CHAPTER 2

NEAR-END CROSSTALK AND FAR-END CROSSTALK

2.1 INTRODUCTION

The high speed digital signal propagates along the transmission lines in the form of transverse electromagnetic (TEM) waves at very high frequency in GHz regime. The signaling in the digital system uses number of transmission lines which are parallel and close to each other. Due to the recent development in the high speed digital design and miniaturization in the sizes, the traces in the PCBs are routed closer to each other. Every traces of a PCB offer the impedance such as self values of inductances and capacitances and also the mutual values between them. When the source line carries the signals, noise currents are induced and are coupled between them due to aforesaid parameters. The induced noise currents are more when switching increases due to the faster rise and fall times. The electromagnetic energy is coupled from one to other when the two transmission lines are in close proximity and is termed as crosstalk. The crosstalk degrades the performance of the system particularly in high speed design. This crosstalk mechanism is mainly dependent on the switching of data patterns, line to line spacing, data rates, and length of the transmission lines and height of the substrate. This chapter analyses the behavior of crosstalk mechanisms in circuit boards and the different types of crosstalk.
2.2 NEAR-END CROSSTALK AND FAR-END CROSSTALK

The signal transmission in a single trace does not create any effect on the design when it is properly terminated. But when adjacent line is present, energy couples from one line to adjacent line generating crosstalk noise. To differentiate these two lines, source is given to the driven line called as active line or the aggressor line and the second line in which energy is coupled known as quiet line or victim line as illustrated in Figure 2.1.

Figure 2.1 Concept of crosstalk phenomena

The one end of the active line is (port1) driven by a source voltage and other end known as far end and is terminated (port2). The quiet line end which is nearer to the stimulus of active line is called as near end and far from the stimulus is termed as far-end. The energy is coupled from the source line to the victim line measured at the near end is termed as near-end crosstalk (NEXT) and coupled energy from the source to the far end of the victim is called as far-end crosstalk (FEXT). In terms of scattering parameters, the near end crosstalk is denoted by $S_{31}$ (or $S_{(3, 1)}$) and far end cross talk is denoted
by $S_{41}$ (or $S(4,1)$). In other way, the near-end crosstalk voltage is the ratio of voltage at the near end of the quiet line to the voltage at the source end and is expressed as $V_{\text{NEXT}}$. The far end crosstalk voltage is the ratio of the voltage at the far-end of the quiet line to the voltage at source and is termed as $V_{\text{FEXT}}$. These two parameters are important in the design of printed circuit boards as it leads to degrade the performance of the system to a larger extent. The crosstalk noise is generated by the coupling mechanism of inductance and capacitance parameters. In high speed system, wider traces are used to carry the signals from one end to other end. These physical design leads to enhance the above said coupling mechanisms. This crosstalk cannot be avoided. But by proper design it is possible to reduce the effects of crosstalk for the better performance of the system.

2.3 TRANSMISSION LINES (PCB TRACES)

Analog and digital signals are transmitted over a long distance between two points by means of transmission lines. These lines have to carry the signals which are at low and high frequency without any distortion.

The different types of transmission lines are

1. Single conductor transmission line (Figure 2.3)

2. Two coupled parallel lines (Figure 2.4)

3. Multi conductor transmission lines (Figure 2.5)

![Figure 2.2 Microstrip conductor (front view)]
2.4 MICROSTRIP TRANSMISSION LINES AND THEIR RELATED CONFIGURATIONS

Microstrip transmission lines are commonly used as impedance controlled interconnects in the PCBs due to their simple design and fabrication. The two types of microstrip lines are surface microstrip and embedded microstrip. A typical microstrip line configuration (Figure 2.3) consists of transmission line as a conductor, a ground plane as a reference plane and for the return path, and separated by a dielectric slab of height.

2.4.1 Single Conductor Transmission Line

The driver is connected to a single line conductor to carry the signal currents and the other end is connected to the load.

