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AN ELECTROMAGNETIC TOPOLOGY APPROACH: CROSSTALK CHARACTERIZATION OF THE UNSHIELDED TWISTED-PAIR CABLE

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Abstract—The inductive effect of near-end crosstalk for a category five unshielded, twisted-pair cable has been verified using the electromagnetic topology simulation method. Crosstalk reduction and its dependency on such parameters as driving signals, circuit configuration and impedance, are studied. The simulation results are consistent with analytical analysis. Results show that the straight-through, differential-generator, twisted-pair receptor model is the most effective configuration to control the near-end crosstalk level. This is due to the influences from both the neutralizing mutual inductance and the single current generator. The simulation results also show that electromagnetic topology-based predictions are valid only for cables that are electrically short. Simulations are carried out using a compaction scheme with a single equivalent circuit. As a result, the unshielded, twisted-pair cable portion of the circuit can be combined with a larger network for analyzing the overall response of the entire network system.

1. INTRODUCTION

Electromagnetic interference (EMI) analysis is a well known technique to determine the performance of network cables by considering emission, immunity, and crosstalk as the dominant components. Emission refers to energy that is radiated or conducted by cables, while immunity refers to the ability of the cable to reject outside signals. Finally, crosstalk is undesirable signal transmission from one cable pair to another. In local area networks (LANs), failure to properly manage EMI can lead to an adverse effect on the integrity of the signal being transmitted. Of all the characteristics of LAN cable operation, crosstalk has the greatest effect on network performance. Similar to electrical noise from outside sources, crosstalk results in severe communication problems for their overall network operation. A network system used with unshielded twisted-pair (UTP) wires is known to reduce interference effects by making the network system an inefficient radiator, which causes the cancellation of unwanted signals by introducing the radiated signal that are equal but opposite to the unwanted signals on all the wires.

EMI analysis of twisted-pair cables have been studied for some time [3, 6, 9–12]. The modeling approach in these analyses is either using the bifilar helical-type model, the chain-parameter model, or the two-wire transmission-line model with twisted sections. Maki et al. [6] investigated the crosstalk margin level with the frequency range up to 100 MHz for a UTP-CAT5 cable, utilized in a 10/100 Base-T home network [5]. Most analysis shows that the resulting crosstalk depends largely on the values of line-termination impedances.

In this work, we present an alternate simulation approach known as the electromagnetic topology (EMT) simulation technique to study the crosstalk induced in four pairs of UTP-CAT5 cables for the frequency range up to a few hundred MHz. Simulation is based on a lumped-circuit transmission-line model similar to the configuration used in the work of Paul and McKnight [9, 10] where they investigated a single-wire generator, two-wire receptor circuit in homogenous media. The wire separation and length are sufficiently small as to ensure the validity of a low-frequency model. The electromagnetic topology technique is a modular simulation method, specifically suited for analyzing large electrical systems through volume decomposition [8]. Details and advantages of this technique, proposed in the early 1980s by the Air Force Research Laboratory (AFRL) at Kirtland AFB, NM, have been reported elsewhere [1]. The main advantage of this technique is to overcome some of the simulation problems associated with large network systems. In an EMT simulation approach, a very large network can be analyzed simply through volume decomposition. Each volume has different shielding levels and the interaction between the volumes is only possible through cables linking the two volumes or through openings and apertures between them. In this paper, we propose a concept of electromagnetic topology simulations to account for the crosstalk caused by signal propagation through connecting cables using the EMT-based code [7]. The key equation of EMT is the BLT (Baum Liu and Tesche) equation to express signals on an entire transmission-line network system [2].

In the simulation setup, we incorporate the multiconductor, transmission-line model with various types of generator, receptor, and impedance arrangements to analyze and compare effective crosstalk suppression on 10/100 Base-T networks. The outcome and advantage of such a simulation approach, besides the validation of topological simulation method, is the ability to isolate a topological circuit element for analyzing cross-talk suppression that can be integrated into a larger network for the overall network response analysis. In Section 2, a brief background of the EMT modeling approach to the crosstalk circuits for twisted-pair cables is provided for crosstalk topological simulations. The simulation setup is explained in detail in Section 3, and the results and discussion are given in Section 4. Finally, Section 5 gives the conclusion.

