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MINIMIZING CROSSTALKS IN UNSHIELDED TWISTED-PAIR CABLES BY USING ELECTROMAGNETIC TOPOLOGY TECHNIQUES

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Abstract—Crosstalk reduction is analyzed for a reconfigured category-five cable network using electromagnetic topology-based simulation. The reconfigured network results in a marked reduction in inductive near-end crosstalk for the unshielded twisted-pair cable network. Analyses show that half-loop shifting of the generator-pair wires placed next to the receptor is the most effective way to control the near-end crosstalk level. This is primarily due to additional coupling sources induced on receptor wires that effectively deactivate the original cross coupling effect. The analysis also reveals the usefulness of electromagnetic topology-based simulations. The technique applied in this paper is applicable for any large network systems. A sub-network compaction scheme is critical in creating the equivalent junctions that provide a significant reduction in total computational time and total computer memory requirement for analyzing large network systems. For a 5.28-m long cable we have considered in this paper, the results are valid up to 10 MHz.

1. INTRODUCTION

Crosstalk management has been the biggest challenge in optimizing the performance of cable networks, consisting of unshielded twisted-pair (UTP) wires. Emission, interference and crosstalk are important parameters that determine the overall cable network performance. To ensure an efficient cable network performance, these parameters must be dealt with by performing a detailed electromagnetic interference (EMI) analysis. For the cable network system consisting of UTP wires, one possible scheme to reduce the interference is introduction of the radiated signals that are equal but opposite of the unwanted signal values on all the wires inside a cable. This results in the subsequent cancellation of unwanted signals, making the network system an inefficient radiator. Crosstalk of twisted pair wires inside a cable is defined as the undesirable signal transmission from one wire pair to all other wire pairs. Similar to electrical noise coming from outside sources, crosstalk results in severe degradation of overall network performance.

A number of studies have been carried out in the past for the EMI analysis involving crosstalk in twisted-pair wires inside various cable types [1–6]. There are three basic models used particularly in these analyses: the bifilar helical-type model, the chain-parameter model, and the two-wire transmission-line model. Maki et al. [2] investigated the crosstalk margin level of a UTP-CAT5 cable in the frequency range up to 100 MHz for a 10/100 Base-T home network [7]. All such analyses showed the resulting crosstalk depended to a large extent on the values of line-termination or load impedances.

In this paper, we present an alternative simulation approach used to investigate crosstalk reduction. We utilize the electromagnetic topology (EMT)-based simulation technique to study the crosstalk induced on twisted pair wires of UTP-CAT5 cables for a frequency up to a few hundred MHz. Simulation is based on a lumped-circuit transmission-line model similar to the configuration used in the work by Paul and McKnight [3, 4] where they investigated a single-wire generator/two-wire receptor circuit in homogenous media. Wire separation and length are sufficiently small to ensure the validity of a low-frequency model. In this paper, we propose a concept of electromagnetic topology simulation to account for the crosstalk caused by signals propagating through connecting cables using the EMT-based CRIPTE code [10]. In our previous crosstalk studies, we showed that crosstalk reduction is possible by twisting either the generator or receptor pairs [12]. However, the type of the cable specified in the study is not commercially available. A modification of the off-the-shelf cable is proposed in this paper to achieve the same objective without having to incur huge additional investment costs for reduced crosstalk cable designs.

The EMT technique is a modular simulation method, specifically suited for the analysis of 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 [9]. The main advantage of this technique is to overcome some of the simulation problems associated with large network systems. In the EMT-based 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 that connect them. The key equation of EMT is the BLT (Baum Liu and Tesche) equation, which treats an entire transmission-line network system in the frequency domain [11].

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

2. CROSSTALK AND TOPOLOGICAL MODELING

2.1. Volume Decomposition Concept

For the EMT approach, consider a large aircraft system whose simplified structure is shown in Fig. 1. In the spirit of the EMT approach, this system is decomposed into five volumes, i.e., fuselage, left wing, right wing, medium, and tail, as shown also in Fig. 1. Junctions and tubes represent physical volumes and interaction paths between volumes, respectively. External driving sources are applied along the tube close to Volume 1 to represent external excitation picked up by the tail section. Using this approach, we treat all the interaction in the network fashion such that the response of the entire structure is

