Modelling the behaviour of twisted pair communication channels

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Abstract: **This paper develops a Transmission-Line Matrix (TLM) method to assess the effects on attenuation and return loss of longitudinal variations along a structured wire cable. Results presented demonstrate the detrimental effects of small variations. The paper also introduces a novel approach to the assessment of coupling based on a hybrid of the TLM method and antenna theory.**

I. INTRODUCTION

Twisted pair communications channels (structured wire cabling) are virtually omnipresent - they are almost exclusively the physical layer component taking signals to and from 'the desk'. Recent advances have required the operational frequency of the cables to increase significantly: standards are in preparation which will extend the frequencies to 600 MHz, 1.2 GHz and beyond. Over recent years, the upper limit on the frequency of operation of structured-wire cabling has been doubling approximately every two years, a similar trend to Moore's Law in microprocessor systems. It can be observed that the rate of increase in working frequency follows personal computer clock speed by approximately one to two years.

The importance of structured-wire cabling is obvious: as processor speeds increase, the desire to send information at higher speeds increases also. Examples of higher rate communications include video net meetings - an unknown concept until relatively recently.

Twisted pair is the medium of choice for Local Area Networks, especially the last few metres to the desk. Hence, in order for this physical layer component not to be a weak link in high speed communication channel, it's operational performance must follow the performance of personal computers.

Clearly, it is vital that the effects of small changes in the structure of a communications channel can be assessed, as these are likely to have a significant effect on the channel performance. These effects will, of course, be more noticeable at higher frequencies

Small geometrical changes may be the result of inappropriate installation techniques such as unnecessary bending and unbending, pigtailing connections, imperfections in the materials used (e.g. dielectrics) or possibly wear on manufacturing equipment such as that used for drawing the conductors. Such changes can have serious implications for the cable secondary parameters, e.g. characteristic impedance, propagation constant and return loss, all of which are application critical and tightly defined by international standards [1,2].

In deciding how to undertake the analysis, there are a number of clear possibilities, these are very briefly compared in the following sub-sections:

A. Equations

It is possible to reduce many of the primary and secondary parameters to families of equations, which are related to dimensions and material properties [3]. This approach has the particular advantage that the precise relationship between one variable, such as dielectric constant, and the cable secondary parameters can be easily identified. While one variable contributes to all secondary parameters, understanding the interrelationship between a variable and several secondary parameters may be problematic but not impossible. The key disadvantage with this approach is that the effects of longitudinal variations such as the geometry changes caused by the bending and unbending operation discussed above are difficult to determine.

B. Experiment

Cables can be designed 'on paper', constructed and their performance measured. This has been the general method of assessment for many years. Such an approach has the advantage of providing information about the way the cable will operate under normal working conditions. The principal disadvantages are that it becomes very difficult to decouple cause and effect. For example, two cables may be manufactured to the same specification using the same equipment and materials, but both may provide slightly different values for the secondary parameters. This is due to small random fluctuations in dimensions and materials. The question is then posed as to what, precisely, has caused this variation. Measurement methods alone are not naturally suited to solving this inverse problem.

C. Numerical Modelling

The creation of a mathematical model of the cable allows greater flexibility in understanding the cause and effect relationship. Generally, there is greater flexibility available to the designer than equations alone, as longitudinal variations can be easily accommodated [4]. Modelling is not hampered by the measurement difficulty of not having precise knowledge of dimensions and material properties nor of effects of the measurement equipment. The disadvantages of a modelling approach are that, using an iterative solution method, computational time and memory resource utilisation may be intense. Further, the precise relationship between the design parameters and the secondary parameters may require greater interpretation than an equation-based solution.

It is the flexibility of numerical modelling which is the basis for this paper. Taken within the wider design framework, an equation-based approach is the ideal first step to analyse the behaviour of a proposed design of a cable or to determine whether a proposed set of secondary parameters are achievable [5]. Measurements allow validation of the final design. Sitting between these two is numerical modelling, which can assess the behaviour according to various tolerance/handling scenarios.

The rest of this paper will overview numerical modelling using TLM (Transmission-Line Matrix) modelling, present results demonstrating the benefit of this method and introduce a field-cricuit hybrid method for coupling prediction.

