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Engineer's Notes

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Bob Smith Termination vs Proper Termination

I have discovered that the Bob Smith termination that is widely used to reduce emissions as a result of common mode signals on a multipair cable is far from optimal. I have developed a technique, presented and demonstrated here; that I feel addresses the problem properly.

In U.S. Patent, 5,321,372 issued 6/14/94, Robert W. (Bob) Smith described a method to reduce the longitudinal or common mode current on multipair conductor systems where the pairs are interrelated in a uniform manner. He alludes to the fact that the pair to pair relationships of a CAT5 cable form transmission lines in themselves. He asserts incorrectly that such transmission lines exhibit a characteristic impedance of approximately 145 ohms. His description is confusing and misleading because he does not define the configuration in which this is supposedly exhibited. He goes on to say that the cable can support and radiate common mode signals. Moreover, he states that there is a method to reduce the common mode radiation by matching the common mode impedance of the cable, and then presents a method of terminating the common mode transmission line, that does not in actuality accomplish that goal. His termination technique does reduce the common mode radiation, but not optimally.

For a CAT5 cable there are two common modes of interest. The first is the pair-wise common mode. The second is the cable-wise common mode. These notes will address the pair-wise common mode. The pair wise common mode has a common mode characteristic impedance that can be readily characterized, while the cable-wise characteristic impedance is grossly dependent on implementation. Actually, the characteristic impedance of the cable-wise common mode is not a meaningful concept except in some well-defined circumstances.

Figure 1 shows a length of CAT 5 cable with each pair shorted.

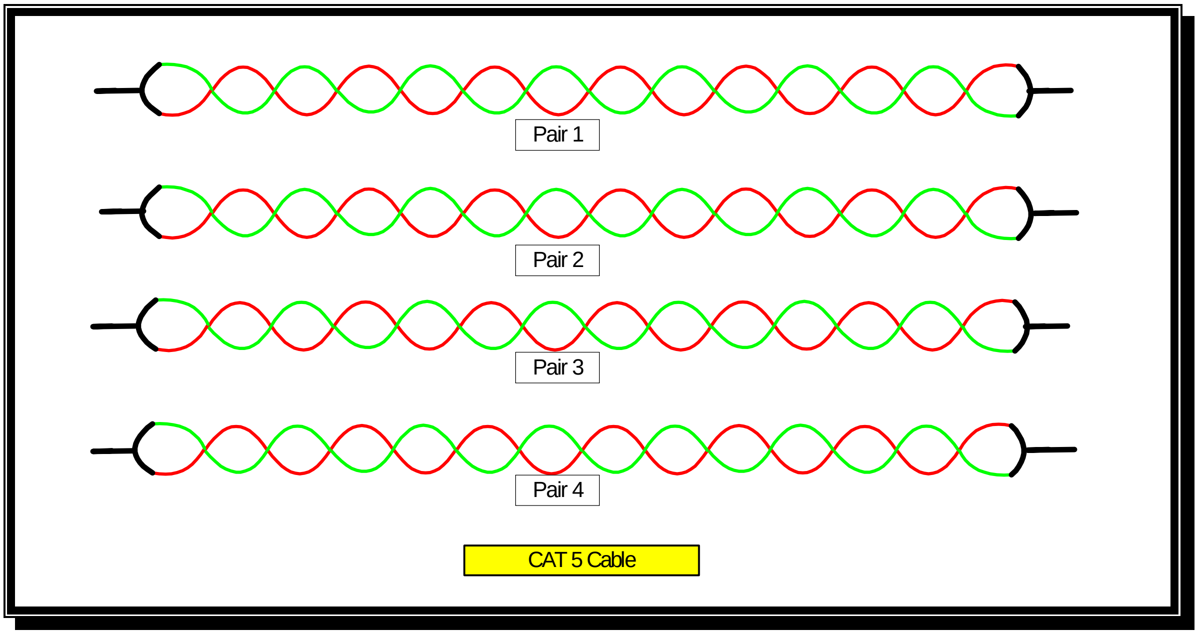

Figure 1 CAT 5 Cable

Next we will look at the pair-wise common mode characteristic impedance relationships within CAT 5 cable. See Figure 2. There are four pairs. There is an intrinsic characteristic impedance between each pair. Due to the approximate symmetry in the construction of the cable, each pair has the same relation with any other pair. It is prudent to define the relationships to be described (Smith doesn't do that). Since the inherent characteristic impedances cannot be measured directly, to verify the theory it is necessary to measure them in combinations and resolve the individual elements.

