LINK PERFORMANCE

Terry Cobb

Introduction

- To ensure that legacy cabling will operate it is important that link performance is not degraded with DTE power.
- A balanced and common mode terminated interface to the cabling is important to maintain that link performance.

Cable Models and Measurements

- **"Issues in High Frequency Cable Models and Measurements" Baxter, Conte, Shariff, ICT 1997, Vol 1 pp.37-41. (attached)**
- **The experiment in the paper demonstrates the change in the reflected conversion mode with common mode termination.**
- **The paper also talks about the importance of all transmission characteristics and how to measure these accurately.**

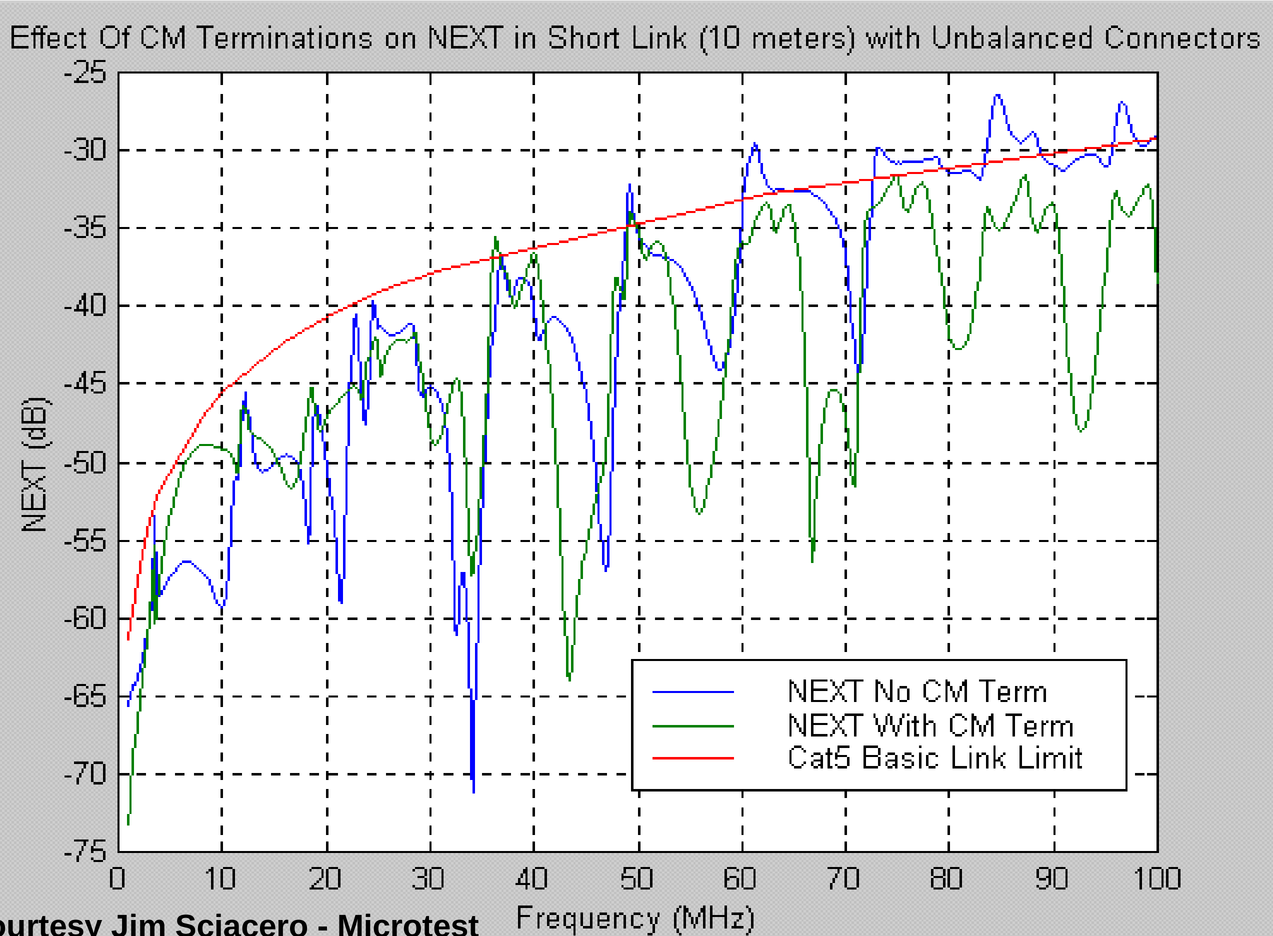
Example - Reflected Modes :