II. TRANSMISSION-LINE MATRIX (TLM) MODELLING - AN OVERVIEW OF CABLE MODELLING

TLM was introduced in the early 1970s [6] as a computer based solution to a physical simulation described in the 1940s [7,8]. The purpose of which was to use voltages and currents on a network of interconnected transmission lines to model the behaviour of electric and magnetic fields. Thus providing the ability to investigate electromagnetic behaviour in, for example, microwave devices. Although much of the early work, and most of the subsequent work, has concentrated on problems in two- and three-space, the iterative solution to signal propagation on transmission-lines is precisely the requirement for the application discussed in section I.

The basis of operation is that the device to be modelled, in this case a cable, is composed of a large number of small segments (connected at nodes). The properties of each segment are predefined and constant across the length of that segment. However, if the length of each segment is sufficiently small, the concatenation of these segments, where each has slightly different parameters, provides a close approximation to smooth variations along the physical cable.

A general transmission-line has the properties of Figure 1 (all parameters are measured per unit length and Δl represents the length of the segment, multiplying these two gives the actual value per segment).

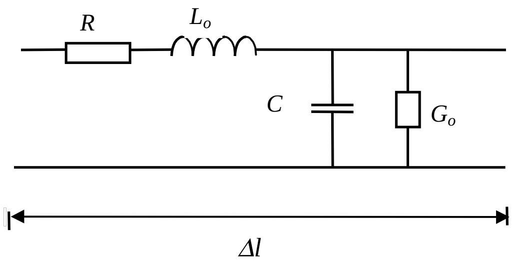

Fig 1. Model of an element of a transmission line of incremental length Δl.

Within TLM there are a number of implementation choices. The reactive components could each be represented by a short length of transmission line with predominantly capacitive or inductive properties. Alternatively, either an open-circuited stub (capacitor) or a short-circuited stub (inductor) could represent the reactive components. The dissipative components are taken into account when currents and voltages are calculated. A further option is that the LC combination could be represented by an impedance ($Z = \sqrt{(L/C)}$) [9].

The solution chosen for the transmission-line model of structured wire cabling is to model the minimum value of the LC combination as an impedance; and extra inductance and capacitance are added using stubs. This variation in L and C, which needs to be accommodated, may come about due to geometry changes along the length of the cable or random variations during manufacture. The benefit of this approach is that the stubs may be omitted if the performance of a 'perfect' cable is being simulated, reducing computational overhead and generally, allowing extra flexibility in the design tool.

Once the equivalent circuit has been identified, reactive elements can be replaced by voltage sources (according to Thevenin's theorem) and the resulting circuit voltages and currents resolved using Millman's parallel generator theorem. Time progresses as a series of small increments, with the voltages and currents being resolved in each of these time increments. Hence, the transient effects of the passage of a signal may be determined. Further, frequency domain data may be obtained using Fourier analysis.

Figure 2 shows the model of two connected TLM segments and the resulting Thevenin equivalent circuit.

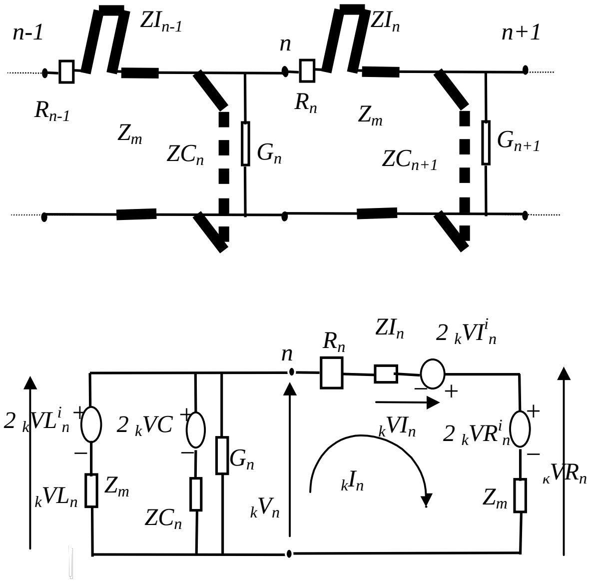

Fig 2 Two segments of a TLM model of a cable showing their connection at node n (upper portion and its Thevenin equivalent).

The nodal voltage at a time step is given by equation 1.

$$
{}_kV_n = \frac{\dfrac{2_kVL^i_n}{Z_m} + \dfrac{2_kVC^i_n}{ZC_n} + \dfrac{2_kVR^i_n - 2_kVI^i_n}{R + Z_m + ZI_n}}{\dfrac{1}{Z_m} + \dfrac{1}{ZC_n} + \dfrac{1}{R + Z_m + ZI_n} + G_n} \qquad (1)
$$

Voltages incident on, and reflected from, the stubs can be readily calculated and used in the iterative solution of the signal propagation along the cable.