2. MODELING METHODOLOGY

2.1. Crosstalk Circuit Models

Near End Crosstalk (NEXT) is a coupled interference signal coming from the adjacent cables at the nearest end of the source. It does not depend on the generator and the receptor cable length. The NEXT value (in decibels) is computed as the difference in amplitude between the test signal and the crosstalk signal and is given by

$$NEXT = 20 \log_{10} \left| \frac{V_{SR}}{V_{SG}} \right|, \tag{1}$$

where V_{SR} is the voltage across the receptor wire at the sending end, and V_{SG} is the voltage across the generator wires at the sending end. Higher negative values correspond to less crosstalk and better cable performance. By design, performance gets worse as the frequency increases. In terms of interference, higher the frequency, higher is the noise coupling on the receptor to reduce the electrical insulation between the interfering generator and the receptor.

Figs. 1 and 2 show the coupling diagrams used for for analyzing the configuration depicted in Fig. 4. Shown in Fig. 1 is the schematic representation of single-wire generator, two-wire receptor circuits with twisted-pair wire sections [i.e., straight-through single-generator, straight-through receptor (STS/STP); twisted-pair single-generator, twisted-pair receptor (TWP/TWP); and straight-through single-generator, twisted-pair receptor (STS/TWP)]. The STS/STP

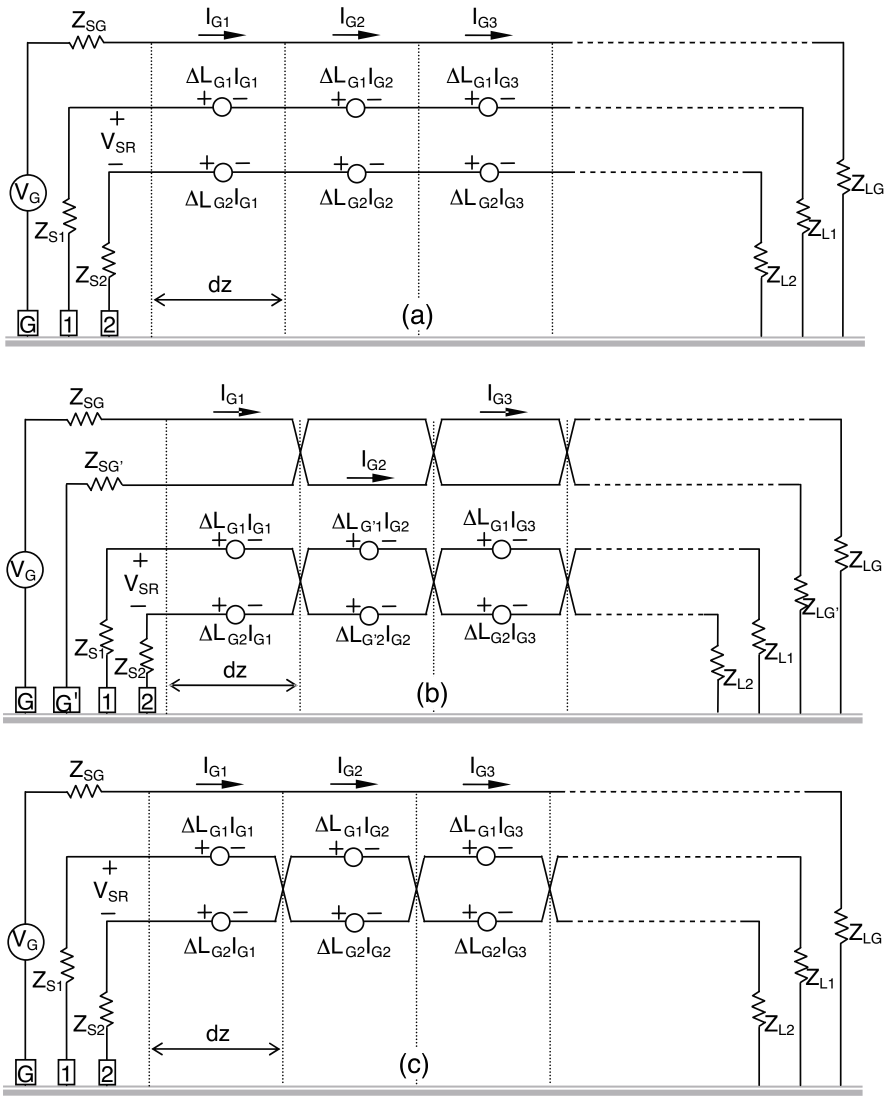

Figure 1. Coupling models driven by single source of configurations (a) STS/STP, (b) TWP/TWP and (c) STS/TWP. $\Delta = jwL$.