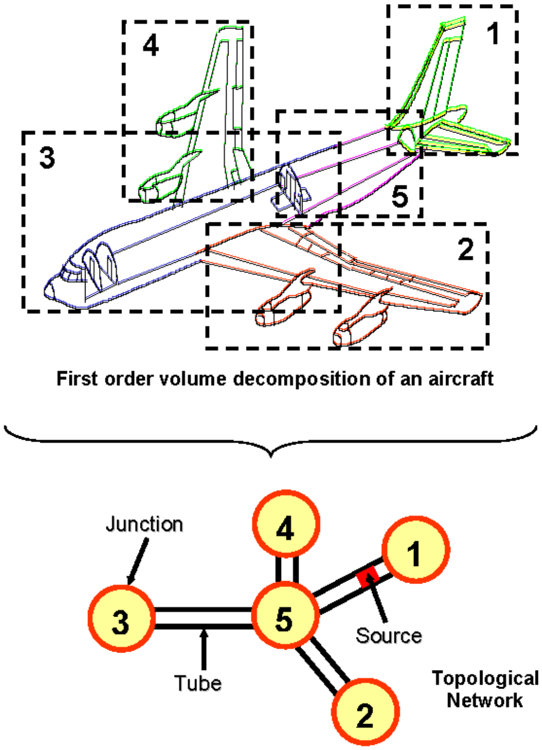


Figure 1. Volume decomposition diagram of a simplified aircraft and its associated topological network.

evaluated via network analysis. The same concept is extended to the crosstalk simulation of twisted-pair wires, which we will discuss in the following sections.

2.2. Half-loop Shifting Method

Near-end crosstalk (NEXT) is a coupled interference signal between adjacent cables at the nearest end of the source and computed as the difference in amplitude between the test signal and the crosstalk signal, given by (in dB)

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

where V_{SR} and V_{SG} are the voltages across the receptor and generator wires at the sending end, respectively. Larger negative values

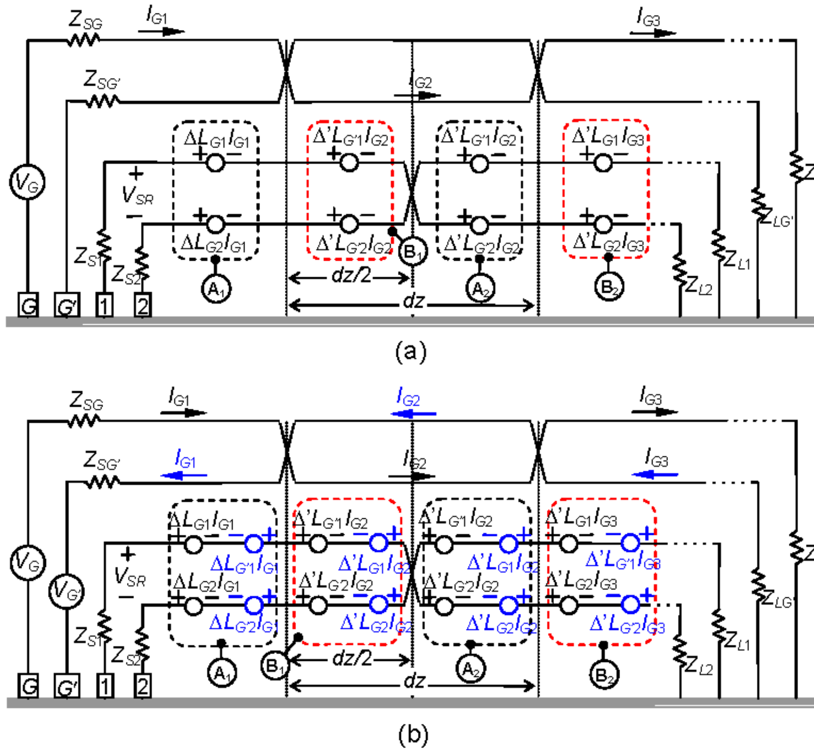


Figure 2. Coupling models of a four-wire cable system with a generator-wire pair shifted to the left by a distance of half-loop length: (a) HLS-TWP/TWP driven by single source, and (b) HLS-TWPD/TWP driven by differential source. Note: $\Delta = jwL$ and $\Delta' = \frac{1}{2}jwL$.

correspond to better cable performance.

