Crosstalk Analysis of Multi-Microstrip Coupled Lines Using Transmission Line Modelling

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Abstract– This paper presents a new analytical method to predict crosstalk of a homogeneous terminated two microstrip coupled lines over a ground plane using Transmission Line (TL) theory. The derived formula is frequency and location dependent, which can be used to quickly estimate the crosstalk of a coupled line. Also, the effect of the geometrical parameters of the lines and load are included in the derived formula. Presented method can be used for the other types of coupled lines including lossy or lossless lines. To verify the accuracy of the introduced method, a few microstrip coupled line structures with different geometrical parameters are considered numerically and experimentally. The results of crosstalk based on the proposed analytical methods, simulation study using High Frequency Structure Simulator (HFSS) and those obtained by measurements are reported and compared with each other. It is shown that our proposed method accurately estimates the amount of crosstalk for a two microstrip coupled lines.

Key word: Crosstalk, Coupled Microstrip Line, Transmission Line (TL).

I. INTRODUCTION

Nowadays, along with the advances of communication systems, there is an increasing demand to design circuits and devices provide higher speed, greater density, less volume using low voltage sources. Besides, in high data rate and secure systems; signal transmissions are often performed using shielded cables. These cables are often grouped together with closely distance due to limited installation space. In these transmission systems, crosstalk is generated, leading to effect on the device performance. So, it is essential to study the coupling mechanism and especial techniques should be applied to reduce the amount of crosstalk. In fact, crosstalk is the transfer of an undesirable signal or electromagnetic wave from one trace or transmission line to the other adjacent one. In practical applications, crosstalk deforms communication signals or electromagnetic waves and spoils the quality of both digital and analog signals. It is observed that crosstalk occurs everywhere including inside an integrated circuit or a chip, over a printed circuit board (PCB), interconnected packages, or any non-shielded or even shielded transmission lines. Crosstalk usually happens due to the mutual coupling due to mutual capacitance and mutual inductance of two adjacent transmission lines [1].

One of the most practical lines to transmit signals is Multi-Conductor Transmission Lines (MTLs), which are widely used in power lines, telephone lines, and network cables. The MTL is a transmission system consisting of several shielded or unshielded conductors with common conductor as a signal return path, which is completed by a ground plane. Mutual coupling causes to penetrate a signal from a line into the near-end and far-end load of and another line, leading to occur crosstalk. This may put limits to the dynamic range and operating bandwidth of the applied MTL.

Variety of methods including analytical and numerical techniques has been presented in literature to calculate crosstalk. A few methods are suitable to predict the amount of crosstalk at low frequencies, while the other ones are appropriate at high frequency applications. The major difference between these proposed methods is the electrical size. Circuit modeling and lumped parameter models are two well-known modeling techniques to predict the amount of crosstalk in a MTL at low-frequency [2-4]. In the proposed methods to measure crosstalk at low frequency, it is assumed that transmission line physical dimensions is much smaller than the electrical wavelength [5]. However, at high frequencies, transmission line physical dimension is considered to

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be greater than quarter-electrical wavelength. In [6], an enhanced TL theory is introduced based on Maxwell's equations, which is simple and suitable for fast computing but the obtained results are not sufficiently precise.

In a few research papers, per-unit-length parameters of a MTL are derived as a function of frequency [7-9]. In [10], a new method is developed to estimate the amount of coupling on parallel-coupled matched terminated TL in time domain, which is only valid for lossless and low dispersive lines. It is shown that the crosstalk formula is in a polynomial forms and it is a function of the geometrical parameters of the structure. In addition to, to simplify the proposed method, a look-up table is created for the polynomial coefficients. It is said that this method is only valid for lossless planar transmission lines with a dielectric constant of 3 up to 5. For conditions that both source and load impedances are large or small compared to the characteristic impedance of the applied TL, an equation is derived in [11] for quick estimation of maximum coupling between the double conductor TL above a ground plane.

In some applications, losses at the terminations of the TL take over the losses in the transmission lines. In this case, paper [12] shows simple equations to estimate the worst case coupling between two lines for weak coupling at high frequencies, which are valid for specified conditions such as the length of the lines to be comparable with or greater than the wavelength of the signal. An approximate formula for crosstalk is introduced in [13], which is valid for infinitely long, lossless and homogeneous TL. The introduced model is a bit ambiguous and useful for weakly coupled lines. Also, it is assumed that characteristic impedances of the lines are approximately fixed over the entire lengths of the culprit and victim circuits. In [14] an expression is obtained to predict maximum amount of crosstalk for a coupled microstrip line, which is represented by a piecewise expressions depends on total electrical length of the culprit line. Overriding losses, the limited frequency range and maximum crosstalk calculation are almost three of the important features of the previous work.

