A FIELD-CIRCUIT APPROACH FOR PREDICTING ELECTROMAGNETIC COUPLING BETWEEN COMMUNICATION CABLES USING TLM AND ANTENNA THEORY

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Abstract: This paper presents the development of a Field-Circuit approach for the calculation of electromagnetic coupling between communication channels. The approach consists of two parts: A circuit model using the Transmission Line Matrix (TLM) method and a field model using antenna theory. The TLM method is used for the modelling of both the interference source cable and the cable under electromagnetic interference threat. Antenna theory is used for the calculation of the radiated electromagnetic fields from the interference source cable (source) and the relevant induced voltages on the other cable (victim). The approach is then used for the prediction of the capacitive coupling between two communication channels, as a result of electromagnetic pulse transmission on the source cable. Electromagnetic coupling as a result of double exponential pulse transmission is also predicted. Effect of the separation between both cables is investigated.

1. Background

Transmission lines and cables represent a substantial part of many communication systems. An electromagnetic field is radiated when a signal is transmitted along a conductor. This field can interfere with signals on neighbouring conductors. As the frequency of the transmitted signal increases, the interference effect becomes stronger. If a user has ever had a telephone call where he or she could hear another conversion faintly in the background, he or she has experienced what is called electromagnetic interference (crosstalk). This interference may occur in different types of transmission media such as digital subscriber loops [1], microstrip transmission lines [2], coaxial cables [3], Multiconductor transmission lines [4] and twisted pair cables [5].

Electromagnetic waves carried by multi-pair cables may be found in a deterministic forms, such as sinusoidal waves, or in non-deterministic forms, such as digital signals and electromagnetic pulses. Waves can also be known signals that can be predicted but most significantly, they can be unknown signals that can not be predicted. Also, transmission channels and cables might be regular, uniform and properly installed. They may also suffer irregularities generated by non-uniform cable [6], poor choice of connectors and mismatching between cables and both ends termination [7]. The performance of such transmission systems at high and very high frequencies can be effected by the electromagnetic interference generated by signals carried by neighbouring channels. Transmitted signals that generate interference between neighbouring channels, can either be internal carried signals, like a telephone signals or they can be a threat signals generated by an outside source such as lightning. To resolve problems rising from such working conditions and interference between communication channels, the coupling between those channels needs to be investigated. This is clearly a non-trivial problem and a flexible solution is required.

Analytical solutions may not satisfy all conditions that contribute to electromagnetic interference between communication channels such as irregularity in cables. Modelling may also require some calculations before using the simulation tool, such as the computation of capacitance and inductance matrices, as the case of multi-conductor TLM models [4]. Generally, available modelling tools, e.g full 3D models, such as TLM and FDTD are expensive in computing time required, money and computer hardware for solving the size of problems resulting from even simple channel coupling geometries. Analytical solutions are not suited to accommodating all the mentioned working conditions. Experiment is difficult as isolation of interference generated by measurement devices from those generated by the interfering outside signal as not easy. Therefore, combining both modelling and analysis in one tool could resolve most if not all difficulties in analysing electromagnetic interference between communication channels. The next section of this paper describes the new approach and to discuss the way of computing electromagnetic coupling between two communication channels.

2. The proposed Field-Circuit approach

In general, approaches to modelling electromagnetic coupling are either deterministic or statistical [1]. Deterministic models [8,9,10] are based on the underlying physical processes. However they are only applicable in the voice frequency range since they ignore random variations of the distributed capacitive and inductive unbalances between pairs which become significant at high frequencies. Statistical models [11,12] prove simpler and more accurate over a wide frequency range than the deterministic models. Using the TLM method another approach is developed [13] for the calculation of radiated electromagnetic fields from cables in the time domain. A similar approach is developed here, where each individual conductor of a cable is treated as an array of dipole antennas. Radiated fields from both conductors of a go-and-return loop are computed in the frequency domain using antenna theory, and this part of the model is considered as a field problem. Induced voltages from such fields on the adjacent pair are induced on the corresponding elements of the victim pair where they are modelled using a 1D TLM approach. This part of the model is considered as a circuit model. The circuit (TLM) model is also used for the modelling of the source cable to compute the signal current on each element. Such currents are needed for the calculation of the interfering radiated fields. A complete description of the new approach is given in detail in the following subsections.