For the investigative purpose, Fig. 2 shows the coupling schematic of a four-wire cable system that has been adapted for the analysis of the configuration of a four-pair cable system shown in Fig. 3. Circuits shown in Figs. 2(a) and 2(b) are schematic representations of a two-wire generator, two-wire receptor circuits driven by single source (V_G) and differential sources (V_G and $V_{G'}$), respectively. Unlike TWP/TWP and TWPD/TWP circuit configurations studied in [12], the generator-wire pair is shifted to the left by a distance of half-loop length ($dz/2$). The circuit in Fig. 2(a) is a half-loop shifted twisted-pair single-generator/twisted-pair receptor (HLS-TWP/TWP). Based on the low-frequency approximation, we consider the case where voltages

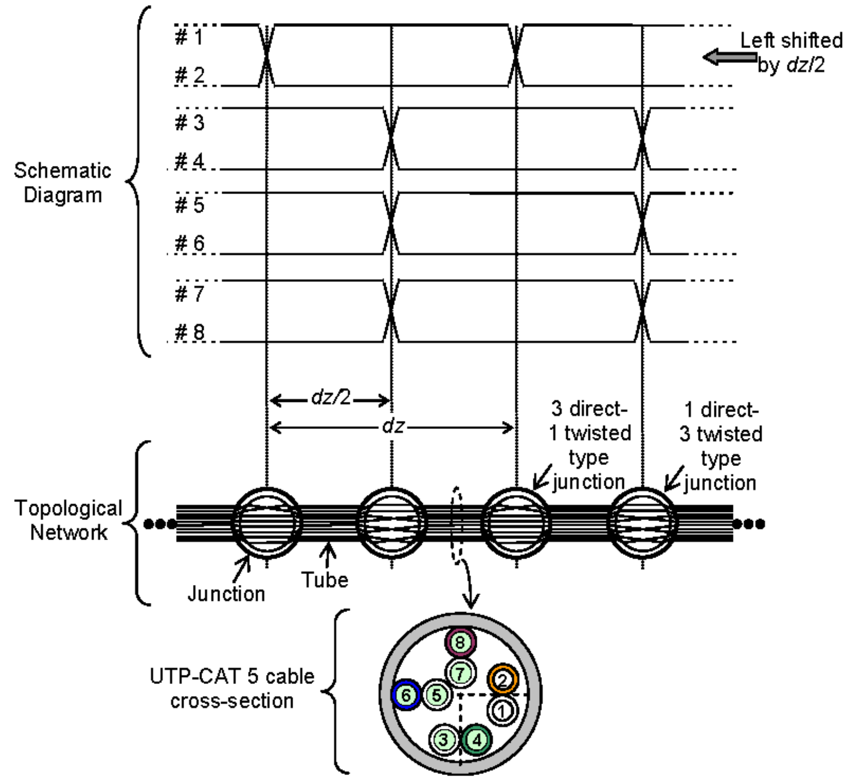


Figure 3. Representations of a four-pair cable system with the proposed half-loop shifting method, the associated junction-tube topological network, and the actual UTP-CAT5 cable cross-section.

and currents of each section are approximately the same [10]. It is important to note that all analytical circuits to be discussed are modeled with balanced loads. As a result, the contribution to the crosstalk on the receptor pair is mainly coming from inductive coupling [4]. The differential voltage between receptor wires at the sending end (V_{SR}) can now be expressed as

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

where Z_{SR} and Z_{LR} are source and load impedances, respectively, L_{G1} and L_{G2} are mutual inductances between the generator wire G and receptor wires 1 and 2, respectively, $L_{G'1}$ and $L_{G'2}$ are mutual inductances between the generator wire G' and receptor wires 1 and 2, respectively, and I_{G1} is the generator current of the first twisted segment. The induced sources due to the original twisted-pair configuration without shifting are labeled with A_n, where n stands for the nth loop on the receptor wires [12]. With the proposed configuration, the identical coupling voltage sources are inductively induced on the left side of the twisted junction on the receptor wires labeled as B_{n-1}. One can see the source cancellation caused by identical sources B_n and A_{n+1} with opposite polarity. Consequently, I_{G1} is the only contributor to the expression for V_{SR} in Eq. (2) for any number of twisted loops. Comparisons of Eq. (2) with the previous equations (i.e., Eqs. (2), (3), and (4) for three different models in Reference 12) show that Eq. (2) resulted in the absolute minimum NEXT value, i.e., maximum crosstalk reduction.

