Differential Signals

The Differential Difference!

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Most of us intuitively understand the nature of a signal propagating down a wire or a trace, even though we might not be familiar with the name given to this type of wiring strategy --- single-ended mode. The term "single-ended" mode distinguishes this approach from at least two other types of signal propagation, differential mode and common mode. These latter two often seem much more complicated to people.

Differential mode*: ** Differential mode signals propagate through a *pair* of traces. One trace carries the signal as we normally understand it, the other carries a signal that is (in theory, at least) exactly equal and opposite. Differential and single-ended modes are not quite as different as they may initially appear. Remember, ALL signals have a return. Single ended mode signals return, typically, through the zero-voltage, or ground, circuit. Each side of a differential signal ***would return through the ground circuit, except that since each signal is exactly equal and opposite, the returns simply cancel (with no part of them appearing on the zero-voltage or ground circuit).

Although I won't spend much time on it in this column, common-mode refers to signals that occur on **both** traces of a (differential) signal pair or on **both** the single-ended trace and ground. This is not intuitively easy for us to understand, because we have trouble envisioning how we can generate signals like that. It turns out that usually *we* don't generate common-mode signals. They are most often noise signals generated by spurious conditions within our circuit or coupled into our circuits from adjacent or outside sources. Common-mode signals are almost always "bad," and many of our design rules are designed to try to prevent them from occurring.

Routing Differential Traces: Although this may appear to be an awkward order, I am going to describe routing guidelines for differential signals before I describe the advantages of using them in the first place. Then, when I discuss the advantages (below), I will be able to explain how the guidelines relate to and support those advantages.

Most of the time (there are some exceptions), differential signals are also high-speed signals. Thus, high-speed design rules normally apply, especially with respect to designing our traces to look like transmission lines[1]. This means we must be careful to design and lay out our traces in such a way that the characteristic impedance of the trace is constant everywhere along the trace.

In laying out differential pairs, we want each individual trace to be identical to its pair. That means, to the maximum extent practical, each trace in a differential pair should have the identical impedance and should be of the identical length. Differential traces are normally routed as pairs, with the distance between them being a constant at every point along the way. Normally, we try to rout differential pairs as closely together as possible.

Differential Signal Advantages: Single-ended signals are normally referenced to some sort of "reference" level. This may be the positive or ground voltage, a device threshold voltage, or another signal somewhere. A differential signal, on the other hand, is referenced only to its pair. That is, if the voltage on one trace (+ signal) is higher than on the other trace (- signal), we have one logical state, if it is lower we have the other logical state (see **Figure 1**). This has several advantages:

(a) Timing is much more precisely defined, because it is easier to control the crossover point on a signal pair than it is to control an absolute voltage relative to some other reference. This is one of the reasons for exactly equal length traces. Any timing control we have at the source could be compromised if the signals arrive at different times at the other end. Furthermore, if signals at the far end of the pair are not exactly equal and opposite, common-mode noise might result which might then cause signal timing and EMI problems.

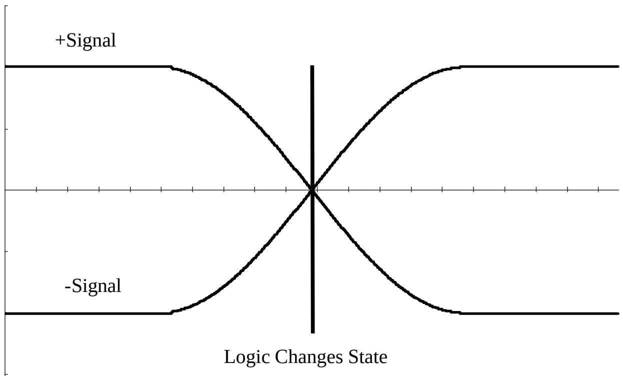

Figure 1
Logic state changes at the single point where the differential signal curves cross.

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(b) Since they reference no other signals than themselves, and since the timing of signal crossover can be more tightly controlled, differential circuits can normally operate at higher speeds than comparable single-ended circuits.

(c) Since differential circuits react to the ***difference*** between the signals on two traces (whose signals are equal and opposite) the resulting net signal is twice as large, compared to ambient noise, as is either of the single-ended signals. Therefore, differential signals, all other things equal, have greater signal/noise ratios and performance.

Differential circuits are sensitive to the difference in the signal level on the paired traces. But they are (relatively) insensitive to the absolute voltage level on the traces compared to some other reference (especially ground). Therefore, differential circuits are relatively insensitive to such problems as ground bounce and other noise signals that may exist on the power and/or ground planes, and to common mode signals that may appear equally on each trace.

Differential signals are somewhat immune to EMI and crosstalk coupling. If the paired traces are routed closely together, then any externally coupled noise will be coupled into each trace of the pair equally. Thus the coupled noise becomes “common mode” noise to which the circuit is (ideally) immune. If the traces were “twisted” (as in twisted pair) the immunity to coupled noise would be even better. Since we can’t conveniently twist differential traces on a PC board, placing them as close together as practical is the next best thing.

Differential pairs that are routed closely together couple closely to each other. This mutual coupling reduces EMI emissions, especially compared to single-ended traces. You can think of this as each trace radiating equal but opposite to the other, thus canceling each other out, just like signals in a twisted pair do! The more closely the differential traces are routed to each other, the greater the coupling, and the less will be the potential for EMI radiation.

Disadvantages: The primary disadvantage of differential circuitry is the increased number of traces. So, if none of the advantages are particularly significant in your application, differential signals and the associated routing considerations are not worth the cost in increased area. But if the advantages make a significant difference in the performance of your circuit, then increased routing area is the price we pay.

Impedance Issues: Differential traces couple into each other. This coupling affects the apparent impedance of the traces, and therefore the termination strategy employed (see Footnote 2 for a discussion on this issue and for suggestions on how to calculate differential impedance.) Calculating differential impedance is difficult. National Semiconductor has some references here, and Polar Instruments offers a standalone calculator (for a fee) that can calculate differential impedance for many different differential configurations[3]. High-end design packages also will calculate differential impedance.

But note that it is the coupling that *directly* affects the differential impedance calculation. The coupling between the differential traces must remain constant over the entire length of the trace(s) or there will be impedance continuities. This is the reason for the “constant spacing” design rule.

Footnotes:

1: See, for example, PCB Impedance Control”, PC Design, March, 1998, and “What’s All This Critical Length Stuff, Anyhow?” PC Design, October, 1999.

2: “Differential Impedance, What’s the Difference,” PC Design, August, 1998

3: See their web page at **http://www.polarinstruments.com/**