Transmission Parameters of Cascaded Systems

[^!] Mohammed M Al-Asadi, [!]Alistair P. Duffy, Kenneth G Hodge, [*]Arthur J Willis & [*]David A Jackson

[!]EMTERC Center, Faculty of Computing Sciences and Engineering, De Montfort University, The Gateway, Leicester LE1 9BH, UK

[*]Brand-Rex Ltd, Glenrothes, Fife KY6 2RS, Scotland, UK

[^]Principle Author + 44 – 116 - 2506157 · alasadi@dmu.ac.uk

Abstract

An equation for the prediction of the Return Loss of cascaded systems has been previously presented and validated. This paper further validates this equation against experimental data obtained for communication channels containing long copper cables and connectors. The paper also presents an analytical approach to the calculation of the propagation constant and hence the calculation of both attenuation and phase constants for a cascaded system based on knowledge of the impedance and the propagation constants of each element. Both the impedance and the propagation constants used in the proposed analysis of every individual component may be obtained analytically or experimentally and are frequency dependent parameters. The attenuation and phase prediction can account for tolerances in impedance and in length of cables and connectors. The validity of the derived equations is confirmed by comparisons presented with measurements and simulations performed using the Transmission-Line Matrix (TLM) method. Implications for Insertion Loss Deviation (ILD) are also considered.

Keywords

Cable; Connectors; Channels; Cascaded systems; Return Loss; Attenuation; Phase constant; Impedance; Modeling.

1. Introduction

The increase in processor speeds has continued constantly over the last couple of decades. As a result of this increase and higher data volume applications, the pressure to communicate faster has not diminished. While optical fiber provides high bandwidth channels, it is generally only suited to back-bone operation. Coaxial cable, a relatively high bandwidth choice for 'the last mile', is relatively expensive and has greater connectivity problems when compared to twisted-pair. Hence, a constantly improving understanding of the operation of structured wire cabling at higher frequencies is fundamental to the ability of communications systems to meet the challenges faced by pressure from the computing and communications content producing sectors.

Although calculations and modeling of the parameters, e.g. the return loss, for individual transmission channels, such as cables under different termination conditions, have been a increasingly investigated in the last few years [1,2,3], relatively little work has been published on the parameters of an overall cascaded transmission channel. This paper addresses the performance of a complete channel.

A typical configuration of a copper cable transmission channel between the source of the transmitted signal and the receiving end is illustrated in figure 1.

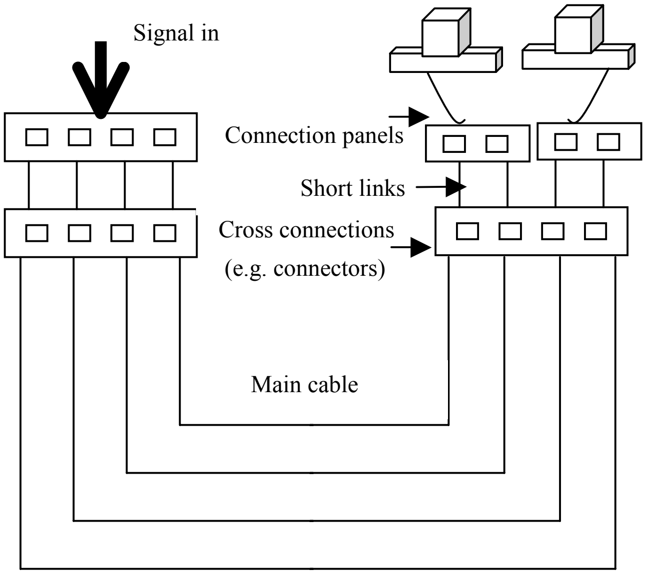

Figure 1. Typical Channel Configuration including short links and connectors

This channel represents a classic cascaded communication system, where each component of the system has its own transmission and reflection parameters. The characteristic impedance of any individual component of such a system may not always perfectly match the characteristic impedance of the neighboring components [4]. This mismatch may result in a significant increase in the return loss value [3]. The impedance mis-matching between system component will also affect the propagation constant measurements[5]. Therefore, the design and development of future facing cabling systems requires a thorough, and detailed, understanding of the secondary transmission characteristics of individual cabling components and their interaction when configured in a system.

This paper presents the development of a general equation for the calculation of the propagation constant and, hence, both attenuation and phase constants of a cascaded system, based on a knowledge of the impedance, the propagation constant and the length of individual parameters of the system. The equation is validated against data obtained by measurements and modeling. In addition to this validation, this paper further validates the return loss equation previously presented against experimental data.

2. Equation Development

2.1 Attenuation and phase constants calculation

A transmission channel containing, for example, four connectors and three cables (two patch links and one horizontal link) can be represented by a two port networks illustrated in figure 2.

