Outline

- Differential transmission lines
- Common mode signaling
- Differential mode signaling
- Mode conversion
- Even and odd modes
- 2-coupled lossless transmission line theory
- Termination techniques
- Differential or Mixed-Mode S-parameters
Differential Transmission Lines

For high data rates, differential signaling is more used due to:

- Radiation is reduced (cancellation of fields)
- Receiver rejects signals that are common to both lines (high CMRR at the receiver)
- Signal voltage amplitudes can be smaller

Electromagnetic Fields in a Microstrip Line
Electric Field Distribution

**Substrate: Air ($\varepsilon_r = 1$)**

![Electric Field Distribution](image1.png)

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Electric Field Distribution (cont.)

**Substrate: FR4 ($\varepsilon_r = 4.5$)**

![Electric Field Distribution](image2.png)
Magnetic Field Distribution

Substrate: Air or FR4

Differential Signaling for High-Speed Links

- Differential signaling can operate at much higher data rates
- High speed links operating in excess of ~1 Gb/s use differential signaling (e.g. Infiniband, PCI-Express).
- Differential signals are already used for high speed clocks

(H. Heck 2002)
Common Mode Signaling

As data rates go up, frequencies increase, lines become antennas (both send and receive) and corrupt the communication (BER, crosstalk, etc)

Differential Mode Signaling

Using differential excitations (differential transmission lines), most of the outside electromagnetic field cancels
Even Mode and Odd Mode

- Practical differential pairs operate at even and odd modes simultaneously
- Even mode – excited in phase with equal amplitudes
- Odd mode – driven 180° out of phase with equal amplitudes

Even Mode and Odd Mode (cont.)

Differential Mode
- Magnetic Field
- Electric Field

Common Mode
- Magnetic Field
- Electric Field

(H. Heck 2002)
(P. Huray and S. Pytel, 2009)
Mode Conversion

- Is produced by asymmetries in the differential pairs
- Can cause a differential signal to be converted to a common mode signal (radiation, crosstalk, etc.)

![Differential Stimulus Differential Response](image)

Lossless Transmission Lines

\[
V(z) = V_0^+ e^{-j\beta z} + V_0^- e^{+j\beta z} \\
I(z) = I_0^+ e^{-j\beta z} + I_0^- e^{+j\beta z} \\
\beta = \omega \sqrt{LC} \\
Z_0 = \frac{L}{\sqrt{C}} \\
V_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}}
\]

\[
\frac{dV(z)}{dz} = -(j\omega L)I(z) \\
\frac{dI(z)}{dz} = -(j\omega C)V(z) \\
\frac{dV}{dz} = -j\omega LI \\
\frac{dI}{dz} = -j\omega CV
\]

\[
-Z_L = j\omega L \\
Y_C = j\omega C
\]
2-Coupled Lossless Symmetrical TLs

\[ \frac{dV_1}{dz} = -j\omega L_s I_1 - j\omega L_m I_2 \]
\[ \frac{dV_2}{dz} = -j\omega L_m I_1 - j\omega L_s I_2 \]
\[ \frac{dI_1}{dz} = -j\omega(C_s + C_m)V_1 + j\omega C_m V_2 \]
\[ \frac{dI_2}{dz} = +j\omega C_m V_1 - j\omega(C_s + C_m)V_2 \]

\[ V = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \quad I = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \]

\[ Y_C = j\omega \begin{bmatrix} (C_s + C_m) & -C_m \\ -C_m & (C_s + C_m) \end{bmatrix} \]

\[ Z_L = j\omega \begin{bmatrix} L_s & L_m \\ L_m & L_s \end{bmatrix} \]

\[ -\frac{d}{dz} \begin{bmatrix} V \\ I \end{bmatrix} = \begin{bmatrix} 0 & Z_L \\ Y_C & 0 \end{bmatrix} \begin{bmatrix} V \\ I \end{bmatrix} \]
**LC Matrices of 2-Coupled TLs**

$$C = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} (C_s + C_m) & -C_m \\ -C_m & (C_s + C_m) \end{bmatrix}$$

$$L = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_s \end{bmatrix}$$

$$Z_0 = ?$$

$$v_p = ?$$

**Even Mode in 2-Coupled Symmetrical TLs**

$$\frac{dV_1}{dz} = -j \omega L_s I_1 - j \omega L_m I_2$$

$$\frac{dV_2}{dz} = -j \omega L_m I_1 - j \omega L_s I_2$$

$$\frac{dI_1}{dz} = -j \omega (C_s + C_m) V_1 + j \omega C_m V_2$$

$$\frac{dI_2}{dz} = j \omega C_m V_1 - j \omega (C_s + C_m) V_2$$

Since $$V_1 = V_2$$ and $$I_1 = I_2$$

$$\frac{dV_1}{dz} = -j \omega (L_s + L_m) I_1$$

$$\frac{dI_1}{dz} = -j \omega C_s V_1$$

The effective $$L$$ and $$C$$ are

$$L_{\text{eff}} = L_s + L_m$$

$$C_{\text{eff}} = C_s$$

Hence

$$Z_{0-\text{even}} = \sqrt{\frac{L_s + L_m}{C_s}}$$

$$v_{p-\text{even}} = \frac{1}{\sqrt{(L_s + L_m)C_s}}$$
Even Mode in 2-Coupled Symmetrical TLs (cont.)

\[ V_1 = V_2 \quad ; \quad I_1 = I_2 \]

\[
Z_{0\text{-even}} = \sqrt{\frac{L_s + L_m}{C_s}} \quad \quad \quad v_{p\text{-even}} = \frac{1}{\sqrt{(L_s + L_m)C_s}}
\]

\( Z_{0\text{-even}} \) is the characteristic impedance of one of the conductors when the coupled line is operated in even mode.

