Progress In Electromagnetics Research M, Vol. 29, 237–251, 2013

NETWORK EXPRESSION FOR COUPLING ANALYSIS OF ARBITRARILY DIRECTED MULTIPLE TRANSMISSION LINES

Sang Wook Park*

National Institute of Information and Communications Technology, Nukuikitamachi 4-2-1, Koganei, Tokyo 184-8795, Japan

Abstract—In this paper, the network expression is proposed for finite-length multiple transmission lines in arbitrary directions. Crosstalk between two bent transmission lines is analyzed using the proposed approach as an example of application. The resultant network function is obtained in the form of an $ABCD$ matrix for two bent transmission lines is obtained. The validity of the proposed approach was confirmed by comparing experimental results with computed results and those simulated by a commercial electromagnetic solver for some bent-line models.

1. INTRODUCTION

Recently, faster data transmission and higher circuit density are the trends in an electronic circuit design of a gigabit digital printed circuit board (PCB). It has been frequently observed, however, an unexpected electromagnetic (EM) coupling problem such as crosstalk that can cause timing violation, false clocking, intermittent data fault, etc.. The problem is highly associated with the effect of multiconductor transmission lines (MTLs) because PCB traces are the largest/longest component in most of all devices on a PCB.

In general, a typical crosstalk model is for parallel transmission lines, or multiconductor transmission lines (MTLs). Crosstalk analysis has been studied for parallel MTLs using network functions based on the telegrapher's equations under the assumption of transverse electromagnetic (TEM) mode propagation or at least quasi-TEM mode propagation [1, 2]. Recently, a new efficient simplification method is proposed for crosstalk prediction of multicoaxial cable bundles [3].

Received 27 January 2013, Accepted 4 March 2013, Scheduled 11 March 2013

* Corresponding author: Sang Wook Park (swpark@nict.go.jp).

However, MTLs in PCBs are not always parallel and of the same length, and those may contain some discontinuities such as vias and bends. These discontinuity effects as well as nearby parallel lines will cause crosstalk, but those effects are not taken into account in the ordinary transmission line theory. A transmission line generates EM ordinary transmission line theory. A transmission line generates electromagnetic fields, and those affect neighboring lines, causing induced currents in the lines. That concept corresponds to crosstalk or coupling in EM-field theory. In circuit theory, the phenomenon is expressed in terms of mutual capacitance and mutual inductance, which is a basic concept of the telegrapher's equations for the MTL theory. These findings suggest that a method of dealing with crosstalk between various types of lines having discontinuities may succeed in combining both concepts.

If a transmission line is in EM fields, an induced current flows through it. This coupling of external fields to transmission lines can be expressed in the so-called modified telegrapher's equations. The differential equations regarding line voltage and current, which were derived from Maxwell's equations, contain forcing terms in external EM-field components [4–6]. Here, the method based on modified telegrapher's equations is called a circuit-concept approach [7]. The coupling between two nonparallel lines has been studied using the approach [11–13], where the riser effect to another line is taken into account but the effect to the line itself is ignored.

The practical pattern of the transmission lines also includes the discontinuity such as bend. The radiation and transmission characteristics are analytically investigated at a bend of a transmission line [14]. A topology of bent differential lines to reduce the common-mode noise was investigated [15]. The crosstalk and reflection for bent lines have been studied by using a nonuniform transmission line approach [16]. This approach can analyze the crosstalk between bent lines by obtaining the simultaneous line parameters along the nonuniform lines. However, the coupling effect from nearby lines cannot be considered, i.e., for bent lines including nonparallel lines. The coupling between two bent lines has been studied by considering coupling effect from all nearby lines using a circuit-concept approach [17]. Here, the expanded circuit-concept approach is proposed to analyze the coupling between lines of various, complicated patterns including discontinuities such as nonparallel lines, bend, vias, and so on. The proposed approach is applied to some bent-line models for the analysis of the coupling phenomenon. Furthermore, the results obtained by the proposed approach are compared with those obtained by the conventional telegrapher's equations.

In this paper, the circuit-concept approach for the crosstalk analysis of 2 finite-length transmission lines is expanded for that of n finite-length transmission lines in a homogeneous medium, where $n > 2$. $2n$-port network expression is derived from the modified telegrapher equations based on the circuit-concept approach. The above approach is applied to the analysis of crosstalk between bent nonparallel and/or parallel lines having risers at line ends. It is assumed that the coupling between parallel lines is weak, for example, less than about -15 dB at the most. Here, the transmission-line models in free space are considered to simplify the model and to make the effect of the crosstalk mechanism clear. The network functions have been derived in the form of an $ABCD$ matrix by taking into account the effect of various line sections. To verify the proposed theory, some experiments have been performed, and the measured results have been compared with the theoretical and simulated results by a commercial solver (HFSS: high-frequency structure simulator). The theoretical results were substantially in agreement with the experimental results.

2. EXPANSION OF EQUATIONS FOR MULTIPLE TRANSMISSION LINES IN ARBITRARY DIRECTION

Figure 1 shows the structure of n finite-length transmission lines above a ground plane ($y_i = 0$). Each line is arbitrarily directed and has angle θ between the lines, and set by each coordinate system whose origin is located at the starting point of a line. The y-axis of each line is always directed normal to the ground. The height of the line is h. The length of the i-th line is l_i.