Geometry or other variations can be accounted for by altering the values of *L* and *C* at a node or series of nodes.

Secondary parameters are obtained by terminating the (far-end) of the transmission-line with an appropriate impedance, injecting a source signal and measuring the forward and backwards travelling waves at the source (near-) end of the cable and at the far end. The forward and backward travelling waves can readily be resolved, allowing the S-parameters to be determined. The source signal can be an impulse, a pulse or a shaped wave.

In order to verify the basic performance of a model, a cable of constant longitudinal geometry was modelled, the near-end input signal and the far-end output signal were obtained and their ratio used to determine the attenuation. This was then used to compare against measured values and values obtained using equations [4]. Figure 3 compares the attenuation value for 100m of Category 5 cable. It will be noted that the variation at 100 MHz is less than 1dB and well within measurement tolerances.

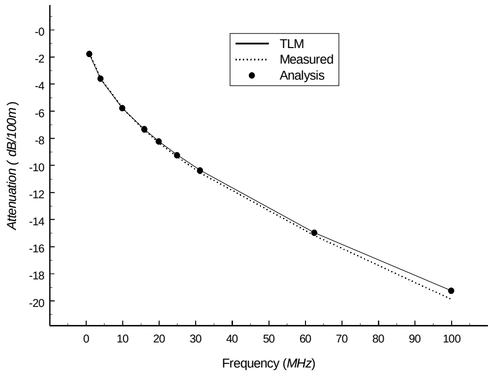

Fig 3. Modelled, measured and computed attenuation for 100 m of Cat-5 cable.

III. A GENERAL CABLE MODEL

Having introduced the modelling technique used for the analysis of cables and verified its performance, this section will describe the effects of periodic variations on a cable and the effects of poorly made terminations.

A. Periodic Variations

Consider a cable deformed as indicated in Figure 4.

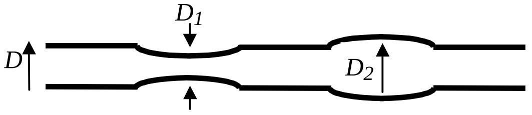

Fig. 4 Deformation effects. The cable has a nominal separation of conductors of D, D_1 represents a reduction in separation and D_2 an increase.

While this represents a stylised case, it is possible that such effects may be obtained by poor handling of the cable while loading it on or unloading it off the drum, for example.

A model of 1 m of cable suffering five such 'expansions' and 'compressions' was undertaken. The basic geometry was that of a Category 5 cable with the difference between D and D_1 and D_2 being 100 µm. The effect of these variations is to alter the values for the primary parameters (particularly inductance and capacitance). In the model, the minimum and maximum values of both L and C are found independently and the minimum value of the impedance for the model is determined, with extra L or C being added by compensatory stubs as described in the previous section. A step source of 10V magnitude was applied at the near end and the forward travelling signal, at both the near and the far-end, was obtained. Figure 5 shows the time domain simulation of the signal propagation and Figure 6 shows the attenuation in the frequency domain.

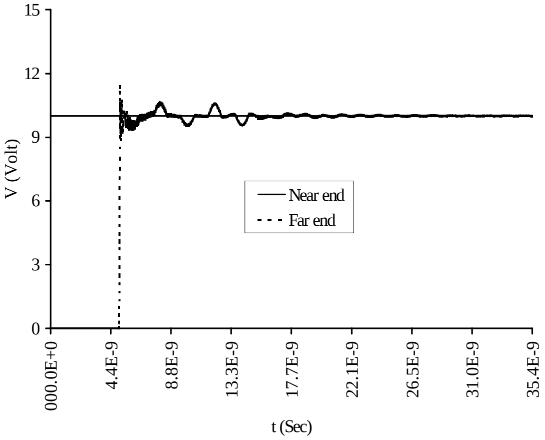

Fig 5 Step response in the time domain.