Differential ($\cong$ Return Loss)
Common
Differential to Common
Common to Differential

Short Link Resonance

- **TIA dealt with a problem that illustrated this: "Short Link Resonance"**
- **An increase in NEXT due to unbalance in connectors on a short link.**
- **NEXT displayed a significant change with common mode termination.**

Short Link Resonance



Courtesy Jim Sciacero - Microtest

Conclusion

- **To ensure that legacy cabling will operate:**

  Balance and common mode termination are required.

- **To verify link performance is not degraded:**

  Test with and without the pairs in the power configuration.

  Tests should be in a typical wiring closet configuration.

  Tests should include at least crosstalk measurements.

Issues in High Frequency Cable Models and Measurements

L.A. Baxter, R.A. Conte and M.A. Shariff

Bell Laboratories
Lucent Technologies
200 Laurel Avenue
Middletown, New Jersey 07748, U.S.A

Abstract: *As the push for higher bandwidth and higher data rates continues, the transmission modeling and measurement techniques used to characterize cabling systems need equal attention. This is especially true if one is concerned with supporting the emerging gigabit applications. This paper discusses some of the limitations of existing models and the need for a more complete description of transmission phenomena in the frequency range of 100 MHz and beyond. In particular, the interaction between common mode and differential signals is not adequately described by low frequency decoupled transmission line models. The need for a more complete description of the interaction of the various modes of propagation naturally leads to the analysis of a coupled multiconductor transmission line also known as modal decomposition. This will allow us to extend and redefine some of the currently used performance metrics to more accurately predict high frequency link behavior from a knowledge of component characteristics.*

1. Introduction

As twisted pair finds more applications in the high frequency range of 100 MHz and beyond, there is a strong need to predict link level behavior from a knowledge of the performance of each individual component comprising the link. This is especially true if one is interested in supporting the high speed LANs currently being developed by a variety of international standards bodies. The well understood concepts of attenuation, NEXT (near end crosstalk), FEXT (far end crosstalk), and return loss must be augmented by a description of the interaction of the various modes of propagation supported by a cable at high frequencies. This interaction is key to understanding Electro-Magnetic Compatibility (EMC) performance. This means a practical definition and measurement procedure for balance at high frequencies must be defined. Balance is well documented in the voice band but extending voice band measurement techniques to high frequency has proved completely impracticable where measurement reproducibility is of prime importance. Thus a re-examination of this problem is necessary.

2. The Need for a Coupled Model

When the first category 5 systems were introduced there was a strong need to understand the susceptibility of these links to external noise fields. The following experiment was conducted to gain some insight into noise pick up from the tightly twisted category 5 data pairs. Figure 1 shows the experimental setup.

