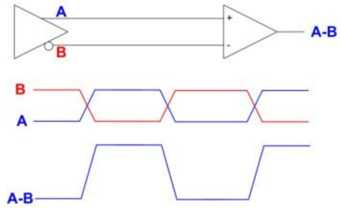
EELE 461/561 – Digital System Design

Module #6 – Differential Signaling

- **Topics**
  1. Differential and Common-Mode Impedance
  2. Even and Odd Mode Impedance
  3. Differential Termination Techniques
- **Textbook Reading Assignments**
  1. 11.1-11.10, 11.14
- **What you should be able to do after this module**
  1. Calculate Z_{diff}, Z_{com}, Z_{odd}, Z_{even} from transmission line parameters
  2. Design Π & T termination networks

Differential Signaling

- **Differential Signaling**
  - A signaling technique which uses two separate lines to send one logic symbol
  - The transmitter sends two complementary signals
  - A differential amplifier at the receiver produces the difference between the inputs (i.e., A-B)

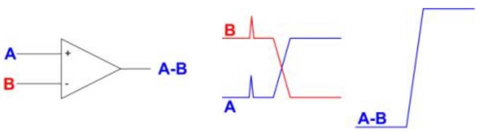


Differential Signaling

- **Advantages**

  1) Common Mode Rejection

  - Any "Common" signal that exists on the two lines will be subtracted out of the final signal.
  - Possible sources of *common* noise are EMI, power supply variation, X-talk, and SSN.

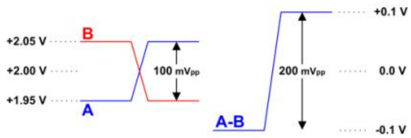


Differential Signaling

- **Advantages**

  2) Higher Receiver Gain

  - since the receiver is a differential amplifier, the resultant signal is actually twice the magnitude of any of the two input signals by themselves.
  - this "voltage doubling" allows more margin in the link (i.e., a smaller signal can be transmitted)

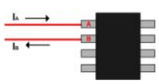


Differential Signaling

- **Advantages**

  3) Less SSN

  - since the two signals are inherently switching in opposite directions, they provide their own return current and lower the maximum possible Ground Bounce on the IC.



  4) Good for Low Cost Cables

  - two inexpensive wires can be wound around each other to form a "Twisted Pair" cable.
  - this type of cable has been proven to provide robust signaling when driven differentially.

Differential Signaling

- **Disadvantages**

  1) # of Pins & Traces

  - It takes twice as many lines to send one logic signal

- Differential Signaling is commonly used on high speed nets such as Clocks.

Voltage Definitions

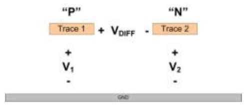
- **Differential & Common Signals**

  - For the two lines used in differential signaling, we define the following voltages:

    V_1 = the voltage on Trace 1 with respect to ground (P)
    V_2 = the voltage on Trace 2 with respect to ground (N)

  - The differential voltage is the difference between the two traces when driven differentially:

    V_{DIFF} = the voltage on Trace 1 with respect to Trace 2



$$V_{DIFF} = V_1 - V_2$$

Voltage Definitions

- **Differential & Common Signals**

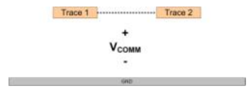
  - The common voltage is the voltage that is present on both Trace 1 and Trace 2. (i.e., "common" to both traces)

  - This can also be thought of as the "DC Offset"

  - Notice that when defining this voltage, Trace 1 and Trace 2 are at the same potential. This in effect *connects* the two traces for the purpose of defining the common voltage.

  - This is defined as the voltage on both Trace1 & Trace 2 to ground.

    V_{COMM} = the voltage on both Trace1 & Trace 2 to ground.



$$V_{COMM} = \frac{1}{2} \cdot (V_1 + V_2)$$

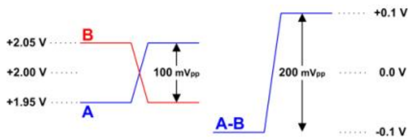
Voltage Definitions

- **Differential & Common Signals**

  - We can define the voltages on Trace 1 and Trace 2 formally as:

$$V_1 = V_{COMM} + \frac{1}{2} \cdot V_{DIFF}$$

$$V_2 = V_{COMM} - \frac{1}{2} \cdot V_{DIFF}$$



$$V_{COMM} = 2.0v$$
$$V_{DIFF} = 0.2v$$

Differential Pair Structures

- **Physical Implementation**

  - We can construct interconnect for differential signaling by adhering to the following constraints:

    1) Each Trace has a Uniform Cross-section

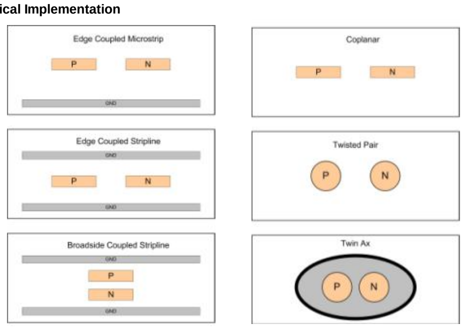
       - Impedance
       - Materials
       - Line Widths
       - Spacing
       - Velocity

    2) Same Electrical Length

       - Physical Length
       - Prop Delay

Differential Pair Structures

- **Physical Implementation**



Impedance Definitions

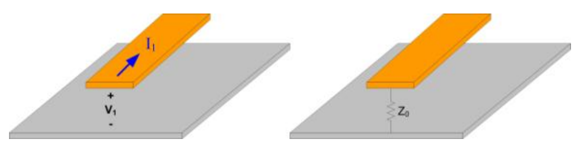
- **Z_0 & Z_{DIFF}**

  - Z_0 is the impedance of <u>*ONE*</u> T-line

  - Z_0 is always defined as:

$$Z_0 = \frac{V}{I}$$

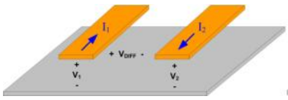
  - Z_0 is defined as the voltage per current on a single trace when all other traces are held at 0v.

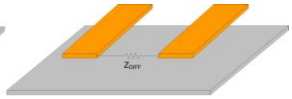


Impedance Definitions

- **Z_0 & Z_{DIFF}**
  - Z_{DIFF} is the impedance observed between Trace 1 and Trace 2 when the lines are driven differentially with V_{DIFF}.
  - Z_{DIFF} is defined as:

$$Z_{DIFF} = \frac{V_{DIFF}}{I_{DIFF}}$$

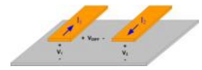




Impedance Definitions

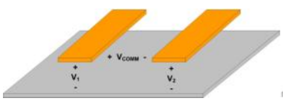
- **Z_0 & Z_{DIFF} for Uncoupled Lines**
  - If the lines are uncoupled (i.e., there is no C_{12} or L_{12}), then we can describe Z_{DIFF} by observing the current flow due to V_{DIFF}.
  - Notice that V_{DIFF} injects current into Trace 1 and the return current flows out of Trace 2.
  - Since both Trace 1 and Trace 2 have the same characteristic impedance (by design), an equal and opposite current will flow in each trace when driven differentially ($I_1=I_2$).
  - In effect, the voltage V_{DIFF} sees I_1 go into the positive terminal and come out of the negative terminal ($I_2=I_1=I_{SE}$).
  - Since by definition V_{DIFF} has twice the magnitude of V_1 or V_2 (we'll call it V_{SE}) when driven differentially, we can put V_{DIFF} in terms of Z_0:

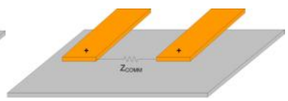
$$Z_{DIFF} = \frac{V_{DIFF}}{I_{DIFF}} = \frac{2 \cdot V_{SE}}{I_{SE}} = 2 \cdot Z_0$$



Impedance Definitions

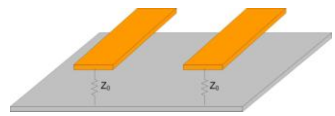
- **Z_0 & Z_{COMM}**
  - Z_{COMM} is defined as the current that flows in the pair due to V_{COMM}
  - V_{COMM} is a voltage that is the same (or common) to both Trace 1 and Trace 2.
  - Since the voltage on Trace 1 and 2 is the same, electrically the traces are *connected*





Impedance Definitions

- **Z_0 & Z_{COMM} of Uncoupled lines**
  - The current that flows due to V_{COMM} will see the single-ended characteristic impedance of each trace to ground.



