The Balanced Interface

By Bill Whitlock

This is the second of seven installments in Bill Whitlock's series on issues that relate to hum and noise pickup and prevention within and between circuits.

The purpose of a balanced audio interface is to efficiently transfer signal voltage from driver to receiver while rejecting noise and interference. Used with suitable cables, balanced interfaces can reject noise caused by ground voltage differences, as well as noise caused by external electric and magnetic fields acting on the cables.

However, the true nature of balanced interfaces is widely misunderstood. For example, "Each conductor is always equal in voltage but opposite in polarity to the other. The circuit that receives this signal in the mixer is called a differential amplifier and this opposing polarity of the conductors is essential for its operation."[3] This, like many explanations in print (some in otherwise respectable text and reference books), describes *signal symmetry*—"equal in voltage but opposite in polarity"—but fails to even mention the single most important feature of a balanced interface:

- Signal symmetry has absolutely nothing to do with noise rejection.
- Impedance is all that matters!

A good, accurate definition for a balanced interface:

"A balanced circuit is a two-conductor circuit in which both conductors and all circuits connected to them have the same impedance with respect to ground and to all other conductors. The purpose of balancing is to make the noise pickup equal in both conductors, in which case it will be a *common-mode* signal, which can be made to cancel out in the load."[4]

In other words, the *impedances*, with respect to ground, of the two signal lines is what defines an interface as balanced or unbalanced. In an unbalanced interface, one line is grounded, making its impedance approximately zero, while the other line has some higher impedance. In a balanced interface, the two lines are made to have equal impedance. It's also important to understand that line impedances are affected by *everything* connected to them. This includes the line driver, the line or cable itself, and the line receiver.

A line receiver uses a differential amplifier to reject common-mode voltages. The IEEE dictionary defines a differential amplifier as "an amplifier that produces an output only in response to a potential *difference* between its input terminals (differential-mode signal) and in which output due to common-mode interference voltages on both its input terminals is suppressed."[5] Because transformers have *intrinsic* differential response, any amplifier preceded by an appropriate transformer becomes a differential amplifier.

The basic theory of the balanced interface (***Fig. 1***) is straightforward. (For purposes of this discussion, assume that the ground reference of Device A has a noise voltage, which I will call "ground noise," with respect to the Device B ground reference.) If you look at the HI and LO inputs of Device B, you can see audio signals (if present) plus the ground noise. If the voltage dividers consisting of $Z_0/2$ and Z_{CM} on each of the lines have identical ratios, you'll see identical noise voltages at the two inputs of Device B. Because there is no difference in the two noise voltages, the differential amplifier generates no output and the noise is rejected.

Because the audio signal from Device A generates a voltage difference between the Device B inputs, it appears at the output of the differential amplifier. Therefore, you can completely reject the ground noise if the voltage divider ratios are perfectly matched. In the real world, you can't perfectly match the voltage dividers to get infinite rejection. However, you can get 120dB of common-mode rejection if you match them to within 0.0001% or 1 part-per-million!

Because the ground noise received from Device A exists on or is *common* to both wires, it is called the *common-mode* voltage, and the differential amplifier provides *common-mode rejection*. The ratio of differential or *normal-mode* (signal) gain to the common-mode (ground noise) gain of the interface is called the *common-mode rejection ratio* or CMRR (called "longitudinal balance" by telephone engineers) and is usually expressed in dB. There is an excellent treatment of this subject in Morrison's book[6].

If you re-draw the interface as shown (***Fig. 2***), it takes the familiar form of a Wheatstone bridge. The ground noise is "excitation" for the bridge and represented as V_{CM} (common-mode voltage). The common-mode impedances of the line driver and receiver are represented by $R_{CM}+$ and $R_{CM}-$. When the + and – arms have identical ratios, the bridge is nulled and zero voltage difference exists

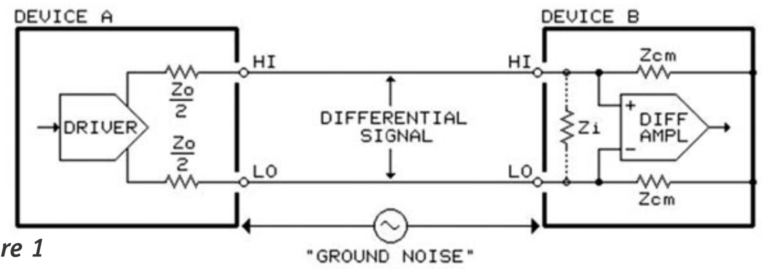

Figure 1

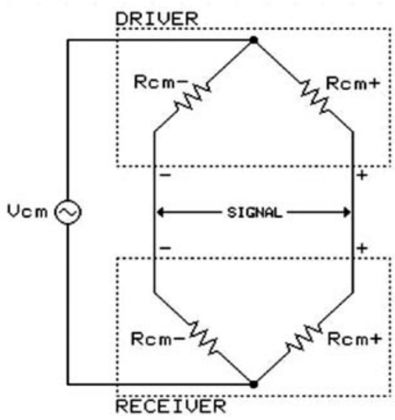

Figure 2

between the lines—infinite common-mode rejection. If the impedance ratios of the two arms are imperfectly matched, *mode conversion* occurs. Some of the (common-mode) ground noise now appears across the line (differential) input as noise that will contaminate the desired signal.

How do you prevent mode conversion in spite of normal component tolerances in mass-produced equipment? Circuit analysis reveals that the bridge is *most* sensitive to small impedance changes in any one of its arms when all arms have the same impedance[7]. It's *least* sensitive when the upper and lower arms have widely differing impedances.

For example, if the lower arms have infinite impedance, no voltage difference can be developed across the line, regardless of how severe the mismatch in upper arm impedances. A similar scenario occurs if the upper arms have zero impedance. Therefore, you can minimize *CMRR degradation* due to *normal component tolerances* by making common-mode impedances very low at one end of the line and very high at the other[8]. The output impedances of virtually all *real* line drivers are determined by series resistors that typically have ±5% tolerances.

Therefore, typical line drivers can have output impedance imbalances in the vicinity of 10Ω. The common-mode input impedances of conventional line receivers are in the 10-50kΩ range, making their CMRR *exquisitely sensitive* to normal component tolerances in line drivers. For example, *the CMRR of the widely used SSM-2141 will degrade about 25dB with only a 1Ω imbalance at the line driver*. Line receivers using input transformers are essentially *unaffected* by imbalances as high as several hundred ohms because their common-mode input impedances are around 50MΩ—over 1000 times that of conventional active receivers.

Note that I have barely mentioned the audio signal. The mechanism that allows noise to enter the signal path works whether an audio signal is present or not. Only balanced *impedances* of the lines stop it. Signal symmetry is simply irrelevant! When subtracted (in the differential amplifier), asymmetrical signals of any given amplitude—a positive signal (such as +1 minus 0 = 1.0), or a negative signal (0 minus –1 = 1.0)—produce exactly the same output as symmetrical signals of the same amplitude (such as +0.5 minus –0.5 = 1.0).

This was summarized in an excerpt from the annex of IEC standard 60268-3: "only the common-mode impedance balance of the driver, line, and receiver play a role in noise or interference rejection. This noise or interference rejection property is independent of the presence of a desired differential signal. Therefore, it can make no difference whether the *desired* signal exists entirely on one line, as a greater voltage on one line than the other, or as equal voltages on both of them. Symmetry of the desired signal has advantages, but they concern headroom and crosstalk, not noise or interference rejection."

In part 3, I'll discuss the history of balanced interfaces, including the ubiquitous 600Ω specification.

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