![Figure 2.3 Single conductor transmission line](image)

The characteristics impedance for the above configuration is given by the Equations (2.1 a) & (2.1 b)

\[
Z_0 = \frac{87}{\sqrt{\varepsilon_r + 1.414}} \ln \left( \frac{5.98h}{0.8w + t} \right) \Omega \quad (15 < w < 25 \text{ mils}) \quad (2.1 \text{ a})
\]
The propagation delay for the above configuration is given by Equation (2.2)

\[ t_{pd} = 85 \sqrt{0.475 \varepsilon_r + 0.67} \text{ in ps/inch} \]  

(2.2)

2.4.2 Two Coupled Parallel Lines

**Figure 2.4 Coupled pair of transmission lines (3D view)**

In a coupled transmission lines, the two conductors are routed adjacent to each other forming parallel lines. Signal energy is mutually coupled following the law of mutual induction. The characteristics impedance is given by the Equation (2.3)

\[ Z_0 = \frac{60}{85 \sqrt{0.457 \varepsilon_r + 0.67} \ln \left( \frac{4h}{0.67(0.87w + t)} \right)} \Omega \]  

(2.3)

and propagation delay is given by Equation (2.4a) & (2.4b).
The propagation delay in odd mode is given by

\[ TD_{\text{odd}} = \sqrt{L_{\text{odd}} C_{\text{odd}}} = \sqrt{(L_{11} - L_{12})(C_{11} + C_{12})} \]  

(2.4a)

The propagation delay in the even mode is given by (2.4a)

\[ TD_{\text{even}} = \sqrt{L_{\text{even}} C_{\text{even}}} = \sqrt{(L_{11} + L_{12})(C_{11} - C_{12})} \]  

(2.4b)

2.4.3. Multi Conductor Transmission Lines

![Multi conductor transmission lines](image)

Figure 2.5 Multi conductor transmission lines

More than two parallel conductors form multi conductor lines to carry the information from one end to other. The characteristics of these lines are determined after forming the equivalent circuits based on their performances.

2.5 MODELING OF TRANSMISSION LINE PARAMETERS

The electromagnetic energy is stored in the system because of the presence of these inductance and capacitance. For a differential length of \( dz \), the magnetic field for of the transmission lines is represented by series inductor \( Ldz \) where \( L \) is the inductance per unit length and the electric field developed between signal conductor to the return path can be modeled as
shunt capacitor \( C_{dz} \) where \( C \) is the capacitance per unit length as shown in Figure 2.6.

![Figure 2.6 Equivalent circuit of transmission lines](image)

The inductance \( L \) in Henry and capacitance \( C \) in Farad in a high speed circuit board are no longer simple parameters. These values are dependent on the signal rate and rise/fall time for unit length and create signal integrity issues.

### 2.6 MODELING OF COUPLED MICROSTRIP LINES

Figure 2.7 shows the equivalent circuit model of coupled microstrip transmission lines with their impedance parameters. To analyze the crosstalk between the coupled lines, the following points are considered.

1. The coupled transmission lines are constituted in the layer 1.
2. The ground plane is used in layer 2.
3. The thickness of the conductors is very small and transverse mode (TEM) of propagation is used.
4. A strong coupling of inductance and capacitance parameters are considered for evaluation.
5. No corrugations are assumed in the conductor layer as it leads the impedance variations.
6. Single ended termination is employed in the configurations.
7. FR4 substrate is employed between conductors to ground.

2.7 EQUIVALENT CIRCUIT OF COUPLED LINES

The following Figure 2.7 shows the equivalent circuit model of two coupled conductor lines for a differential length of \( \Delta z \) with assumed RLC having usual parameters. The conductor 1 is an aggressor line and conductor 2 is a victim line with third as ground. The impedances per unit length are represented by the following Equations (2.5 a,b,c &d ). The diagonal elements for inductance (L) and capacitance (C) matrices are self terms and off-diagonal elements are mutual terms.

\[
\begin{bmatrix}
R_1 + R_g & R_g \\
R_g & R_2 + R_g
\end{bmatrix}
\]  

(2.5a)

\[
\begin{bmatrix}
L_1 & M_{12} \\
M_{12} & L_2
\end{bmatrix}
\]  

(2.5b)

Figure 2.7 Equivalent circuit of coupled lines

Resistance matrix (R) is given by Equation (2.5a)

Inductance matrix (L) is given by Equation (2.5b)
Capacitance matrix \((C)\) is given by Equation (2.5c)

\[
(C) = \begin{bmatrix}
C_{11} + C_{12} & -C_{12} \\
-C_{12} & C_{22} + C_{12}
\end{bmatrix}
\] and

\[
\begin{align*}
(C) &= \begin{bmatrix}
G_{11} + G_{12} & -G_{12} \\
-G_{12} & G_{22} + G_{12}
\end{bmatrix} \tag{2.5c}
\end{align*}
\]

Conductance matrix \((G)\) is given by Equation (2.5d)

\[
(G) = \begin{bmatrix}
G_{11} + G_{12} & -G_{12} \\
-G_{12} & G_{22} + G_{12}
\end{bmatrix}
\] \tag{2.5d}

### 2.8 ELECTROMAGNETIC APPROACH OF CROSSTALK

To understand the behavior of the transmission lines on high speed system, the characteristics of electrical parameters can be understood from the Figure 2.8. When the transmission lines carries a voltage signal \(V_i\), a potential difference is developed between the signal path and ground conductor. The signal line is at \(V_i\) volts and the ground is at 0 volts.