For a half-loop shifted, twisted-pair differential-generator/twisted-pair receptor (HLS-TWPD/TWP) circuit shown in Fig. 2(b), both generator wires are driven by differential input sources. The use of differential signaling technique, also known as balanced input, has distinct advantages by providing immunity to noise pickup and crosstalk between channels. The receptor differential voltage is expressed as

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

Similar to the HLS-TWP/TWP model, the source cancellation is the main reason for better crosstalk reduction. Also, as the case with the expression for V_{SR} in Eq. (2), I_{G1} is the only contributor for V_{SR} in Eq. (3) for any number of twisted loops. Furthermore, the equivalence of (L_{G1}-L_{G2}) and ($L_{G'1}$-$L_{G'2}$) could cause V_{SR} to be even more effective in crosstalk reduction.

2.3. Topological Network of the Half-loop Shifted Circuit

For an eight-wire cable system, a schematic diagram is shown in Fig. 3. The generator and receptor wires are labeled as #1-2 and #3 through 8, respectively. The generator pair is shifted to the left by the distance of the half-loop length. Each junction characterizes a cable connection for all the direct and twisted type generator-wire and receptor-wire pairs. Each tube represents each section of the actual UTP-CAT5 cable with associated cross-section geometry shown in Fig. 3. Traveling waves at each junction are related to each other through a propagation matrix. Using the BLT equation [2] with scattering parameters at junctions and propagation parameters along tubes, the cable signals, which are functions of traveling waves, can be expressed as

$$\{[I] - [S][\Gamma]\} \cdot [W(0)] = [S] \cdot [Ws], \tag{4}$$

where $[I]$, $[S]$, and $[\Gamma]$ are the identity, network scattering, and propagation supermatrices, respectively. The terms $[W(0)]$ and $[Ws]$ are the outgoing and source traveling wave supervectors, respectively.

3. SIMULATION SETUP

The cross-sectional area of the cable is shown in Fig. 3. It consists of eight dielectric-coated cylindrical conducting wires held together as four sets of two wire pairs inside the cable jacket. Details are discussed in [12]. The companion LAPLACE code, which is based on the Method of Moments, is used to determine capacitance and inductance matrices from the cable cross-sectional dimension. In our EMT-based simulation, a 5.28-m long cable is divided into 264 tubes of homogenous sections with a length of 2 cm each. The junction characterizes the connection between two 2-cm tubes, either one direct-three twisted or three direct-one twisted type, for the configurations shown in Fig. 3. Since the entire length of cable turned out to be a large number of junctions and tubes by considering as many as eight conductor wires, the direct calculation of the BLT equations is very time consuming. However, it is possible to break the spread network into many sub-networks, and then treat each sub-network separately using the diakoptics technique, which is suitable for the repeated analysis of a large number of sub-networks with a slight difference seen in elements of all the sub-networks [13]. Such a compaction technique allows for much faster calculations by creating the equivalent junctions. Consequently, there is no need to re-compute all sub-network contributions to a large network at various frequencies. For our case, each sub-network is created from 25 tubes (tws_8w_1g_y4.t) representing a section of 48-cm long cable, as shown at the bottom portion of Fig. 4. The junctions 2 through 25 represent one direct-three twisted (twst6_str2.s) and three direct-one twisted (twst2_str6.s) type connections where the junctions 1 and 26 represent open-circuited terminations. The junction names (number) are in order they were created, having no significant effects on simulation results. An equivalent junction (tws6_cpx.seq) is then created through compaction. The upper portion of Fig. 4 shows the topological network of the final integration of 12 tubes, 11 equivalent junctions, and 2 impedance junctions, corresponding to a 5.28-m long UTP-CAT5 cable for the HLS-TWP/TWP and HLS-TWPD/TWP circuit configurations found in Fig. 2.

