ECEN689: Special Topics in High-Speed Links Circuits and Systems
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Lecture 7: Channel Time-Domain Response

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Announcements

• HW2 due 2/5

• No class next week

• Reading
  • Will post some material on TDR and network analyzers (S-parameters)
  • Link signaling papers
Agenda

• S-parameters revisited
• Impulse response generation
• Eye diagrams
• Inter-symbol interference (ISI)
Formal S-Parameter Definitions

\[ s_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} = \text{Input reflection coefficient with the output port terminated by a matched load (} Z_L = Z_0 \text{ sets } a_2 = 0) \]

\[ s_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} = \text{Output reflection coefficient with the input terminated by a matched load (} Z_S = Z_0 \text{ sets } V_s = 0) \]

\[ s_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} = \text{Forward transmission (insertion) gain with the output port terminated in a matched load.} \]

\[ s_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} = \text{Reverse transmission (insertion) gain with the input port terminated in a matched load.} \]
S-Parameters with Arbitrary Termination

\[ s'_{11} = s_{11} + \frac{s_{12} s_{21} \Gamma_L}{1 - s_{22} \Gamma_L} \quad (a_2 \neq 0) \]

\[ s'_{22} = s_{22} + \frac{s_{12} s_{21} \Gamma_S}{1 - s_{11} \Gamma_S} \quad (a_1 \neq 0) \]

- I believe this is what the network analyzer reports for \( s_{11} \) and \( s_{22} \) when a matching network is not used.
**S-Parameter Test Circuits & Meaning**

**[Sackinger]**

<table>
<thead>
<tr>
<th>Circuit</th>
<th>Equations</th>
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| ![Circuit Diagram](image) | $S_{11}(s) = \frac{V_{i,\text{reflected}}}{V_{i,\text{incident}}} = \frac{V_i - R_0 I_i}{V_i + R_0 I_i} = \frac{V_i - V_s}{V_s}$  
$S_{21}(s) = \frac{V_{o,\text{transmitted}}}{V_{i,\text{incident}}} = \frac{V_o - R_0 I_o}{V_i + R_0 I_i} = \frac{V_o}{V_s}$  
$S_{22}(s) = \frac{V_{o,\text{reflected}}}{V_{o,\text{incident}}} = \frac{V_o - R_0 I_o}{V_o + R_0 I_o} = \frac{V_o - V_s}{V_s}$  
$S_{12}(s) = \frac{V_{i,\text{transmitted}}}{V_{o,\text{incident}}} = \frac{V_i - R_0 I_i}{V_o + R_0 I_o} = \frac{V_i}{V_s}$  

$S_{21}(s) = [1 + S_{11}(s)]A(s)$  
where $A(s)$ is loaded voltage gain

If $a_1$ and $a_2$ are not equal to zero for the appropriate measurements, these are “formally” $s_{11}'$, $s_{21}'$, $s_{22}'$, $s_{12}'$.
S-Parameter Channel Example

- Advanced TCA backplane test system
- Vector Network Analyzer
- Surface mount SMA launch
- Settings
  - 50 MHz – 15 GHz, 10 MHz step
  - IF BW 300 Hz
  - Leveled output power -5 dB
  - 4 averages

[ Peters, IEEE Backplane Ethernet Task Force ]
S-Parameter Channel Example
(4-port differential)

Data from 50MHz to 15GHz in 10MHz steps

\[
\begin{align*}
\begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
&= \begin{bmatrix}
S_{d11} & S_{d12} & S_{d13} & S_{d14} \\
S_{d21} & S_{d22} & S_{d23} & S_{d24} \\
S_{d31} & S_{d32} & S_{d33} & S_{d34} \\
S_{d41} & S_{d42} & S_{d43} & S_{d44}
\end{bmatrix} \\
&= \begin{bmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{bmatrix}
\end{align*}
\]
S-Parameter Channel Example

T20 Backplane Channel

Frequency (GHz)

$S_{21}$, $S_{11}$ (dB)
Impulse Response

- Channel impulse responses are used in
  - Time domain simulations
  - Link analysis tools

\[
Y(\omega) = H(\omega)X(\omega)
\]

\[
y(t) = h(t) * x(t) = \int_{-\infty}^{\infty} h(t-\tau)x(\tau)\]

\[
h(t) = F^{-1}\{H(w)\}\]
Generating an Impulse Response from S-Parameters

- Perform the inverse Fourier transform on the s-parameter of interest

- Step 1: For ifft, produce negative frequency values and append to s-parameter data in the following manner

\[ S(-f) = S(f)^* \]

\[ h(t) = F^{-1}\{S(\omega)\} \]
Increasing Impulse Response Resolution

- Could perform ifft now, but will get an impulse response with time resolution of

$$\frac{1}{2 f_{\text{max}}} = \frac{1}{2(15 \text{GHz})} = 33.3 \text{ps}$$

- To improve impulse response resolution expand frequency axis and “zero pad”

For 1ps resolution: zero pad to +/-500GHz
Channel Impulse Response

- Now perform ifft to produce impulse response
- Can sanity check by doing an fft on impulse response and comparing to measured data
Channel Transient Response

Input Data

Channel Impulse Response

Channel Output
Eye Diagrams

Use a precise clock to chop the data into equal periods.

Overlay each period onto one plot.

[Walker]
Eye Diagrams vs Data Rate

Channel Frequency Response

Frequency (GHz) vs Channel Response (dB)

1 Gb/s Eye

2 Gb/s Eye

5 Gb/s Eye
Eye Diagrams vs Channel

Channel Responses

Frequency (GHz)

Channel Response (dB)

7" Desktop/0Conn

17" Refined BP/2Conn

17" Legacy BP/2Conn

Desktop 5Gb/s Eye

Refined BP 5Gb/s Eye

Legacy BP 5Gb/s Eye

Time (ps)

Voltage (V)
Inter-Symbol Interference (ISI)

- Previous bits residual state can distort the current bit, resulting in inter-symbol interference (ISI)
- ISI is caused by
  - Reflections, Channel resonances, Channel loss (dispersion)
ISI Impact

- At channel input (TX output), eye diagram is wide open

- As data pulses propagate through channel, they experience dispersion and have significant ISI
  - Result is a closed eye at channel output (RX input)

[Meghelli (IBM) ISSCC 2006]
Next Time

- Channel pulse response model
- Modulation schemes