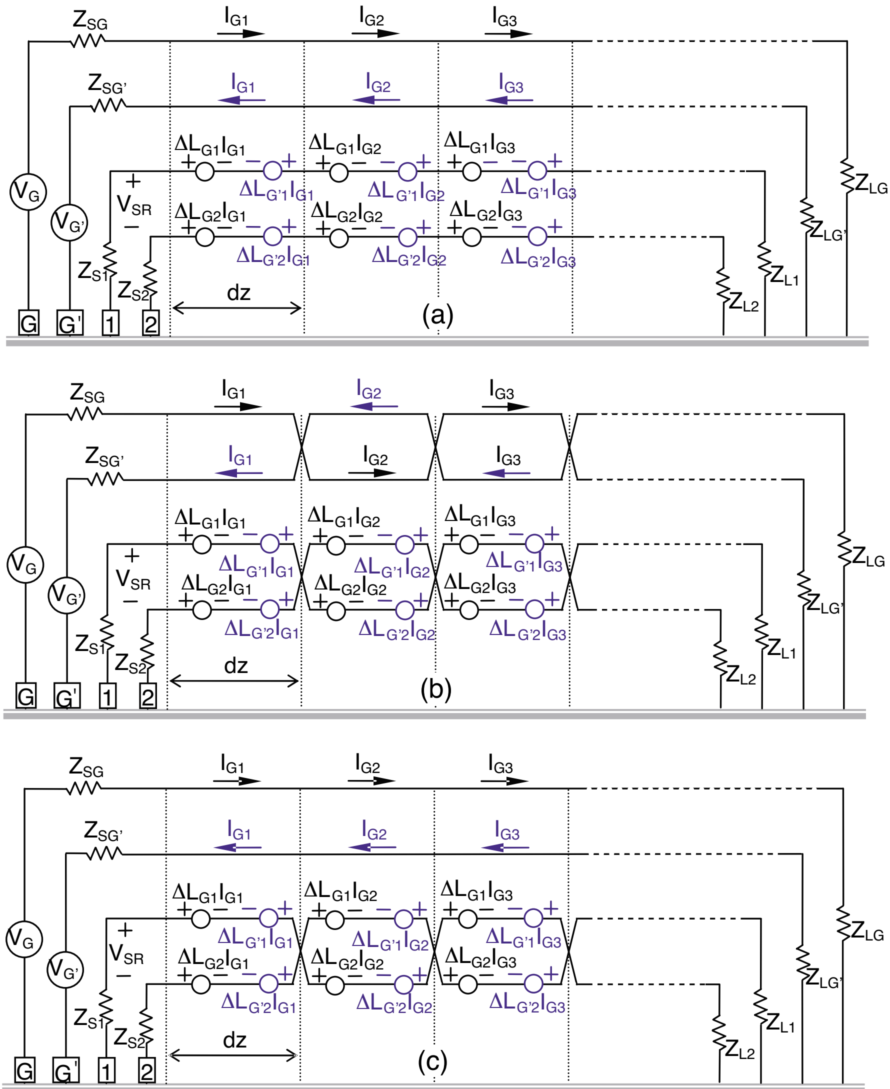

Figure 2. Coupling models driven by differential source of configurations (a) STD/STP, (b) TWPD/TWP and (c) STD/TWP. $\Delta = jwL$.

model, shown in Fig. 1(a), is the simplest configuration [i.e., only single wire for the generator (G) and untwisted receptor pair (1-2)]. Based on the low-frequency approximation, we assume that the voltages and currents in each section are approximately identical [10]. The differential voltage between receptor wires at the sending end is then given by

$$V_{SR} = \left[\frac{Z_{SR}}{Z_{SR} + Z_{LR}}\right] j\omega dz(L_{G1} - L_{G2})(I_{G1} + I_{G2} + I_{G3} + \cdots), \quad (2)$$

where Z_{SR} and Z_{LR} are source and load impedances, respectively, L_{G1} and L_{G2} are the mutual inductances between the generator and receptor wires. I_{Gn} is the generator current associated with the nth dz-long wire segment.