When a transmission line is excited by EM fields, a current is

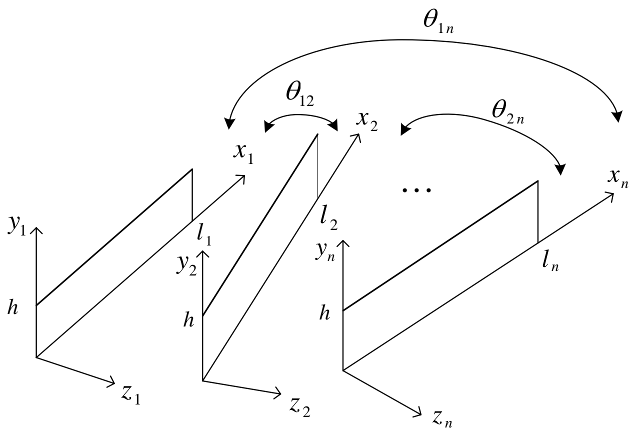


Figure 1. Multiple finite-length transmission lines with each coordinate system.

induced in the line. This coupling phenomenon can be expressed by the telegrapher's equations in terms of line voltage, V, and current, I, under the assumption of transverse electromagnetic TEM mode propagation [4–10]. The differential equations have forcing terms denoting the effects due to the external EM fields. To distinguish those equations from ordinary telegrapher's equations, they are called modified telegrapher's equations. The analytical technique based on the modified telegrapher's equations is called the circuit-concept approach. The coupling between neighboring transmission lines can be considered as a phenomenon similar to the coupling mentioned above. That is, EM fields due to one line cause coupling in another line and vice versa.

The coupling between n finite-length transmission lines shows that one line driven by a lumped source within a terminal acts as a transmitting antenna. This line is referred to as a generator line. The other passive lines play the role of a receiving antenna, and are referred to as receptor lines. Considering line 1 as a receptor line, the modified telegrapher equations for the line voltage $V_1(x)$ and current $I_1(x)$ can be expressed as

$$-\frac{d}{dx}\begin{bmatrix} V_1(x_1) \\ I_1(x_1) \end{bmatrix} = \begin{bmatrix} 0 & j\omega L_1 \\ j\omega C_1 & 0 \end{bmatrix}\begin{bmatrix} V_1(x_1) \\ I_1(x_1) \end{bmatrix} + \sum_{i=2}^{n}\begin{bmatrix} V_{fi}(x_1) \\ I_{fi}(x_1) \end{bmatrix}, \tag{1}$$

where C_1 and L_1 are the per-unit-length self-capacitance and self-inductance on line 1, respectively, and ω is the angular frequency. The forcing terms, $V_{fi}(x_1)$ and $I_{fi}(x_1)$, are caused by the EM fields generated from currents on line 2, 3, ..., n. The summation of forcing terms in the right-hand side of (1) results in the induced voltage and current on line 1. The solution of (1) is given as

$$\begin{bmatrix} V_1(0) \\ I_1(0) \end{bmatrix} = F_1(l_1)\begin{bmatrix} V_1(l_1) \\ I_1(l_1) \end{bmatrix} + \sum_{i=2}^{n}\int_0^{l_i} F_1(x_1')\begin{bmatrix} V_{fi}(x_1') \\ I_{fi}(x_1') \end{bmatrix} dx', \tag{2}$$

where $F(x)$ is a chain matrix and expressed as

$$F_1(x_1) = \begin{bmatrix} \cos\beta_1 x_1 & jZ_{01}\sin\beta_1 x_1 \\ j\dfrac{1}{Z_{01}}\sin\beta_1 x_1 & \cos\beta_1 x_1 \end{bmatrix} \tag{3}$$

Here, Z_{01} and β_1 are the characteristic impedance and propagation constant of line 1, respectively. Terms, V_{fi} and I_{fi}, standing for the distributed voltage and current sources along the i-th line, that is, the magnetic and electric coupling, respectively, can be written in terms of the vector potential $\mathbf{A}(A_x, A_y, A_z)$ of the external electric field of

$\mathbf{E}(E_x,\, E_y,\, E_z)$ and the magnetic flux density of $\mathbf{B}(B_x,\, B_y,\, B_z)$:

$$\begin{bmatrix} V_{fi}(x_1') \\ I_{fi}(x_1') \end{bmatrix} = \begin{bmatrix} -j\omega \int_0^h B_z dy' \\ -j\omega C_1 \int_0^h E_y dy' \end{bmatrix} = \begin{bmatrix} -j\omega \int_0^h \left(\frac{\partial A_{yi}}{\partial x} - \frac{\partial A_{xi}}{\partial y} \right) dy' \\ C_1 \left(\omega^2 \int_0^h A_{yi} dy' + \frac{\nabla \cdot \mathbf{A}_i}{\mu_0 \epsilon_0} \Big|_{y'=0}^{y'=h} \right) \end{bmatrix} \tag{4}$$