4. SIMULATION RESULTS

Computed near-end crosstalk levels (1 kHz–100 MHz), induced on the receptor-wire pair 3-4, are shown in Fig. 5. Plots shown in Fig. 5(a) are the results of using the HLS-TWP/TWP model when the Generator Wire 1 is driven by a +0.5 V source with the load impedances of 1 Ω and 1 kΩ, respectively. The figure also shows the cable cross-sectional geometry with the active wires labeled as 1-2 for the generating wires and 3-4 for the receptor wires. Fig. 5(a) shows significant suppression in crosstalk levels at low frequencies and elevated levels of crosstalk during a standing wave region at high frequencies. One can also see the crosstalk induced on the receptor wires is higher at high frequencies when the load impedance is 1 Ω as compared to the load impedance of 1 kΩ. The reason is that, regardless of the capacitive coupling, the inductive coupling depends on the generator current. Low impedances on the generator wire results in a higher value of the generated current. The inset plots are the crosstalk levels (1 kHz–100 MHz) of different models from previous study (STP/STP, TWP/TWP, and STS/TWP models in [12]). Compared to the results obtained by using the proposed model with those shown in the inset, the HLS-TWP/TWP model gives the best crosstalk reduction. The technique of shifting the generator loops improves the effectiveness of crosstalk reduction, i.e., at 1 kHz, the NEXT values of the HLS-TWP/TWP model are approximately between −140 and −150 dB while the best value of those in the inset is approximately −120 dB. The different performances of crosstalk suppression can be directly explained by Eq. (2). The source cancellation, due to the induced sources with opposite polarities on both sides of the twisted junction (B_n and A_{n+1}), causes the reduction of the induced voltage as discussed above. Simulations also showed that the multi-conductor transmission line based simulation is less

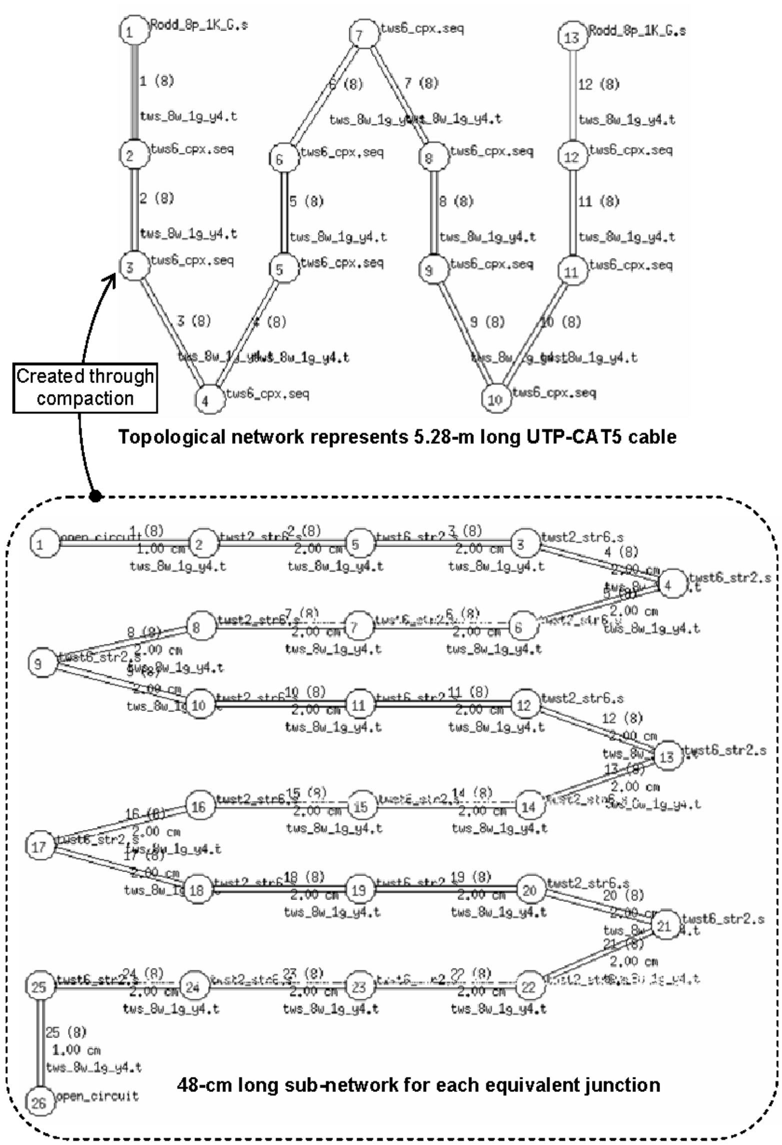


Figure 4. Simulation setup for HLS-TWP/TWP and HLS-TWPD/TWP circuit configurations where each subnetwork is created from 25 tubes representing an equivalent junction of a 48-cm long cable. The topological network of the final integration of 12 tubes, 11 equivalent junctions, and two impedance junctions represents a 5.28-m long UTP-CAT5 cable.