In this paper, a high frequency TL model is used to predict the amount of crosstalk for a two terminated parallel-coupled transmission lines above a ground plane. The equations are derived in such a way that the effects of both victim and culprit lines are simultaneously considered. Moreover, the effects of terminated impedance to the lines are included. The obtained expression is a function of frequency, location point of view on the line, which can be used for either lossless or lossy lines using per-unit-length capacitance of the lines. It should be said that the proposed method is not valid for non-insulated and closely spaced TLs. Therefore, the amount of coupling is further improved compared with the results of recently published method using Method of Moment (MOM). Furthermore, applying realistic boundary conditions and employing a new method for crosstalk calculation lead to obtain accurate amount of crosstalk.

II. THEORY OF THE PROPOSED METHOD

Figure (1) shows a two coupled line transmission system between a source and load, which are normally called culprit and victim respectively. The terms V_v, I_v and V_c, I_c are the absolute value of the victim circuit voltage and current and the absolute value of the culprit circuit voltage and current, respectively. Three important conditions including uniform line and homogeneous media are assumed in our investigation. Also, weak coupling is supposed in all coupling region.

To study the behavior of the coupled line in Fig. 1, a voltage source with *rms* value of V_s with output impedance of Z_S is applied at the input terminal of the culprit line terminated by load Z_L and it is assumed that a travelling wave is pumped along z direction from source toward the load. It is shown that voltage signal across at the point z of the culprit and victim lines are given by equation (1a) and (1b) respectively [4, 5].

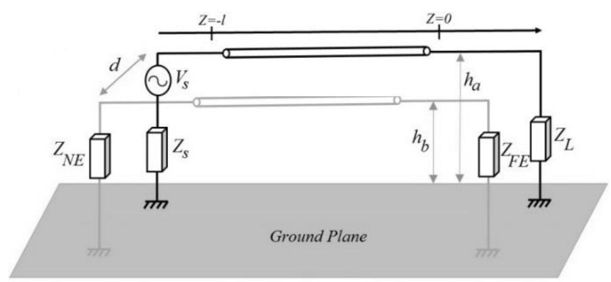

Figure 1: The victim and culprit transmission lines model.

$$V_c = \frac{T_{in}}{1-\Gamma_S\Gamma_L e^{-\gamma l}}\left[e^{-\gamma z}+\Gamma_L e^{+\gamma z}\right]V_S \tag{1a}$$

$$V_v = \frac{1}{1-\Gamma_F\Gamma_N e^{-\gamma l}}\left[e^{-\gamma z}+\Gamma_F e^{+\gamma z}\right]V_{0v} \tag{1b}$$

In which V_{0v} is voltage amplitude for the victim's line, which it is caused by the coupling effect with culprit line. In addition to γ is propagation constant. Furthermore, reflection coefficients of victims' line, Γ_F and Γ_N are reflection coefficients, which are given by equation (2a) and (2b), in which victim line characteristic impedance is designated by Z_{0v}.

$$\Gamma_F = \frac{Z_{FE}-Z_{0v}}{Z_{FE}+Z_{0v}} \tag{2a}$$

$$\Gamma_N = \frac{Z_{NE} - Z_{0v}}{Z_{NE} + Z_{0v}} \quad (2b)$$

The other parameters of the equations (1a) and (1b) are also defined using equations (3a) to (3e).

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (3a)$$

$$\Gamma_S = \frac{Z_s - Z_0}{Z_s + Z_0} \quad (3b)$$

$$T_{in} = \frac{2Z_{in}}{Z_{in} + Z_s} \quad (3c)$$

$$\Gamma_S = \frac{Z_s - Z_0}{Z_s + Z_0} \quad (3d)$$

$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)} \quad (3e)$$

For a coupled multi-conductor transmission lines that convey TEM or Quasi-TEM waves, voltage and current signals are related to each other by matrix equation (4) [4, 5].

$$\mathbf{I} = \upsilon_p \mathbf{C}\mathbf{V}^{+}\left[e^{-\gamma z} - \mathbf{\Gamma}^{\mathrm{T}} e^{+\gamma z}\right] \quad (4)$$

In (4), $\mathbf{I}$ and $\mathbf{V}^{+}$ are current and voltage vector of the culprit and victim lines, $\mathbf{\Gamma^T}$ represents transpose of reflection coefficients matrix and $\mathbf{C}$ designated per-unit-length capacitance matrix, which depends on the geometrical parameters of the coupled lines and υ_p is phase velocity of the line.