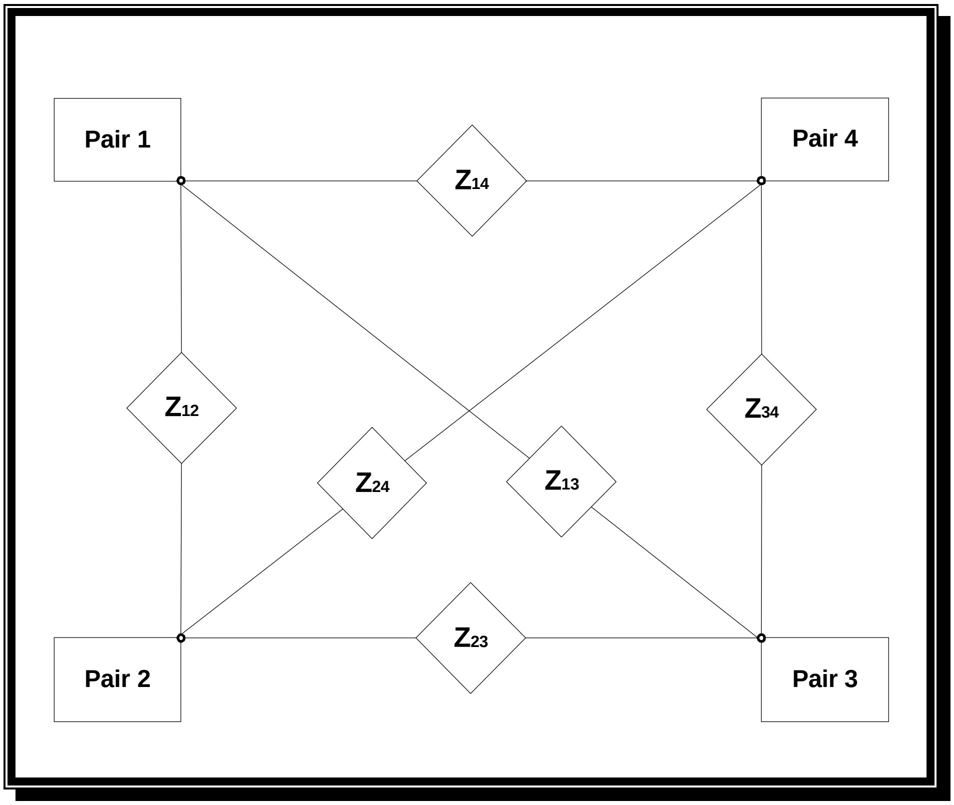

Figure 2 CAT 5 Cable – Pair-Wise Characteristic Impedances

First, there is the relationship between any two pairs (Z_{1-1}). This parameter is somewhat meaningless in application because all four pairs are interrelated, but it is useful and can be characterized none-the-less. The second and more meaningful relationship is the characteristic impedance of one pair relative to the other three pairs (Z_{1-3}). The third is the relationship of two pairs to the other two pairs (Z_{2-2}). For the case of one pair versus any other pair with the two remaining pairs floating, the measured characteristic impedance is approximately[1] 100 ohms. For the case of one pair versus the other three pairs tied together the measured characteristic impedance is approximately 70 ohms. For the case of two pairs tied together vs. the other two pars tied together the measured characteristic impedance is approximately 50 ohms. Nowhere does there exist a relationship that I can see where the characteristic impedance is anywhere near Smith's stated 145 ohms.

