EMC Course Notes 2024

Propagation Modes and Electrical Balance

Propagation Modes

Three-Conductor Transmission Lines

A transmission line that has two closely spaced conductors supports one mode of propagation, the TEM mode. A transmission line that has three closely spaced conductors supports two independent TEM propagation modes. Examples of common three-conductor transmission lines include trace pairs over a ground plane on a printed circuit board and shielded twisted wire pairs.

Consider the configuration with two parallel traces over a plane illustrated in Figure 7.1. Two signals can be sent down the trace pair by driving each trace relative to the ground plane. Both signals exhibit TEM propagation, but the propagation modes are not independent. Electric and magnetic fields created by the signal driven on Trace 1 induce voltages and currents on Trace 2 and vice versa. This is crosstalk.

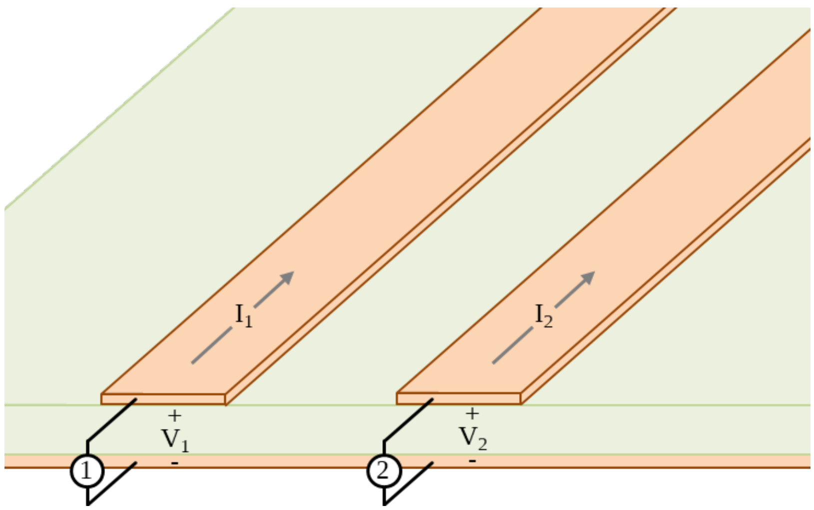

Figure 7.1. Signals on parallel traces.

However, it is possible to identify orthogonal TEM modes that propagate independently of one another. In the case where one of the three conductors is labeled "ground," it is useful to define two independent modes of propagation as follows:

- A *differential-mode* excited by driving the two traces relative to each other as indicated in Figure 7.2a. In this case, the differential-mode signal voltage is $V_{DM} = V_1 - V_2$, where V_i is the voltage of trace i relative to ground.
- And a *common-mode* excited by driving the two traces with the same voltage relative to ground as indicated in Figure 7.2b. The common-mode signal current is $I_{CM} = I_1 + I_2$, where I_i is the current on trace i.

The common-mode current flows out on both traces and returns on the plane underneath them. If the traces have the same impedance to the plane, the common-mode current on each trace will be the same and the trace pair is *electrically balanced*. If the traces do not have the same impedance to the plane (e.g., one trace is wider than the other), then one trace carries more of the common-mode current and the trace pair is unbalanced.