2.1 TLM model of the source cable

The primary parameters of a single pair cable R_o, L_o, C_o and G_o per unit length *Dl* can be obtained as in references [6] and [7], where one segment of a single pair cable or a transmission line is illustrated. A 1D TLM model of two neighbouring segments of a regular single pair cable is illustrated as in figure 1.

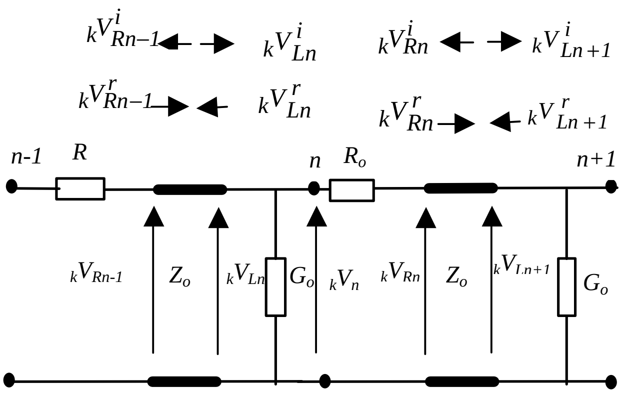

Figure 1. 1D TLM model of a regular cable.

The impedance Z_o is given as:

$$Z_o = \sqrt{\frac{L_o}{C_o}} \tag{1}$$

and the time required for a wave to travel from one end of the TLM node to the other end is:

$$\Delta\ t = \sqrt{L_o C_o} \tag{2}$$

Incident and reflected voltages at both ends of node *n* can be defined as:

$_kV^i_{Ln}$ is the incident voltage at the left side of node *n* and at the k^{th} time step.

$_kV^r_{Ln}$ is the reflected voltage from the left side of node *n* and at the k^{th} time step.

Similarly, incident voltages at any side of any node and reflected voltages from any side of any node can be defined. Looking from both sides of the connection node, *n,* between the two segments of the network of figure 1, Thevenin equivalent circuit can be obtained as in figure 2.

Using the parallel generator theory [14], the total voltage at the TLM node n and the node current can be calculated as:

$${}_kV_n = \frac{\dfrac{2\,{}_kV^i_{Ln}}{Z_o} + \dfrac{2\,{}_kV^i_{Rn}}{Z_o + R_d}}{\dfrac{1}{Z_o} + \dfrac{1}{Z_o + R_d} + G_d} \tag{3}$$

$${}_kI_n = \frac{{}_kV_n - 2\,{}_kV^i_{Rn}}{Z_o + R_d} \tag{4}$$

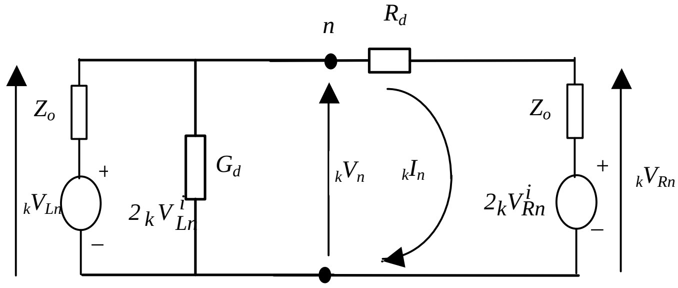

Figure 2. Thevenin equivalent circuit of figure1.

As described in [3] and [4], reflected and incident voltages at any point of the cable can be computed. Since the two wires of the cable represents the go-and-return paths of the signal current, if a current *I* propagates through the 1st wire of the cable, then the current *–I* propagate through the 2nd wire of the same cable and at the same segment (TLM node).