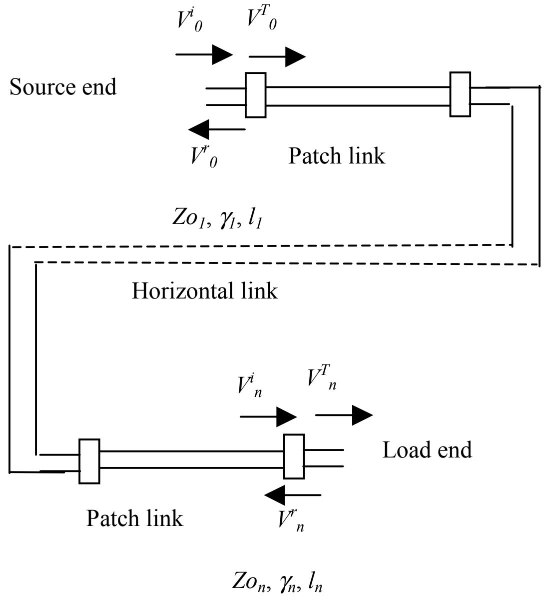

Figure 2. Two-port network representation of a representative channel, illustrating the properties of each component

Taking into account the complex propagation constant, the incident voltage at any part of the system is given as:

$$V_j^i = V_{j+1}^T \cdot e^{-\gamma_j l_j} \tag{1}$$

where j indicates the j th component from the source end, γ is the propagation constant of the jth component and l is the physical length of that component. The superscript T implies a transmitted signal. Similarly, transmitted and reflected voltages at the connection between a channel component and the following one are given respectively as:

$$V_j^T = V_j^i \frac{2\cdot Z_{o\,j+1}}{Z_{o\,j+1}+Z_{o\,j}} \tag{2}$$

$$V_j^r = V_j^i \frac{Z_{o\,j+1}-Z_{o\,j}}{Z_{o\,j+1}+Z_{o\,j}} \tag{3}$$

Similarly, incident, reflected and transmitted voltages from, and at, all the channel components can be obtained. Following a similar approach to the approach reported in [3], the relationship between the overall voltage incident into the far end of the channel and the voltage transmitted from the source into the 1st segment of the channel can be obtained as:

$$\frac{V_n^i}{V_0^T} = \left[\prod_{k=1}^{k=n-1} \frac{2\cdot Z_{ok+1}}{Z_{ok+1}+Z_{ok}}\right]\cdot e^{-\left(\sum_{m=1}^{m=n}\gamma_m\cdot l_m\right)} \tag{4}$$

where n is the number of components cascaded in the channel. To aid visualization and analysis, the channel illustrated in figure 2 can be replaced by one segment of cable having a length that is equivalent to the overall length of the channel as illustrated in figure 3. This can be achieved under the condition that the characteristic impedance of this cable is adjusted so that the relation between the incident voltage reaching the end of the cable and the transmitted voltage from the source is equivalent to that given in equation 4.

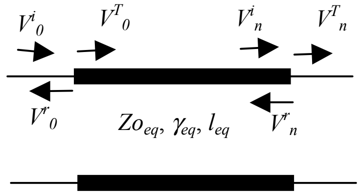

Figure 3. Equivalent circuit to the channel illustrated in figure 2

For the above circuit, the relation between the received voltage at the far end and the incident voltage at the near end of the circuit is given as:

$$\frac{V_n^i}{V_0^T} = e^{-\gamma_{eq} l_{eq}} \tag{5}$$

where γ_{eq} is the desired equivalent propagation constant of the whole channel illustrated in figure 2 and l_{eq} is the equivalent physical length of the equivalent circuit illustrated in figure 3 and given as:

$$l_{eq} = \sum_{k=1}^{k=n} l_k \tag{6}$$

Comparing equations 4 and 5 leads to:

$$e^{-\gamma_{eq} l_{eq}} = \left[\prod_{k=1}^{k=n-1} \frac{2\cdot Z_{ok+1}}{Z_{ok+1}+Z_{ok}}\right]\cdot e^{-\left(\sum_{m=1}^{m=n}\gamma_m \cdot l_m\right)} \tag{7}$$

Taking the natural logarithm for both sides of the above equation gives:

$$-\gamma_{eq} l_{eq} = \ln\left(\left[\prod_{k=1}^{k=n-1} \frac{2\cdot Z_{ok+1}}{Z_{ok+1}+Z_{ok}}\right]\cdot e^{-\left(\sum_{m=1}^{m=n}\gamma_m \cdot l_m\right)}\right) \tag{8}$$

Equation (8) can be simplified to the following form:

$$-\gamma_{eq} l_{eq} = \ln\left[\prod_{k=1}^{k=n-1} \frac{2\cdot Z_{ok+1}}{Z_{ok+1}+Z_{ok}}\right] - \left(\sum_{m=1}^{m=n}\gamma_m \cdot l_m\right) \tag{9}$$

