A	lm1
		B	lm2
		S	

Eye Doctor Summary

- Measuring signal at transmitter guarantees maximum signal fidelity – minimizes measurement error
- Simulating channel and interconnects provides accurate and repeatable measurements
- S-parameters of compliance channel can be defined in specification
- Standard equalizers defined in software allow measurements on closed eyes independent of specific implementations