Fig. 1(b) shows the TWP/TWP model which is the most common configuration for a UTP-CAT5 cable where both generator and receptor circuits are formed by the twisted-pair wires (G-G' and 1-2). In this case, only single wire of the generator circuit is driven. From the circuits shown in the figure, the receptor differential voltage can be found as

$$\begin{aligned} V_{SR} \; = \; & \left[\frac{Z_{SR}}{Z_{SR} + Z_{LR}}\right] j\omega dz[(L_{G1} - L_{G2})(I_{G1} + I_{G3} + \cdots) \\ & -(L_{G'1} - L_{G'2})(I_{G2} + I_{G4} + \cdots)]. \end{aligned} \quad (3)$$

One would notice that the drop of the voltage in (3) from (2) depends on the neutralizing mutual inductance (NMI) term $(L_{G'1} - L_{G'2})$.

Similarly, the receptor differential voltage for the STS/TWP model, as shown in Fig. 1(c), is given by

$$V_{SR} = \left[\frac{Z_{SR}}{Z_{SR} + Z_{LR}}\right] j\omega dz(L_{G1} - L_{G2})(I_{G1} - I_{G2} + I_{G3} - \cdots), \quad (4)$$

Based on the assumption of the equality of the current on each section [10], V_{SR} in (4) will be formed by single current generator (SCG) I_{G1} if the number of twisted-pair sections is odd.

For the circuits shown in Fig. 2, both generator wires are driven differently by using differential input sources. The use of differential signaling technique, also known as balanced input, has distinct advantages in providing immunity to noise pickup and crosstalk between channels. This is based on the fact that the signal of interest generates equal but opposite currents on a balanced pair of wires while cross couplings are induced equally in a similar way. The generator-receptor circuits in Fig. 2 can also be classified as straight-through differential-generator, straight-through receptor

(STD/STP); twisted-pair differential-generator, twisted-pair receptor (TWPD/TWP), and straight-through differential-generator, twisted-pair receptor (STD/TWP). Fig. 2(a) shows the STD/STP model where the generator circuit is driven by a differential input signal causing the two coupling voltage sources with opposite direction on the receptor wires. The receptor differential voltage is given by given by

$$V_{S12} = \left[\frac{Z_{SR}}{Z_{SR}+Z_{LR}}\right] j\omega dz\{(L_{G1}-L_{G2})-(L_{G'1}-L_{G'2})\} \cdot(I_{G1}+I_{G2}+I_{G3}+\cdots). \tag{5}$$

One can observe that the NMI term $(L_{G'1} - L_{G'2})$ can cause V_{SR} to reduce as compared to V_{SR} given in (2) for the untwisted-wire cases.

The TWPD/TWP model shown in Fig. 2(b) is the most common configuration for the UTP-CAT5 cable where both generator and receptor circuits are formed by the twisted-pair wires. In this case, both wires of the generator circuit are driven. The receptor differential voltage can be easily given by

$$V_{S12} = \left[\frac{Z_{SR}}{Z_{SR}+Z_{LR}}\right] j\omega dz\{(L_{G1}-L_{G'1})-(L_{G2}-L_{G'2})\} \cdot(I_{G1}+I_{G2}+I_{G3}+\cdots). \tag{6}$$

One can see that the voltage across receptor wires derived in (6) is same as (5).

Finally, we consider the STD/TWP model shown in Fig. 2(c), which consists of the untwisted generator pair and the twisted receptor pair, where the receptor differential voltage is given by

$$V_{S12} = \left[\frac{Z_{SR}}{Z_{SR}+Z_{LR}}\right] j\omega dz\{(L_{G1}-L_{G2})-(L_{G'1}-L_{G'2})\} \cdot(I_{G1}-I_{G2}+I_{G3}-\cdots). \tag{7}$$

Comparing the expression for V_{SR} in (4), we can see that I_{G1} is acting only as a contributor. Furthermore, the equivalence of $(L_{G1} - L_{G2})$ and $(L_{G'1} - L_{G'2})$ could cause V_{SR} to be even smaller.