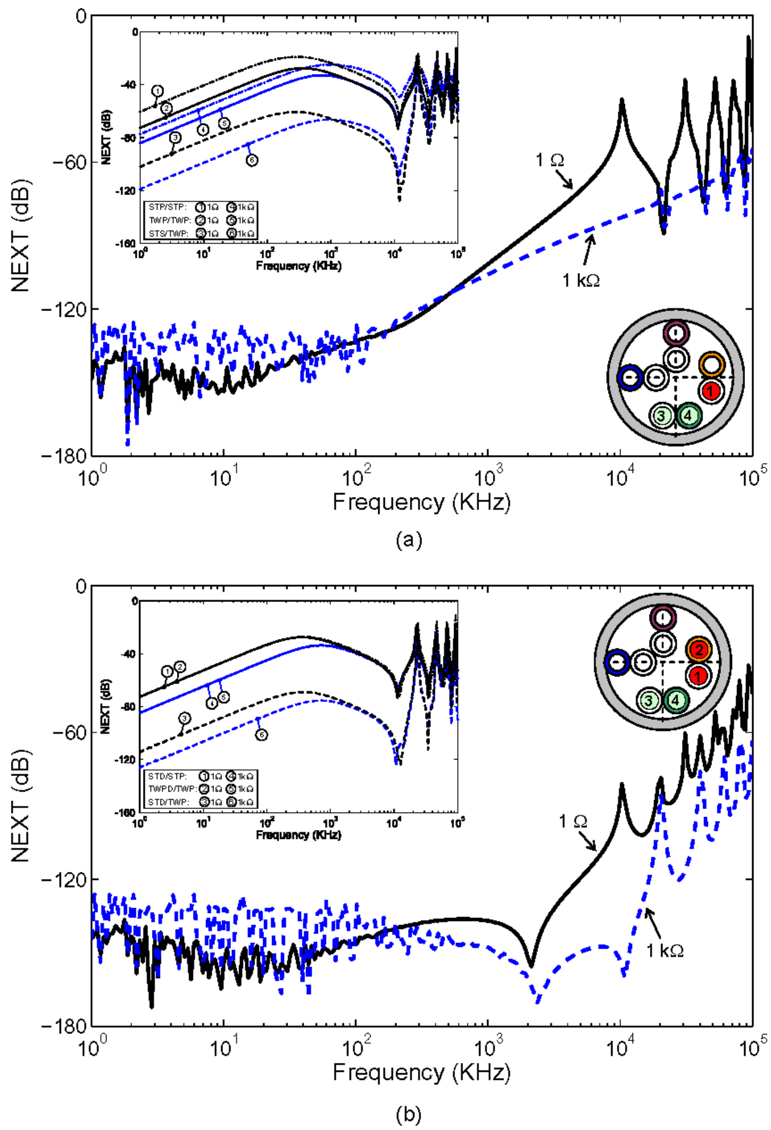


Figure 5. NEXT levels across Conductors 3 and 4 as functions of the source and load impedances ($1\,\Omega$ and $1\,\mathrm{k}\Omega$) in the frequency domain for coupling circuits driven by (a) $+0.5$ V source on Conductor 1 and (b) ±0.5 V on Conductors 1 and 2. The plots shown in the inset are the results using different crosstalk models from the previous study [12].

