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# Crosstalk Analysis of Uniform and Non-Uniform Lossy Microstrip-Coupled Transmission Lines

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**Abstract– In this paper, an analytical method is presented to precisely estimate the crosstalk of uniform and non-uniform microstrip-coupled transmission lines in frequency domain using Modified Transmission Matrix. The obtained expression is quantitatively related in terms of the geometrical parameters of the coupled lines. A straightforward procedure is presented to obtain a closed form formula to accurately determine the crosstalk of a microstrip-coupled line. Several structures are considered to confirm the validity of the presented method. It is shown that the obtained results are in a good agreement with those obtained by simulation and measurement. Moreover, the feature selective validation (FSV) procedure is used to determine the proximity value between the measured results and the proposed method datasets.**

**Key word:** Crosstalk, Transmission Line (TL), Transmission Matrix.

## I. INTRODUCTION

Nowadays, commercial electrical systems are toward designs, which are low profile, but short distance between the TLs creates strong coupling leading to degrading system performance by deteriorating signal shape and introducing errors [1]. Crosstalk between the two or more conductors causes interference to the adjacent lines that must be known in the design procedure.

Variety of methods has been proposed for modeling the crosstalk of multi-conductor transmission line (MTL) [2-4]. These methods categorized into two numerical and analytical groups. Different numerical techniques including Method of Moments (MOMs) and Finite Difference Time Domain (FDTD) have been reported in literature to study the crosstalk characteristics of different structures. In spite of the accuracy of these methods, they consume lots of time and need large amount of memory and they show an ambiguous relationship between geometrical parameters of the TL and crosstalk that do not allow intelligent modification of the system.

Paul [5] introduced the near-end and far-end idea of crosstalk based on matrix equations in frequency domain. The crosstalk reaction for circuits at low frequencies is presented by Paul [6, 7] and Olsen [8]. This concept is based on a summation of inductive, capacitive, and common impedance coupling mechanisms.

In [9] a simple technique is introduced for crosstalk estimation of MTL at low frequencies. This technique is applied only for a shielded uniform multi coaxial cable bundles and can be applied in those cases, in which the terminated impedances are enough larger or smaller than the victim and culprit characteristic impedance. Author [10] solved the TL equations for a microstrip line in symbolic form based on Jarvis model. His solution is valid only for lossless and symmetrical line under the weak coupling condition.

In [11] the transmission line with strong coupling is studied. The applied TL is divided into unit cells. The length of each cell is considered to be one tenth of the wavelength. Using this model, the near and far-end crosstalk expressions is derived only for low frequencies. In this method discontinues between each unit cell is neglected. In [12], it is assumed that the TL length to be infinitely long. The authors claim that the introduced formula for estimation of the maximum crosstalk is valid only for lossless and homogeneous TL with finite length.

In this paper, a straightforward method is presented to quickly predict crosstalk and its frequency response for uniform and non-uniform microstrip coupled lines. The obtained formula relates the amount of crosstalk to the geometrical parameters of the lined

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using modified transmission matrix based on per-unit-length parameter of the coupled lines.

## II. MATHEMATICAL FORMULATION

A general transmission coupled line of length $l$ is shown in Fig. 1. The culprit line is driven by a source and a current and voltage wave is flowing through load impedance $Z_L$. Another current and voltage wave is induced in the victim line, which is terminated by loads $Z_{NE}$, near end impedance and $Z_{FE}$, far end impedance. The flowing voltage wave in culprit and the induced voltage signal in the victim line are designated by $V_C$ and $V_V$ respectively. The characteristic impedance of the culprit and victim line is nominated by $Z_{0C}$ and $Z_{0V}$ respectively. Three important conditions are assumed in our proposed investigation. First, a homogeneous line is assumed in our study. Second, the induced current and voltage back in the culprit line due to victim line is ignored. Third, the crosstalk signals create by placing source only in the culprit line.