Hence the overall propagation constant of a channel containing *n* components and having overall length given in equation 6, can be given as:

$$\gamma_{eq} = \frac{-\ln\left[\prod_{k=1}^{k=n-1} \frac{2\cdot Z_{ok+1}}{Z_{ok+1}+Z_{ok}}\right] + \left(\sum_{m=1}^{m=n}\gamma_m \cdot l_m\right)}{\sum_{i=1}^{i=n} l_i} \tag{10}$$

All the elements of the above equation are known, hence the overall propagation constant can be obtained. Since impedance values of the above equation and propagation constants of all individual elements are complex quantities and are frequency dependent, the obtained overall propagation constant is a complex quantity and is frequency dependent. Given that the propagation constant of any transmission line is [6]:

$$\gamma = \alpha + j\beta \tag{11}$$

where α is the attenuation of that circuit and β is the phase constant, the attenuation constant of the whole channel, per unit length, the insertion loss can be obtained, in *dB*, from equation 10 as:

$$\alpha_{eq} = \mathrm{Re}\left[\frac{-\ln\left[\prod_{k=1}^{k=n-1} \frac{2\cdot Z_{ok+1}}{Z_{ok+1}+Z_{ok}}\right] + \left(\sum_{m=1}^{m=n}\gamma_m \cdot l_m\right)}{\sum_{i=1}^{i=n} l_i}\right]\cdot 8.686 \tag{12}$$

and the overall phase constant of the same channel can be obtained from:

$$\beta_{eq} = \mathrm{Im}\left[\frac{-\ln\left[\prod_{k=1}^{k=n-1} \frac{2\cdot Z_{ok+1}}{Z_{ok+1}+Z_{ok}}\right] + \left(\sum_{m=1}^{m=n}\gamma_m \cdot l_m\right)}{\sum_{i=1}^{i=n} l_i}\right] \tag{13}$$

2.2 Insertion Loss Deviation (ILD) calculation

The total attenuation (insertion loss) of a channel is normally calculated by adding up the attenuation of all the components: this is referred to as the channel insertion loss or the channel attenuation [7]. This is only an approximation, but one which is easy to calculate and relatively accurate if the impedances of the individual channels are close to being matched. In fact, the channel measured insertion loss (overall attenuation) is higher than the result obtained using this approximate method. This difference is due to signal reflection, and re-reflection, between channel components produced as a result of impedance mis-match. Insertion Loss Deviation (ILD) is the difference between the actual insertion loss as measured on a channel and that obtained as a result of adding up the components' attenuation. Hence it can be given as:

$$ILD = \alpha_{eq} - \sum_{k=1}^{k=n}\alpha_k \tag{14}$$

It should be mentioned here that *ILD* is a relatively new term [7] but it is an increasingly important parameter that should be taken into account when assessing channel performance.

Numerical modeling also provides a tool to obtain the overall attenuation constant as well as other operational parameters. This is discussed in the following section.

3. TLM Model

Transmission-Line Matrix (TLM) modeling technique is used for the simulation of twisted pair cables and the mis-matching effects on short link performance [8]. It is a widely used tool for the modeling of microwave devices, circuits and electromagnetic fields simulations. Here, the method reported in [4,8] is again used for the calculation of the attenuation constant of the transmission channel described earlier in this paper. Knowing the incident and reflected voltages at both near and far ends of the transmission channel modeled using the TLM method, the overall attenuation constant of the channel can be obtained. Due to the fact that TLM is a time domain method, Fourier Transformation is used for the calculation of the frequency domain data. The overall attenuation constant is then computed using the following equation:

$$\alpha = -20\log\left|\frac{V_F^r}{V_N^i}\right| \tag{15}$$

V^r_F is voltage incident into the load at the far end.

V^i_N is the incident voltage from the source at the near end of the TLM model.

The value obtained using equation 15 can then be used for the validation of the overall attenuation value of the transmission channel obtained using the developed equation 12.

4. Validation

This section deals with the validation of the equations published in reference [4] and those developed and reported in this paper.

4.1 Return Loss Equation Against Measurements

The return loss equation reported in [4] states that:

$$RL=-20\log\left[\frac{Z_1-Z_s}{Z_1+Z_s}+\left[\sum_{k=1}^{k=n}\left\{\left(\prod_{i=1}^{i=k}\left(\frac{2\cdot Z_i}{Z_i+Z_{i-1}}\cdot\frac{2\cdot Z_{i-1}}{Z_i+Z_{i-1}}\right)\right)\right\}\right.\right.$$
$$\left.\left.\cdot e^{-2\left\{\sum_{j=1}^{j=k}\gamma_j l_j\right\}}\cdot\frac{Z_{k+1}-Z_k}{Z_{k+1}+Z_k}\right]\right]$$

It was initially compared with data from a common equation obtained from [6], and against data obtained using the TLM approach.