![Figure 2.8 Creation of crosstalk](image)

This potential difference establishes an electric field between the conductors. From Magnetic Ampere’s law, line integral of the magnetic field around the closed path is equal to the current enclosed by that path and hence a magnetic field is established around the conductor. The signal which is
travelling along the conductors establishes a strong electric and magnetic field orthogonally. The source current $I_S$ in the aggressor produce fluxes and links with the victim causing voltages at the near-end and at far-end interpreted as mutual inductance $L_M$. If at the near-end $z = 0$ and at far-end $z = L$, then the crosstalk coefficients are given by the following Equations (2.6 & 2.7).

Crosstalk coefficient at the near-end is,

$$Crosstalk_{\text{NEAR-END}} = \frac{V_{\text{VICTIM,}z=0}}{V_{\text{SOURCE}}}$$ (2.6)

Crosstalk coefficient at the far-end is,

$$Crosstalk_{\text{FAR-END}} = \frac{V_{\text{VICTIM,}z=L}}{V_{\text{SOURCE}}}$$ (2.7)

The above crosstalk coefficient is interpreted by S-Parameters as $S(3,1)$ and $S(4,1)$ for the NEXT and FEXT respectively (otherwise $S_{31}$ or $S_{41}$).

2.9  MODEL OF THE PROPOSED DESIGN

Figure 2.9  Front view of coupled microstrip lines on PCB with FR4 substrate

For the Figure 2.9 the dimensions are as follows. Length $L = 40$mm; width of the traces $w = 2.35$mm; spacing $s = 1.95$mm; thickness of conductor
t = 1.35 mils; substrate height h = 1.20 mm; δ= 0.02. The coupled line design in 3D view is shown in Figure 2.10.

![Figure 2.10 3D view of coupled microstrip lines on a PCB](image)

Figure 2.10 3D view of coupled microstrip lines on a PCB

Figure 2.11 shows the PCB traces with ports where

- $S_{11}$ - Return loss.
- $S_{21}$ - The ratio of output of the wave at port 2 to the input at port 1 [INSERTION LOSS]
- $S_{31}$ - The ratio of output wave at port 3 to the input at port 1. This is a measure of the crosstalk parameter at the near end [NEXT]
- $S_{41}$ - The ratio of output at port 4 due to the input at port 1. This is an important parameter for the measure of far end crosstalk [FEXT].
2.10 ODD AND EVEN MODES OF TRANSMISSION LINES

The electromagnetic field between two parallel lines interacts with each other through the mutual capacitance and mutual inductance. These interactions cause effective variations in the impedance and time delay (TD) of the line.

Odd mode (differential mode) for Electric fields and Odd mode (differential mode) for Magnetic fields is shown in Figure 2.12.

![Figure 2.12 Odd mode](image)

Even mode (common mode) for Electric fields and Even mode (common mode) for Magnetic fields is shown in Figure 2.13.

![Figure 2.13 Even mode](image)

In the odd mode, the effective capacitance is given by $C_{odd}$ and effective inductance is $L_{odd}$. When the two conductors are in different potentials, the effective mutual capacitance is added causing switching patterns to increase. The induced current flows in opposite directions in odd mode cancelling the effects of mutual inductance. In even mode, same
potential exists in between the two conductors and the effective capacitance is given by the ground capacitance \( C_{11} \) only. But the effective mutual inductance increases to \( L_{11} + L_{12} \) due to addition of current components.