To simplify expression in a derivation process, a procedure to derive the resultant network equation is shown by using only typical equations. First, consider vector potential, $\mathbf{A}(A_x,\, A_y,\, A_z)$, generated by a current in i-th straight line section of length l_i in the x-direction and the risers in the y-direction at both ends. By taking account of the image current, the vector potential components can be estimated at an arbitrary point $(x_i,\, y_i,\, z_i)$. The straight-line current $I_i(x_i')$ generates the x-component of

$$A_{xi} = \frac{\mu_0}{4\pi} \int_0^{l_i} \left\{ \frac{e^{-j\beta_i R_{x1}}}{R_{x1}} I_i\left(x_i'\right) - \frac{e^{-j\beta_i R_{x2}}}{R_{x2}} I_i\left(x_i'\right) \right\} dx', \tag{5}$$

where

$$\begin{aligned} R_{x1} &= \sqrt{(x_i - x_i')^2 + (y_i - h)^2 + z_i^2} \\ R_{x2} &= \sqrt{(x_i - x_i')^2 + (y_i + h)^2 + z_i^2} \end{aligned} \;. \tag{6}$$

And the currents at vertical risers, $I_i(0)$ and $I_i(l_i)$, generate the y-component of

$$A_{yi} = \frac{\mu_0}{4\pi} \int_{-h}^{h} \left\{ \frac{e^{-j\beta_i R_{y1}}}{R_{y1}} I_i(0) - \frac{e^{-j\beta_i R_{y2}}}{R_{y2}} I_i(l_i) \right\} dy', \tag{7}$$

where

$$\begin{aligned} R_{y1} &= \sqrt{x_i^2 + \left(y_i - y_i'\right)^2 + z_i^2} \\ R_{y2} &= \sqrt{(x_i - l_i)^2 + \left(y_i - y_i'\right)^2 + z_i^2}. \end{aligned} \tag{8}$$

The line current $I_i(x_i')$ can be expressed in terms of the line voltage $V_i(l_i)$ and current $I_i(l_i)$ at the line end, $x_i' = l_i$, as

$$I_i\left(x_i'\right) = j\frac{V_i(l_i)}{Z_{0i}} \sin\beta_i\left(l_i - x_i'\right) + I_i(l_i)\cos\beta_i\left(l_i - x_i'\right). \tag{9}$$

Thus, by using (9), the vector-potential components for each line section and riser can be expressed in terms of terminal voltage $V_i(l_i)$ and current $I_i(l_i)$:

$$\begin{aligned} A_{xi} \;=\; & \frac{\mu_0}{4\pi} \left\{ \int_0^{l_i} \left(\frac{e^{-j\beta_i R_{x1}}}{R_{x1}} - \frac{e^{-j\beta_i R_{x2}}}{R_{x2}} \right) \right. \\ & \left. \cdot \begin{bmatrix} j\frac{1}{Z_{0i}} \sin\beta_i(l_i - x_i') \\ \cos\beta_i(l_i - x_i') \end{bmatrix} dx' \right\} \begin{bmatrix} V_i(l_i) \\ I_i(l_i) \end{bmatrix}, \end{aligned} \tag{10}$$

$$A_{yi} = \frac{\mu_0}{4\pi}\left\{\int_{-h}^{h}\begin{bmatrix} j\frac{\sin\beta_i l_i}{Z_{0i}}\frac{e^{-j\beta R_{y1}}}{R_{y1}} \\ \cos\beta_i l_i \frac{e^{-j\beta_i R_{y1}}}{R_{y1}} - \frac{e^{-j\beta_i R_{y2}}}{R_{y2}}\end{bmatrix} dy'\right\}\cdot\begin{bmatrix} V_i(l_i) \\ I_i(l_i)\end{bmatrix}. \quad (11)$$

When we consider the model where the fields due to the i-axis-line current affect the j-axis line, the relationship between vector potential components of the x_i-y_i-z_i and x_j-y_j-z_j coordinate systems is expressed as follows by letting angles between the systems be θ_{ij},

$$\begin{bmatrix} A_{xj} \\ A_{yj} \\ A_{zj}\end{bmatrix} = \begin{bmatrix}\cos\theta_{ij} & 0 & -\sin\theta_{ij} \\ 0 & 1 & 0 \\ \sin\theta_{ij} & 0 & \cos\theta_{ij}\end{bmatrix}\begin{bmatrix} A_{xi} \\ A_{yi} \\ A_{zi}\end{bmatrix}. \quad (12)$$

Using (10), (11) and (12), the second term on the right side of (2) is written in terms of voltage, $V_i(l_i)$, and current, $I_i(l_i)$, at the terminal of the x_i-axis line in the following form:

$$\int_0^{l_j} F(x')\begin{bmatrix} V_f(x') \\ I_f(x')\end{bmatrix} dx' \equiv \tilde{F}'_{ji}\begin{bmatrix} V_i(l_i) \\ I_i(l_i)\end{bmatrix}. \quad (13)$$

Applying (2) and (3) to line 1 leads to

$$\begin{bmatrix} V_1(0) \\ I_1(0)\end{bmatrix} = F(l_1)\begin{bmatrix} V_1(l_1) \\ I_1(l_1)\end{bmatrix} + \sum_{i=2}^{n}\tilde{F}'_{1i}\begin{bmatrix} V_i(l_i) \\ I_i(l_i)\end{bmatrix}. \quad (14)$$