  - This means the voltage observes $Z_0//Z_0$:

$$Z_{COMM} = Z_0 \,//\, Z_0 = \frac{1}{2} \cdot Z_0$$

Uncoupled Lines

- **Impedance Definitions**
  - Last time we described the impedances of uncoupled lines (i.e., $C_{12}=0$, $L_{12}=0$).
  - We saw that the voltage pattern that is driven on the line effects the impedance, where:

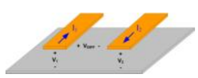
V_1	= The single-ended voltage of trace 1 with respect to ground (same as V_2)
V_{DIFF}	= The Differential voltage between trace 1 and trace2
V_{COMM}	= The Common voltage that exists on both trace 1 and 2

  - We defined the "uncoupled" impedances for each of these voltages as:

$$Z_0 = \frac{V_1}{I_1} = \sqrt{\frac{L_{11}}{C_{11}}}$$

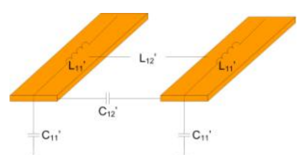
$$Z_{DIFF} = 2 \cdot Z_0$$

$$Z_{COMM} = \frac{1}{2} \cdot Z_0$$



Coupled Lines

- **Mutual Capacitance & Mutual Inductance**
  - Now let's add coupling to the pair of lines:



  - The amount of coupling (C_{12} & L_{12}) depends on the distance between the pairs.

Coupled Lines

- **Mutual Capacitance & Mutual Inductance**

  - As the lines are brought closer together:

  C_{12} = will *increase* due to the reduction in distance between the conductors

  C_{11} = will *decrease* because the conductor of the adjacent trace begins to block the E-fields that were originally going to the ground plane

  L_{12} = will increase because the Magnetic Field Lines are larger as you get closer to the current source that is creating the fields

  L_{11} = will *increase slightly* due to eddy currents that are caused due to the adjacent trace altering the Magnetic Field line path.

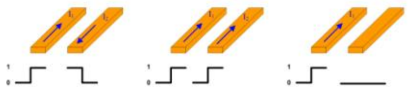
  NOTE: When the fields from an adjacent trace cause a voltage to develop in a victim trace, we call that L_{12}. The Eddy currents are modeled as L_{11} because they result in increased current in the original line due to its own Magnetic Field Lines.

Modes

- **Modes**

  - We can see that the voltage pattern that we drive onto the pair of lines heavily influences the impedance that the signal will see:

Case 1: Differential Case 2: Common Case 3: Single Trace



Case 1: For this pattern, the most ΔQ, ΔV, and ΔI exists between the pair.

Case 2: There is **Zero** ΔQ or ΔV between the pair.

Case 3: This is how C_{12} & L_{12} are defined (i.e., the mutual C & L between the signal of interest and an arbitrary neighboring trace when all neighboring traces are all held at 0v)

Modes

- **ODD & EVEN Modes**

  - There are two special voltage patterns on a differential pair that result in *undistorted* signals

  - We call these two special stimulus patterns **Modes**

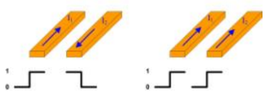
  - A Mode simply refers to the voltage pattern that we drive the pair with.

  - We define the two modes as:

  ODD = we drive the pair with equal & opposite voltages (i.e., a differential voltage)

  EVEN = we drive the pair with the same voltage on both lines (i.e., a common voltage)

ODD Mode EVEN Mode



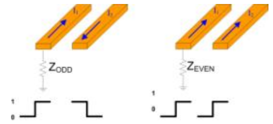
Modes

- **ODD & EVEN Impedances**

  - We define two more impedances for these special cases:

  - Z_{ODD} = the impedance of a **single trace** when the pair is driven with an ODD Mode

  - Z_{EVEN} = the impedance of a **single trace** when the pair is driven with an EVEN Mode



Z_{ODD}

- **ODD Mode Impedances**

  - Z_{ODD} is used when there is coupling between the traces.

  - Z_0 & Z_{ODD} are related to each other as follows:

  - Z_0 : is the impedance of a single trace when the other trace is held at 0v.

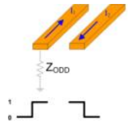
  - Z_{ODD} : is the impedance of a single trace when the other trace is driven with an equal and opposite voltage.