The general expressions for effective capacitance and inductance values for odd and even mode propagation is given by the following expressions

\[
\begin{align*}
C_{\text{odd}} &= C_{11} + C_{12} \quad \text{(odd mode)} \\
C_{\text{even}} &= C_{11} - C_{12} \quad \text{(even mode)} \\
L_{\text{odd}} &= L_{11} - L_{12} \quad \text{(odd mode)} \\
L_{\text{even}} &= L_{11} + L_{12} \quad \text{(even mode)}
\end{align*}
\]

The effective impedance in odd mode \( Z_{\text{odd}} \) from Equation (2.8)

\[
Z_{\text{odd}} = \sqrt{\frac{L_{\text{odd}}}{C_{\text{odd}}}} = \sqrt{\frac{L_{11} - L_{12}}{C_{11} + C_{12}}} \quad (2.8)
\]

The effective impedance in even mode \( Z_{\text{even}} \) from Equation (2.9)

\[
Z_{\text{even}} = \sqrt{\frac{L_{\text{even}}}{C_{\text{even}}}} = \sqrt{\frac{L_{11} + L_{12}}{C_{11} - C_{12}}} \quad (2.9)
\]

The propagation delay in odd mode \( TD_{\text{odd}} \) from Equation (2.10)

\[
TD_{\text{odd}} = \sqrt{L_{\text{odd}}C_{\text{odd}}} = \sqrt{(L_{11} - L_{12})(C_{11} + C_{12})} \quad (2.10)
\]

The propagation delay in the even mode \( TD_{\text{even}} \) from Equation (2.11)

\[
TD_{\text{even}} = \sqrt{L_{\text{even}}C_{\text{even}}} = \sqrt{(L_{11} + L_{12})(C_{11} - C_{12})} \quad (2.11)
\]
2.11 MODELING OF CROSSTALK MECHANISM

The coupling of electromagnetic energy from one conductor to other conductor relay on the following facts.

i) Like charges repel each other

ii) Moving electrons creates magnetic field that induce currents in the adjacent conductors

2.11.1 Concept of Crosstalk

The Figure 2.14 shows two parallel conductors (traces) adjacent to each other on the same plane. One of the traces carrying current is called as aggressor line and the other in which the current will couple is called as victim line. They generate two types of crosstalk mechanisms to the forward crosstalk and backward crosstalk to the far-end and near-end. It is due to the inductive coupling ($L_M$) and capacitive coupling ($C_M$).

Figure 2.14 Concept of NEXT and FEXT
The two coupled conductors (traces) of a PCB adjacent to each other on the same plane is considered for the analysis of crosstalk mechanisms. One of the traces carrying the signal current is called as aggressor line and the other in which the electromagnetic energy will couple is called as victim line. They generate two types of crosstalk mechanisms as forward and backward crosstalk due to the inductive and capacitive coupling to call as total crosstalk.

2.11.2 Capacitive Coupled Crosstalk

Due to capacitive coupling, the voltage from the driver $V_0$ from the source divides into two voltages as $V_{NE}$ and $V_{FE}$ called backward and forward voltage respectively. The source voltage $V_0$ injects a current $I_C$ through the mutual capacitance $C_m$ on the victim line for a load impedance of $Z_0$.

The far-end voltage ($V_{FEcap}$) and near-end voltage ($V_{NEcap}$) for unit length is given by the following Equations (2.12) and (2.13) respectively.

\[
V_{FEcap} = \frac{z_0 C_m V_0}{2t_r} \tag{2.12}
\]

\[
V_{NEcap} = \frac{c_m v_0 z_0}{4t_{pd}} \tag{2.13}
\]

Where $t_r$ is the rise / fall time and $t_{pd}$ propagation delay of the signal.
For the crosstalk analysis, let us assume the active line (aggressor line) is carrying the signal current along its length. The electrons while flowing through this aggressor line will couple through the mutual capacitance ($C_M$) a point in the victim line. As like charges repel each other, the electrons at this point repel the electrons at the victim line. Hence the electrons at the victim line will move in both the direction shown in Figure 2.15. Therefore there will be two components both in forward and backward directions in the victim line. This effect is due to the mutual capacitor $C_{12}$ (or $C_m$) across the lines which initiates crosstalk mechanism and is termed as capacitive crosstalk. The current at the far-end of the victim line is $I_{CF}$, and near-end of the victim line is $I_{CN}$ (the first letter of the suffix indicates the current is due to the mutual capacitance or inductance and the second letter is due to near-end or far-end).
The concept capacitive crosstalk can be understood from the following Figures 2.16a, 2.16b & 2.16c.