Considering the i-th line as a receptor line, a similar matrix equation can be obtained. If the elements of chain matrices are defined as

$$F(l_i) \equiv \begin{bmatrix} a_{ii} & b_{ii} \\ c_{ii} & d_{ii}\end{bmatrix}, \quad \tilde{F}'_{ji} \equiv \begin{bmatrix} a_{ji} & b_{ji} \\ c_{ji} & d_{ji}\end{bmatrix}, \quad (15)$$

consequently, $2n$-port network for the n finite-length transmission lines can be obtained as (16)

$$\begin{bmatrix} V_1(0) \\ V_2(0) \\ \vdots \\ V_n(0) \\ I_1(0) \\ I_2(0) \\ \vdots \\ I_n(0)\end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} & b_{11} & b_{12} & \dots & b_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} & b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} & b_{n1} & b_{n2} & \dots & b_{nn} \\ c_{11} & c_{12} & \dots & c_{1n} & d_{11} & d_{12} & \dots & d_{1n} \\ c_{21} & c_{22} & \dots & c_{2n} & d_{21} & d_{22} & \dots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \dots & c_{nn} & d_{n1} & d_{n2} & \dots & d_{nn}\end{bmatrix}\begin{bmatrix} V_1(l_1) \\ V_2(l_2) \\ \vdots \\ V_n(l_n) \\ I_1(l_1) \\ I_2(l_2) \\ \vdots \\ I_n(l_n)\end{bmatrix} \quad (16)$$

3. CIRCUIT MODEL FOR TWO BENT TRANSMISSION LINES

The parallel transmission lines can be easily analyzed by using the multiconductor transmission-line (MTL) theory based on the telegrapher's equations. In nonparallel lines of weak copling, we might be able to obtain the solution by applying a cascading technique mentioned later to some models, but may be unsuccessful in obtaining sufficiently good results. Such an example is discussed in Section 4. Coupling phenomena occur between all neighboring lines as well as parallel lines. Therefore, the ordinary transmission-line theory is not applicable to nonparallel lines. Here, a technique applicable to such problems is considered

A model of two bent lines is considered as shown in Fig. 2. Each bent line consists of two straight-line sections. In the figure, a different coordinate system is set for each line section, x_i-y_i-z_i coordinates. The four line sections are of different length l_i in the x_i directions and of the same line height, $y_i = h$, above a ground plane. Here, it is assumed that the characteristic impedance of each line section is approximated as that of the isolated line because the line arrangement, except for the purpose of coupling, is for weak coupling in many cases.

Let us consider the bent line consisting of line Sections 1 and 2 shown in Fig. 2 and discuss the expression of the terminal voltage and current, $V_1(0)$ and $I_1(0)$. Applying (2) and (3) to line Section 1 leads to

$$\begin{bmatrix} V_1(0) \\ I_1(0) \end{bmatrix} = F(l_1) \begin{bmatrix} V_1(l_1) \\ I_1(l_1) \end{bmatrix} + \sum_{i=1}^{4} \tilde{F'}_{1i} \begin{bmatrix} V_i(l_i) \\ I_i(l_i) \end{bmatrix}. \tag{17}$$

For $i = 1$ in this case, the EM fields due to the x_1-axis-line current are taken into account in the expression of $ABCD$ matrix of the x_1-axis line itself. Therefore, only the riser effect, $\mathbf{A}(0,\, A_{y1,1},\, 0)$, should be

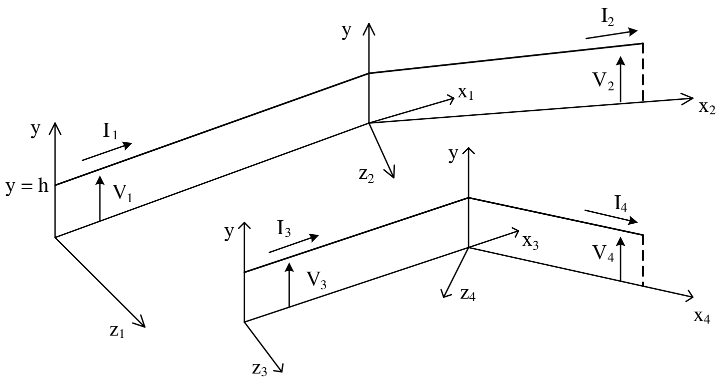


Figure 2. Model for two bent lines consisting of two straight-line sections and their coordinate system.

taken into account in calculating the second term on the right side of (17). Therefore, the second term on the right side of (17) is written in the form of

$$\sum_{i=2}^{4} \tilde{F}'_{x1,i} \begin{bmatrix} V_i(l_i) \\ I_i(l_i) \end{bmatrix} + \tilde{F}''_{1y,12} \begin{bmatrix} V_2(l_2) \\ I_2(l_2) \end{bmatrix} + \tilde{F}''_{1y,34} \begin{bmatrix} V_4(l_4) \\ I_4(l_4) \end{bmatrix} \tag{18}$$

where $\tilde{F}'_{x1,i}$ denotes the contribution due to x_1-component fields from the x_i-axis line. Term $\tilde{F}''_{1y,12}$ denotes the components due to the riser currents at ports 1 and 2, and $\tilde{F}''_{1y,34}$ denotes those at ports 3 and 4. Considering the continuity conditions at the bent points or connecting points of two line sections, the following equations should hold:

$$V_1(l_1) = V_2(0),\ I_1(l_1) = I_2(0) \quad \text{and} \quad V_3(l_3) = V_4(0),\ I_3(l_3) = I_4(0).$$

