Differential Signaling

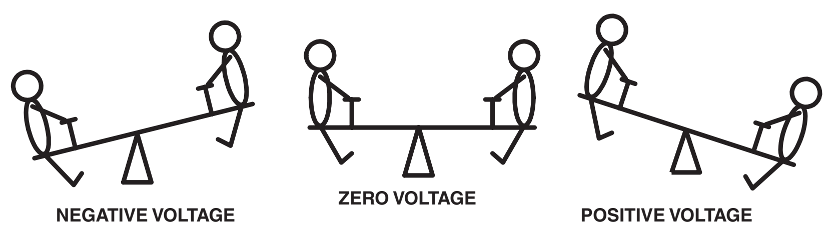
May 2001 Application Note AN6019

What is a Differential Signal?

A differential signal is one that represents a value as the difference between two physical quantities. In a strict sense, all voltage signals are differential, as a voltage can only be measured with respect to another voltage. In some systems the reference against which a voltage is measured is the system 'ground.' Signaling schemes in which 'ground' is used as the voltage measurement reference are called single-ended. This term is used because signals are represented by a voltage on a single conductor.

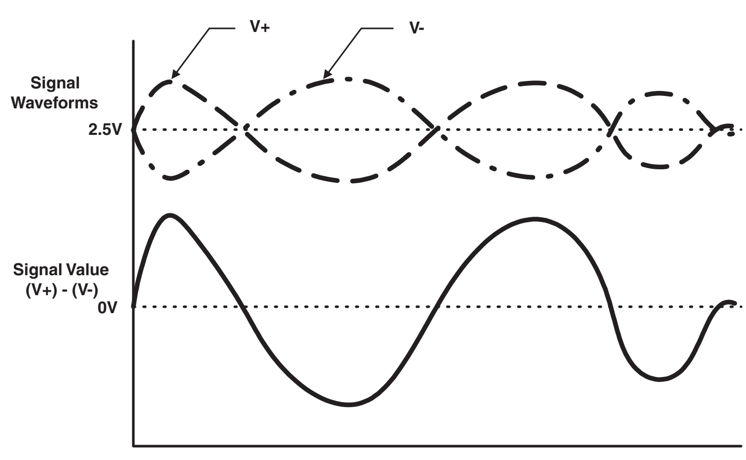
A differential signal, on the other hand, is carried on two conductors. The signal value is the difference between the individual voltages on each conductor. Although not necessary, the average of the two voltages will often remain the same. One way to visualize a differential signal is as two people on a seesaw; as one goes up, the other goes down - but their average position remains the same. To continue the seesaw analogy, a positive value may be represented by the left person being higher than the one on the right, while a negative value is represented by the right person being higher. Zero is represented when the two people are level with each other.

Figure 1. Differential Signaling with a Seesaw



Electrically, the two seesawyers are replaced by a pair of wires labeled V+ and V-. When V+ > V-, the signal is defined as positive, while when V+ < V-, the signal is defined to be negative.