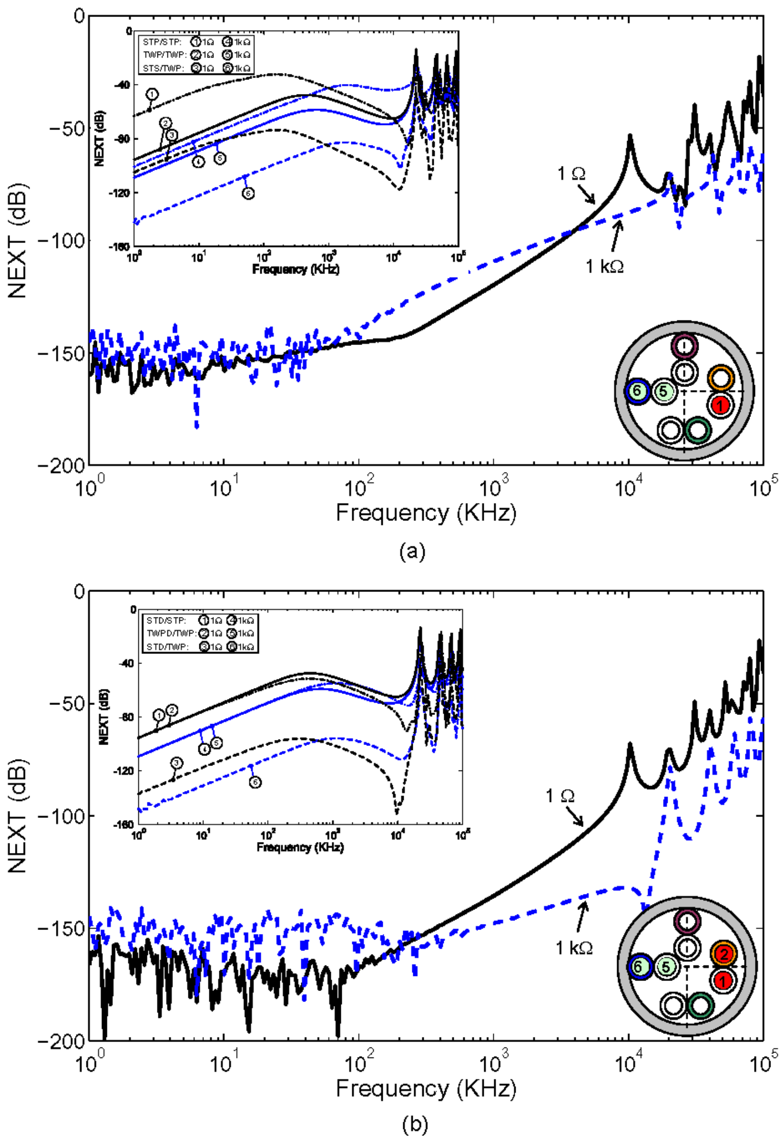
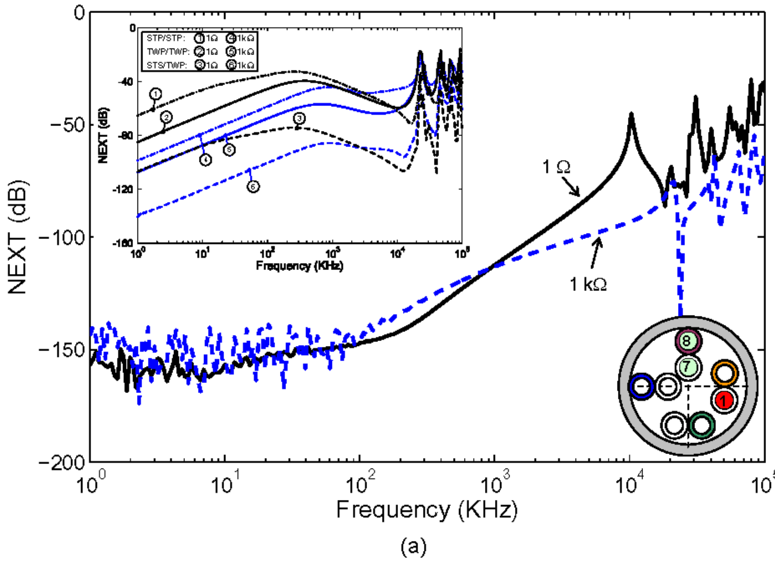


Figure 6. NEXT levels across Conductors 5 and 6 as functions of the source and load impedances ($1\,\Omega$ and $1\,\mathrm{k}\Omega$) in the frequency domain for coupling circuits driven by (a) $+0.5\,\mathrm{V}$ source on Conductor 1 and (b) $\pm 0.5\,\mathrm{V}$ on Conductors 1 and 2. The plots shown in the inset are the results using different crosstalk models from the previous study [12].