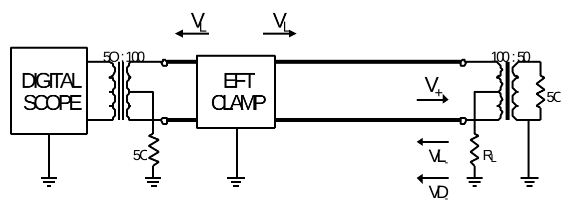


Figure 1: Laboratory Setup for Susceptibility Testing

An Electronic Fast Transient (EFT) clamp was used as a common mode noise source to simultaneously excite all conductors of the cable. Measurements were then made on the differential noise observed at the near end of the cable. The common mode termination at the far end of the link (R_L) was varied in an attempt to study its effect on the observed differential noise. This resulted in some very interesting data on wave scattering at terminations. The total length of cable used was approximately 100 meters with the EFT clamp 1 to 2 meters from the end where the differential noise was measured using a digital scope. Only one pair of the cable was used as a differential path, all other conductors were grounded at both ends of the link creating a transmission line consisting of 2 signal conductors and a ground path. The transformers used at both ends of the link were highly balanced laboratory quality magnetics. The EFT clamp excites the line as a common mode source and causes a signal V_L to propagate in both directions away from the source of the disturbance. One would therefore expect to observe a noise spike at the scope soon after the excitation of the EFT. Depending upon the attenuation of the link and reflections at the far end, one may or may not see the effect of the wave which was initially launched toward the far end termination. The first measurement was made with the far end common mode termination R_L open. The measured differential noise pulse is shown in figure 2 and it was quite surprising to find a large spike approximately 1 μ sec after the initial excitation, especially as both ends of the link were properly terminated differentially.

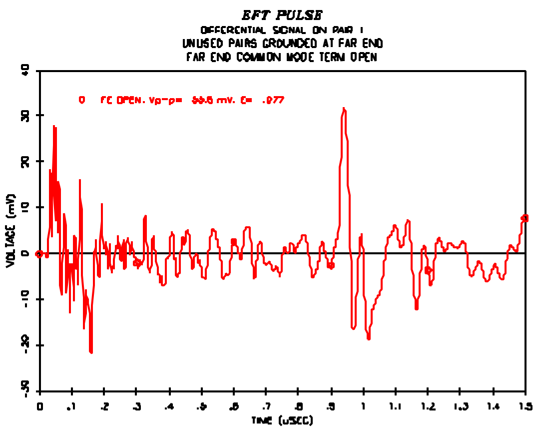


Figure 2: Response with Common Mode Termination Open

The next measurement was with R_L shorted and is shown in figure 3.

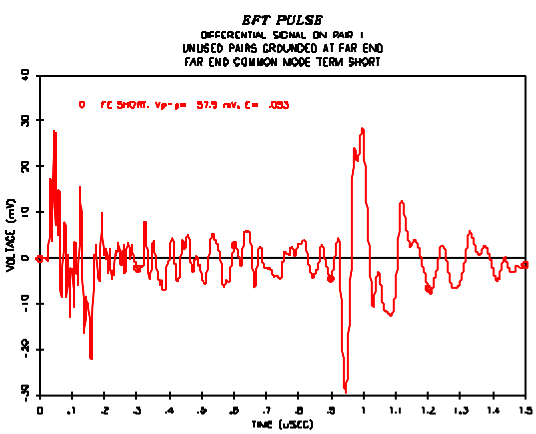


Figure 3: Response with Common Mode Termination Shorted

Now the spike at 1 μ sec appears to be inverted but the waveform prior to 1 μ sec is similar to that of the previous figure. The last measurement was made with $R_L = 50\ \Omega$ and is shown in figure 4. The noise spike at 1 μ sec is substantially reduced in amplitude from the previous two measurements. By superimposing the above three plots on the same axes (figure 5) it becomes clear what is happening. All three measurements are in excellent agreement up to the time of 1 μ sec, after that they disagree completely. The measurement prior to 1 μ sec results from the initial common mode wave propagating toward the digital scope and is the same in all three cases.

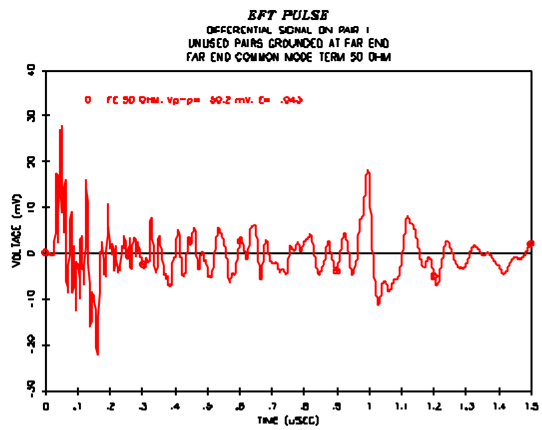


Figure 4: Response with Common Mode Termination $R_L = 50\ \Omega$

Primarily we see the common mode to differential conversion of the termination at the scope along with the conversion from the short length of cable between the EFT clamp and the scope. After 1 μ sec the reflected differential and common mode waves V_D and V_L from the far end of the link arrive at the scope and are different depending upon the scattering at the far end.