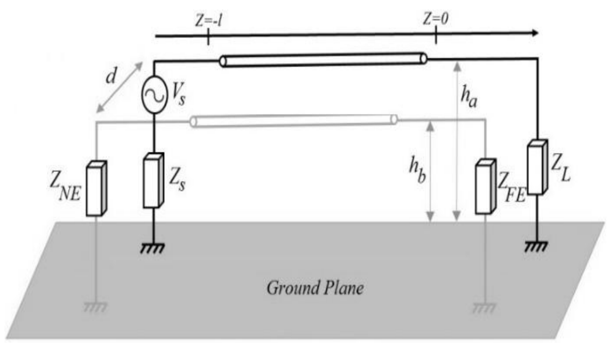


**Figure 1:** The general transmission coupled line circuit.

At high frequencies and from the transmission line theory, the voltage and current are not constant across the length of the line. Similarly, in [5] and more recently in [12-14], general description of crosstalk can be expressed as.

$$CT = V_V / V_C \tag{1}$$

In special case, the near-end and far-end crosstalk between the culprit and victim line is developed using definition (1). The proposed crosstalk expressions in this paper can be employed for high frequency. But at low frequencies and in cases that the $Z_L$, $Z_{NE}$ are enough larger than $Z_{0c}$ and $Z_{0v}$, all proposed equation can be used. The voltage along the culprit and victim lines can be expressed as the following [15].

$$V_c = V_c^+ e^{-\gamma z} + V_c^- e^{+\gamma z} \tag{2a}$$

$$V_v = V_v^+ e^{-\gamma z} + V_v^- e^{+\gamma z} \tag{2b}$$

In the above equations, $V_c^+$ and $V_c^-$ are the incident and reflected voltage wave along the culprit line. Also, $V_v^+$ and $V_v^-$ are the incident and reflected voltage wave along the victim line. Propagation constant is represented by $\gamma$. For a coupled transmission line that convey TEM or Quasi-TEM waves, voltage and current signals are related by equation (3) [4, 15].

$$\mathbf{I} = \upsilon_p \mathbf{C} \left\{ \mathbf{V}^+ e^{-\gamma z} - \mathbf{\Gamma}^{\mathrm{T}} \mathbf{V}^+ e^{+\gamma z} \right\} \tag{3}$$

In equation (3), **I** and $\mathbf{V}^+$ show the current and voltage vector of the culprit and victim lines respectively. $\mathbf{\Gamma}^{\mathrm{T}}$ and **C** represent transpose of reflection coefficients matrix and per-unit-length capacitance matrix respectively. Also, $v_p$ is phase velocity of the propagated wave along the TL. The per unit length capacitance depends on the geometrical parameters and physical properties of the TL [3].

A multi-conductor transmission line is considered as an $n$-port network. For a transmission line with double conductor, a 2×2 *ABCD* matrix is used for modeling the TL. Fig. 2 shows the black box model and equation (4) is used to represent voltage and current of the network ports.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{4}$$

However, for a MTL circuits an $n \times n$ *ABCD* modified transmission matrix is used to represent the relation between input and output voltages and currents. For a double conductor transmission line above an infinite ground plane, as shown in Fig. 1, a four-port network as shown in Fig. 3 with a modified transmission matrix in terms of the voltages and currents of the ports given by equation (5).

$$\begin{bmatrix} V_1 \\ I_1 \\ V_3 \\ I_3 \end{bmatrix} = [\mathbf{A}] \begin{bmatrix} V_2 \\ I_2 \\ V_4 \\ I_4 \end{bmatrix} \tag{5}$$

In (5) matrix **A** is a 4-by-4 matrix of the double conductor coupled lines, while $V_i$ ($i$=1, 2, 3, 4) and $I_i$ ($i$=1, 2, 3, 4) are defined by equations (6a) through (6d).