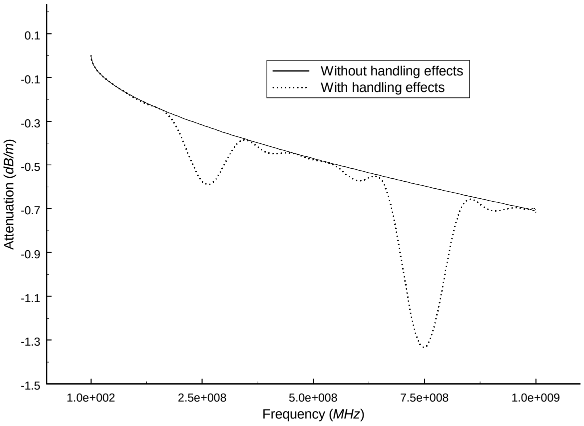

Fig 6 Attenuation constant as a function of Frequency (solid line - uniform cable, dashed line - with longitudinal variation).

The large dips in the attenuation curve occur with a frequency interval that represents a half wavelength corresponding to the mean distance between deformations. A more random variation produces much less readily interpreted results, but does provide useful physical insight.

If the return loss is computed for this cable, the amount of signal received back at the near end is significantly increased, as may be expected from the nature of the parameter: it is heavily dependent on variations in impedance values. The simulation results are given in Figure 7.

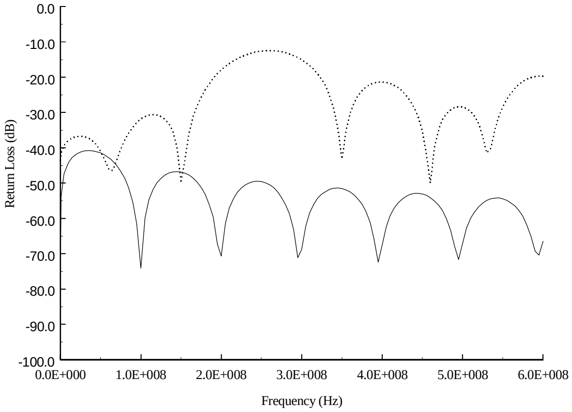

Fig 7 Return loss of the deformed cable (dashed line) compared with the uniform cable (solid line).

It is informative to note the changes in both the location and the number of the nulls in Figure 7.

This sub-section has illustrated how variations in the cable may affect the secondary parameters and how these may be determined.

B. Pig-tailing

A small variation in the geometry of a cable has been shown to have large effects on the secondary parameters. It is still not uncommon to see 'pig-tailed' terminations. Occasionally this is simply through ease of construction, occasionally through necessity, but often as a side-effect of connector pin separations not matching the core separations of a transmission line. However, small variations in dimensions can provide significant variations in performance. Consider a 1m patch cord where the nominal separation between the wire centres is approximately 1mm and the ends of the wires (the connector end) is separated by 2.5 mm with a transition length of 10mm. The near and far ends are terminated in their characteristic impedance The effect on attenuation will be as shown in Figure 8.

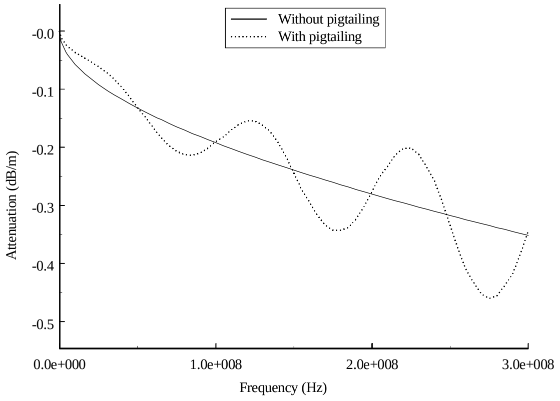

Fig 8 Attenuation for a 'pigtailed' 1m link (dashed line) compared to a uniform cable (solid line).

The most significant result is that the return loss increases dramatically. Fig 9 illustrates this.

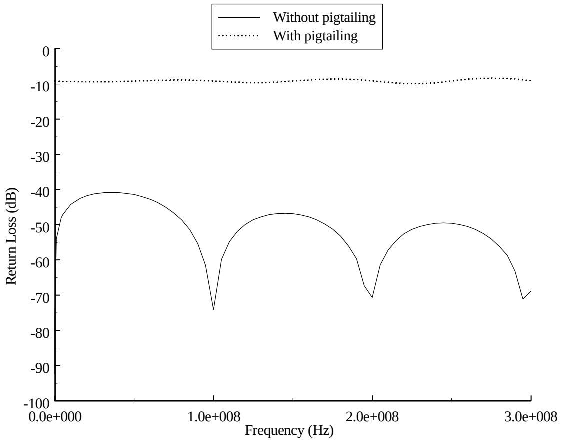

Fig 9 Return loss for a 'pigtailed' 1 m link (dashed line) compared with a uniform cable (solid line).