Figure 2. Differential Signal Waveforms and Single-ended Equivalent



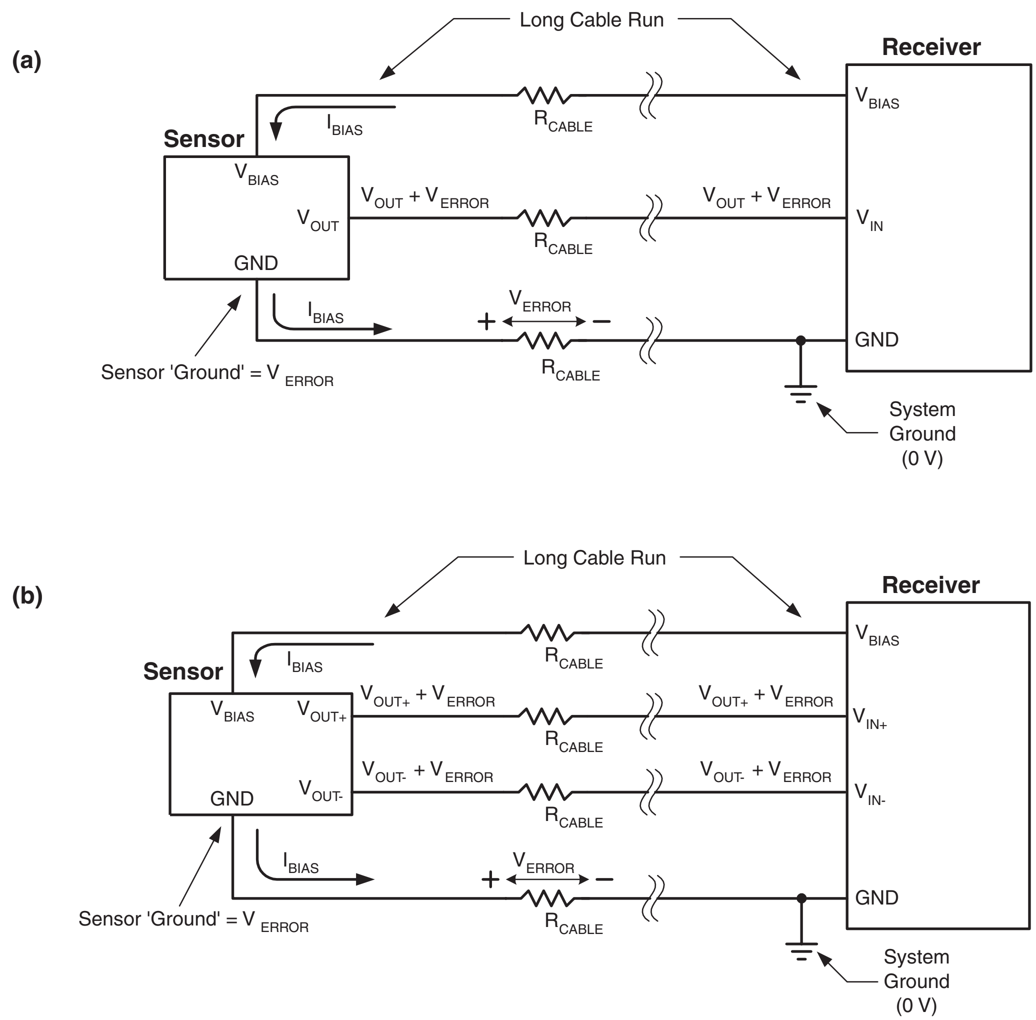
The average voltage around which the differential pair of Figure 2 swings is set to 2.5V and is after referred to as the 'common-mode' component of the differential signal. Offsetting the pair in this way provides the maximum range of signal swing when the individual members of the pair are limited to a 0-5V excursion. This is often the case when operating from a single 5V power supply.

Benefits of Differential Signaling

By moving from a single-ended to a differential signaling scheme, one replaces a single wire with a pair of wires, and doubles the complexity of any associated interface circuitry. What tangible benefits does differential signaling provide to justify this increase in complexity and cost?

The first benefit of differential signaling is that because you are controlling the ‘reference’ voltage, smaller DC signals can be easily discriminated. In a ground-referenced, single-ended scheme, the exact value of the signal measured depends on the consistency of ‘ground’ within a system. The further apart the signal source and the signal receiver are, the greater the likelihood that there will be a discrepancy in the values of their local grounds. In a differential signaling system, the recovery of signal value from a differential signal is largely independent of the exact value of ‘ground,’ within certain limits.

Figure 3. Single-ended (a) vs. Differential (b) Signal Transmission



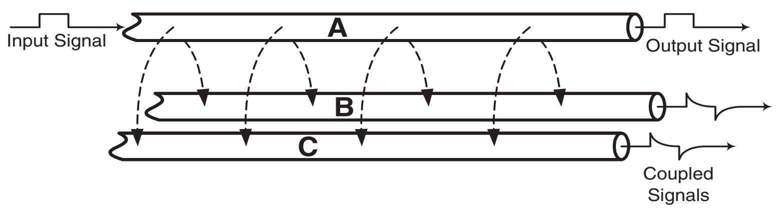
An example illustrating this effect in a single-ended system is shown in Figure 3a. Here, the bias current (I_{BIAS}) required to operate the sensor assembly introduces a voltage error (V_{ERROR}) along the ground-return line. Because the output of the sensor is referenced to its local ground, the actual voltage appearing at the signal output (V_{OUT}) will be $V_{OUT} + V_{ERROR}$. Since the current drawn along the signal line will typically be very small, there will not usually be a significant voltage drop along it. This combination of a voltage drop along the ground lead combined with no voltage drop in the signal lead results in a measurement error which will be roughly proportional to cable length.

In a differential signaling system, such as the one shown in Figure 3b, there will still be an error from ground voltage shifts errors, which will be reflected as errors in each of the differential signal output lines (V_{OUT+}, V_{OUT-}). In this case, however, because V_{ERROR} adds equally to both of the differential output signals, it is ignored as it does not change the difference between the signals.