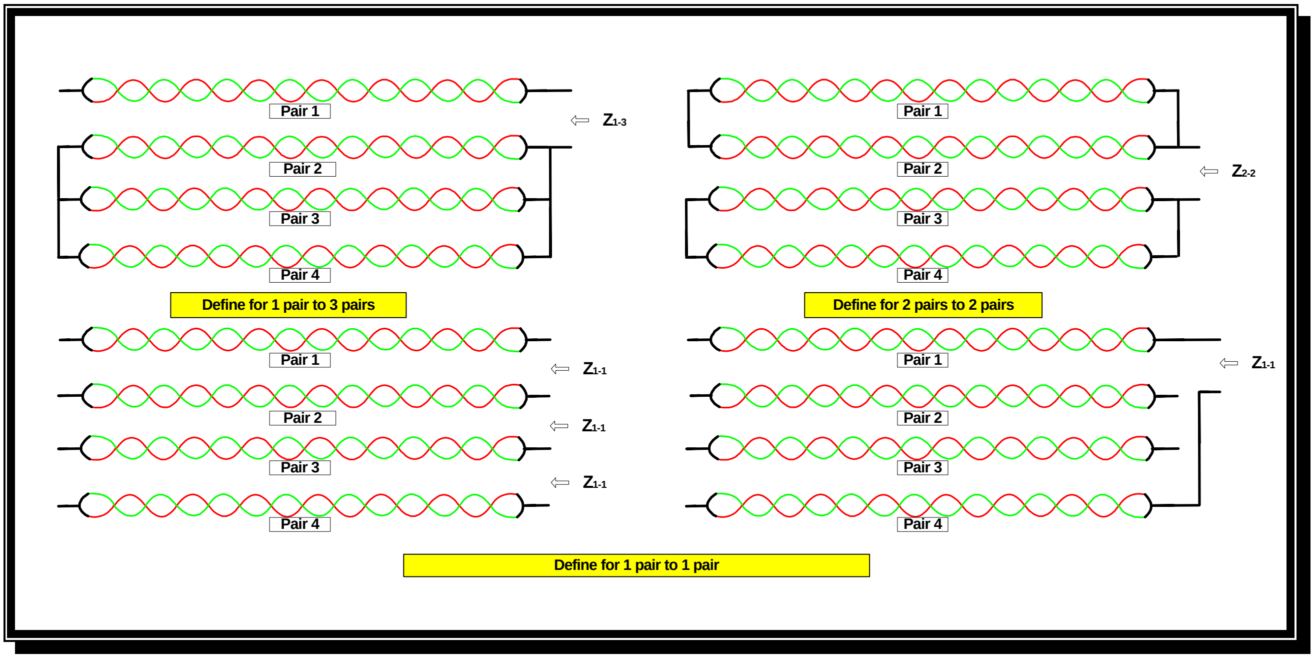

Figure 3 Relationship Definitions

Figure 3 shows the definitions of some of the possible measurable characteristic impedances.

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[1] From the measurements I have made, in a given cable, a variation as great as +/-15% appears to be the norm.

Table 1 shows some measured data samples. These were taken using the Agilent 4396B Network Analyzer.

Table 1 Sample Data

Type Cable	ID	1-3 A Ohms	1-3 B Ohms	2-2 Ohms	1-1 A Ohms	1-1 B Ohms	1-1 C Ohms
CAT 5	1	69.6	72.2	58.9	93.5	101	99.5
CAT 5	2	73.8	75.0	42.8	117	90.0	116
CAT 5	3	72.4	73.2	61.6	97	108	102
CAT 5E	1	72.5	72.9	42.3	113	90.0	117
CAT 5E	2	67.5	69.4	58.5	91	100.5	95
CAT 6	1	85.8	85.2	70.0	114	120	117

Analysis

Analysis of the measured values to determine the inherent characteristic impedance values is complex. See Figure 3.

$$Z_{1\text{-}3(1,234)} = Z_{14} // Z_{12} // Z_{13}$$

$$Z_{2\text{-}2(12,34)} = Z_{14} // Z_{23} // Z_{13} // Z_{24}$$

$$Z_{1\text{-}3(1,234)} = Z_{12} // \text{(Complicated combination of } Z_{14}, Z_{34}, Z_{23}, Z_{13}, Z_{24}\text{)}$$

This does not appear to be readily manageable. Therefore, I accomplished a simulation selecting values for Z_{nn} to give values something near the measured data. From this, the intrinsic characteristic impedance Z_{nn} appears to be in the vicinity of 200 ohms. I suggest that the value of Z_{nn} varies along the length of the cable as well as from pair to pair.

To properly terminate the common mode transmission lines, the following is presented.