This equation has then been used for the calculation of a transmission channel containing two patch links of 112.7Ω impedance and a horizontal FTP cable (Gigaplus cable) of 99.1Ω impedance. The length of each patch was 2m while the length of the horizontal cable was 305m.

The effects of the connectors have been ignored in these calculations. Results obtained from both measurements and calculations are shown in figure 4.

For a similar transmission channel having the same length as both patches and the horizontal FTP cable, but with an impedance of the patch cable of 105.1Ω while the impedance of the horizontal cable was 98.7Ω, the overall return loss was measured and calculated using equation 26 of reference [4].

Determination of the return loss, generated as a result of different terminations, of a long channel by measurements may include the structural return loss generated as a result of coarseness of the cable geometry due to random manufacturing factors, handling, etc. [9]. While this adds extra features (fine-grain detail) to the results, the analytical solution predicts the performance envelope with excellent precision. This is clear from both figures 4 and 5.

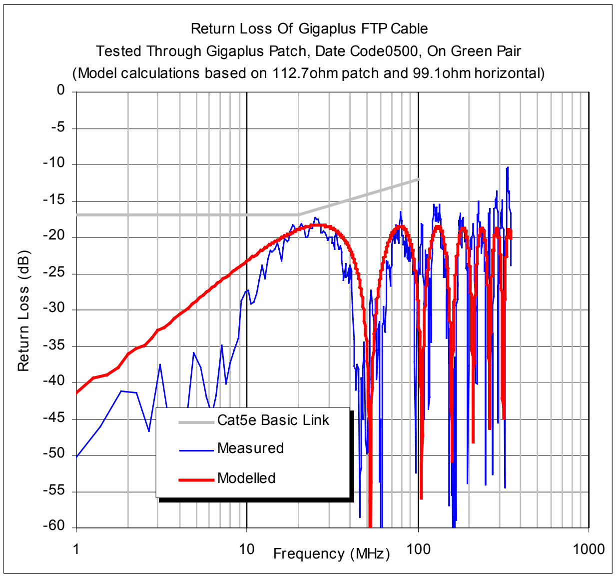

Figure 4. Return loss validation against measurement for a long 7-segment channel.

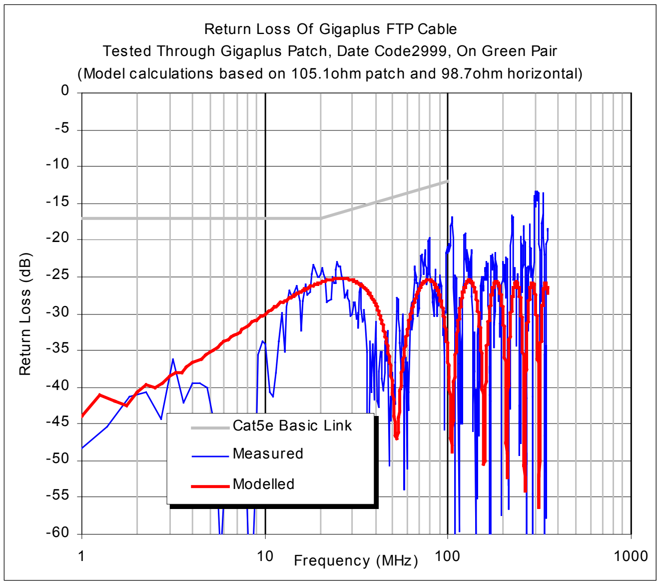

Figure 5. Reproduction of figure 4 using cables with different impedance values

4.2 Attenuation Equation Against TLM

Detailed derivation of the TLM model of a regular and irregular cable is given in both references [8] and [9]. The model developed in these references was then used for the prediction of handling effects, pig-tailing and short link performance under different working conditions. It was also used in reference [4] for the prediction of the overall return loss of a cascaded transmission channel.

TLM model was used for the calculation of the overall attenuation constant of the channel using equation 15 for a 3-segment transmission channel containing a Category 5 cable of 1 meter length connected at both ends via two connectors of 1 cm length. The nominal impedance of both connectors and the cable was 96Ω. Terminating with a matched impedance, the overall attenuation constant was then calculated using equation (12) and plotted along with that obtained using the TLM model for a range of frequencies as illustrated in figure 6.