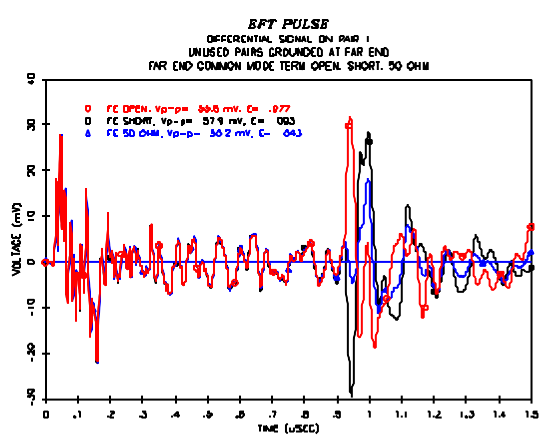


Figure 5: Superposition of All 3 Responses

After 1 μ sec we see both the conversion of the near end termination as well as the effects of scattering at the other end of the link. The time of 1 μ sec is consistent with the round trip delay of a wave traveling 200 meters with a propagation velocity of 2/3 the speed of light, which is a common propagation velocity found in cables of the type being measured. It is clear that there is a strong interaction and conversion between common mode and differential waves propagating on the line and scattering at terminations. Performance metrics for both the line and terminations need to be developed which reflect this interaction.

3. The Multiconductor Line and Balanced Transmission

Many of the concepts associated with the analysis of multiconductor line are simply extensions of those arising from a two conductor line. Consider a line consisting of n conductors and ground. Let V(x) and I(x) define a vector of voltages and currents on each of the conductors at a distance x from the origin. Let Y(x) denote a matrix of shunt admittances between the conductors and Z(x) denote a matrix of series impedances, then the defining equations become

$$\frac{dV(x)}{dx} = -Z(x)\,I(x) \qquad (3.1)$$

$$\frac{dI(x)}{dx} = -Y(x)\,V(x) \qquad (3.2)$$

which are vector extensions of the traditional 1 dimensional line. This system can be readily solved as a coupled first order differential equation

$$\frac{d}{dx}\begin{bmatrix} V(x) \\ I(x) \end{bmatrix} = \begin{bmatrix} 0 & -Z(x) \\ -Y(x) & 0 \end{bmatrix}\begin{bmatrix} V(x) \\ I(x) \end{bmatrix} \qquad (3.3)$$

This yields the system transfer function T(x) relating voltages and currents at the origin to voltages and currents at some other point on the line. We will denote A(x) to be the coefficient matrix on the right hand side of equation 3.3. When the line is uniform and homogeneous T(x) is easily seen to be the exponential of A. Then under fairly general conditions the solution of equation 3.3 will be a linear combination of eigenvectors of A (denoted by m_i) weighted by exponentials of the form e^{l_i} where l_i is the eigenvalue corresponding to m_i. This is easily verified by direct substitution. The vectors m_i are called the modes of the system and also have the extremely useful property that they are eigenvectors of T(x) with corresponding eigenvalues e^{l_i} i.e.,

$$T(x)\,m_i = e^{l_i x}\,m_i \qquad (3.4)$$

Thus if one excites the line with a combination of voltages and currents as defined by a given mode, the output from the line will be a scaled replica of the input. A mode can be thought of as an input voltage and current vector which propagates through the line and appears at the output in a form which is directly proportional to the input. The propagation constant for a particular mode is given by l_i which may be different for distinct modes. Also since the eigenvectors associated with distinct eigenvalues will be independent, under fairly general conditions the collection of distinct modes will span the space of all possible combinations of voltages and currents within the cable. In other words every possible voltage/current state in the cable can be **uniquely** decomposed into a linear combination of modes. This suggests a natural transmission scheme for sending signals through a cable containing n distinct modes. We simply map the i[th] signal into the i_{th} mode of propagation for the cable and separate out the distinct modes at the output to recover the original signals.