$$\begin{cases} V_1 = V_c(z = -l) \\ V_2 = V_c(z = 0) \end{cases} \tag{6a}$$

$$\begin{cases} I_1 = I_c(z = -l) \\ I_2 = I_c(z = 0) \end{cases} \tag{6b}$$

$$\begin{cases} V_3 = V_v(z = -l) \\ V_4 = V_v(z = 0) \end{cases} \tag{6c}$$

$$\begin{cases} I_3 = I_v(z = -l) \\ I_4 = I_v(z = 0) \end{cases} \tag{6d}$$

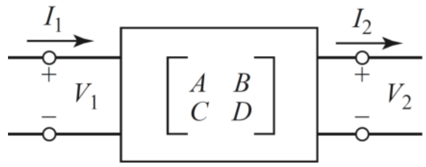


**Figure 2:** TL parameter model of a two port network.

Based on the definition of the elements of the modified transmission matrix [15], it can be shown that for a double conductor transmission line, *ABCD* matrix is given by equation (7).

$$\begin{bmatrix} \cosh\gamma l & Z_1\sinh\gamma l & 0 & Z_2\sinh\gamma l \\ Y_1\sinh\gamma l & \cosh\gamma l & -Y_2\sinh\gamma l & 0 \\ 0 & Z_2\sinh\gamma l & \cosh\gamma l & Z_3\sinh\gamma l \\ -Y_2\sinh\gamma l & 0 & Y_3\sinh\gamma l & \cosh\gamma l \end{bmatrix} \tag{7}$$

In which equations (8a) through (8f) define the required impedances and admittances. In these equations $C_C$, $C_V$ and $C_m$ are culprit self per-unit-length capacitance, victim self per-unit-length capacitance and mutual per-unit-length capacitance respectively.

$$Z_1 = \frac{C_V}{\upsilon_p\left[C_C C_V - C_m^2\right]} \tag{8a}$$

$$Z_2 = \frac{C_m}{\upsilon_p\left[C_C C_V - C_m^2\right]} \tag{8b}$$

$$Z_3 = \frac{C_C}{\upsilon_p\left[C_C C_V - C_m^2\right]} \tag{8c}$$

$$Y_1 = \upsilon_p C_C \tag{8d}$$

$$Y_2 = \upsilon_p C_m \tag{8e}$$

$$Y_3 = \upsilon_p C_V \tag{8f}$$

By applying the boundary conditions at $z = 0$ and $z = -l$ using equations (9a) through (9d) for the coupled line a specific solution is obtained.

$$V_1 = V_s - Z_s I_1 \tag{9a}$$

$$V_2 = Z_L I_2 \tag{9b}$$

$$V_3 = -Z_{NE} I_3 \tag{9c}$$

$$V_4 = Z_{FE} I_4 \tag{9d}$$

Finally, based on crosstalk definition in (1) and it can be seen that for a uniform transmission line, crosstalk (*CT*) is given by equation (10), which is valid only for a uniform TL.

$$\text{CT}=\frac{Z_{NE}Z_{FE}(Z_2 - Z_L Y_2 Z_{NE})\sinh\gamma l}{-Z_L\left[(Y_1 Z_{FE} + Z_1 Z_{NE})\sinh\gamma l + (Z_{NE}Z_{FE} + Z_{NE}^2)\cosh\gamma l\right]} \tag{10}$$