Resultantly, the equations for line Sections 1 and 2 can be written in the following form after rearrangement:

$$\begin{bmatrix} V_1(0) \\ I_1(0) \end{bmatrix} = F(l_1) \begin{bmatrix} V_1(l_1) \\ I_1(l_1) \end{bmatrix} + F_{12} \begin{bmatrix} V_2(l_2) \\ I_2(l_2) \end{bmatrix} + F_{14} \begin{bmatrix} V_4(l_4) \\ I_4(l_4) \end{bmatrix}. \tag{19}$$

where $F_{1n}\,(n = 2, 4)$ denote the coefficient matrices of the terminal voltage, $V_n(l_n)$, and current, $I_n(l_n)$, which mean the contribution due to the line of ports $n-1$ to n. We can also obtain a similar matrix equation for another bent line consisting of line Sections 3 and 4. As a result, the final $ABCD$ matrix for two bent lines is led as

$$\begin{bmatrix} V_1(0) \\ V_3(0) \\ I_1(0) \\ I_3(0) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2(l_2) \\ V_4(l_4) \\ I_2(l_2) \\ I_4(l_4) \end{bmatrix}, \quad \begin{aligned} A &= F(l_1)\{F(l_2) + F_{22}\} + F_{12} \\ B &= F(l_1)F_{24} + F_{14} \\ C &= F(l_3)F_{42} + F_{32} \\ D &= F(l_3)\{F(l_4) + F_{44}\} + F_{34} \end{aligned} \tag{20}$$

where submatrices A, B, C, and D are 2×2. From the $ABCD$ matrix, we can estimate the crosstalk characteristics in scattering matrix.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The frequency responses of some models have been estimated with a vector network analyzer to verify the proposed approach. A basic transmission-line model is fabricated with a wire that has a 0.5-mm diameter and 4-mm height above an aluminum ground plane. Then, the characteristic impedance of the isolated line is about 208 Ω. All parallel-line sections had a 5-mm space between the lines. In the experimental model, EM source was excited at the line of ports 1 through 3, and then the line of ports 2 through 4 was a victim line.

Ports 1 and 2 are moved 2 cm for the sake of connecting connectors in all test models. Measurements of near-end (port 2) and far-end (port 4) crosstalk characteristics, S_{21} and S_{41}, were performed for lines that terminated with $50\,\Omega$. The theoretical results of near- and far-end crosstalk characteristics obtained by the proposed approach and the results using a commercial solver (HFSS), and the measured results are shown in Figs. 4, 5, and 7 to 10.

The first model is shown in Fig. 3; one line is straight, and another is bent at an angle of 45° and is 20-cm long. The parallel line of Section 2 in the figure is 7.8-cm long. In this model, near-end crosstalk characteristics were also studied using the cascading technique and compared those with other results to show that the cascading technique cannot efficiently estimate crosstalk because discontinuity effects are not considered in the technique. That is, the crosstalk analysis was performed by using an ordinary transmission-line theory because of weak-coupling assumption. Assuming that transmission lines in Sections 1 and 3 are of an isolated single line and only the parallel lines in Section 2 play a role of crosstalk, we can obtain an overall $ABCD$ matrix by cascading each section as

$$\begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} \begin{bmatrix} A_2 & B_2 \\ C_2 & D_2 \end{bmatrix} \begin{bmatrix} A_3 & B_3 \\ C_3 & D_3 \end{bmatrix}. \tag{21}$$

The magnitude of near-end crosstalk characteristics calculated by the cascading technique is shown in Fig. 4(a) compared with other results. From the figure, it is confirmed that the results of the cascading technique definitely do not agree with other results. This difference occurs because the method does not consider the coupling effects between any other neighboring lines, except the parallel lines.