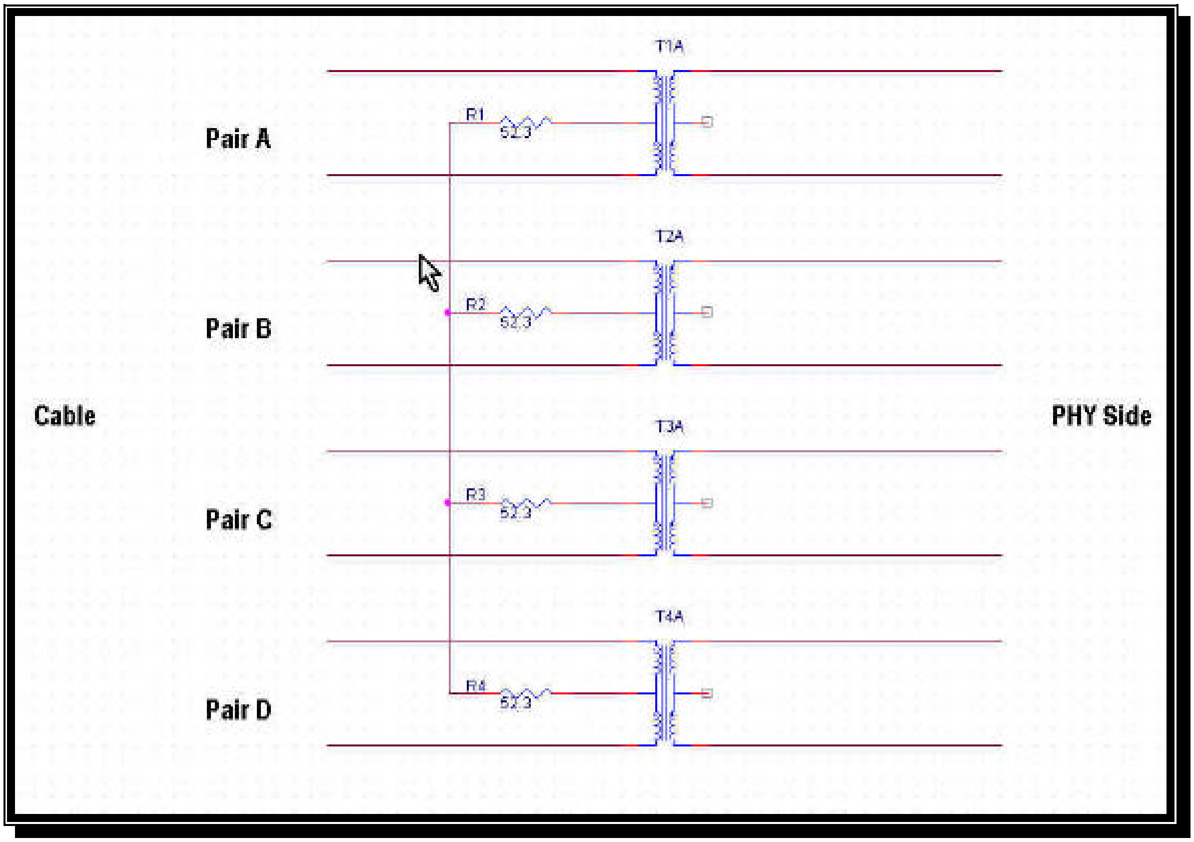
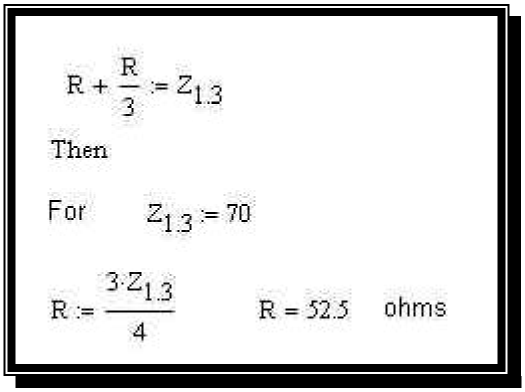


Figure 4 Termination Applied

One way to visualize a method of termination is terminate the Z_{1-3} characteristic impedance. First, that transmission line must be terminated with a value equal to its characteristic impedance. A single resistor termination will accomplish this, however the other three pairs are not tied together in normal use. A more general approach, in theory, is to form a resistor network comprised of four resistors of equal value, one in series with the other three in parallel. Then compute the resistance value such that the network matches the Z_{1-3} characteristic impedance of the cable. See Figure 5.



$$R + \frac{R}{3} := Z_{1.3}$$

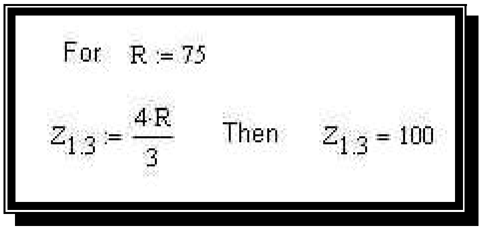
Then

For $Z_{1.3} := 70$

$$R := \frac{3 \cdot Z_{1.3}}{4} \qquad R = 52.5 \quad \text{ohms}$$

Figure 5 Matching Equations

Smith claims that all four resistors should be 75 ohms.



For $R := 75$

$$Z_{1.3} := \frac{4 \cdot R}{3} \qquad \text{Then} \qquad Z_{1.3} = 100$$

Figure 6 Smith's Termination

This means that a 75 ohm resistor in all four terminations would match a common mode impedance of 100 ohms for Z_{1-3}. But Smith claims the characteristic impedance of “some” common mode configuration that he is attempting to match is 145 ohms. Being as I don't know what configuration he is talking about and no configuration I can envision is anywhere near 145 ohms, I can only conclude that his numbers and approach to deriving them are wrong. Additionally, his matching technique, given a common mode characteristic impedance, does not produce a match.