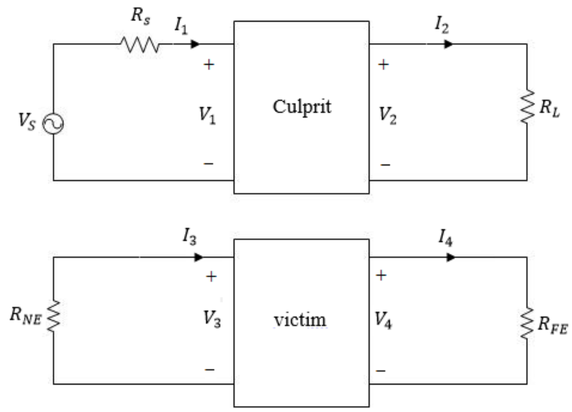


**Figure 3:** A double conductor transmission line modeled as a four-port network.

For the non-uniform structure, the TL is dived into a few series uniform sections with a specific modified transmission matrix $\mathbf{A}_i$ ($i$=1,2,…,$N$). It is assumed that the TL can be divided into $N$ uniform section and each $\mathbf{A}_i$ elements are determined from equations (7) and (8). According to the current direction in Figure (3) for the culprit and victim lines, the total modified transmission matrix $\mathbf{A}_T$ is determined by multiplying the modified transmission matrix of different sections as follows.

$$\mathbf{A}_T = \prod_{i=1}^{N}\mathbf{A}_i \tag{11}$$

By specifying the each elements of $\mathbf{A}_T$, the crosstalk value can be calculated using equation (10).

## III. DETERMINATION OF ACCURACY

For experimental validation of the proposed method, four coupled microstrip structure with substrate physical length and wide equal to 50 mm is fabricated on TLY062 substrate with the relative permittivity of 2.2, thickness of 1.56 mm and loss tangent = 0.0009. It is known from [15] that for microstrip lines, effective dielectric constant $\varepsilon_e$, dielectric attenuation constant $\alpha_d$ and conductor attenuation constant $\alpha_c$ can be determined by the equations (12).

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1+12h/W}} \tag{12a}$$

$$\alpha_d = \frac{\beta\sqrt{\varepsilon_r}(\varepsilon_e - 1)\tan\delta}{2\sqrt{\varepsilon_e}(\varepsilon_r - 1)} \tag{12b}$$

$$\alpha_c = \frac{R_s}{Z_0 W} \tag{12c}$$

$$R_s = \sqrt{\frac{\omega\mu_0}{2\sigma_c}} \tag{12d}$$

In which $h$ and $W$ are substrate height and strip width respectively. The relative permittivity material and tangent loss of the substrate is depicted by $\varepsilon_r$ and $\tan\delta$ respectively. Also, $R_s$ is the surface resistance of the strip with conductivity of $\sigma_c$. By determining the attenuation conductor constant and attenuation dielectric constant, the complex propagation constant can be calculated by the equation (13).

$$\gamma = \alpha + j\beta \tag{13a}$$

$$\alpha = \alpha_c + \alpha_d \tag{13b}$$

In (13), $\beta$ represents the phase constant of the propagated wave on the line. It should be noted that in both measurement and simulation process $S_{21}$ of the coupled lines is regarded as the crosstalk. It should be noted that experimental test have done inside an echoic chamber.

The simple, asymmetric, periodic and bend coupled microstrip line are considered to confirm the accuracy of the proposed method. Fabricated picture of all structures is presented in figure (4) [20]. The equation (10) is enough to predict frequency dependent crosstalk of the first structure due to the uniformity. For the other structures, each of these lines can be considered as the cascading of a series of uniform sections. For each uniform section, its modified transmission matrix is obtained using equation (8) and then using equation (10), the amount of coupling is predicted.

The crosstalk estimation based on the proposed method including the measured and simulated results for different structures are plotted in Fig. 5 to Fig. 8 versus frequency. It can be seen that the predicted amount of crosstalk based on our proposed method are in a good agreement with those obtained by simulation and measurements. By decreasing the distance between the lines, the amount of crosstalk is increased.

It is believed that the small difference in results is due to fabrication imperfections. Moreover, in microstrip structures, inequality between the physical and electrical lengths creates a frequency responses difference [16]. Understanding these factors helps the designer to determine a permissible fabrication tolerance in order to improve a desired achievement. It is very important to note that the discontinuity between each uniform section for the second to fourth structures is ignored, but the results of the proposed method is very close to the experimental results.

