Impedance Terminations

What's the Value

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There is a lot of confusion in the industry about "differential impedance." I wrote a column last August[1] specifically on this topic. In hindsight I can see that the article may have been too specific, because it looked specifically at differential impedance, and not at impedance in general. The article pointed out that in the case of differential signals, a transmission line terminating resister needs to be adjusted by a correction factor related to the coupling between two traces. But in fact, **IT IS ALWAYS TRUE** that the proper terminating resister for a transmission line needs to be adjusted for adjacent trace coupling! Here's why:

Figure 1 illustrates a typical (transmission line) trace with voltage V1, impedance Zo and current i. Figure 1 (b) illustrates the general case of two traces fairly close together. By convention we call the intrinsic impedance of trace 1 Z11 (instead of Zo) and that for trace 2 Z22. The coupling coefficient between the traces is k, so the induced current from trace 2 into trace 1 has a magnitude k*i2. Thus the total current on trace 1 is i1 + k*i2. Now here's the bad news: The voltage at any place on Trace 1 Is:

V1 = i1*Z11 + k*i2*Z11

Therefore, the impedance on trace 1 **at any point** is:

V1/i1 = Z11 + Z11*k*i2/i1 Eq. 1

Lets define a term Z12 = Z11*k*i2/i1. This is that portion of the impedance of trace 1 caused by mutual coupling from trace 2. When we do this, we get the impedance along trace 1 as

V1/i1 = Z11 + Z12 Eq. 2

You will find this equation in almost all textbooks that discuss signal networks and generalized signal analyses. Eq. 2 can be generalized for any number of traces and is often expressed in matrix algebra form. These kinds of signal analysis problems are usually solved using matrix algebra.

Since this is the impedance along Trace 1 **at any point**, it is also the impedance at the end point. It is, therefore, the proper terminating impedance for the trace. Therefore, **all** transmission lines need to be terminated, **not** in their characteristic impedance Zo, but in a terminating resistance Zo **adjusted for** this coupling impedance. That's the bad news.

Now what are the practical implications for this? Let's look at several cases.

- If trace 2 is far away, then k is very small. In this case, Z12 is negligible and is ignored.
- If i2 is zero then Z12 is zero and has no effect.
- If i2 is very small compared to i1, then Z12 is very small and can be ignored.

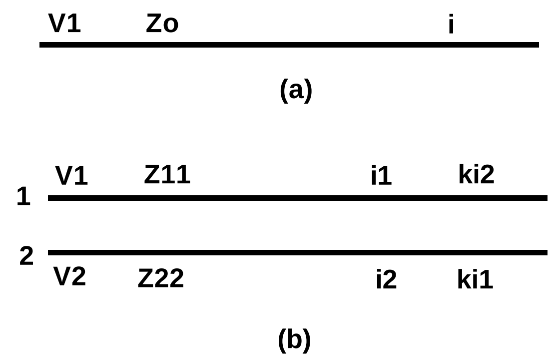

Figure 1.
Single trace (a) and coupled traces (b)

- If i2 is constant, then k is zero – only **changing** currents couple into adjacent traces.

So far, even though it is true that the terminating resister must be adjusted for Z12, the adjustment is zero or negligible and is ignored. But here is a more troubling case. What if trace 2 is close to trace 1, caries a significant current, and that current is totally uncorrelated with i1? By uncorrelated I mean there is no relationship whatever between the two currents. This is typical for most cases where signal buses route close together across a board. For the purposes here lets think of current i2 as being purely random in nature.

In this case we **would** adjust for Z12 if we could. But Z12 is a random variable and is constantly changing. Therefore, what value do we use? Well the **average** value of Z12 is zero, so we do not adjust for it and we continue to use simply Zo as the best choice for the terminating resister. That doesn't mean that there won't be noise on Trace 1 caused by this coupled current. There most certainly will be. In fact we know that noise as crosstalk!

So, even though it is true that we should always adjust trace terminations to correct for adjacent trace coupling, it turns out that in almost every case the correct adjustment is zero. That's the good news. And that's why we rarely see this discussed.

Now, let's take a very special case. Suppose current i2 is **exactly** correlated with i1. Then, at least conceptually, we know exactly what Z12 is and we should always adjust for it. The adjustment may be plus or minus, depending on the correlation.

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When is i2 correlated with i1? In the case of differential signals, i2 is exactly –i1 (minus i1) and in the case of common mode signals i2 is exactly equal to i1. So for differential signals the proper trace termination is Z11-Z12 and for common mode signals the proper termination is Z11+Z12. It is easy to say this. It is a little more difficult to actually calculate it! I discuss the calculation issues in the previous article.

Now, many of us have seen the expression that differential impedance is 2*(Z11-Z12). Where does the factor 2 come from? Well, the proper termination for **each** trace is Z11-Z12. That is the case if we were terminating to ground (half way between V1 and V2). But if i1 equals -i2 and if both terminating resisters were connected to ground, there would be no net current through ground. Every increment of current through R1 would return through R2. So why connect them to ground? There is no benefit to connecting them to ground, since ground is not needed at all. And there is one big disadvantage to connecting them to ground. Even the best ground has some noise on it. Why would you connect a noise source (ground) to your signals if you didn't need to? The answer is that you most assuredly would not. What you would do is connect Trace 1 directly to Trace 2. The correct value for this termination would be R1 + R2 or 2*R1 or 2*(Z11-Z12). That's where the differential impedance formula comes from!

The case for common mode signals differs in only two respects. The sign of Z12 is changed, so the correct termination is Z11+Z12, and the common mode termination impedance is calculated as (Z12+Z12)/2. This is because both terminating resisters **do** connect to ground in the common mode case, so they appear to the circuit as a pair of parallel resisters. Therefore, the common mode impedance is expressed as the parallel equivalent of the two terminations.

Footnotes

1. "Differential Impedance, What's the Difference", PC Design, August, 1998, p.34