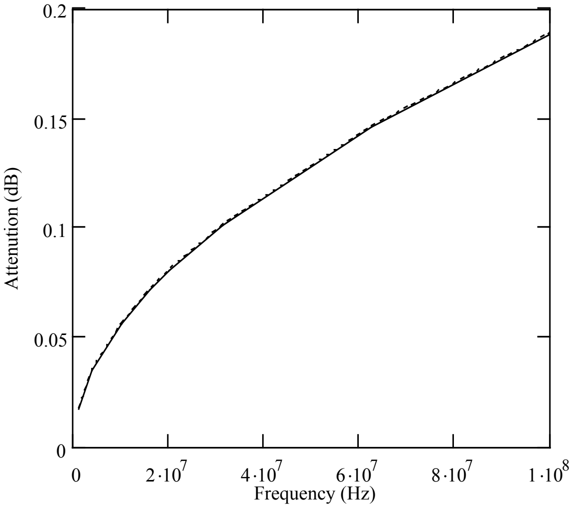

Figure 6. Attenuation constant for a 3-segment channel (1m cable) obtained using the new equation (Solid line) and using the TLM method (Dotted line)

Similarly, the overall attenuation constant of a 7-segment cascaded channel was obtained using both approaches and plotted in figure 7. The length of each patch link is 1*m* and the length of the horizontal cable is 10*m*. The impedance of the patch links and the horizontal cables are similar to those used for the production of figure 6. Both figures 6 and 7 show a very good agreement between both sets of results, hence they confirm the validity of the derived equation.

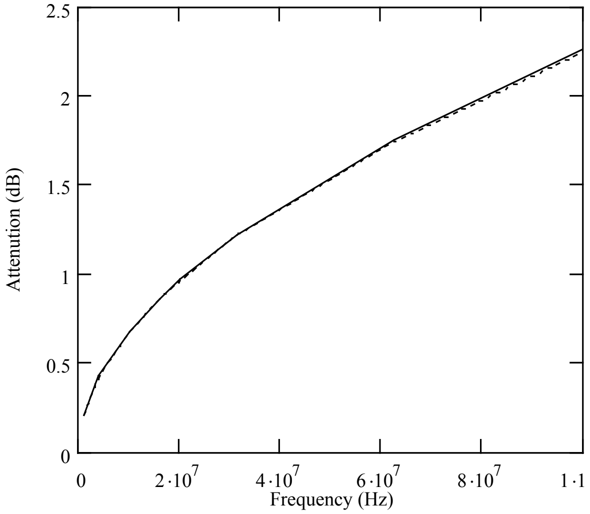

Figure 7. Attenuation constant for a 7 segment channel, using a 10m cable and 1m links, obtained using the new method (Solid line) and the TLM (Dashed line)

To calculate the insertion loss deviation, the overall attenuation of the transmission channel needs to be calculated using the traditional method. Figure 8, shows the overall attenuation constant of the 10*m* channel calculated using both the traditional approach and the new method.

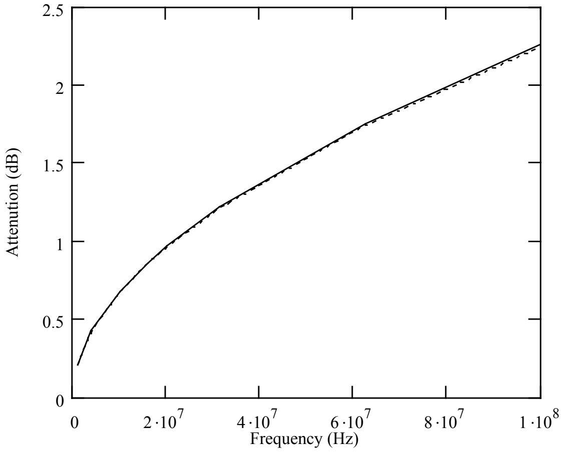

Figure 8. Attenuation constant for a 7 segments channel, using a 10m cable and 1m links, obtained using the new method (Solid line) and the adding up method (Dashed line)

Figure 9 illustrates the Insertion loss deviation calculated from the difference between both values of figure 8 and using equation 14.

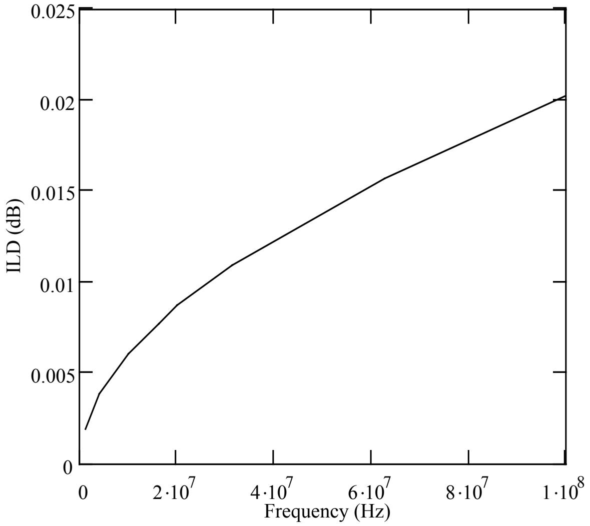

Figure 9. Insertion loss deviation, *ILD*, for the 7-segment 10*m* channel

5. Implementation and Results

After validating the performance of equation (12), it was then used for the calculation of the overall attenuation constant of a practical communication channel containing 7-segments as described earlier and for different termination conditions. The insertion loss deviation *ILD* was also computed.