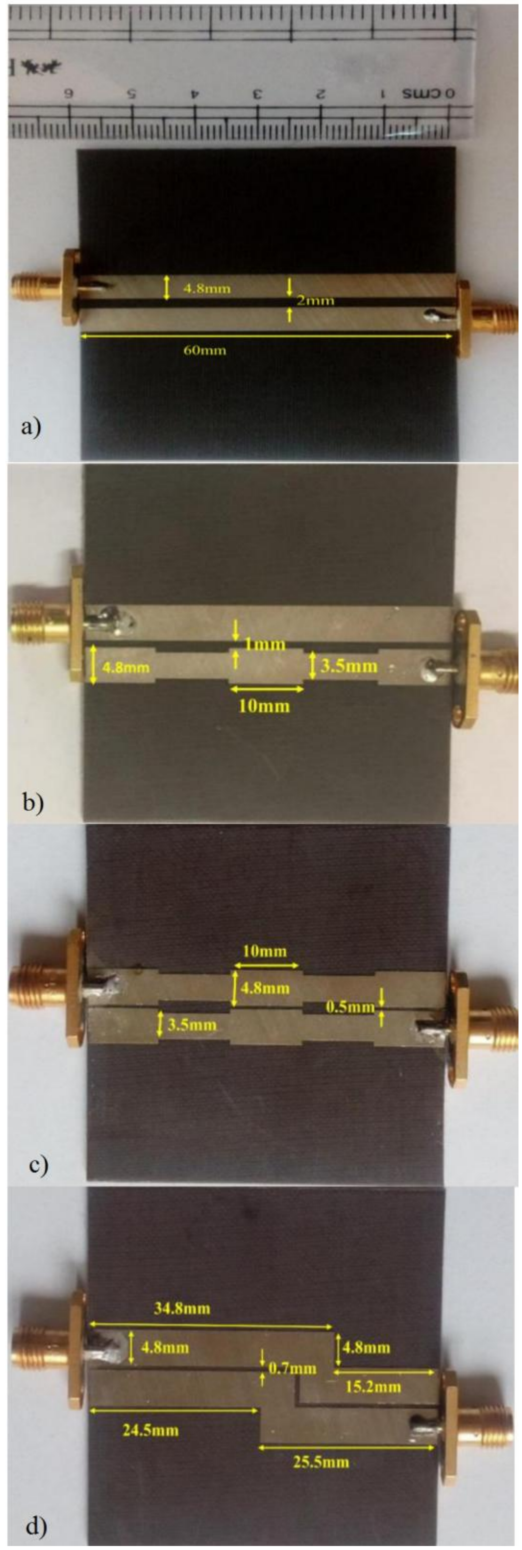


**Figure 4:** The fabricated different coupled, a) simple line, b) asymmetric lines, c) periodic line, d) line with $90^0$ bend.