While the problem of local ground shifts is common when signals are transmitted over a distance, the same effects can also be seen on smaller scales, such as between different printed circuit boards in a single assembly. Depending on the circumstances, and the required accuracy, there are times when it may even make sense to use differential signaling to transmit voltages signals between different parts of the same circuit board!

The second major benefit of differential signaling is that it is highly immune to outside electromagnetic interference (EMI) and crosstalk from nearby signal conductors. An interference source will affect each side of a differential signal almost equally if the two conductors in a differential pair are routed closely together, be they part of a cable or traces on a printed circuit board (PCB). An example of how this works is shown in Figure 4. A signal on wire ‘A’ can couple (through mutual capacitance or inductance) to other nearby wires, in this case labeled ‘B’ and ‘C’.

Figure 4. Signal Coupling to a Differential Pair



Because both the ‘B’ and ‘C’ conductors are close to each other, their coupling to the ‘A’ conductor will be roughly equal. This will result in similar amounts of cross-talk (interference) being impressed on both the ‘B’ and ‘C’ conductors. If ‘B’ and ‘C’ were single-ended signals, this additional noise might be difficult to identify and remove. Because the signal value in a differential system is determined by the difference in voltages, however, any signal occurring equally on the two conductors, such as noise, can be removed from the signal.

In addition to being less susceptible to interference, differential signals also tend to produce less electromagnetic interference (EMI) than single-ended signals. This is because changes in signal level (dV/dt, dI/dt) in the two conductors create opposing electromagnetic fields that tend to cancel each other out, reducing crosstalk and spurious emissions.

A third benefit provided by differential signaling is the ability to easily and accurately process ‘bipolar’ signals in a single-supply system. To handle a bipolar signal in a single-ended, single-supply system, one must establish a virtual ground at some arbitrary voltage between ground and the supply rail (often at the midpoint). Positive signals are represented by voltages above virtual ground, and negative signals are represented by voltages less than virtual ground. The virtual ground must then be accurately distributed throughout the system. For a differential signal, no such virtual ground is needed, allowing one to process and transmit bipolar signals with a high degree of fidelity without relying on the stability of a virtual ground.

Additionally, a differential signaling system provides twice the dynamic range for a given amount of signal swing. For example, in a system operating from a single +5V power supply, a single-ended signal may only be able to swing between 1V and 4V. A single-ended system using this voltage range with a 2.5V virtual ground, would have an effective signal range of +/-1.5V around 2.5V. A differential signaling system with the same signal swing would be able to represent signals over a +/3V magnitude; twice the dynamic range of the single-ended system.

When to Use Differential Signal Processing

Because differential signal processing does have a cost associated with it in terms of increased component and interconnection costs, it is not necessarily the best approach to every signal processing system. In many situations, however, differential signal processing can provide performance benefits that outweigh the additional costs:

1. **When the signals are small.**
   When handling very small signals, with amplitudes measured in millivolts or microvolts differential signal processing can yield significant benefits in maintaining signal integrity. Because of reduced sensitivity to power-supply noise, signals coupling from nearby conductors, and local ground shifts, a fully differential amplifier can often provide better noise and voltage offset performance than a single-ended one.
2. **When there is a lot of noise.**
   In certain applications, ambient electrical noise can be comparable to full-scale signal levels. One common example of such an environment is under the hood of an automobile, where noise from the ignition system can wreak havoc with improperly designed electronics. In a situation such as this, a differential circuit handles a high degree of common-mode noise on both the power supply and signal inputs, and still recovers the 'real' signal from the noise.
3. **When signals need to run over a distance.**
   Because differential signaling reduces the effects of local ground shift, it can be useful when it is necessary to send a signal a significant distance. Depending on the application, a 'significant' distance may be as little as a few inches across a printed circuit board.
4. **When the signal source is balanced to begin with.**
   Many signal sources are naturally 'balanced', and readily provide signals in differential form. This is especially true for sensors and transducers, where a Wheatstone bridge is often used to develop an output signal. In cases such a these, it is almost always necessary to process the signal differentially, at least in the 'front-end' amplifier electronics.

Conclusion

Differential signaling is a method for handling analog signals that can be useful in situations where maintaining a high degree of signal integrity is important. Increased noise immunity, reduced susceptibility to local ground shifts and the ability to easily represent bipolar signals in systems operating from single power supplies are just a few of the benefits of differential signaling.

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