5.1 Matched conditions

The attenuation was obtained under matching conditions, where the impedance of both patch links illustrated in the 7-segment channel shown in figure 2, match the impedance of the horizontal cable. Connectors were assumed to have the same impedance. Results for a 1*m* patch and a 10*m* cable were reported earlier as plotted as in figures 7 and 8.

For a similar channel having a 2*m* links and a 100*m* cable, the overall attenuation constant is computed using both the new equation and the summation approach. Results are plotted in figure 10.

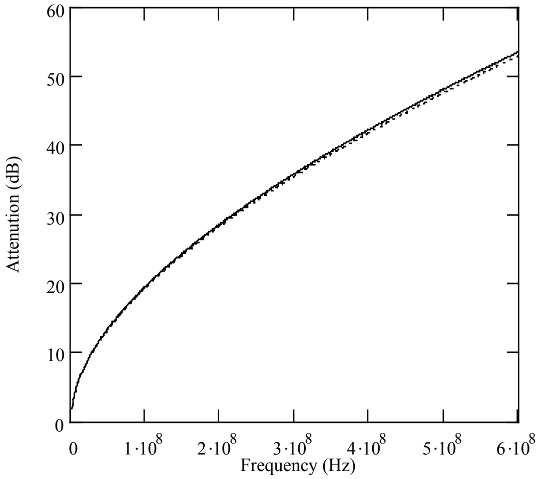

Figure 10. Overall attenuation for a 100*m* channel using the new equation (solid line and the summation method (dotted line).

For a channel of two patch links and one horizontal cable where the impedance of both patch links mismatches the impedance of the cable, the overall attenuation of the channel and the ILD were also computed using both the new equation and the summation approach. For different lengths of cables and different impedance values, the following tests are carried out, it should be noted that the impedances used are illustrative and not representative of actual channels:

- 2m-10m-2m channel, where the impedance of the 1st link, the cable and the 2nd link are 83,5Ω-96Ω and 74.5Ω respectively, the overall attenuation was calculated using both methods and plotted as in figure 11. The *ILD* was also computed and plotted as in figure 12

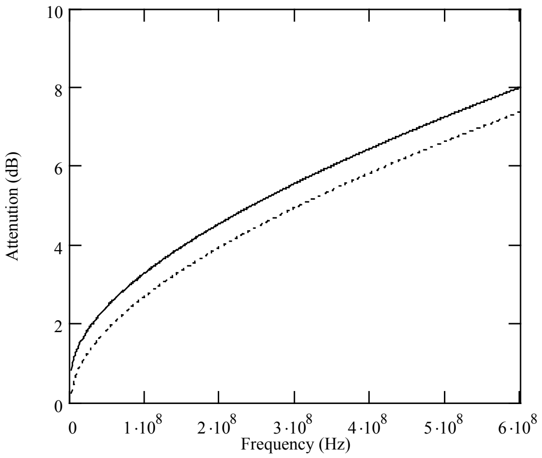

Figure 11. Attenuation for a 14 m channel, new equation (solid line) and summation approach (dotted line)

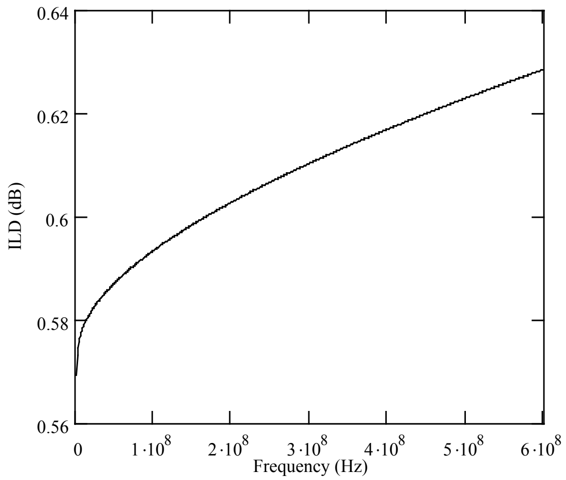

Figure 12. Insertion Loss Deviation of the results presented in figure 11

- For the above channel, where the impedances are 122.5Ω-96Ω and 74.5Ω respectively, the overall attenuation was also calculated using both methods and plotted as in figure 13. The ILD was also computed and plotted as in figure 14