Applying boundary conditions at $z = 0$ does not provide new information because it yields homogeneous equation systems, but by applying boundary conditions at $z = -l$ for victim line, V_{ov} / V_S is obtained. This condition is expressed by equation (5a).

$$V_v(z = -l) = -Z_{NE} I_v(z = -l) \quad (5a)$$

Substituting (1a) and (1b) in (5a) and regarding crosstalk definition by equation (5b)

$$CT = \frac{V_v}{V_c} \quad (5b)$$

It can be shown that the amount of crosstalk is given by (6).

$$CT = \frac{Z_{NE}\upsilon_p C_m [k_2 e^{-\gamma l} - k_1 e^{\gamma l}]}{Z_{NE}\upsilon_p C_v [k_4 e^{-\gamma l} - k_3 e^{\gamma l}] + [k_4 e^{-\gamma l} - k_3 e^{\gamma l}]} \times \frac{k_3 e^{-\gamma z} + k_4 e^{\gamma z}}{k_1 e^{-\gamma z} + k_2 e^{\gamma z}} \quad (6)$$

In equation (6), the following definitions are used.

$$k_1 = \frac{T_{in}}{1 - \Gamma_L \Gamma_S e^{-\gamma l}} \quad (7a)$$

$$k_4 = \frac{\Gamma_F}{1 - \Gamma_F \Gamma_N e^{-\gamma l}} \quad (7b)$$

$$k_3 = \frac{1}{1 - \Gamma_F \Gamma_N e^{-\gamma l}} \quad (7c)$$

$$k_4 = \frac{\Gamma_F}{1 - \Gamma_F \Gamma_N e^{-\gamma l}} \quad (7d)$$

For a double conductor TL, which is studied in this paper, C_v and C_c are self per-unit-length capacitance of the victim and culprit lines respectively and C_m represents the mutual per-unit-length capacitance between the two lines.

In most practical applications, usually reflected signals have very small magnitude, which can be approximately ignored and also, the amount of crosstalk is important at the end of the lines. Therefore, a formula to predict crosstalk under the mentioned assumption is useful.

Based on TL theory, voltage signals along culprit and victim lines are expressed by equation (8) [15, 16].

$$V_c = V_c^{+}\left\{e^{-\gamma z} + \Gamma_L e^{\gamma z}\right\} \quad (8a)$$

$$V_v = V_v^{+}\left\{e^{-\gamma z} + \Gamma_F e^{\gamma z}\right\} \quad (8b)$$

In the above equations, V_c^{+} and V_v^{+} represent the incident voltage waves, from left to right direction as shown in Fig. 1 for the culprit and victim lines respectively. Z_{0c} and Z_{0v} are characteristic impedances of the culprit and victim lines, which are given by equations (9a) and (9b) [4].

$$Z_{0c} \approx \frac{1}{\upsilon_p (C_c + C_m)}, \quad (9a)$$

$$Z_{0v} \approx \frac{1}{\upsilon_p (C_v + C_m)} \quad (9b)$$

Substituting (8a), (8b) and (4) in (5a), boundary condition at source terminal of the victim line, equation (10) is obtained for crosstalk calculation.

$$CT = \frac{kC_m \upsilon_p}{\frac{1}{Z_{0v}}\left\{\frac{e^{\gamma l} - \Gamma_F e^{-\gamma l}}{e^{\gamma l} - \Gamma_L e^{-\gamma l}}\right\} + \frac{1}{Z_{NE}}\left\{\frac{e^{\gamma l} + \Gamma_F e^{-\gamma l}}{e^{\gamma l} - \Gamma_L e^{-\gamma l}}\right\}} \quad (10)$$

In which k is given by equation (11).

$$k = \frac{1+\Gamma_F}{1+\Gamma_L} \tag{11}$$

In special cases, in which load and far-end impedances are much greater or much lower than the transmission line characteristic impedances, the absolute value of the load and far-end reflection coefficients is assumed to be close to 1 with good approximation and equation (10) is rearranged by (12).

$$CT \approx \frac{\upsilon_p C_m}{\frac{1}{Z_{0v}} - j\frac{\cot(\gamma l)}{Z_{NE}}} \tag{12}$$

It can be seen from (12), for a low loss line, that there are frequencies at which the line length is an odd multiple of quarter of wavelength, maximum value of crosstalk is occurred. As a result, in this case, equation (13) is derived using equation (12), which shows the corresponding worst coupling value. This is the same expression for crosstalk as it is published in [3].

$$CT \approx \frac{C_m}{C_v + C_m} \tag{13}$$

Also, according to equation (12), there are frequencies that the length of the line is a multiple of half a wavelength. At these frequencies, no crosstalk is happened independent of the geometrical parameters of the line and its terminated impedances. In this case, equation (13) is not valid.