  NOTE: when there is NO coupling, $Z_0 = Z_{ODD}$

  - Z_{DIFF} is still defined as before, with the exception that:

  - $Z_{DIFF} = 2 \cdot Z_0$ if there is **no** coupling

  - $Z_{DIFF} = 2 \cdot Z_{ODD}$ if there **is** coupling

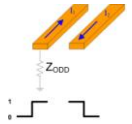


Z_{ODD}

- **ODD Mode Impedances**

  - When there is coupling, we define Z_{ODD} as:

$$Z_{ODD} = \sqrt{\frac{L_{ODD}}{C_{ODD}}}$$



- **C_{ODD}**

  - Remember that C_{12} is defined as the capacitance of a line when all other conductors are at 0v.

  - When driven with an ODD Mode, the single trace will experience twice as much C_{12} coupling:

$$C_{12} = \frac{\Delta Q}{\Delta V} = \frac{2 \cdot Q_{SE}}{V_{SE}}$$

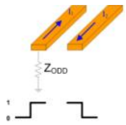
  - This yields a total C_{ODD} of:

$$C_{ODD} = C_{11} + 2 \cdot C_{12}$$

Z_{ODD}

- **L_{ODD}**
  - When driven with an ODD Mode, the current on Trace 2 induces a mutual inductive voltage on Trace 1
  - This voltage creates a current that is in the same direction of I_1
  - This in effect *lowers* the inductance as seen by a signal since more flux is being generated with the same incident signal.
  - This yields a total L_{ODD} of:

$$L_{ODD} = L_{11} - L_{12}$$

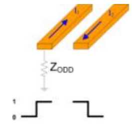


Z_{ODD}

- **Z_{ODD}**
  - We now use the definitions of C_{ODD} & L_{ODD} to get Z_{ODD} & $T_{D\text{-}ODD}$

$$Z_{ODD} = \sqrt{\frac{L_{11} - L_{12}}{C_{11} + 2 \cdot C_{12}}}$$

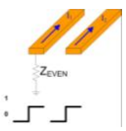
$$T_{D-ODD} = \sqrt{(L_{11} - L_{12}) \cdot (C_{11} + 2 \cdot C_{12})}$$



Z_{EVEN}

- **EVEN Mode Impedances**
  - Z_{EVEN} is used when there is coupling between the traces.
  - Z_0 & Z_{EVEN} are related to each other as follows:
    - Z_0 : is the impedance of a single trace when the other trace is held at 0v.
    - Z_{EVEN} : is the impedance of a single trace when the other trace is driven with the same voltage.

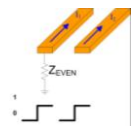
    NOTE: when there is NO coupling, $Z_0 = Z_{EVEN}$
  - Z_{COMM} is still defined as before, with the exception that:
    - $Z_{COMM} = (1/2) \cdot Z_0$ if there is **no** coupling
    - $Z_{COMM} = (1/2) \cdot Z_{EVEN}$ if there **is** coupling



Z_{EVEN}

- **EVEN Mode Impedances**
  - When there is coupling, we define Z_{EVEN} as:

$$Z_{EVEN} = \sqrt{\frac{L_{EVEN}}{C_{EVEN}}}$$



- **C_{EVEN}**
  - Remember that C_{12} is defined as the capacitance of a line when all other conductors are at 0v.
  - When driven with an EVEN Mode, the single trace will experience no C_{12} coupling because there is no charge transferred between the lines:

$$C_{12} = \frac{\Delta Q}{\Delta V} = \frac{0}{\Delta V}$$

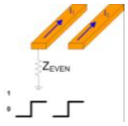
  - This yields a total C_{EVEN} of:

$$C_{EVEN} = C_{11}$$

Z_{EVEN}

- **L_{EVEN}**
  - When driven with an EVEN Mode, the current on Trace 2 induces a mutual inductive voltage on Trace 1
  - This voltage creates a current that is in the opposite direction of I_1
  - This in effect *raises* the inductance as seen by a signal since less flux is being generated with the same incident signal.
  - This yields a total L_{EVEN} of:

$$L_{EVEN} = L_{11} + L_{12}$$

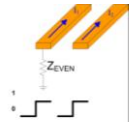


Z_{EVEN}

- **Z_{EVEN}**
  - We now use the definitions of C_{EVEN} & L_{EVEN} to get Z_{EVEN} & $T_{D\text{-}EVEN}$

$$Z_{EVEN} = \sqrt{\frac{L_{11} + L_{12}}{C_{11}}}$$

$$T_{D-EVEN} = \sqrt{(L_{11} + L_{12}) \cdot (C_{11})}$$



Differential Terminations

- **Terminations**

  - We've seen how the voltage pattern on a pair of coupled lines greatly influences the impedance that a voltage traveling down **one** of the lines will observe:

  - An example of this would be to take a coupled line and calculate the impedance observed by one side of the pair under different voltage patterns:

C_{11} = 3pF C_{12} = 1pF
L_{11} = 7.5nH L_{12} = 1nH

1) Trace 1 is driven while Trace 2 is held at 0v: $Z_O = \sqrt{\dfrac{L_{11}}{C_{11}+C_{12}}} = \sqrt{\dfrac{7.5nH}{3pF+1pF}} = 43\Omega$

2) The two traces are driven with an ODD Mode: $Z_{ODD} = \sqrt{\dfrac{L_{11}-L_{12}}{C_{11}+2\cdot C_{12}}} = \sqrt{\dfrac{7.5nH-1nH}{3pF+2\cdot 1pF}} = 36\Omega$

3) The two traces are driven with an EVEN Mode: $Z_{EVEN} = \sqrt{\dfrac{L_{11}+L_{12}}{C_{11}}} = \sqrt{\dfrac{7.5nH+1nH}{3pF}} = 53\Omega$

Differential Terminations

- **Terminations**

  - So what do we do?

  - If the lines were Single-Ended, then each of these patterns will likely occur on the bus.

  - This will cause reflections because there is no perfect termination value that will always terminate the line.

  - The only option for a Single-Ended situation is to move the traces further apart in an attempt to reduce C_{12} & L_{12}.

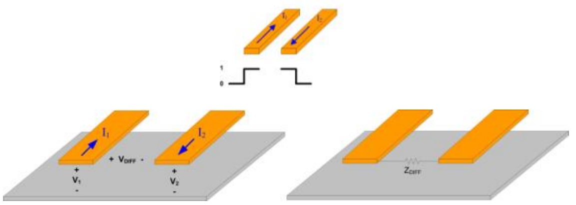
  - This would have the effect of making $Z_0=Z_{ODD}=Z_{EVEN}$ and an appropriate termination value can be selected.

ODD Mode Terminations

- **Terminating the ODD Mode**

  - However, if we are using Differential Signaling, then we know that the voltage pattern applied to the pair will always be complementary.

  - This means that the ODD Mode will observe Z_{DIFF} as it travels down the pair.



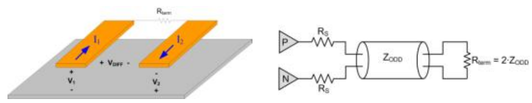
ODD Mode Terminations

- **Terminating the ODD Mode**

  - To terminate the ODD Mode, we simply insert a termination resistor at the end of the line that has $R_{term} = Z_{DIFF}$

  - We can put Z_{DIFF} in terms of Z_{ODD} if there is coupling on the line: $R_{term} = Z_{DIFF} = 2\cdot Z_{ODD}$

  - We can put Z_{DIFF} in terms of Z_0 if there is **NO** coupling on the line: $R_{term} = Z_{DIFF} = 2\cdot Z_0$



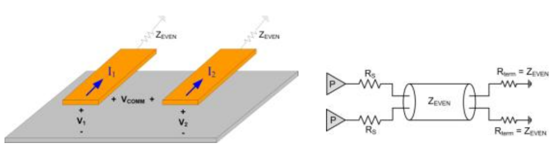
EVEN Mode Terminations

- **Terminating the EVEN Mode**

  - To terminate the EVEN Mode, we simply insert termination resistors at the end of the line that results in $R_{term} = Z_{COMM}$

  - We want V_{COMM} to see $Z_{COMM} = (1/2)\cdot Z_{EVEN}$

  - This takes the form of two resistors to ground on each of the lines equal to Z_{EVEN}



Termination Networks

- **Terminating Both Modes**

  - Now we have a problem! When we put both the ODD mode termination and the EVEN mode termination in our circuit, the values of each resistor alters the effective resistance observed by each of the modes.

  - This results in *neither* Mode being terminated properly.