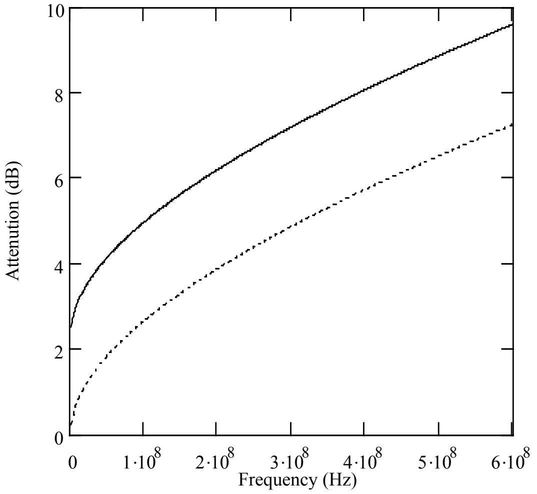

Figure 13. Reproduction of figure 11 for different matching conditions, new equation (solid line) and summation approach (dotted line)

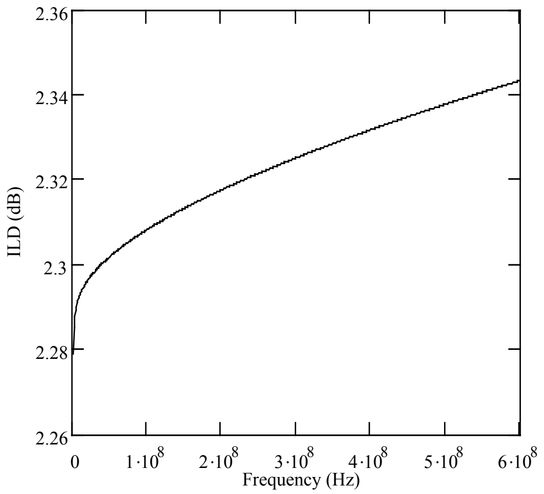

Figure 14. Insertion Loss Deviation, *ILD,* for results presented in figure 13.

- 2m-100m-2m channel, where the impedance of the 1st link, the cable and the 2nd link are 83,5Ω-96Ω and 74.5Ω respectively, the overall attenuation was calculated using both methods and plotted as in figure 15. The *ILD* was also computed and plotted as in figure 16

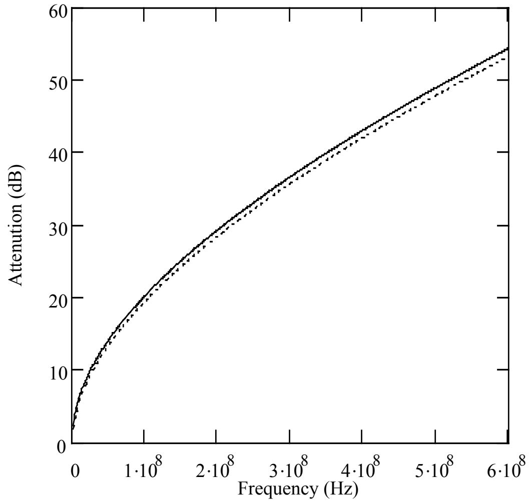

Figure 15. Overall attenuation for a mis-matched 104*m* channel, new equation (solid line) and summation approach (dotted line)

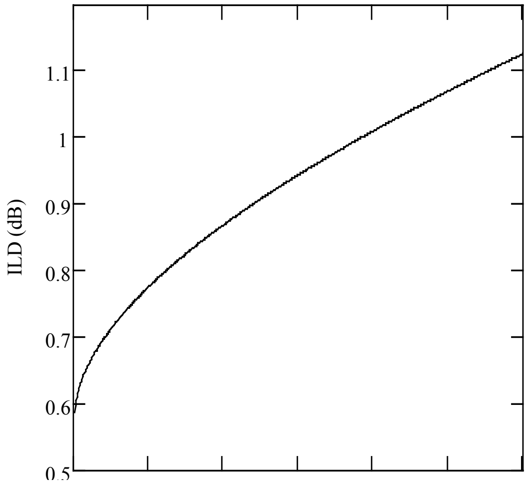

Figure 16. Insertion Loss Deviation of the results presented in figure 15

- For the same long channel, where the impedances are again changed to 122.5Ω-96Ω and 74.5Ω respectively, the overall attenuation was also calculated using both methods and plotted as in figure 17. The ILD was also computed and plotted as in figure 18

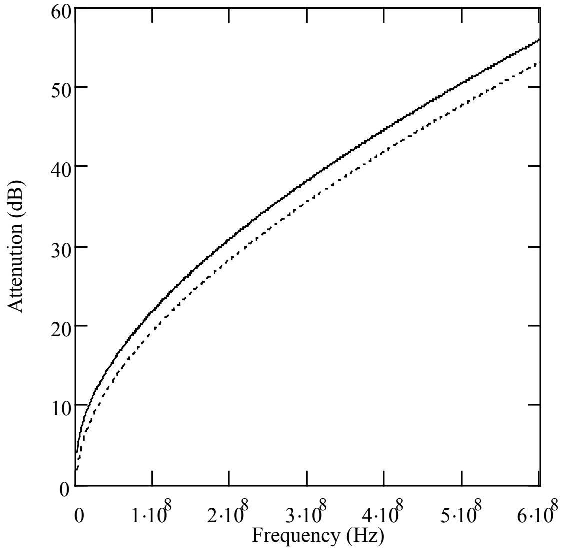

Figure 17. Reproduction of figure 11 for different matching conditions, new equation (solid line) and summation approach (dotted line)