I assert that he hasn't presented a really workable solution to the problem he has recognized. Nonetheless, "the Bob Smith termination" method is applied worldwide with great acclaim. For CAT 5 and CAT 5E cable an improvement in return loss achieved by replacing the 75 ohm resistors by 52.3 ohm resistors, would be from 15 dB to more than 28 dB, given a variation in common mode impedance of +/- 5 ohms. The variation of common mode characteristic impedance is taken into account in the calculation of return loss.

Termination Type	Termination Resistor - Ohms	Common Mode Impedance - Ohms	Return Loss dB
Bob Smith	75	65	13.5
Bob Smith	75	70	15
Bob Smith	75	75	16.9
Proper	52.3	65	29
Proper	52.3	70	>40
Proper	52.3	75	28

Verification - Physical

A physical method to verify this is important. Fortunately, there is a relatively simple method for doing so. That method is to configure a length of cable with the termination resistors, then insert a common mode pulse while monitoring that insertion with an oscilloscope. A pulse generator with an output impedance of 50 ohms and a rise time of approximately 1 nanosecond was used. See Figure 7. If the cable is properly matched, no reflection should be seen. If not, a reflection will be observed. Terminations of three values were applied at each end of a cable seven feet long. The resistor values employed were sets of 52.3, 75 and 100 ohms. The cable employed was 7 feet long.

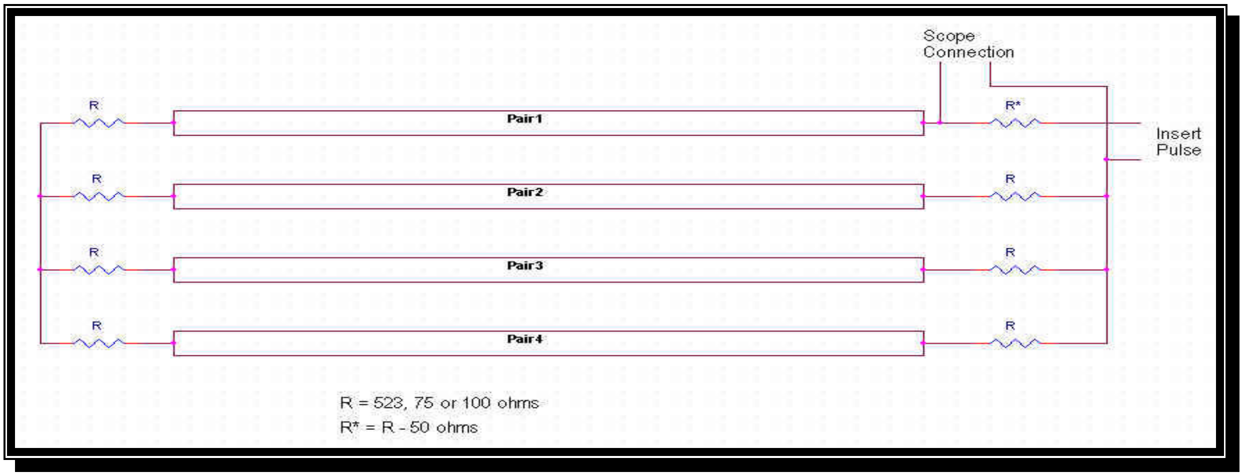
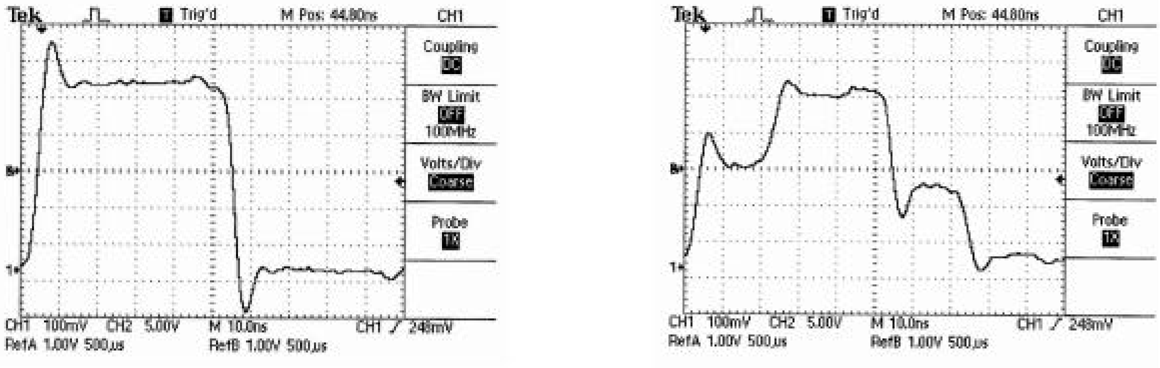