From the above analytical models, we notice that voltages V_{SR} in (5) through (7) are the same as (2) through (4) with additional NMI terms. Also, it should be pointed out that all circuits discussed above use the balanced load configuration for the generator and receptor circuits. This type of configuration gives the results without any complicated modeling of the "floor" coupling effect [10]. As a result, the contribution to the crosstalk on the receptor is mainly coming from inductive coupling between the generator and receptor wires.

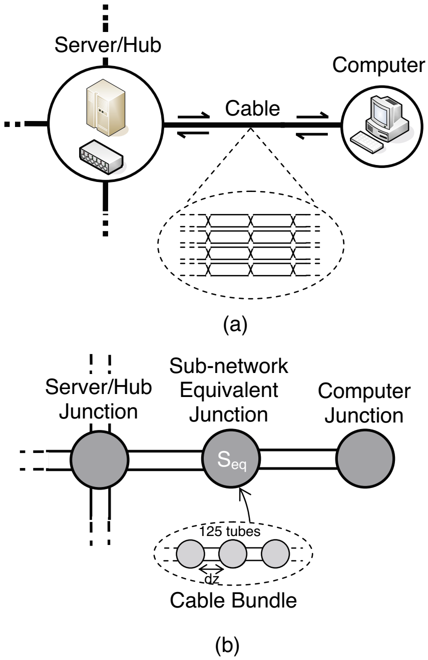

Figure 3. (a) Simple configuration of computer network and (b) associated topological network composed by junctions and tubes.

2.2. Topological Network Approach

A typical computer network for study crosstalk is shown in Fig. 3(a), where its constituents include a server hub, computers, and UTP-CAT5 cables consisting of eight conductor wires. The associated topological network is shown in Fig. 3(b), where it has been topologically decomposed into sub-volumes (junctions) interacting with each other through preferred paths (tubes). Junctions represent loads, branching of cables, or input impedance of electronic systems in the computer housing. Input and output waves are related to each other through a scattering matrix. Tubes between two junctions represent the homogenous sections of cable harness based on the multiconductor transmission-line theory. The per-unit capacitance, inductance, and characteristic impedance matrices generated from the companion LAPLACE code are used to characterize the tube. Traveling waves at each end are related to each other through a propagation matrix. Based on the multiconductor transmission-line concept with scattering parameters at junctions and propagation parameters along tubes, cable signals can be obtained through the BLT equation [2], given by

$$\{[I] - [S][\Gamma]\} \cdot [W(0)] = [S] \cdot [Ws], \tag{8}$$

where $[I]$, $[S]$, and $[\Gamma]$ are the identity, network scattering, and propagation supermatrices, respectively. Terms $[W(0)]$ and $[Ws]$ are the outgoing and source wave supervectors, respectively. The general solution of the BLT equations is expressed in the frequency domain. The advantage of using the EMT technique is that all volumes are treated independent from each other.

3. CABLE SIMULATION SETUP

3.1. Cable

The per-unit values of cable parameters obtained from the LAPLACE code is based on the Method of Moment method [4]. The cross-sectional configuration and details of the cable are shown in Fig. 4, where it consists of eight dielectric-coated cylindrical conductors held together by four pairs inside the cable jacket. Each of the eight conductors is also designed with the per unit length resistance of $100\,\mathrm{m}\Omega/\mathrm{m}$. Each circular contour for the conductor and dielectric

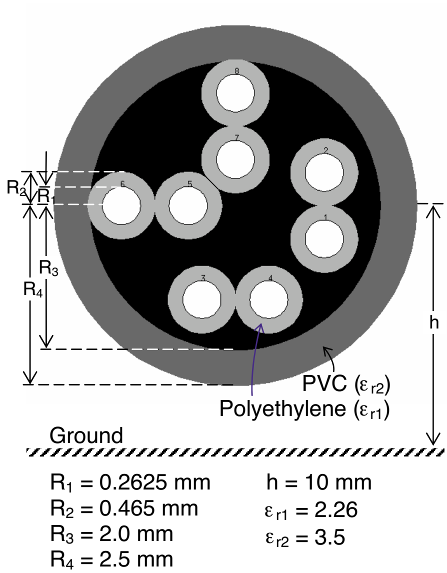

Figure 4. Cross-sectional view of the UTP-CAT5 cable consisting of four-pair conductors.

surface is expressed by 10 expansion functions (1 + 9 cosine terms). A triangular contour for the ground plane is expressed by 30 linear distribution functions.