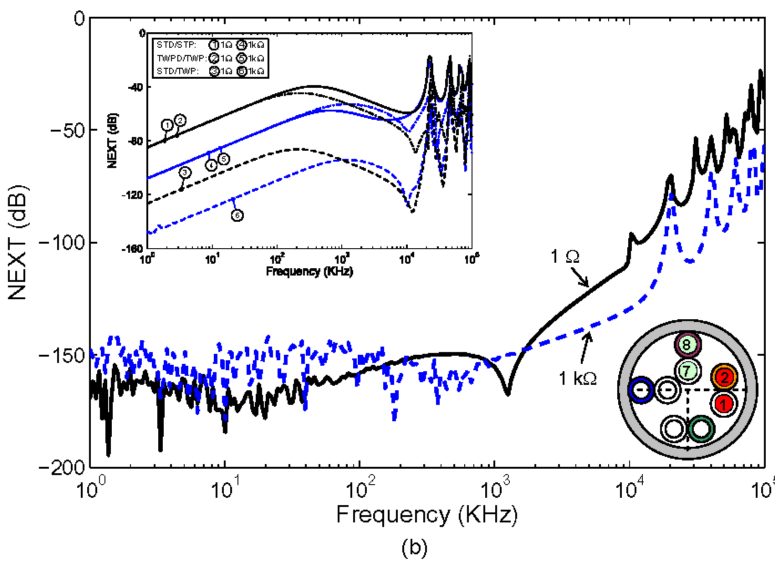


Figure 7. NEXT levels across Conductors 7 and 8 as functions of the source and load impedances ($1\,\Omega$ and $1\,\mathrm{k}\Omega$) in the frequency domain for coupling circuits driven by (a) $+0.5\,\mathrm{V}$ source on Conductor 1 and (b) $\pm 0.5\,\mathrm{V}$ on Conductors 1 and 2. The plots shown in the inset are the results using different crosstalk models from the previous study [12].

consistent when the length of the cable is considered electrically long or when curves enter the frequency of standing-wave region at above 1 MHz for a 5.28-m long UTP-CAT5 cable (see Figs. 5, 6, and 7).

The effects of using the balanced input technique are examined in the next simulation. The results are compared with those obtained by driving a single wire generator. The computed NEXT results on the receptor-wire pair 3-4 using the HLS-TWPD/TWP model are shown in Fig. 5(b) when generator wires 1 and 2 are driven, respectively, by $+0.5$ V and -0.5 V sources. Compared with the results presented in Fig. 5(a), one can see the further enhancement in crosstalk reduction in the region of 100 kHz to 10 MHz. In this case, the NEXT level depends less on the current and more on the difference of 'L_{G1}-L_{G2}' and '$L_{G'1}$-$L_{G'2}$', particularly for the 1-kΩ load impedance case. Another comparison is made with the plots shown in the inset where the associated crosstalk circuit models using the balanced input technique as discussed in a previous study (STD/STP, TWPD/TWP, and STD/TWP models in [12]). At 1 kHz, the NEXT values of the HLS-TWP/TWP model are approximately between -140 and -150 dB while the best value in side the inset is approximately -130 dB. The similar results can be seen for the receptor-wire pairs 5-6 and 7-8 as the associated computed results are shown in Figs. 6 and 7, respectively, for both types of driving signals.

Since the crosstalk circuit model used in this paper considers no dielectric coating and no transmission-line loss, some discrepancy is expected between the analytical results and the EMT calculations. The EMT calculations take into account non-homogenous media and the current attenuation associated with the computer code-modeled UTP-CAT5 cable.

5. CONCLUSION

We have modeled the crosstalk in a typical unshielded twisted pair cable (UTP-CAT5) in the 10/100 Base-T type LANs using the electromagnetic topological simulation approach. To apply a large complex electrical network system, the entire network is first topologically decomposed into a large number of tubes and junctions by accounting all the direct and twisted pair wires. Then the compaction technique is used to reduce a large network matrix into manageable equivalent junctions, thus saving the total computational time. Also, we have investigated the near end-crosstalk as functions of various influencing parameters, such as the excitation source, load impedances, and the conductor pair location. Analysis of the EMT based calculations and analytical approach show that the

NEXT value is an important simulation parameter used to assess the overall crosstalk levels. The results also suggest that the HLS-TWP/TWP and HLS-TWPD/TWP models are the most effective configurations in controlling the NEXT level, due to the influence coming from cancellation of the multiple sources on both sides of the twisted pair junction. For the final remark, it means if one makes a simple modification to the commercially available less expensive UTP-CAT5 cable by applying the half-loop shifting technique, it is possible to achieve a significant reduction in crosstalk, leading to much more acceptable levels of crosstalk for both the low and high load impedances.

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