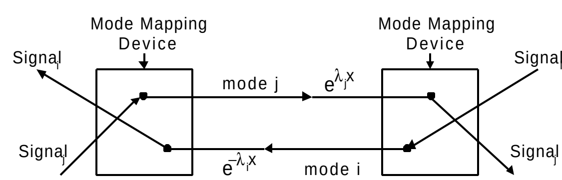


Figure 6: Generalization of Balanced Transmission

Separation is possible due to the independence of the modes. The advantage of this scheme is that since there is no coupling between the modes during propagation (equation 3.4) there will be no NEXT (near end crosstalk) nor any FEXT (far end crosstalk). Such a *'mode mapping'* scheme is shown in figure 6. This concept will allow us to generalize cable balance and define a component metric which directly relates to system level performance. We consider a cable with n pairs and 2n conductors plus ground. The voltage on the conductors of pair i are placed in (2i-1)th and 2ith position and the currents in locations 2n+2i-1 and 2n+2i. We can define a cable to be *balanced* if and only if its transfer function T(x) has n eigenvectors of the form shown in figure 7. Here ‘a’ is a constant relating voltage to current for this particular mode. With this definition of cable balance the mode mapping device of figure 6 can be called a *generalized balun*. The reason for using a transformer or balun with transmission systems is to map the transmitted signal into one of the differential mode eigenvectors of the cable connecting the transmitter and receiver. Twisting the pairs in a multipair cable effectively forces the eigenvectors to take the form of figure 7. In practice

$$m_i = \left[\begin{array}{c} 0 \\ \vdots \\ 0 \\ 1 \\ -1 \\ 0 \\ \vdots \\ 0 \\ a \\ -a \\ 0 \\ \vdots \\ 0 \end{array}\right] \begin{array}{l} \\ \\ \\ \leftarrow \textit{voltage on conductor } i \\ \leftarrow \textit{voltage on conductor } i+1 \\ \\ \\ \\ \leftarrow \textit{current on conductor } i \\ \leftarrow \textit{current on conductor } i+1 \\ \\ \\ \\ \end{array}$$

Figure 7: State Vector for Balanced Transmission

the degree to which the 0 entries of figure 7 actually differ from 0 is a direct measure of the imbalance of the cable.

Now consider the situation where a perfectly balanced signal is applied to exactly one pair of an unbalanced cable. Since the cable does not have a true differential mode for this pair, this signal must actually excite several different modes of propagation to meet the boundary conditions. Each mode may propagate with a different propagation constant and scatter differently at both ends of the cable due to the boundary conditions presented by the impedances of the signal source and load terminations. The net result is that every conductor of the cable may have a non zero voltage and current. These unintended signals represent both NEXT and FEXT for the cable in question. Furthermore, it is likely that each individual conductor may have a different amount of noise indicating that a perfectly balanced signal has generated both differential and common mode noise on each pair of the cable. A similar situation occurs when an unbalanced signal is applied to a perfectly balanced cable. It is this *modal misalignment* between the applied signal and the modes of the cable which generate both differential and common mode noise. When the applied signal excites more than one mode of propagation, NEXT and FEXT results.