4. SUB-NETWORK COMPACTION

In simulations, a 5-m long cable is divided into 125 uniform tubes with a length of 4 cm for each tube. The junction characterizes the connection between two 4-cm tubes, which can be direct or twisted type for the circuit configurations shown in Figs. 1 and 2. Since the entire length of the cable is comprised of a large number of junctions and tubes that contain as many as eight conductor wires, the direct calculation using the BLT equations is cumbersome and time consuming. The matrix size required for such an exercise is large ($2 \times 8 \times 125 = 2000$), i.e., 2 directional junctions, 8 conductor wires, and 125 tubes. If we consider the case where waves are traveling in and out of the load junctions (concept of junction scattering), then it is possible to represent the whole cable network as a single equivalent junction, as shown in Fig. 3(b). As a result, the original matrix can be reduced to $2 \times 8 \times 2 = 32$, which reduces the computational time significantly. In addition, to realize a topological network with different terminal equipment, we only need to change boundary junctions without having to work out the entire topological network. Under this setup, simulations were carried out to predict the near end crosstalk for various parameters, such as the load impedance, the conductor pair location, and the cable driving source. The NEXT values are calculated using (1) through (7) by applying a test signal to one cable pair and measuring the crosstalk signals received by other cable pairs.

5. SIMULATION RESULTS

Fig. 5 show the results of NEXT levels (1 kHz–100 MHz) induced on the receptor pair 3-4 with termination impedances of 1 Ω and 1 kΩ. Fig. 5(a) also shows the results for the STS/STP, TWP/TWP, and STS/TWP models by driving the generator wire 1 with a 0.5 V source. Fig. 5(a) shows linear curves at low frequencies and standing waves at high frequencies. It shows that the crosstalk induced on the receptor wires is higher when the termination impedance is 1 Ω, e.g., at low frequencies, the value of Curve 1 is approximately 16-dB higher than that of Curve 4 (15 kΩ termination impedance) for the STP/STP model. The reason is that, regardless of the capacitive coupling due to the balanced-load configuration, the inductive coupling depends only on the generator current. Low impedances on the generator

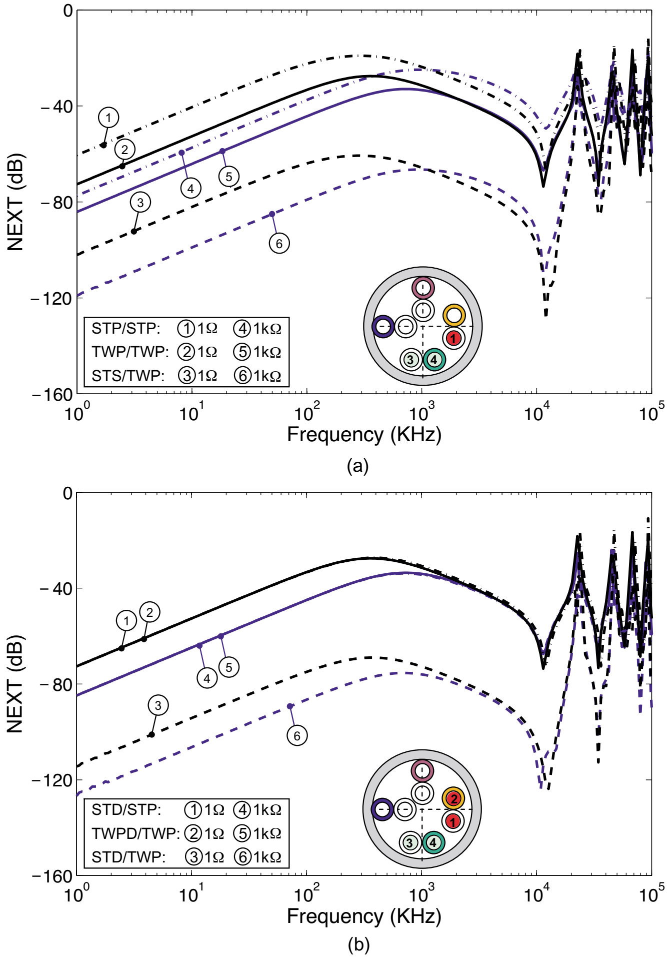

Figure 5. NEXT levels across conductors 3 and 4 as a function of the source and load impedances (1 Ω and 1 kΩ) in frequency domain for coupling circuits driven by (a) +0.5 V source on conductor 1 and (b) ± 0.5 V on conductors 1 and 2.