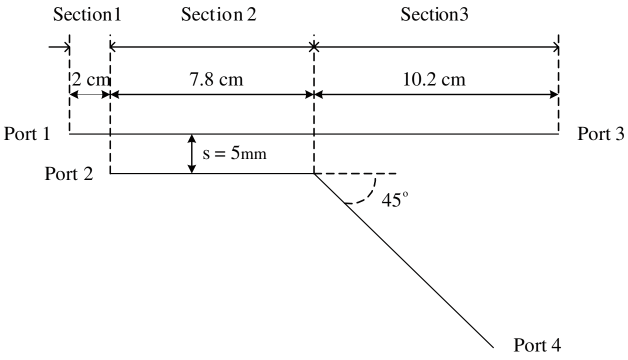
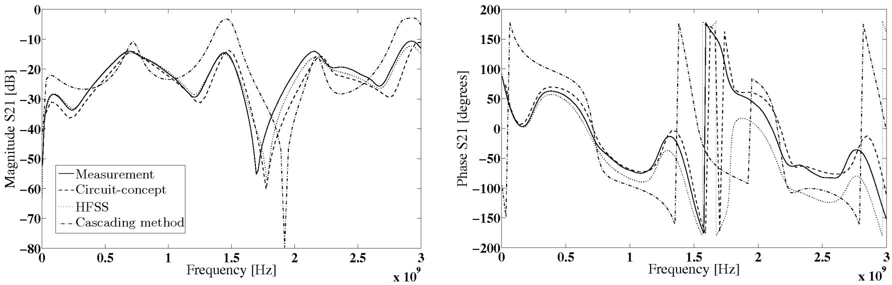
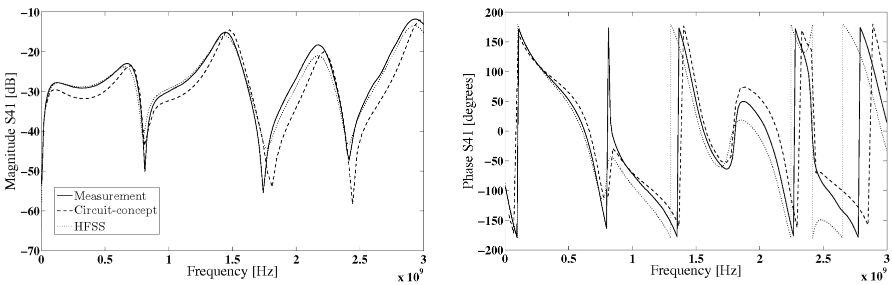


Figure 3. Partially parallel bent line model: a straight line and a bent line.



(a) (b)

Figure 4. Near-end crosstalk, S_{21}, characteristics: (a) amplitude and (b) phase for the model of a straight and a bent lines. The solid line, dashed line, dotted line, and dash-dotted line indicate the measured, circuit-concept approach, HFSS, and cascading technique results, respectively.



(a) (b)

Figure 5. As in Fig. 4, but for far-end crosstalk, S_{41}.

Therefore, the cascading technique using transmission line theory seems insufficient to predict crosstalk sufficiently well. On the contrary, the proposed approach is based on the concept that the external EM fields causing the coupling are generated from not only nearby parallel lines but also by neighboring nonparallel lines, risers, and bent corners. The theoretical results obtained by the approach are in good agreement with the measured and the simulated (HFSS) results.

The next model is a bent parallel transmission line. The configuration of bent parallel lines having 90° can often be found in modern circuits. The crosstalk was also estimated for 90° bent parallel lines of two types, as shown in Figs. 6(a) and (b). The A-type model is bent once at an angle of 90° and the B-type model is bent twice at an angle of 45°. All A-type ports are located at the same position with respect to those of the B-type on the ground plane. The total

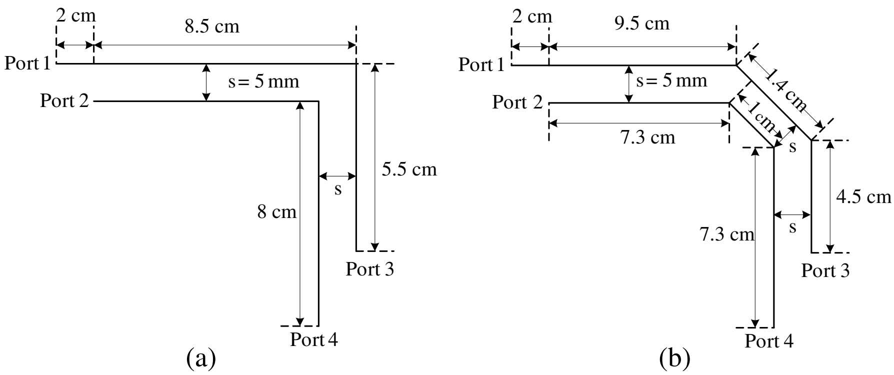


Figure 6. (a) 90°-bent parallel line model having one corner: A-type and (b) 90°-bent parallel line model having two corners: B-type.

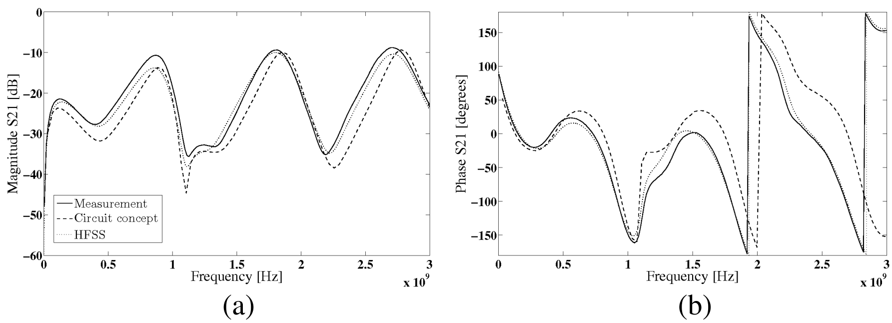


Figure 7. Near-end crosstalk, S_{21}, characteristics for A-type model in Fig. 6(a): (a) amplitude and (b) phase. The solid, dashed, and dotted lines indicate the measured, circuit-concept approach, and HFSS results, respectively.

length of the parallel-line section in the A-type model is 16 cm and the separation between the lines is 5 mm. On the other hand, the parallel line length of the B-type is different from that of the A-type model. The line of ports 1–3 is 15.4 cm and that of ports 2–4 is 15.6 cm to maintain a separation of 5 mm under the condition of maintaining the same port positions in two models. If we try to apply the conventional MTL equations using the cascading technique to these models, the coupling effects of extra lines not contained in the parallel parts at the corner section cannot be taken into account. On the other hand, the proposed approach can also treat the coupling effects of the extra parts.