Using equivalent circuit model of transmission line, which supports TEM waves, the complex propagation constant is given by equation (14a), in which attenuation constant consists of two components including α_c and α_d, which are conductor and dielectric loss of the line respectively.

$$\gamma = \alpha + j\beta \tag{14a}$$

$$\alpha = \alpha_c + \alpha_d \tag{14b}$$

Therefore, by determining conductor and dielectric attenuation constants of the line; crosstalk is estimated using equation (6) or (10).

III. SIMULATION AND MEASUREMENT RESULT

To verify the accuracy of the proposed theory and to estimate the crosstalk of a double conductors line, a microstrip line including two strips having width of W is considered, which is shown in Fig. 2. For microstrip lines, effective dielectric constant, dielectric loss and conductor loss are given by equations (15) [5].

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12h/W}} \tag{15a}$$

$$\alpha_d = \frac{\beta\sqrt{\varepsilon_r}(\varepsilon_e-1)\tan\delta}{2\sqrt{\varepsilon_e}(\varepsilon_r-1)} \tag{15b}$$

$$\alpha_c = \frac{R_s}{Z_0 W} \tag{15c}$$

$$R_s = \sqrt{\frac{\omega\mu_0}{2\sigma_c}} \tag{15d}$$

In the above equations h and W are dielectric substrate thickness and strip width respectively. Also, ε_r and $\tan\delta$ *is* relative permittivity material and tangent loss of the substrate. R_s is surface resistance of the conductor with conductivity of σ_c. The microstrip line are made using TLY062 substrate with electrical characteristics of ε_r=2.2, h=1.56 mm and tan loss of 0.002. Fig. 3 shows the photos of the fabricated coupled lines and the measurement setup.

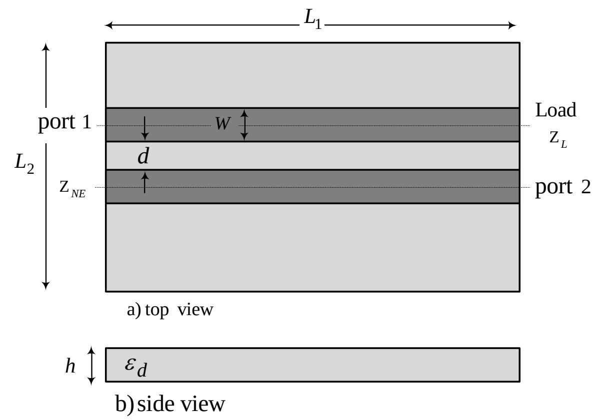

Figure 2: The structure of the two conductor microstrip lines and the geometrical parameters.

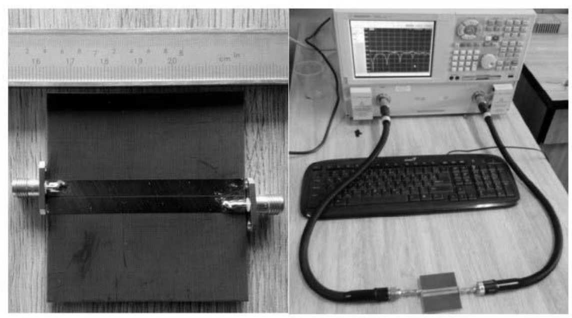

Figure 3: The photo of the fabricated coupled lines and the experimental setup.

At first, a parametric analysis is carried out to study the effect of d, distance between the two strips; on crosstalk. Three different cases are used in our investigation. The geometrical parameters of different cases including self per-unit-length capacitance and mutual per-unit-length capacitance are listed in Table 1.

The coupled lines are numerically investigated using High Frequency Structure Simulator (HFSS) and S_{21} is considered as the crosstalk of the two strips. In addition to, in measurement process S_{21} of the coupled lines is considered as the crosstalk between the two strips.

Table 1: The geometrical parameters of three microstrip coupled line under investigation.