wire could only result in a high value of current generated. Another observation is that the STS/TWP model provides the best crosstalk reduction while the STS/STP model gives the worst performance. In other words, twisting either the generator or the receptor pairs improves the effectiveness of crosstalk reduction. At 1 kHz and 1 Ω, the NEXT value of the STS/STP model is −60 dB while the STS/TWPs is approximately −100 dB. The difference in crosstalk suppression can be

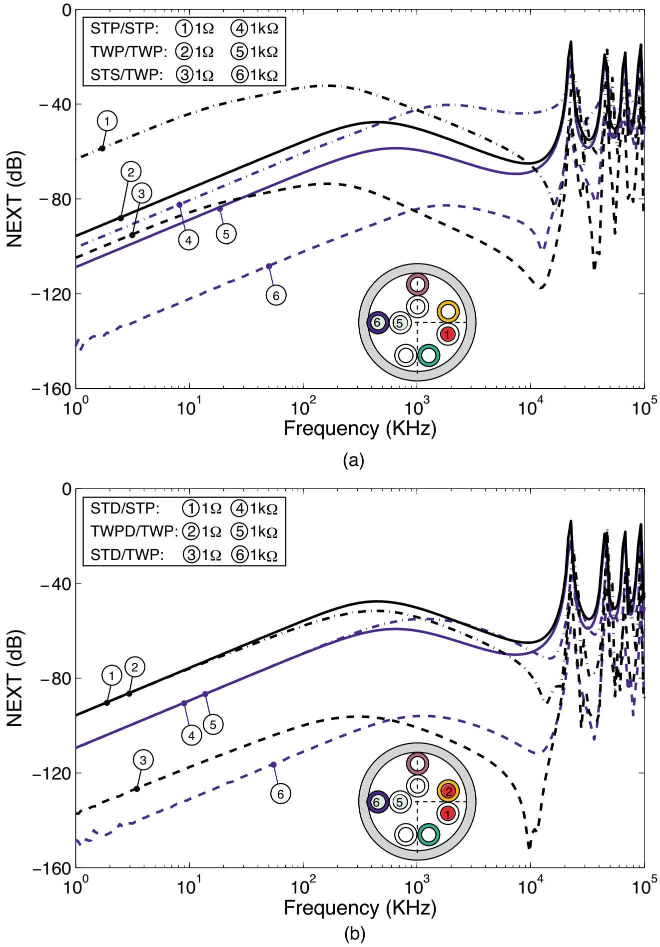

Figure 6. NEXT levels across conductors 5 and 6 as a function of the source and load impedances ($1\,\Omega$ and $1\,\mathrm{k}\Omega$) in frequency domain for coupling circuits driven by (a) $+0.5\,\mathrm{V}$ source on conductor 1 and (b) $\pm\, 0.5\,\mathrm{V}$ on conductors 1 and 2.

directly explained by equations (2) through (4). The NMI term in (3) and the SCG term in (4) cause the reduction of the induced voltage. Simulations also showed that the multiconductor, transmission-line simulation is less reliable when the length of the cable is considered electrically long or when the frequency is in the standing-wave region, i.e., above 1 MHz.