  - We want to create a termination network that accomplishes the following:

    1) V_{DIFF} observes $Z_{DIFF} = 2\cdot Z_{ODD}$
    2) V_{COMM} observes $Z_{COMM} = (1/2)\cdot Z_{EVEN}$

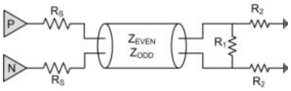
  - There are two differential termination topologies that can accomplish these objectives:

    1) Π-Termination
    2) T-Termination

Termination Networks

- **Π Termination**

  - We can use a Π Network consisting of 3 resistors in order to terminate both modes.



  - Let's start with the EVEN Mode:

    - V_{COMM} puts the same potential at both ends of R_1, this means no current flows through R_1 so it effectively is an *open*.

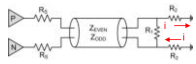
    - this means that V_{COMM} observes the two R_2 resistors to ground in parallel. This sets the value for R_2.

$$Z_{COMM} = \frac{1}{2} \cdot R_2 = \frac{1}{2} \cdot Z_{EVEN}$$

$$R_2 = Z_{EVEN}$$

Termination Networks

- **Π Termination**



  - Now we move to the ODD Mode:

    - V_{DIFF} puts a differential voltage across R_1. This causes an equal & opposite current to flow through the R_2 resistors.

    - This current through the R_2's causes a "virtual short" between the resistors

    - The resultant resistance that V_{DIFF} sees is: $R_1 // (R_2 + R_2)$

    - We can use our selection for R_2 in order to solve for R_1 which will yield a termination value for the ODD Mode.

$$Z_{DIFF} = R_1 // (2 \cdot R_2) = \frac{2 \cdot R_1 \cdot R_2}{R_1 + 2 \cdot R_2} = 2 \cdot Z_{ODD}$$

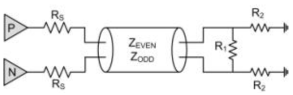
$$\frac{2 \cdot R_1 \cdot Z_{EVEN}}{R_1 + 2 \cdot Z_{EVEN}} = 2 \cdot Z_{ODD}$$

$$R_1 = \frac{2 \cdot Z_{EVEN} \cdot Z_{ODD}}{Z_{EVEN} - Z_{ODD}}$$

Termination Networks

- **Π Termination**

  - This network allows us to select our resistor values in terms of Z_{ODD} & Z_{EVEN}, which are directly calculated from the electrical parameters of the transmission lines (C_{11}, C_{12}, L_{11}, L_{12})



$$R_1 = \frac{2 \cdot Z_{EVEN} \cdot Z_{ODD}}{Z_{EVEN} - Z_{ODD}} \qquad R_2 = Z_{EVEN}$$

Termination Networks

- **T Termination**

  - We can also use a T Network consisting of 3 resistors in order to terminate both modes.

  - Let's start with the ODD Mode:

    - V_{DIFF} will cause an equal & opposite current to flow through the R_2 resistor. These currents will cancel each other out, creating a "virtual ground" between the R_1 resistors.

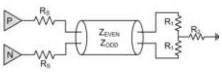
    - this means that V_{DIFF} observes the two R_1 resistors in series with each other. This sets the value for R_1.

$$Z_{DIFF} = 2 \cdot R_1 = 2 \cdot Z_{ODD}$$

$$R_1 = Z_{ODD}$$

Termination Networks

- **T Termination**



  - Now we move to the EVEN Mode:

    - V_{COMM} puts a common voltage across the R_1 & R_2 network.

    - The equivalent resistance of this network from V_{COMM} to GND is:

$$Z_{COMM} = (R_1 // R_1) + R_2$$

    - We can use our selection for R_1 in order to solve for R_2 which will yield a termination value for the EVEN Mode.

$$Z_{COMM} = (R_1 // R_1) + R_2 = \frac{1}{2} \cdot R_1 + R_2 = \frac{1}{2} \cdot Z_{EVEN}$$

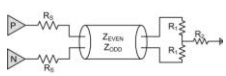
$$\frac{1}{2} \cdot Z_{ODD} + R_2 = \frac{1}{2} \cdot Z_{EVEN}$$

$$R_2 = \frac{1}{2} \cdot (Z_{EVEN} - Z_{ODD})$$

Termination Networks

- **T Termination**

  - This network allows us to select our resistor values in terms of Z_{ODD} & Z_{EVEN}, which are directly calculated from the electrical parameters of the transmission lines (C_{11}, C_{12}, L_{11}, L_{12})



$$R_1 = Z_{ODD} \qquad R_2 = \frac{1}{2} \cdot (Z_{EVEN} - Z_{ODD})$$