Odd Mode in 2-Coupled Symmetrical TLs

\[
\frac{dV_1}{dz} = -j\omega L_s I_1 - j\omega L_m I_2 \quad \quad \quad \frac{dV_2}{dz} = -j\omega L_m I_1 - j\omega L_s I_2
\]

\[
\frac{dI_1}{dz} = -j\omega(C_s + C_m)V_1 + j\omega C_m V_2 \quad \quad \quad \frac{dI_2}{dz} = j\omega C_m V_1 - j\omega(C_s + C_m)V_2
\]

Since \( V_1 = -V_2 \) and \( I_1 = -I_2 \)

\[
\frac{dV_1}{dz} = -j\omega(L_s - L_m)I_1 \quad \quad \quad \frac{dI_1}{dz} = -j\omega(C_s + 2C_m)V_1
\]

The effective \( L \) and \( C \) are

\[
L_{\text{eff}} = L_s - L_m \quad \quad \quad C_{\text{eff}} = C_s + 2C_m
\]

Hence

\[
Z_{0\text{-odd}} = \sqrt{\frac{L_s - L_m}{C_s + 2C_m}} \quad \quad \quad v_{p\text{-odd}} = \frac{1}{\sqrt{(L_s - L_m)(C_s + 2C_m)}}
\]
Odd Mode in 2-Coupled Symmetrical TLs (cont.)

\[ V_1 = -V_2 ; \quad I_1 = -I_2 \]

\[ Z_{0\text{-odd}} = \frac{L_s - L_m}{\sqrt{C_s + 2C_m}} \]

\[ v_{p\text{-odd}} = \frac{1}{\sqrt{(L_s - L_m)(C_s + 2C_m)}} \]

\( Z_{0\text{-odd}} \) is the characteristic impedance of one of the conductors when the coupled line is operated in odd mode.

(D. M. Pozar, Microwave Engineering, Wiley, 2005)
Distributed Capacitances in Coupled Lines (cont.)

\[ C_{\text{eff}} = C_s \]

\[ C_{\text{eff}} = C_s + 2C_m \]

\[ C_{\text{eff}} = \frac{1}{\sqrt{L_s C_s}} \]

\[ C_{\text{eff}} = \frac{1}{\sqrt{(L_s + L_m)C_s}} \]

\[ C_{\text{eff}} = \frac{1}{\sqrt{(L_s - L_m)(C_s + 2C_m)}} \]

\[ Z_0 \] and \( v_p \) for Even and Odd Modes

- If \( Z_0 \) is the characteristic impedance of each isolated conductor, and \( v_p \) is the propagation velocity or wave speed in each isolated conductor

\[ Z_0 = \frac{L_s}{C_s} \]

\[ v_p = \frac{1}{\sqrt{L_s C_s}} \]

- Since

\[ Z_{0-\text{even}} = \frac{L_s + L_m}{C_s} \]

\[ v_{p-\text{even}} = \frac{1}{\sqrt{(L_s + L_m)C_s}} \]

\[ Z_{0-\text{odd}} = \frac{L_s - L_m}{C_s + 2C_m} \]

\[ v_{p-\text{odd}} = \frac{1}{\sqrt{(L_s - L_m)(C_s + 2C_m)}} \]

- Then

\[ Z_{0-\text{odd}} < Z_0 < Z_{0-\text{even}} \]

\[ v_{p-\text{even}} < v_{p-\text{odd}} < v_p \]
Termination Techniques

- A single-resistor termination for each conductor is not enough for coupled lines
- Proper terminations are needed to avoid reflections in both even and odd modes
- The most common termination networks are the T and Pi configurations

T-Termination

\[
R_c = \frac{1}{2} (Z_{0\text{-even}} - Z_{0\text{-odd}}) \\
R_d = Z_{0\text{-odd}}
\]
Pi-Termination

\[ R_c = Z_{0\text{-even}} \]

\[ R_d = \frac{2Z_{0\text{-even}}Z_{0\text{-odd}}}{Z_{0\text{-even}} - Z_{0\text{-odd}}} \]

Adding Buffers for Differential Signaling

- 😊 Differential to Differential
- 😃 Differential to Single-ended
- 😃 Single-ended to Single-ended
S-Parameters for Two-Coupled Lines

Four-port single-ended device

Stimulus

Return Loss (RL)
Insertion Loss (IL)
Near End Crosstalk (NEXT)
Far End Crosstalk (FEXT)

Response

Port 1
Port 2
Port 3
Port 4

Single-ended to Balanced S-Parameters

Differential-Mode Stimulus
Common-Mode Stimulus

Differential-Mode Response
Common-Mode Response

Naming Convention:

S_{mode res.} mode stim., port res., port stim.

(M. Resso, 2005)
Balanced, Differential or Mixed-Mode S-Param.

Stimulus

Differential in, differential out: Behavior of differential signals

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Differential Signal</th>
<th>Common Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1</td>
<td>$S_{DD11}$</td>
<td>$S_{DC11}$</td>
</tr>
<tr>
<td>Port 2</td>
<td>$S_{DD12}$</td>
<td>$S_{DC12}$</td>
</tr>
<tr>
<td></td>
<td>$S_{DD21}$</td>
<td>$S_{DC21}$</td>
</tr>
<tr>
<td></td>
<td>$S_{DD22}$</td>
<td>$S_{DC22}$</td>
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</tbody>
</table>

Response

Differential in, common out: Behavior of mode conversion (EMI Emissions)

<table>
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</tr>
<tr>
<td></td>
<td>$S_{CD22}$</td>
</tr>
</tbody>
</table>

Common in, common out: Behavior of common signals

$S_{CC11}$  $S_{CC12}$  $S_{CC21}$  $S_{CC22}$

(M. Resso, 2005)