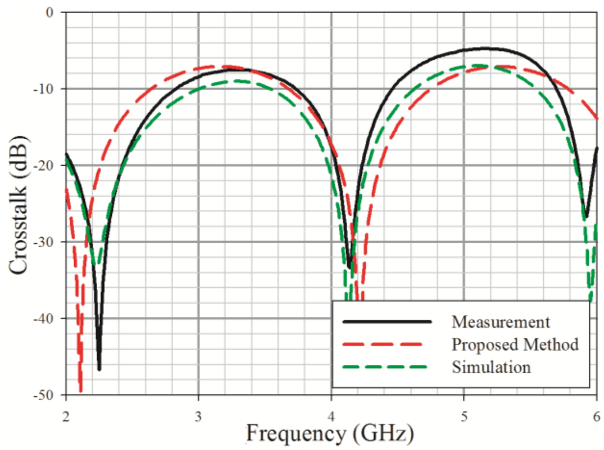


**Figure 5:** The simulated, measured and results of the proposed method for the simple coupled line.

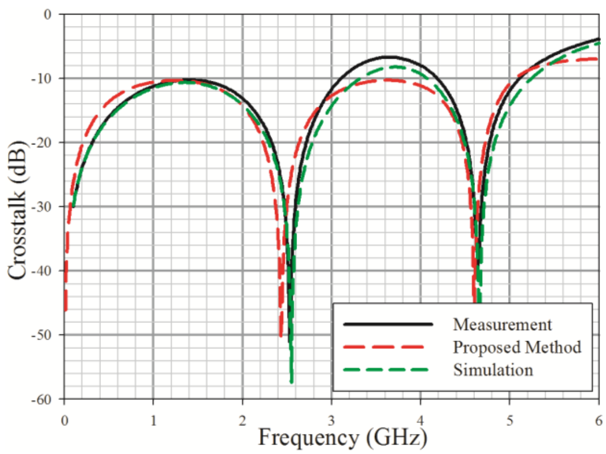


**Figure 6:** The simulated, measured and results of the proposed method for the asymmetric coupled line.

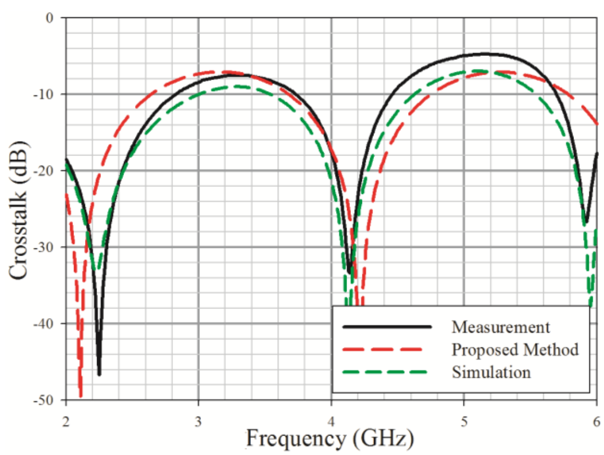


**Figure 7:** simulated, measured and results of the proposed method for the periodic coupled line.

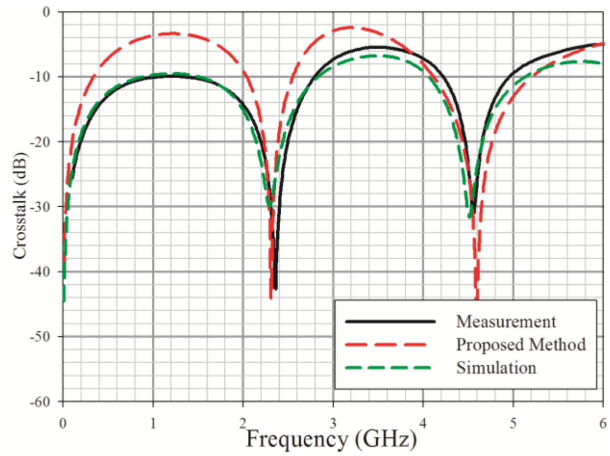


**Figure 8:** simulated, measured and results of the proposed method for the bend coupled line.

As can be seen from the results pictures, there are few frequencies that the line length is multiple of half a wavelength and odd multiple of half a wavelength. In these frequencies the crosstalk value of the coupled line is minimum and maximum respectively that the proposed method predicts these frequencies with an acceptable accuracy. It should be noted that for the microstrip lines and at very high frequencies, it is necessary to take into account the frequency dispersion of the effective dielectric constant and the change in characteristic impedance with frequency.

The values of amplitude difference measure (ADM) and feature difference measure (FDM) evaluated by using the feature selective validation (FSV) procedure [17] and [18] respect to the IEEE Standard P1597.1 [19] are shown in the Figure (9a) to Figure (9d). The FSV procedure is used to determine the proximity value between the measured results and the proposed method datasets. The ADM and FDM values are separated into six classes: Excellent (EX), Very Good (VG), Good (G), Fair (F), Poor (P), and Very Poor (VP). The charts show a reasonable agreement between the measured results with those obtained by our proposed method [17-19].