Currents calculated at the TLM nodes of the source cable as a result of wave transmission on the cable are required for the calculation of the radiated fields from both wires of the source cable.

2.2 Radiated fields calculations

A single wire can be considered as a single dipole antenna, where the overall length of the wire represents the length of the antenna, the concept on which this analysis is built is to represent the conductors as an array of dipoles connected in series. Hence, current may flow from one dipole element to another as in the case of current flow between the segments of a transmission line or cable.

The unit length *Dl* of the TLM model representing the cable can be chosen after taking into account the wavelength of the transmitted signal and other geometric factors. As each conductor is represented by an array of dipoles, the number of dipoles in the wire should equal the number of the TLM nodes in the model of the cable. Therefore the length (height *h*) of each elementary dipole equals the unit length of the TLM node.

The above procedure is needed to produce the position of each dipole along the height of the wire in the *z* direction. This is important so that the relative positions of the source and victim pairs can be calculated for the field problem of the model. The first point of the antenna position on the co-ordinate system represents the position of the near end of one wire of the cable. Since a single wire of the source cable is replaced by an array of dipoles connected in series, and the length of each dipole equivalent to that of the TLM node, the current carried by each dipole equals to that calculated using the TLM for the corresponding node. Similarly the second wire is also represented by a similar array of dipoles carrying the same currents in the opposite directions. One array of dipoles representing either wire is illustrated as in figure 3.

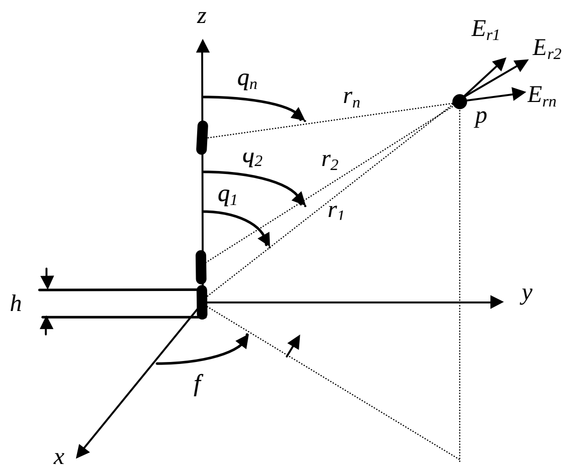

Figure 3. Array of single dipoles represents a single wire of a cable.

For a single dipole of the array shown in figure 3, as the potential vector is in the z direction only [15], both magnetic and electric fields, $\mathbf{H_x}$, $\mathbf{H_y}$ and $\mathbf{E}_z$ are obtained as:

$$\mathbf{H_x} = \frac{Ih(y-y_o)e^{-jkr}}{4p\ r^2} \cdot \left[\frac{-1}{r} - jk\right] \tag{5}$$

$$\mathbf{H_y} = \frac{Ih(x-x_o)e^{-jkr}}{4p\ r^2} \cdot \left[\frac{-1}{r} - jk\right] \tag{6}$$

$$\mathbf{E_z} = \frac{w\ m\ Ihe^{-jkr}}{4p\ r^2k^2} \cdot \left\{\left[-k + \frac{3k(z-z_o)^2}{r^2}\right] + j\left[\frac{1}{r} - rk^2 - \frac{3(z-z_o)^2}{r^3} + \frac{k^2(z-z_o)^2}{r}\right]\right\} \tag{7}$$

Fields radiated from the whole wire to a known point p, can be calculated as the resultant field of those radiated from all the elements of the dipole array contained in the wire using the principle of superposition. Therefore the resultant **H** field in both x and y directions can be given respectively as:

$$\mathbf{Hr_x} = \sum_{i=1}^{i=N_{\max}} \mathbf{H_x}(i) \tag{8}$$

$$\mathbf{Hr_y} = \sum_{i=1}^{i=N_{\max}} \mathbf{H_y}(i) \tag{9}$$

where $N_{\max}$ is the number of dipoles represent the single wire. The total H field at the point p can then be calculated as:

$$\mathbf{H_t} = \sqrt{\mathbf{Hr_x}^2 + \mathbf{Hr_y}^2} \tag{10}$$

While the resultant **E** field produced by a the wire in the z direction can be given as:

$$\mathbf{Er_z} = \sum_{i=1}^{i=N_{\max}} \mathbf{E_z}(i) \tag{11}$$

Using a similar set of equations, radiated fields from the 2[nd] interference source conductor can be calculated. Hence, the overall radiated fields at point, p, on each wire of the interference victime cable can be obtained as a resultant of radiated fields from all elements of both wires of the source cable. It should be mentioned that all **H** and **E** quantites are complex and results can be obtained for both amplitude and phase. Calculation of both radiated fields at the location of the victim pair lead to the calculation of both induced voltage and current at that pair. As this paper deals with the capacitive coupling, only the radiated **E** fields are considered. Knowing the resultant $\mathbf{E_z}$ field, the induced voltage (potential) along the 1[st] wire of the receiving pair can be calculated as:

$$Vr_{n1,p} = -Er_{n1,p} \cdot h \tag{12}$$

where h is the length of each element of the antenna array (i.e the unit length of the TLM model) in meters and $Er_{k1\ ,p}$ is the resultant received E field at the point or segment p of the 1[st] wire of the n pair of the cable. The induced voltage from the radiated fields of the source cable, which represents the induced potential difference between both wires of the victim pair, and at the k^{th} time step is given as:

$${}_kVi_{n,p} = {}_kVr_{n1,p} - {}_kVr_{n2,p} \tag{13}$$

Induced voltages calculated here are used for the calculation of the induced overall waves on the victim cable as a results of interference from signals transmitted on the source cable.

2.3 TLM model of the victim cable

For the calculation of electromagnetic coupling, the near end of the source pair is connected to a voltage source and the far end of the pair is terminated with the nominal impedance of the cable. While both ends of the victim pair are terminated with the nominal impedance of the cable. The induced voltages at every incremental length of the receiving pair are injected into the TLM model of the victim cable at the appropriate locations. For simplicity, the TLM model of a general node, g, between two TLM segments of the victim cable pair is discussed. Using a similar approach, both near and far ends of the victim cable can be treated. The connection between any two adjacent TLM nodes of the victim cable is similar to that illustrated in figure 1. In here, the induced voltage connected between both wires via an impedance equivalent to the input impedance of the receiving antenna [15], which, in this case, equals the characteristic impedance of the cable. The Thevenin equivalent circuit of a victim TLM model for the general node g is illustrated as in figure 4.

At the time where voltages are induced on the victim cable as a result of the interference from the transmitted signal on the source cable, nodal voltage and current of the above circuit can be obtained as:

$${}_kV_{n,g} = \frac{\dfrac{{}_kVi_{n,g}}{Z_o} + \dfrac{2\,{}_kVL^i_{n,g}}{Z_o} + \dfrac{2\,{}_kVR^i_{n,g}}{Z_o + R_o}}{\dfrac{1}{Z_o} + \dfrac{1}{Z_o} + \dfrac{1}{Z_o + R_o} + G_o} \tag{14}$$

$${}_kI_{n,g} = \frac{{}_kV_{n,g} - 2\,{}_kVR^i_{n,g}}{Z_o + R_o} \tag{15}$$

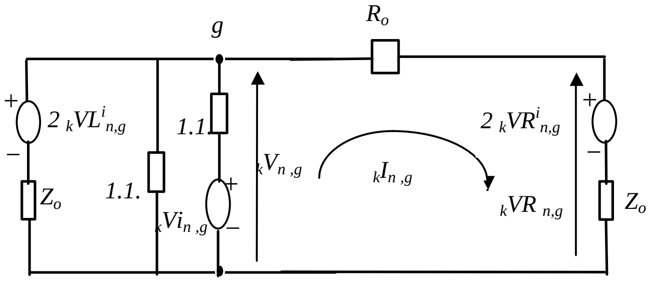

Figure 4. Thevenin equivalent circuit of a general node of the victim cable.