4. Reflection Coefficient and Balanced Loads

At the boundaries of a multiconductor line, it is possible that an incident mode is reflected or scattered into many different modes by the terminating impedances in either the source or load. To analyze this situation we must note that the general solution to equation 3.3 consists of a voltage/current wave traveling in the positive x direction and another such wave traveling in the negative x direction [1]. We will denote these waves by V_+, I_+, V_-, I_- and the total voltage and current by V and I respectively. It can also be shown [1] that the relation between the voltage and current waves traveling in the same direction is given by the characteristic impedance matrix Z_0. Thus

$$V = V_+ + V_- \qquad (4.1)$$

$$I = I_+ - I_- \qquad (4.2)$$

$$V_+ = Z_0\, I_+ \qquad (4.3)$$

$$V_- = Z_0\, I_- \qquad (4.4)$$

The load termination Z_L forces the condition

$$V = Z_L\, I \qquad (4.5)$$

The combination of equations 4.1 - 4.5 yield a multitude of relationships only one of which will be presented here. Namely,

$$V_- = \left(Z_L - Z_0\right)\left(Z_L + Z_0\right)^{-1} V_+$$

or

$$r_V = (Z_L - Z_0)(Z_L + Z_0)^{-1}$$

where r_V is defined as the voltage reflection coefficient matrix. This is a natural extension of the one dimensional concept to many dimensions. If we use a coordinate system in which the i^{th} mode m_i is denoted by a vector with a 1 in the i^{th} position and zeros elsewhere, and transform r_V into this coordinate system we have the off diagonal elements describe the scattering of mode i into mode j when the wave defined by mode i strikes the termination. This could be a conversion from differential to common mode or common mode to differential depending upon the particular modes supported by the cable. We can now define a termination to be balanced if and only if the reflection coefficient matrix associated with pure differential and pure common mode modes of propagation is diagonal. Otherwise we have conversions between the various modes at the termination. This conversion process is clearly demonstrated in figures 2 through 5.

5. Impact on Measurements

In the past, a description of cable transmission in terms of differential quantities has been adequate, and most cable measurements focused exclusively on differential parameters. It is now known that conversions from differential to common mode and common mode to differential can not be neglected if one is to obtain a complete description of transmission at high frequencies. This implies that measurement techniques need to be developed to carefully examine these conversions. In fact, the quantities to be measured are exactly those described in the preceding paragraphs. For terminations one needs to quantify the voltage reflection coefficient matrix, and for cables one needs propagation constants (eigenvalues) and a description of the actual modes (eigenvectors). Some attempts have been made to address this need using baluns to measure conversions from differential to common mode and the reverse. These attempts have met with limited success for a number of reasons. One of the most severe is that the balance of the magnetics has always been comparable with the balance of the quantities being measured. The measured data has inherently been corrupted by the measurement process. It has been extremely difficult to manufacture wide band magnetics with balance an order of magnitude better than category 5 components and at this point in time this has not yet been achieved by balun manufacturers. Secondly, the normalizations which have been proposed to *calibrate out* balun characteristics have been somewhat arbitrary and resulted in a fair degree of uncertainty. These normalizations are not really suited for precise measurements. These problems can be overcome by measuring the unbalanced parameters associated with a multiport network of the device in question and then performing precise computations to extract differential and common mode parameters. Such data acquisition requires a multiport network analyzer with an extremely stable switching network. This measurement process is commonly referred to as modal decomposition [2] and is actively being developed and refined by a number of companies in the cabling industry.

6. Conclusion

The need to describe the interaction between the various modes of propagation in a multipair cable naturally leads to the study and analysis of a multiconductor line. It has been shown that it is possible to define cable balance and termination balance in such a way that these component metrics directly relate to system level performance. In fact, if one computes the transfer function for a terminated line or cascaded lines, the mathematical expressions would involve eigenvalues, eigenvectors, and reflection coefficients as they have been described here. Link level performance is built upon these component concepts. It is also clear that a wealth of information can be obtained if one has access to matrix data describing the transfer function T(x) and the reflection coefficient matrix or some equivalent quantities. Modal decomposition hold the promise of being able to achieve this. Once this process is perfected it will be possible to obtain a detailed description on coupled transmission in multipair cables.

References

[1] R.A. Conte, A Tutorial on Modal Scattering in Multiconductor Transmission Lines, Submitted to TIA/EIA 568, Revised June 27, 1996.

[2] Yanagawa, K.Yamanaka, T Furukawa, A. Ishihara, "A Measurement of Balanced Transmission Lines Using S-Parameters", IEEE IMTC, 1994, pp. 866-869, 1994.