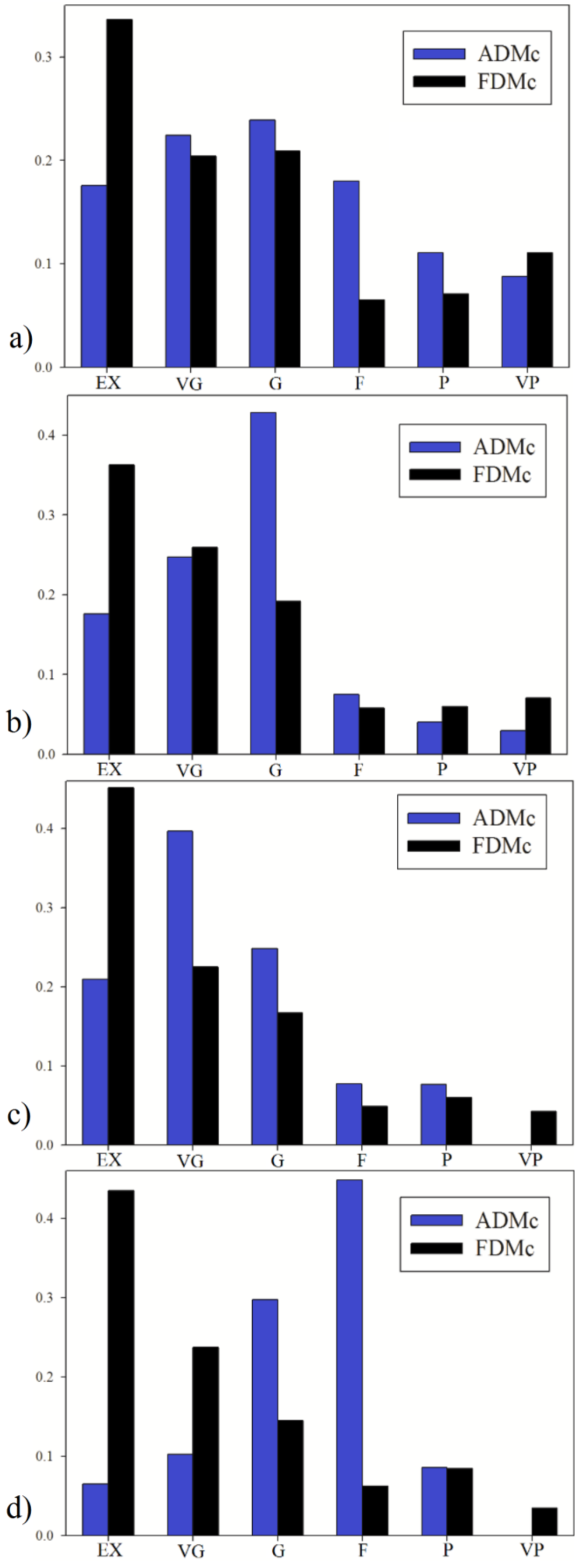


**Figure 9:** The FSV results for different lines a) structure I b) structure II, c) structure III, d) structure IV.

## VI. Conclusion

In this paper, a straightforward expression is offered to quick estimate crosstalk of uniform and non-uniform transmission lines in the frequency domain by use of the modified transmission matrix. The introduced procedure can be quantitative in terms of physical characteristics of the transmission line. Based on the modified transmission matrix, a close form formula is presented to determine the quick prediction of crosstalk. Since the periodic or non-uniform transmission lines can be considered as series combinations of a cascade connection of two or more n-port networks, a straightforward procedure are introduced that can estimate crosstalk with the appropriate accuracy by using the modified transmission matrix. All studies are done in this paper taking into account the losses. Several structures are considered to confirm the validity of the presented approach. It can be seen that the results are in reasonable agreement with the simulation and measurement, which verify the precision of the proposed method. Also, the FSV procedure is used to determine the proximity value between the measured results and the proposed method datasets.

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