In the B-type model, the same concept can be applied, and the resultant $ABCD$ matrix can be obtained by a procedure similar to that of the previous model. The results are shown in Figs. 7 to 10. It can also be seen that the results of the proposed approach agree well with the measured results and the HFSS results for magnitude and phase of the near- and far-end crosstalks in both models. The B-type 90° bent parallel line is usually more popular than the A-type. If we examine the graphs of the characteristics of the two types and compare the crosstalk level between them, the peaks of the characteristics of the A-type are slightly higher than those of the B-type in thesed models. In addition, the depths of the minimum points of near-end crosstalk seem different, but, generally, the characteristics are very similar to each other.

From the comparison results, it is confirmed that the proposed approach is good for estimating crosstalk between various line configurations because the magnitude and phase results are in good agreement with the measured and the computed results obtained by a

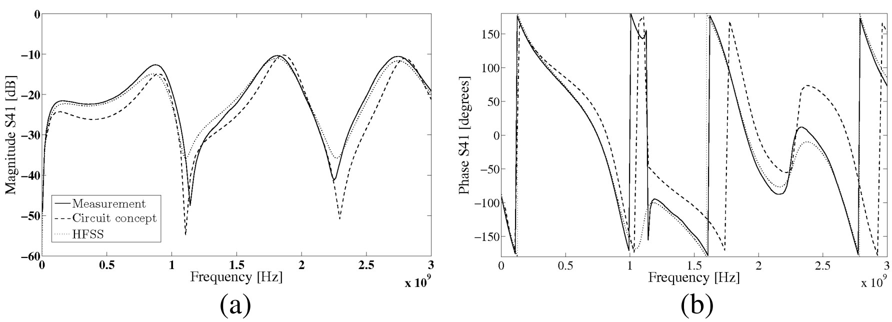


Figure 8. As in Fig. 7, but for far-end crosstalk, S_{41}.

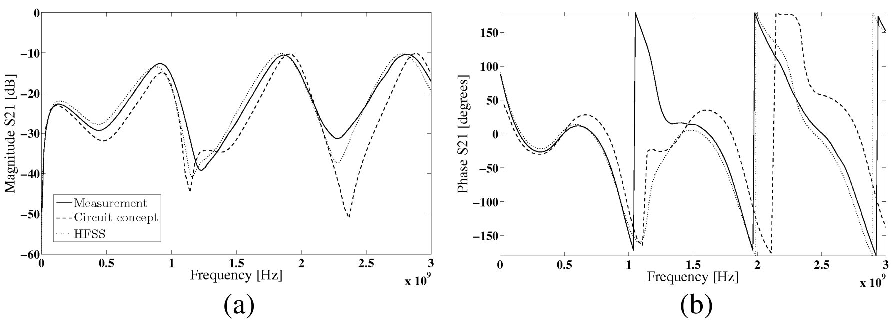
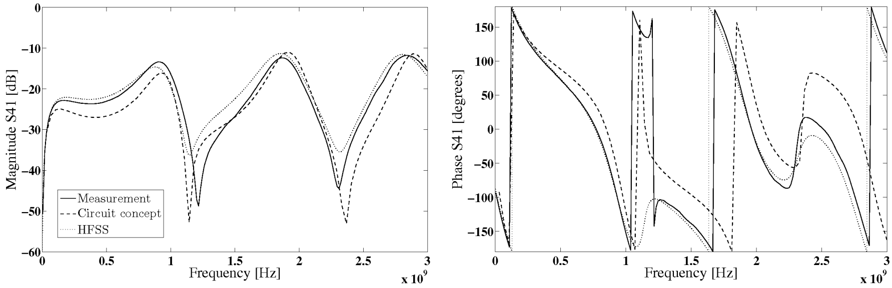


Figure 9. Near-end crosstalk, S_{21}, characteristics for B-type model in Fig. 6(b): (a) amplitude and (b) phase. The solid line, dashed line, and dotted line indicate the measured, circuit-concept approach, and HFSS results, respectively.



(a) (b)

Figure 10. As in Fig. 9, but for far-end crosstalk, S_{41}.

commercial solver (HFSS). The approach is formulated supposing that the EM fields that cause coupling are generated by neighboring lines and by terminal risers, and those due to the risers affect the line itself. This finding suggests the predicted coupling mechanism is correct.