**Figure 2.16a** $I_{CN}$ and $I_{CF}$ directions due to $C_M$ at a point 'P'

**Figure 2.16b** Noise current directions due to $C_M$ at a point 'Q'
The Figures 2.16a, 2.16b & 2.16c shows the directions of current from aggressor line to victim line through mutual capacitance $C_M$. At the specific point ‘P’ on the aggressor line, the electrons as well as the current is coupled to the second line and divides into two as $I_{CN}$ and $I_{CF}$ to the near-end and far-end respectively. The Figure 2.16b shows the capacitance $C_M$ is at point ‘Q’ of the parallel lines and $I_{CN}$ is the current reached to the near-end and $I_{CF}$ is the current at the far-end and the Figure 2.16c shows the $C_M$ is at far-end ‘R’.

As the signal voltage starts from the driver due to faster rise/fall times capacitive noise currents are induced in the victim line and divides into two halves one to near-end and other to far-end. As the rising edge emerges from the driver this current goes up. It continues to go to a steady condition is reached in the aggressor and saturation of the current in the victim. So the time delay of the near-end current at victim is two times of the time delay and increases as that of the rise/fall time of the signal. When the signal reaches the
far-end terminating impedance of the aggressor line, there is no more coupled noise.

Another half will travel to the far-end in similar way and at the speed of signal edge in the aggressor line leaving the noise current in the far-end. Once the voltage pulses reaches the far-end of the aggressor line, the forward coupled current becomes zero leaving the near-end current only. As the pulses are changing continuously, the induced noise currents also more scaling the value of the mutual capacitance and increases with rise time of the voltage pulses. So the shorter the rise/fall time, more the noise currents at the two ends of the victim.

Therefore, the near-end crosstalk exists with two times of the time delay and far-end crosstalk exists one time of the time delay of the signal propagation depending on the modes of operation. The above concept is explained in the Figure 2.17 where the current $I_{CF}$ is greater than $I_{CN}$ for the faster rise/fall time.

![Figure 2.17 Capacitive crosstalk](Figure 2.17 Capacitive crosstalk)
2.11.3 **Inductively Coupled Crosstalk**

While the current is flowing through the aggressor line, a magnetic field is developed around the line following the Maxwell’s Ampere’s law. This field intersects with the victim line inducing current through the mutual inductance $L_M$ following the Faraday’s law. The direction of the current is opposite to that of the aggressor line following the Lenz’s law. The noise current in the victim takes the direction to the near-end as shown in Figure 2.18 and causes a crosstalk termed as inductively coupled crosstalk.

![Figure 2.18 Concept of inductive coupled crosstalk](image)

The forward crosstalk due to the mutual inductance $L_M$ is $V_{FE_{ind}}$ given by the Equation (2.14).

$$V_{FE_{ind}} = \frac{L_m v_0}{2 z_0 f_r}$$  \hspace{1cm} (2.14)
The forward crosstalk due to the inductance (L) presents in the trace the near-end voltage $V_{NEind}$ for a driver voltage $v_0$ is given by the Equation (2.15).

$$V_{NEind} = \frac{L_m v_0}{4L}$$  \hspace{1cm} (2.15)

From the expressions, the increase in the rise time causes more crosstalk with the self and mutual inductances. The following Figure 2.19 shows the concept of inductive coupling for the coupled lines with PCB. From the concept of inductive noise as seen from the figure the induced current in the victim always takes a direction opposite to the driven current in the aggressor. Moving in the forward direction in the active line, more and more noise couples to the victim at the far-end which will be the derivative of current in the driver. The forward crosstalk in the victim takes the magnitude and direction along with the aggressor and distributed over the entire length. Because of this reason the impact of far-end crosstalk is more on the signal integrity. The rise and fall times of the driver current induces the forward and backward crosstalk on the victim expressed in the Equations (2.15).

![Figure 2.19 Concept of inductively coupled noise due to $L_M$](image-url)
The following Figure 2.20a, 2.20b & 2.20c shows the noise current directions in the victim line due to the time changing the driver current from low to high. When the considered mutual inductance is at the near-end, the noise current takes place to the near-end at point `P` as shown in Figure 2.20a. The induced noise current reaches to the near-end considering $L_M$ at the middle point ‘Q’ of the lines as depicted in the Figure (2.20b). The Figure 2.20c shows the direction of noise current when the driver current reaches the terminating resistor of the aggressor line at point ‘R’.