Up to this point, induced waves on the victim cable as a result of electromagnetic interference from the travelling wave on the source cable could be calculated. Next section describes the procedure of implementing the Circuit-Field model.

3. Initial conditions and procedure of the Field-Circuit approach

As the transmitted signal is injected on the source cable, fields start radiating from both conductors and the coupling mechanism between the source cable and the receiving (victim) cable has virtually immediate effect. Hence, coupling calculations should start immediately and progress dynamically as the leading edge of the propagating signal travels along the source pair. To proceed with the use of this model, initial conditions for both field and circuit models should be set as follows:

1. Initial incident and reflected voltages on both cables are set to zero.
2. The same incremental length should be used for both source and victim TLM models.
3. The length of every elementary dipole of the dipole array should equal the incremental length of the TLM model. Hence, the number of the TLM nodes of the source and the number of the TLM nodes of the victim are equal and the same as the number of dipoles constituting the antenna array of both cables.
4. The near end of the source cable is connected to a source voltage via source impedance. The far end of the same cable is terminated by a load equivalent to the characteristic impedance of the cable. While in the case of the victim cable, both near and far ends are terminated by the nominal impedance of the cable.
5. The dimensions and the frequency of operation and the amplitude of the source voltage are input to the program.

The procedure of interfacing both TLM and field models is described as follows:

1. The TLM model of the source cable runs for a time step (iteration). The current profile of both wires of the source cable is calculated at each segment of the TLM model. Incident and reflected voltages, nodal voltages and currents at each segment of the source model are computed and saved as initial conditions for the next time step.
2. The current profile is provided to the field model (radiation model) of the source cable. Radiated *E* and *H* fields from the source cable are calculated at the centre of both wires of the receiving cable. Using equations 10 and 11, the resultant *H* and *E* fields received at the victim cable are calculated as a function of the radiated fields from all segments of the source cable.
3. Using equations 12, induced voltages at each segment of the victim cable and on both wires are calculated. Using equation 13, the potential difference between both wires of the victim cable and at each segment of the cable is calculated.
4. The potential difference calculated at point 3 is presented as a voltage source connected at each segment of the TLM model of the victim pair via an impedance equivalent to the output impedance of the antenna model: the same value as the characteristic impedance of the cable.
5. The TLM model of the victim cable runs for one time step. The incident and reflected voltages at each element of the victim TLM model are calculated. Therefore, voltages and currents at all TLM segments can be computed.
6. The incident and reflected voltages at all segments of the victim cable TLM model, are saved to be used as an initial conditions for the next iteration.
7. The TLM model of the source cable runs for another iteration: Points 1 to 6 are repeated.
8. As a result of interfacing both the TLM and field models of both the source and the victim cables, a voltage profile of the victim cable as a result of radiated fields from the source cable are obtained.

The next section illustrates the application of the Circuit-Field coupling model.

4. Implementation and results

To illustrate the operation of the proposed model, it is implemented for the investigation of coupling between two closely spaced channels illustrated in figure 5.

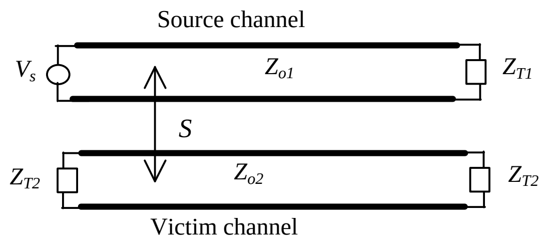

Figure 5. Schematic diagram of two coupled channels.