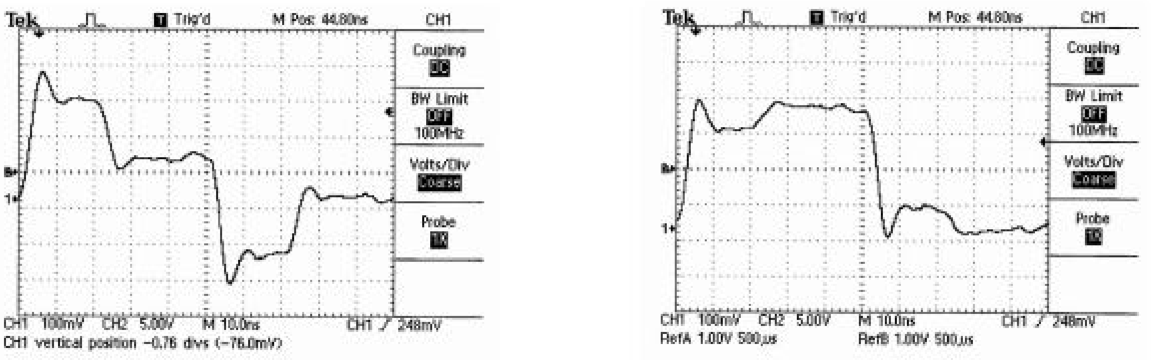
Figure 7 Verification Setup

The series of scope presentations in Figure 8 show implementations of the various terminations for comparison. The fact that a termination in the vicinity of 52.3 ohms is proper for the match can be clearly seen. For calibration purposes, several conditions are shown. The first scope presentation shows the output of the pulse generator with no load. The second shows the cable connected to the pulse generator as in Figure 7 and the far end open circuited. The third is the same conditions with the far end short-circuited. The remaining three scope presentations show the results for the three values of the termination resistance. It is clear that for the 100 ohm and 75 ohm resistances there is a reflection, whereas, with 52.3 ohms there is not. The conclusion is that in the vicinity of 52.3 ohms is correct and that Bob Smith's 75 ohm value is not correct.



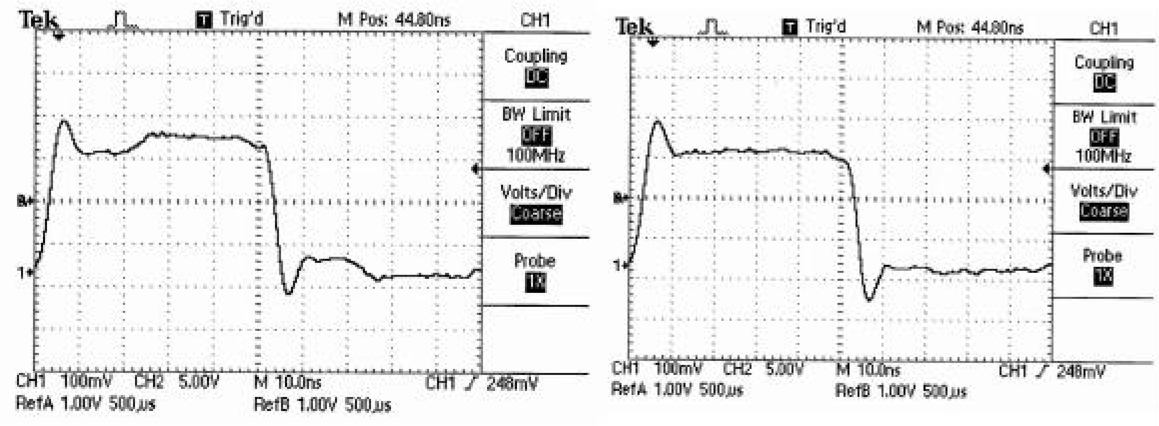
Pulse general - No Cable

Termination - Open



Termination - Shorted

Termination - 100 Ohms



Termination - 75 Ohms

Termination - 52.3 Ohms

Figure 8 Reflection Match Views

As a note, CAT6 cable has a higher common mode impedance. This is expected due to the significant difference in its construction. It is anticipated that also due to its method of construction that the characteristic impedances will be much more uniform both vs. each other and along the length of the cable. I have only measured one CAT6 cable and that one cable yielded 86.5 ohms for $Z_{1\text{-}3}$.