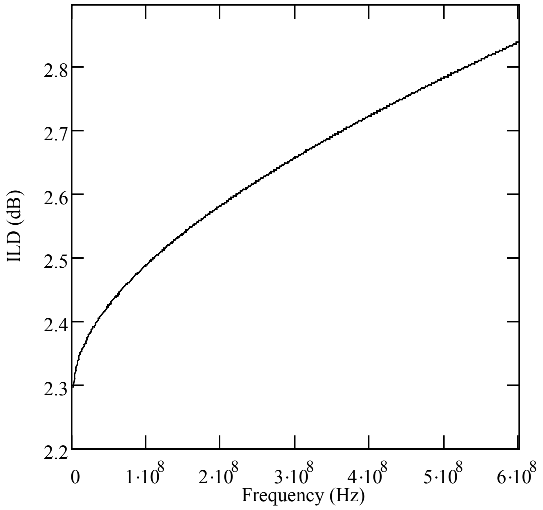

Figure 18. Insertion Loss Deviation of the results presented in figure 17

All the above tests illustrate the need to understand the effects of mismatching in both short and long channel on the channel's overall attenuation constant.

6. Discussion and Conclusion

An equation has been developed for the calculation of the propagation constant of a cascaded system containing many segments, each having different impedance values and different propagation constants. This equation has led to the development of an equation for the calculation of the overall attenuation constant of the system. It has also led to the development of an equation for the calculation of the overall phase constant of the cascaded system as function of the impedance and the propagation constant of each element. The new equation has been validated against the TLM modeling method.

Traditionally, the overall attenuation constant of a communication channel containing many segments of different lengths, different impedance and different propagation constants, was obtained by summing the attenuation constants of all the elements. While this is a simple calculation, it is only approximate. With increasing errors as shorter channels are considered, or where cascaded channels consisting of similar components is being considered. This is clear from results illustrated in section 5. The discussion on Insertion Loss Deviation (ILD) supports the need to treat the system attenuation calculation with care.

Further work is underway to validate and apply the phase constant calculation.

7. References

[1] T. Y. Otoshi, "Maximum and minimum return losses from a passive two-port network terminated with a mismatched load" May 1994, 18 *IEEE Trans on MTT, Vol.42, No. 5,* pp. 787-792.

[2] A. Umek, "Modeling the structural return loss in twisted pair cables", 10th IEEE Mediterranean Electrotechnical conference, MeleCon 2000, Vol.1, pp. 173-176.

[3] I. T. Sylla, M. Slamani, B. Kaminska, F. M. Hossein and P. Vincent, 1998, "Impedance Mismatch and Lumped Capacitance effects in High Frequency Testing" *16th IEEE VLSI Test Symposium Proceedings,* pp. 239-244.

[4] M. M. Al-asadi, A. P. Duffy, K. G. Hodge and A. J. Willis, 2000, "Return loss prediction for cascaded systems", *Proceedings of the 49th IWCS symposium*, pp. 578-585.

[5] D. C. Degroot, D. K. Walker, and R. B. Marks, 1996, "Impedance Mismatch effects on propagation constant measurements" *IEEE 5th Topical meeting, Electrical performance of electronic packaging,* pp. 141-143.

[6] S. Ramo, J. R. Whinnery and T. Van Douzer, *Fields and waves in communication electronics*, 2nd ed., 1984

[7] P. Kish, April 2000 "The effect of network cabling on Bit Error Rate performance", NORDX/CDT, white paper,12 pages.

[8] M. M. Al-asadi, A. P. Duffy, K. G. Hodge and A. J. Willis, 1999, "Analysing link performance in high frequency transmission systems", *Proceedings of the 13th Zurich EMC conference*, pp. 117-120.

[9] M. M. Al-asadi, A. P. Duffy, K. G. Hodge and A. J. Willis, 1997, "Modeling as a tool for analysing handling effects in structured wire cabling", *IEE 10th Int. Conf. On EMC, Warwick, UK,,* pp. 131-136.

Authors Biographies

Mohammed M Al-Asadi, Alistair P Duffy, Kenneth G Hodge and Artuhr J Willis: for photos and biographies, please see paper 04_01 in these proceedings.

David A. Jackson holds a BSc(Hons) in Electrical and Electronic Engineering from Abertay University, Dundee, Scotland. His career has been dominated by the design of test systems, initially as a Research and Development engineer working on test facilities for microprocessor systems. He has spent over 16 years in the cable industry designing and implementing radio frequency test methods.