![Figure 2.20a](image)

**Figure 2.20a** The direction of flow of the noise current when mutual inductance at the near-end point 'P'

![Figure 2.20b](image)

**Figure 2.20b** Direction of noise current $L_M$ is at centre ‘Q’
Figure 2.20c Direction of noise current when mutual inductance at the far-end 'R'

The closed loop is formed for the driver current from the aggressor line to victim through the mutual inductance $L_M$ which causes a crosstalk voltage in the two ends of the victim line. The aggressor wave produces a voltage of pulse that have the widths equal to the edge rate of the current and travels at the two ends of the victim line. The signal transition from low to high initiates a backward noise voltage to the near-end ($V_{NE}$) while high to low transition causes a voltage to the far-end ($V_{FE}$) of the victim line.

2.11.4 Total Crosstalk

The total crosstalk due to capacitive and inductively coupled mechanisms is expressed in the following Figure 2.21. Both the coupled mechanisms depending on the driver current are changing. The faster the rise time stronger is the coupling effects and the more is the crosstalk. While observing the direction of the crosstalk, the capacitive coupled crosstalk moves to near-end from aggressor line to victim line through the mutual
capacitance and takes the timing of 2 TD where TD represents the time delay
given by the Equations (2.4 a & b).

At the near-end, the capacitive and inductive noise currents are
added together to give rise to near-end crosstalk (NEXT). At the far-end, the
noise current due to mutual capacitance is opposite to the noise currents
induced by inductively coupled one. Therefore, the FEXT is due to the
difference of capacitive and inductively coupled noise currents at the far-end
and the changing driver current coupled with $L_m$ at the far-end of the
aggressor line.

In parallel lines, the inductive and capacitive crosstalk is present
simultaneously and is expressed by the following equations.

The far-end crosstalk (FEXT) for unit length is given by Equation
(2.16)

$$V_{FEXT} = \frac{\left( z_0 C_m - \frac{L_m}{z_0} \right)}{2t_r} V_0$$

(2.16)

and the near-end crosstalk (NEXT) is given by Equation (2.17)

$$V_{NEXT} = \frac{1}{4} \left( \frac{C_m}{C} + \frac{L_m}{L_{11}} \right) V_0$$

(2.17)

and the net current at the near-end is the sum of the noise currents $I_{NE}$
produced by mutual capacitance and by mutual inductance ($I_{LN} + I_{CN}$) and at
the far-end the net current $I_{FE}$ is the difference of the two currents ($I_{LN} - I_{CN}$).
Figure 2.21a Total crosstalk parameters at the near-end `P` due to $L_M$ and $C_M$.

Figure 2.21b Total crosstalk parameters at point `Q` due to $L_M$ and $C_M$.
When the driver current is changing, the total crosstalk at the near-end of the victim line is the addition of the two noise currents generated due to mutual capacitance and mutual inductance. These two currents are added together at the near-end. At the far-end, the noise currents are the difference of the two currents as depicted in the Equations (2.16) and (2.17). The Figures 2.21a, 2.21b & 2.21c shows the total crosstalk mechanisms when considering three situations as P, Q and R. Note that at the near-end the inductive crosstalk follows the capacitive crosstalk. At the far-end both have opposite signs of noise currents.

\[ I_{NE} = I_{CN} + I_{LN} \]  
\[ I_{FE} = I_{CF} - I_{LF} \]
where

\[ C_M \] - mutual capacitance
\[ L_M \] - mutual inductance
\[ t_r \] - rise/fall time of driver
\[ V_0 \] - source voltage
\[ z_0 \] - source impedance
\[ I_{NE} \] - total near-end current
\[ I_{FE} \] - total far-end current
\[ I_{CN} \] - near-end crosstalk current due to mutual capacitance
\[ I_{LN} \] - near-end crosstalk current due to mutual inductance
\[ I_{CF} \] - far-end crosstalk current due to mutual capacitance
\[ I_{LF} \] - far-end crosstalk current due to mutual inductance
\[ V_{FEXT} \] - far-end crosstalk voltage
\[ V_{NEXT} \] - near-end crosstalk voltage
\[ V_{FE\text{ind}} \] - far-end crosstalk voltage due to mutual inductance only
\[ V_{FE\text{cap}} \] - far-end crosstalk voltage due to mutual capacitance only
\[ V_{NE\text{ind}} \] - near-end crosstalk voltage due to mutual inductance only
\[ V_{NE\text{cap}} \] - near-end crosstalk voltage due to mutual capacitance only