Analysis - Theoretical

Figure 1 shows the model for computation of the termination resistor given Z_{nn} and R, the termination resistor. The theory is that when the input impedance is equal to the value of R/3 + $Z_{1\text{-}3}$ then the cable is matched. The value used for Z_{nn} was 200 ohms, which is close to correct. With this value for $Z_{nn,}$ R turns out to be 52.3 ohms. This agrees with the pulse reflection test.

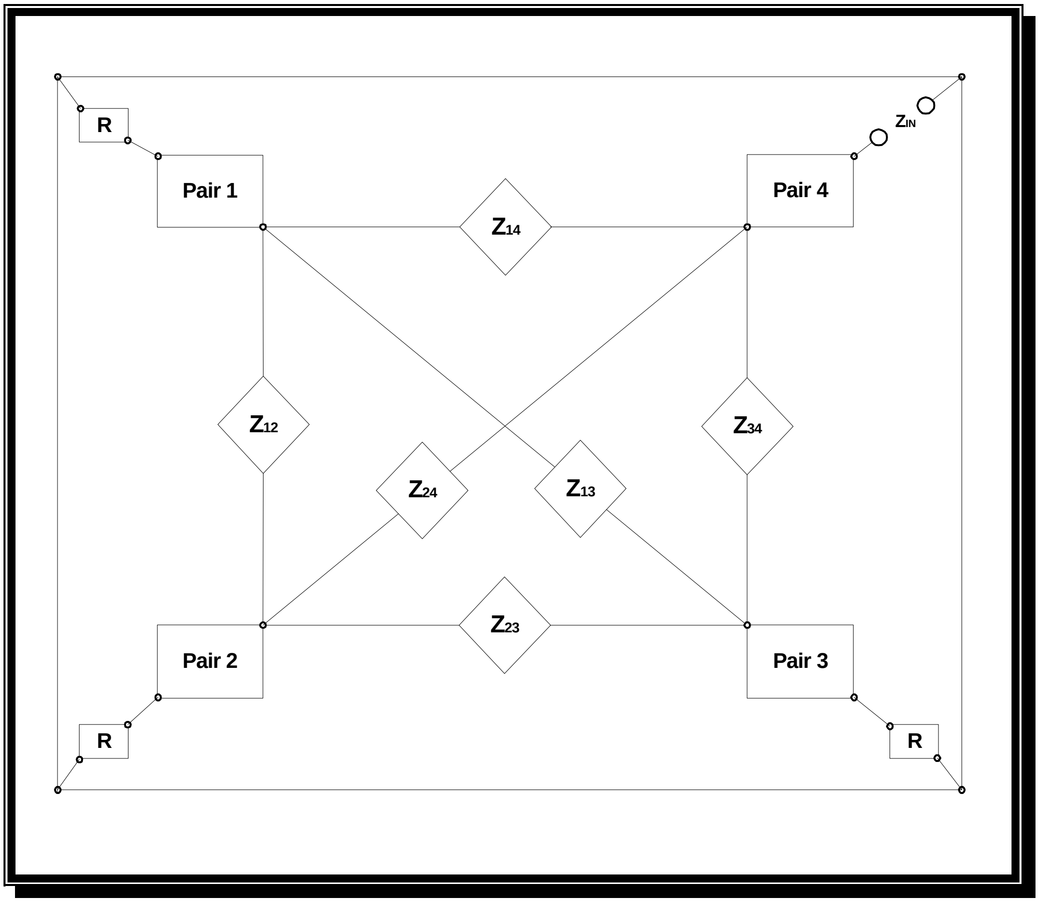


Figure 9 Model for Analytic Computation of Match

The solution is simple and obvious - once viewed. In Figure 9, short pair 1 to pair 2 to pair 3. See Figure 10. In this case we have the $Z_{1\text{-}3}$ characteristic impedance and the three resistors, R are tied in parallel, yielding R/3 for the resistors. Then looking into the terminals indicated, the impedance will clearly be Znn/3 plus R/3. Thus, R+ R/3 equal to Znn/3 would be the proper match resistance.