Each channel has the following dimensions:

- 1 m length.
- 0.94 mm is the distance between the centres of both wires.
- 0.53 mm is the diameter of each wire.
- 10 mm is the unit length of the TLM model and hence is the length of each dipole of the antenna array.
- *s* is the separation between both cables

Coupling responses for two types of electromagnetic waves are obtained. Those are the normal pulse and the double exponential pulse. For different pulse width and different values of *s*, the following set of results is obtained:

a. For a narrow pulse propagating along the source cable, where *s*=5 *cm*, the induced voltage along the victim cable is computed. The result is plotted in figure 6 where the x-axis represents time in *nS*, the y-axis represents the location along the cable (TLM node) and the z-axis represents the amplitude in *mV*.

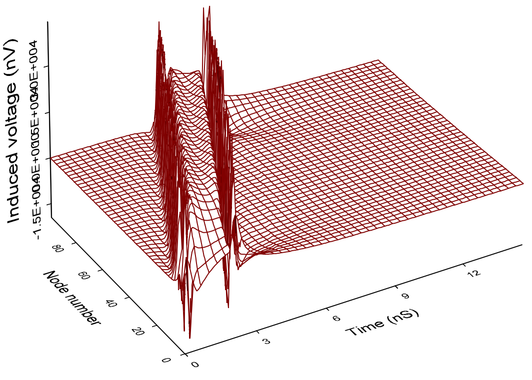

Figure 6. Narrow pulse response *s = 5 cm*.

b. Increasing the distance between the cables, *s*, to 25 *cm* and keeping the same width of the source pulse, the induced pulse on the victim as also computed along the cable and plotted as in figure 7.

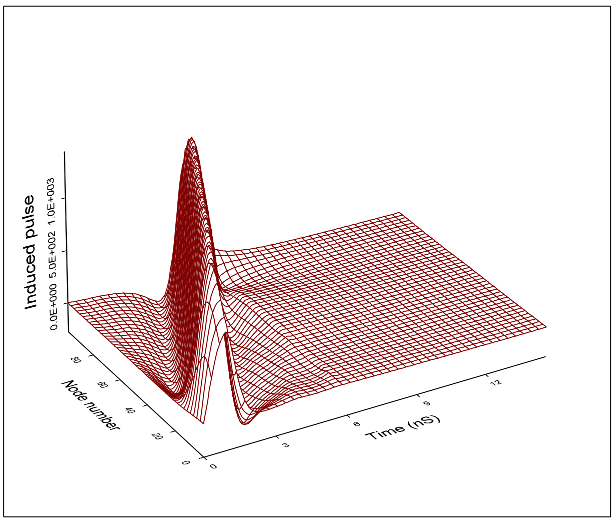

Figure 7. Narrow pulse response *s = 25 cm*.

c. To illustrate the effects of the pulse width on the induced voltages on the victim cable, a wider pulse is applied to propagate on the source cable. Again for a separation of 5 cm only the induced voltage along the victim cable is computed and plotted as in figure 8.

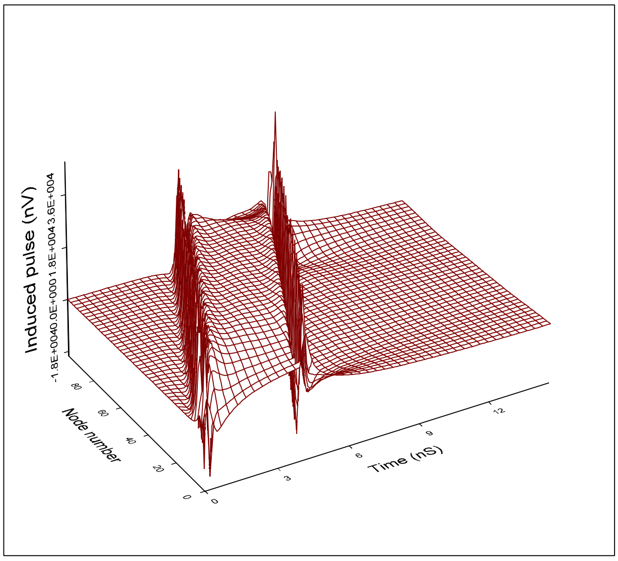

Figure 8. Wide pulse response *s = 5 cm*.

d. Similarly, the induced voltage on the victim cable for the same pulse but with increasing *s* to 25 *cm* is also computed and plotted as in figure 9.