Having applied TLM to assess the effects of geometric variations in the cable, it should be noted that these results would be difficult to obtain analytically because of the concatenated changes required to be assessed. Further, the measurements would be difficult because of the precise control required in creating cable deformations.

The following section addresses the problem of predicting coupling between transmission lines.

IV. COUPLING

One of the most difficult of problems to solve is that of predicting the unwanted coupling between signal carrying pathways, of particular interest here are communications cables. Analytical solutions are difficult, as they require the [L][R][C][G] matrices to be determined for each position along the cable where the geometry varies. For structured wire cables, this is continuous due to the laying up of the conductors. Measurement provides most of the information about coupling mechanisms but, as has been identified before, it is difficult to control the problem conditions precisely enough (nor be able to alter one parameter exclusive to all the others). Generally, modelling is also not a favoured approach as a full three-dimensional analysis would require significant memory and long run times.

A possible technique to capitalise on the strengths of modelling while minimising the run-time and memory requirements is as follows.

1. Model the signal flow on the source (threat) channel using a standard 1D transmission line as previously described.
2. Treat each segment of the transmission-line as an elemental (Hertzian) dipole and use radiation equations and superposition to determine the amount of signal induced in the victim transmission-line.
3. Use a modified transmission-line matrix model to inject the 'threat' signals in the victim cable (the modification is to add a voltage source in each node the value of which depends on the level of coupling)
4. Run the simulation one iteration at a time, enabling transient effects to be modelled. This allows both time and frequency domain information to be extracted in the same manner as discussed previously.

This Field-Circuit hybrid model allows the modelling of cables of varying geometries and orientations. In order to illustrate the behaviour of the model, consider two parallel pairs of conductors, where each pair is separated by approximately 1mm. (The use of parallel pairs is for ease of illustration). If a square pulse is injected at the near end of the threat transmission line and output taken at each node along the victim transmission-line, Figures 10 and 11 result when the separation is varied.

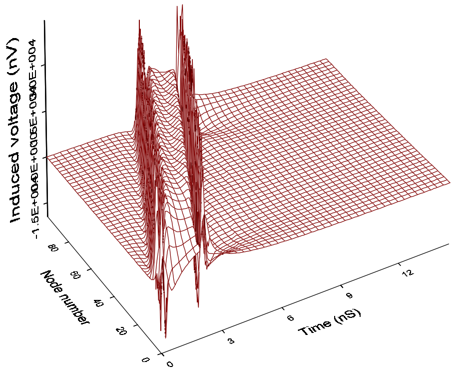

Fig 10 Coupling between two communications channels (5 cm separation between pairs, 1 m length of channel)

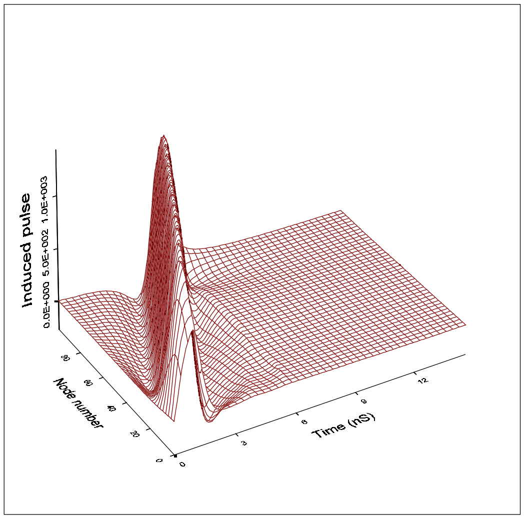

Fig 10 Coupling between two communications channels (25 cm separation between pairs, 1 m length of channel)

The results indicate the predominance of the high rate of change of voltage in the coupling mechanism, particularly in the close coupled case, which is predominantly near-field coupling. The far-coupled case indicates a lower dependence on the high rate of change of signal and more on the signal strength.

V. DISCUSSION

Numerical modelling using the Transmission-Line Matrix (TLM) technique has been described, discussed and implemented. It has been shown that it is a useful weapon in the cable designer's armoury sitting alongside measurements and direct analysis

A hybrid technique using 1D models of transmission lines and antenna array modelling has been used to investigate the coupling between two channels.

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