5. CONCLUSION

The circuit-concept approach was expanded for the crosstalk analysis of arbitrarily directed multiple transmission lines in a homogeneous medium. The approach has been applied to the analysis of crosstalk between two bent lines including the risers at both ends of a line in the frequency domain. A line through which current flows generates EM fields, and these induce a current on a neighboring line. The proposed approach considers coupling as an effect of the EM fields caused by neighboring lines. The coupling effect causes distributed voltage and current sources on the victim line. Using the proposed approach, the telegrapher's equations were modified so that the effect of external fields on a victim line was modeled. Discontinuity effects, such as the riser effect and the bent corner effect, can be easily taken into account by the proposed approach. The results calculated by the proposed approach were compared with the measured and the simulated results to estimate whether the discontinuity effect can be modeled accurately in the approach. The proposed approach satisfactorily predicts the crosstalk for two bent lines including risers at both ends of a line with the result that the discontinuity effects are modeled well in the equation.

Due to this expansion the derived equations are expected to be easily applied to crosstalk analysis of a variety of bend structures and more complex structures such as via fences and guard traces, etc. Because of the complexity of PCB structures, it is essential to predict

EM coupling using 1-D analysis which provides the great efficiency of calculation such as the expanded circuit-concept approach developed in this study. For applying the proposed approach to an inhomogeneous medium such as a PCB, a method is being developed for estimating EM fields in it. The proposed approach can be easily expanded for analyzing coupling phenomenon in an inhomogeneous medium and, as the future work, we will analyze a complex configuration of trace lines on a PCB.

REFERENCES

1. Paul, C. R., *Analysis of Multiconductor Transmission Lines*, Wiley-Interscience, New York, 1994.
2. Sato, R., *Transmission Line Circuit*, Corona, Tokyo, 1966.
3. Liu, L., Z. Li, J. Yan, and C. Gu, "Simplification method for modeling crosstalk of multicoaxial cable bundles," *Progress In Electromagnetics Research*, Vol. 135, 281–296, 2013.
4. Taylor, C. D., R. S. Satterwhite, and C. W. Harrison, "The response of a terminated two-wire transmission line excited by a nonuniform electromagnetic field," *IEEE Trans. on Antennas and Propag.*, Vol. 13, No. 6, 987–989, Nov. 1967.
5. Paul, C. R., "Frequency response of multiconductor transmission lines illuminated by an electromagnetic field," *IEEE Trans. on Electroman. Compat.*, Vol. 18, 183–190, Nov. 1976.
6. Agrawal, A. K., H. J. Price, and S. H. Gurbaxani, "Transient response of multiconductor transmission lines excited by a nonuniform electromagnetic field," *IEEE Trans. on Electromagn. Compat.*, Vol. 22, 119–129, May 1980.
7. Kami, Y. and R. Sato, "Circuit-concept approach to externally excited transmission lines," *IEEE Trans. on Electromagn. Compat.*, Vol. 27, No. 4, 177–183, Nov. 1985.
8. Kami, Y. and R. Sato, "Analysis of radiation characteristics of a finite-length transmission line using a circuit-concept approach," *IEEE Trans. on Electromagn. Compat.*, Vol. 30, No. 2, 114–121, May 1988.
9. Kami, Y. and R. Sato, "Transient response of a transmission line excited by an electromagnetic pulse," *IEEE Trans. on Electromagn. Compat.*, Vol. 30, No. 4, 457–462, Nov. 1988.
10. Paul, C. R., "Efficient numerical computation of the frequency response of cable illuminated by an electromagnetic field," *IEEE Trans. on Microwave Theory and Tech.*, Vol. 22, No. 4, 454–457, Apr. 1974.

11. Kami, Y. and R. Sato, "Crosstalk of finite-length transmission lines in arbitrary directions on the same ground," *1992 IEEE Intn. Symp. on Electromagn. Compat.*, 247–250, Aug. 1992.
12. Liu, W. and Y. Kami, "Analysis of coupling between transmission lines in arbitrary directions," *1998 IEEE Intn. Symp. on Electromagn. Compat.*, 952–957, Denve, Aug. 24–28, 1998.
13. Xiao, F., W. Liu, and Y. Kami, "Analysis of crosstalk between finite-length microstrip lines: FDTD approach and circuit-concept modeling," *IEEE Trans. on Electromagn. Compat.*, Vol. 43, No. 4, 573–578, Nov. 2001.
14. Nakamura, T., N. Hayashi, H. Fukuda, and S. Yokokawa, "Radiation from the transmission line with an acute bend," *IEEE Trans. on Electromagn. Compat.*, Vol. 37, No. 3, 317–325, Aug. 1995.
15. Shiue, G. H., W. D. Guo, C. M. Lin, and R. B. Wu, "Noise reduction using compensation capacitance for bend discontinuities of differential transmission lines," *IEEE Trans. on Adv. Pack.*, Vol. 29, No. 3, 560–569, Aug. 2006.
16. Ye, C., E. Li, and Y. S. Gan, "Crosstalk and reflection for curvilinear conductors by utilizing a non-uniform transmission line approach," *IEEE Trans. on Adv. Pack.*, Vol. 25, No. 2, 302–306, May 2002.
17. Park, S. W., F. Xiao, D. C. Park, and Y. Kami, "Analysis of coupling between two bent transmission lines by a circuit-concept approach," *The 2006 4th Asia-Pacific Conference on Environmental Electromagnetics*, 736–739, Aug. 2006.