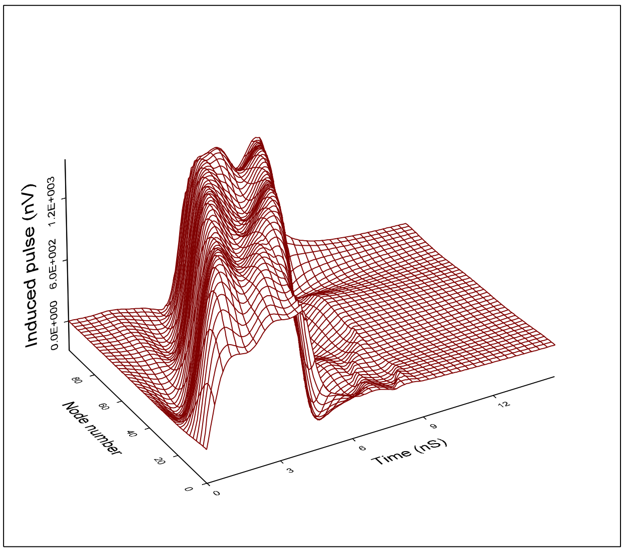

Figure 9. Wide pulse response *s = 25 cm*.

e. To illustrate the operation of the new approach for different interfering wave shapes and to provide a good understanding for the coupling phenomena between communication channels, a double exponential wave-form is applied. It is left to propagate along the source cable and the induced wave on the victim cable is calculated along the cable and plotted as in figure 10.

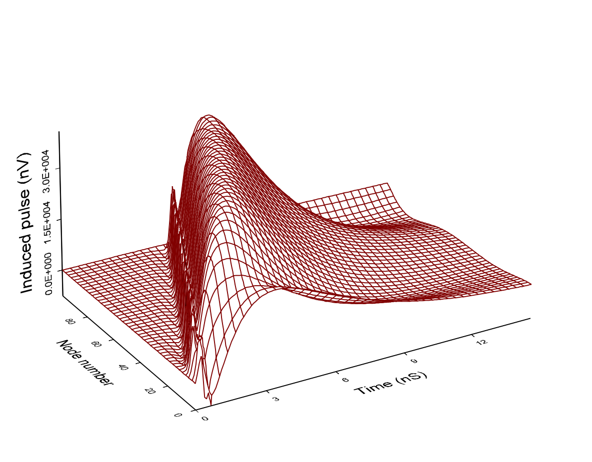

Figure 10. Double exponential pulse response *s = 5 cm*.

5. Discussion and conclusion

The use of an approach combining TLM modelling and antenna radiation theory for the investigation of electromagnetic interference between communication channels was presented. The model was used to compute the capacitive coupling between two cables separated by a distance *s*. Induced voltages on the victim cable as a result of propagation of normal electromagnetic pulse and a double exponential on the source cable were computed. By changing the width of the pulse and the separation between the channels, the effect of different working conditions on the induced voltage on the victim cable was investigated.

Although the paper only discusses coupling between uniform and regular channels, it can also be used for the investigation of channels irregularities on coupling phenomena using the irregular TLM model established in references [6] and [7].

It is obvious that close-coupled channels are more important than far coupling, as the induced voltages on the victim cable have higher amplitude. This is exactly what is obtained here by changing the separation between the two-coupled cables. If a wave is already transmitted on the victim channel, then the amplitude of this wave may suffer some changes related to the induced waves generated by the interference from the source channel.

Effects of the shape of the interfering wave were also investigated using a double exponential wave that represents a lightning strike pulse or other discharge phenomena. The advantage of this approach is that it covers both circuit and field coupling between channels.

The proposed approach is simple, flexible and computationally efficient. The method discussed in this paper considers only the TEM mode of propagation. Natural enhancements of this method are the inclusion of the antenna-mode which will account for common-mode currents, and retardation effects. These are currently being developed.

6. References

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