	Case I	Case II	Case III
W (mm)	4.8	4.8	4.8
d (mm)	0.5	1	2
h (mm)	1.56	1.56	1.56
L_1 (mm)	60	60	60
L_2 (mm)	60	60	60
C_m (pF)	0.925	0.755	0.515
C_C, C_V (pF)	0.579	0.621	0.637

The results of the crosstalk including those of the proposed theoretical method based on equation (10), measured and simulated ones are plotted in Fig. 4 to Fig. 6 versus frequency from 2 GHz to 6 GHz for different values of d. Apart from a small shift at a few frequencies, the measured results agree well with those obtained by simulation and those of the proposed method. It is believed that, the small frequency shift is due to the difference in the physical and electrical lengths of the strips. At the open end of a microstrip line with a width of W, the fields do not stop abruptly, but extend slightly further because of the effect of fringing field. This phenomenon makes the electrical and physical length of a microstrip strip to be slightly different.

It can also be seen that, the proposed theoretical modeling predict accurately the amount of crosstalk. There are few frequencies that the strip length is multiple of half a wavelength. At these frequencies the crosstalk of the coupled line is the lowest along mentioned frequency range. It is said that this is due to input impedance of the culprit strip, which is equal to the load impedance. Because of large impedance of the load, reflection coefficient at port 1 is nearly close to one, and so no power is transmitted to culprit strip. In other words, coupled power to victim strip is small or even no coupling is occurred, that proposed method predicts this phenomenon very well. Moreover, at a few frequencies over the mentioned frequency range, crosstalk is maximum. These are at frequencies, while the length of strips is odd multiple of half a wavelength, which are confirmed by equation (13).

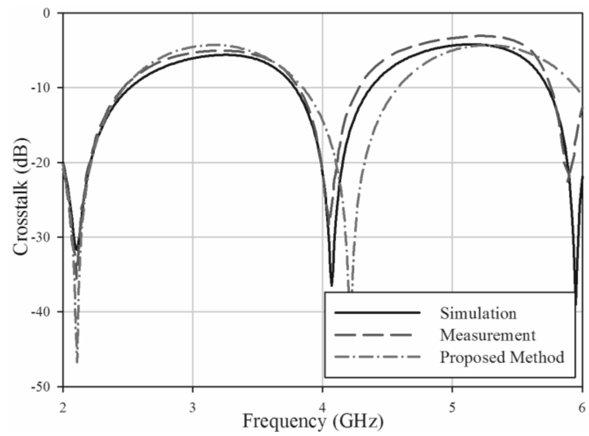

Figure 4: The simulated, measured and results of the proposed method in case of I, d=0.5 mm.

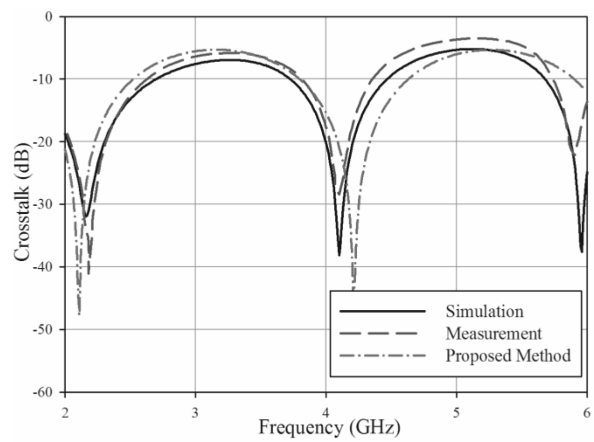

Figure 5: The simulated, measured and results of the proposed method in case of II, d= 1 mm.

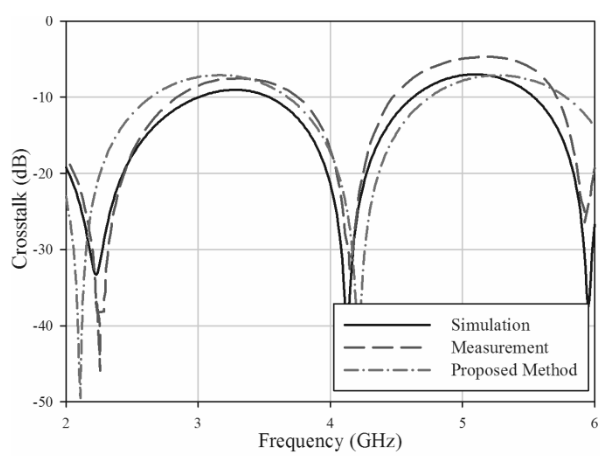

Figure 6: The simulated, measured and results of the proposed method in case of III, d= 2 mm.