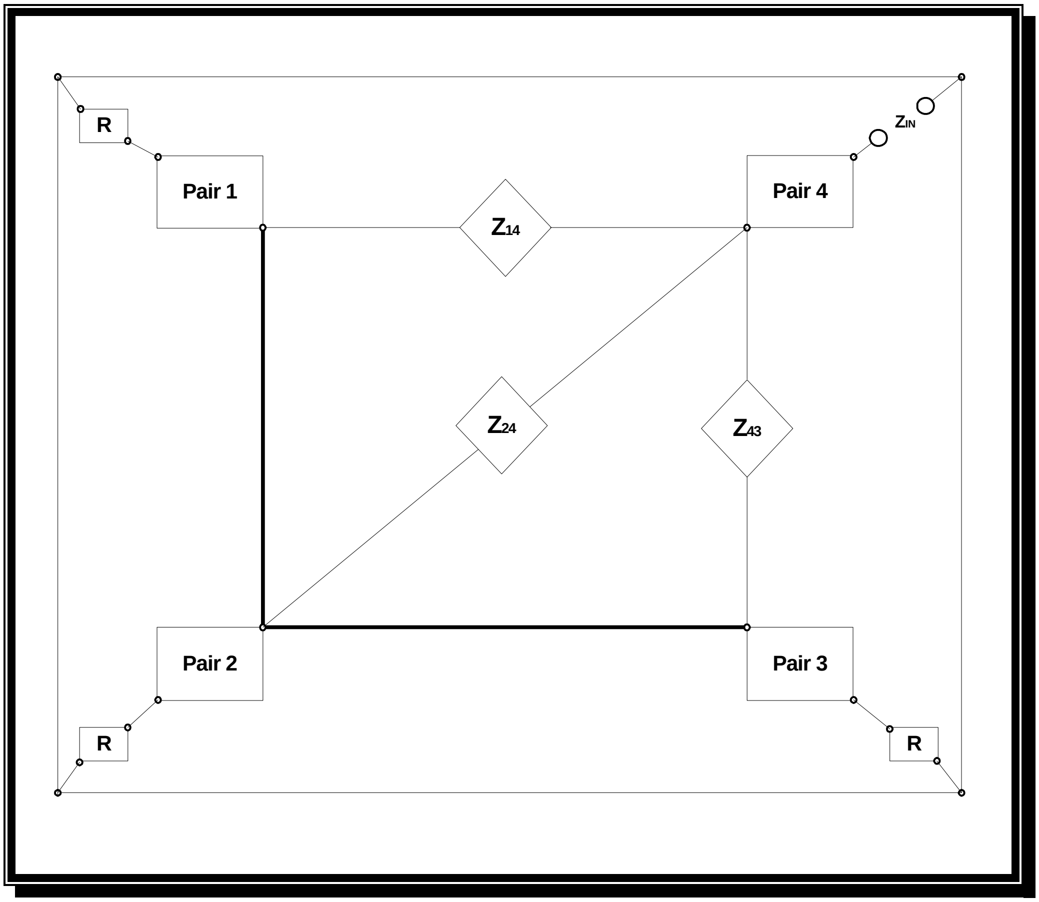


Figure 10 Pairs 1, 2 & 3 Shorted Together

Now, if the short is removed, due to symmetry, nothing is changed since no current flows through Z_{13}, Z_{12} and Z_{23}. This verifies that the approach reported above is correct.

As the values of Znn depart from symmetry, the analysis is no longer strictly correct. However, for practical purposes, the departure for real CAT5 cable is not really significant.

CAT6 Cable

As stated above, the common mode characteristic impedance of CAT6 cable will be higher than for CAT5 and CAT5e cable. The proper common mode termination for CAT6 cable will be about 66 ohms vs the 52.3 ohms for CAT5 cable. If it is envisioned that there will be a mixture of CAT5 and CAT6 in a predominance of installations, then a compromise value between the two would probably be appropriate.

Acknowledgement

This work was performed while the author was an employee of Cicada Semiconductor. Vitesse Semiconductor has since purchased Cicada Semiconductor.

Further Work

It is necessary to characterize more cable of different types and from different manufacturers in order to determine more accurate and meaningful values for the pair to pair characteristic impedance.

Jim Satterwhite
President &
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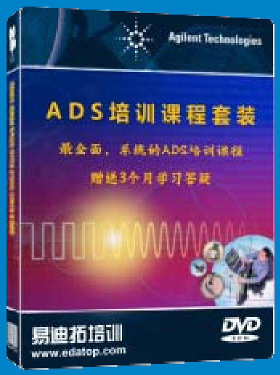

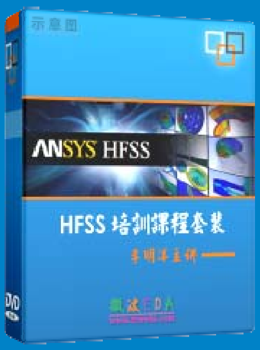

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