The next simulation examines the effects of using the balanced

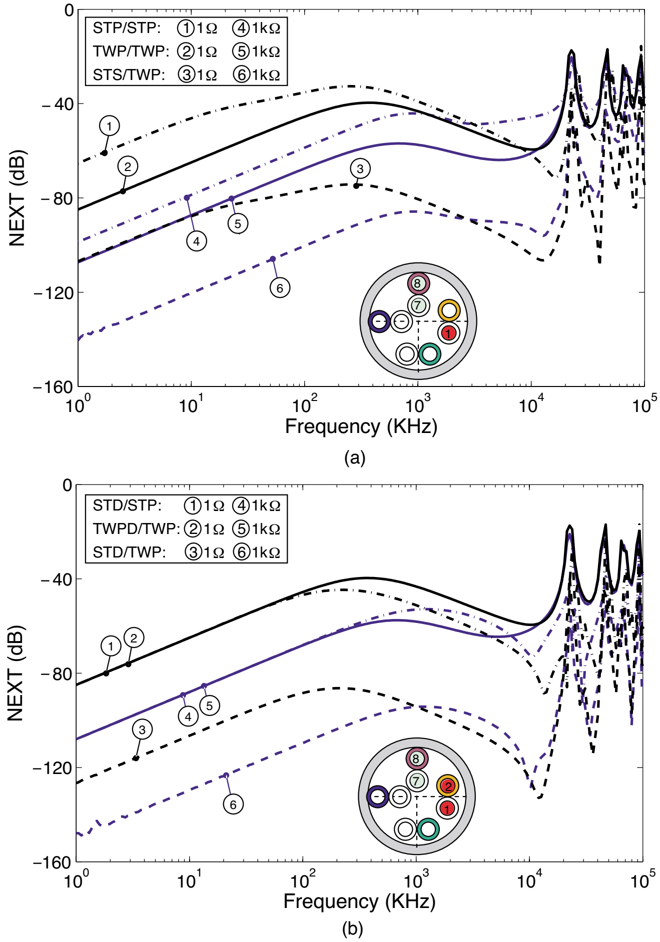

Figure 7. NEXT levels across conductors 7 and 8 as a function of the source and load impedances ($1\,\Omega$ and $1\,\mathrm{k}\Omega$) in frequency domain for coupling circuits driven by (a) $+0.5\,\mathrm{V}$ source on conductor 1 and (b) $\pm\,0.5\,\mathrm{V}$ on conductors 1 and 2.

input technique. The results are compared with those obtained by driving a single wire generator. The computed NEXT results on the receptor pair 3-4 using the STD/STP, TWPD/TWP, and STD/TWP models are shown in Fig. 5(b). Generator Wires 1 and 2 are at $+0.5\,\mathrm{V}$ and $-0.5\,\mathrm{V}$, respectively. Compared with the results presented in Fig. 5(a), we can see an increased reduction in crosstalk. The reason for an increased reduction seen in Curves 1, 3, 4, and 6 is the neutralizing mutual inductance created by the second driven generator wire. The improvement of crosstalk reduction is hardly noticeable for Curves 3 and 4. Analysis of the simulation results are consistent with the analytical expression of all models shown in equations (2) through (7). Clearly, we can see that twisting of the conductor pairs results in introducing the SCG-type enhancement, while balancing the input signal results in introducing the NMI term. The same can be said for the receptor pairs 5-6 and 7-8 as seen in Figs. 6 and 7, respectively, for both types of driving signals.

In this paper, we only considered the crosstalk circuit models for cables with no dielectric coating and no transmission-line loss. As a result, some discrepancy is expected between the analytical results and the EMT calculations. The discrepancy accounts for non-homogenous media and current attenuation associated with the computer code-modeled UTP-CAT5 cable.

6. CONCLUSION

We have successfully analyzed the crosstalk in a typical unshielded twisted-pair cable (UTP-CAT5) for the 10/100 Base-T type LANs using the electromagnetic topological method, which is derived from multiconductor transmission-line theory. To apply such analysis to a large complex electrical network system, the entire network has to be topologically decomposed into a large number of tubes and junctions to account for twisted sections. Then, these twisted sections are further compacted into a single equivalent junction for more efficient computation; thus reducing the total computational time. Also, we have investigated the near end crosstalk under various parameters, such as the load impedance, the conductor pair location, and the cable driving source. The electromagnetic topology-based calculations can be used effectively in identifying some important parameters that contribute to reducing the crosstalk level. The simulation results suggest that the STD/TWP model is the most effective configuration to control the NEXT level, mainly due to the influence of the NMI term and the SCG effect. A typical UTP-CAT5 cable with TWP/TWP or TWPD/TWP model provides a satisfactory level of crosstalk for both low and high impedances. Based on the simulation results, we concluded that electromagnetic topology-based predictions are valid only for cables that are electrically short.

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