Fig. 7 to Fig. 9 provide the values of Amplitude Difference Measure (ADM) and Feature Difference Measure (FDM) evaluated by using the Feature

Selective Validation (FSV) technique [17] and [18] according to the recent IEEE Standard P1597.1 [19], for an important quantification of the comparison between the measured datasets and proposed method results values in Fig. 4 to Fig. 6. Based on these figures of merit, the comparison of two data sets can be ranked. The range of values for the ADMc, and FDMc can be separated into six classes, each with a natural language descriptor: Excellent (EX), Very Good (VG), Good (G), Fair (F), Poor (P), and Very Poor (VP). It can be seen that the measured results agree with those obtained by our proposed method reasonably [17-19].

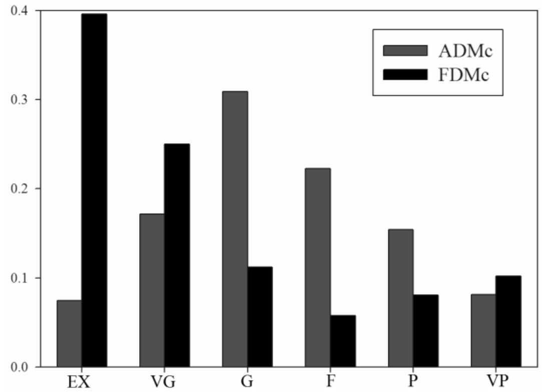

Figure 7: The FSV results for the comparison in Fig. 4.

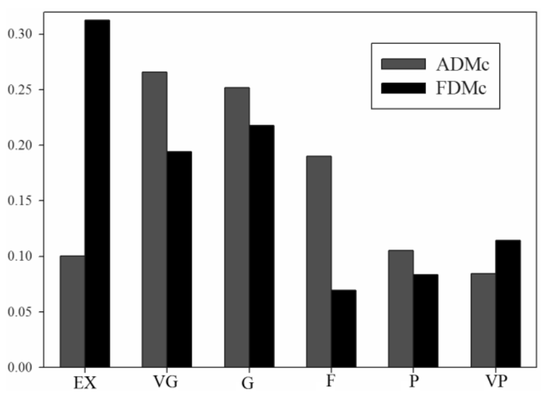

Figure 8: The FSV results for the comparison in Fig. 5.

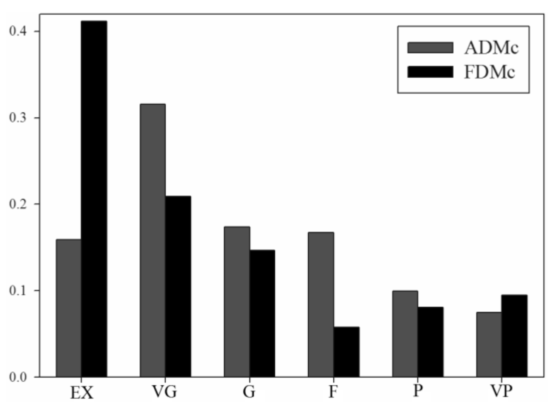

Figure 9: The FSV results for the comparison in Fig. 6.

VI. Conclusion

In this paper, a new theoretical method is introduced to estimate crosstalk of a two parallel-coupled strips of microstrip line. Using transmission line theory based on incident and reflected waves in a coupled line, voltage and current formulation along the transmission lines are derived and a simple and precise formula is obtained to estimate the amount of crosstalk. Also, the derivation formula, will be included the effect of geometrical parameters and the load impedances that connected to the end terminals of transmission lines. Since the crosstalk expression is a function of the self and mutual per-unit-length capacitance, the method of moment is used to figure of the per-unit-length capacitance for increase accuracy of the estimated coupling. Obtained formula is frequency and point view location dependent that can be used for quick and exact estimation for the crosstalk of the homogeneous and non-homogeneous transmission lines. Presented equations can be used for lines with weak and medium coupling, with any length in comparison to the electrical wavelength and for both lossy and lossless transmission line. The validity of the proposed equation has been verified using 3D full-wave simulator (HFSS 2015) and measurement data. The estimated coupling values match reasonably well with those of measurements, commercial field solvers and results available in literature. Therefore, the introduced method could be approached to the practical engineering and are applicable for any type of the multi-conductor transmission lines with little change.

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