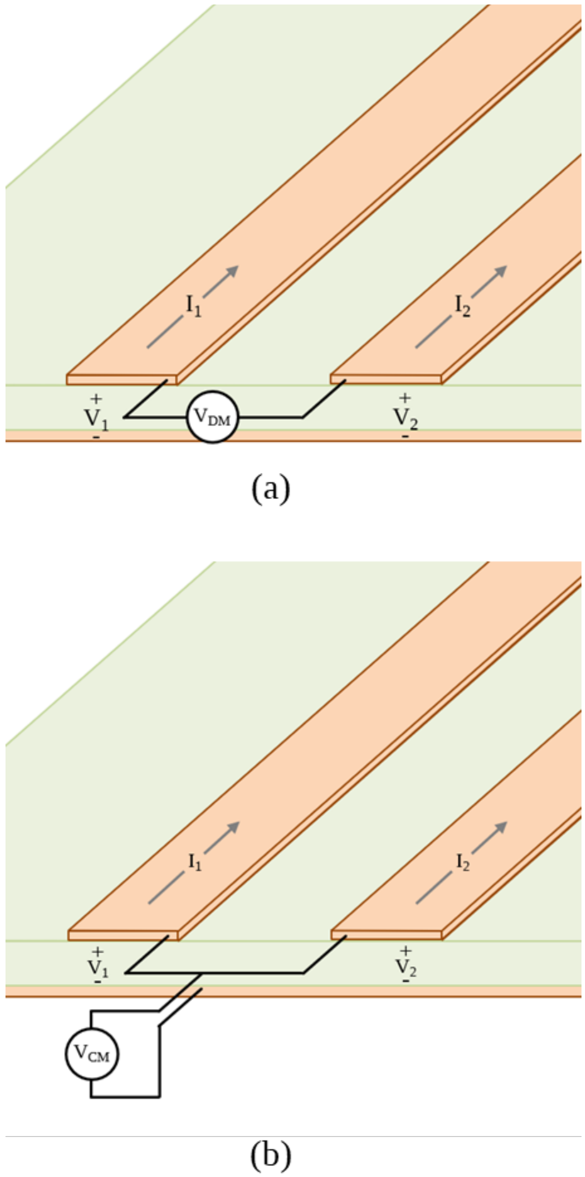

Figure 7.2. Driving a trace pair (a) differential-mode and (b) common-mode.

The amount of electrical imbalance can be quantified as the percentage of the total common-mode current that flows on each trace. The *current division factor* (or *imbalance factor*) is the ratio of the current on Trace 1 to the total common-mode current,

$$h = \frac{I_1}{I_1 + I_2} . \tag{7.1}$$

For balanced transmission lines, (e.g., two identical traces), $h = 0.5$. If all the current flows on Trace 1, then $h = 1$, and if all the current flows on Trace 2, then $h = 0$. The value of the current division factor is always between 0 and 1, with values closer to 0.5 indicating a greater level of balance. For TEM propagation, the current division factor is a function of the geometry and materials. It is independent of the signal sources and terminations.

With the help of the current division factor, the voltages and currents associated with each propagation mode are uniquely defined in terms of the voltages and currents on each conductor,

$$
\begin{aligned}
V_{DM} &= V_1 - V_2 \\
V_{CM} &= hV_1 + (1-h)V_2 \\
I_{DM} &= (1-h)I_1 - hI_2 \\
I_{CM} &= I_1 + I_2 \ .
\end{aligned}
\tag{7.2}
$$

Common-mode propagation and differential-mode propagation are orthogonal, meaning they are both independent and, together, account for all the power propagating in the transmission line. A signal propagating in one of these modes is not affected by a signal propagating in the other mode. Any signal voltage or current propagating on the three-wire transmission line can be fully expressed in terms of its common-mode and differential-mode components,

$$
\begin{aligned}
V_1 &= V_{CM} + (1-h)V_{DM} \\
V_2 &= V_{CM} - hV_{DM} \\
I_1 &= I_{DM} + hI_{CM} \\
I_2 &= -I_{DM} + (1-h)I_{CM} \ .
\end{aligned}
\tag{7.3}
$$

If we launch one common-mode signal and one differential-mode signal, each effectively travels in its own propagation mode and there is no crosstalk between the two. The characteristic impedance of the common-mode transmission line is, $Z_{CM} = Z_1 \| Z_2$, where Z_1 and Z_2 are the partial impedances of each trace to the reference plane as illustrated in Figure 7.3. The characteristic impedance of the differential-mode transmission line is, $Z_{DM} = Z_{12} \| (Z_1 + Z_2)$. Because the two propagation modes are orthogonal, no power is converted from one mode to another unless the cross-sectional geometry changes in a way that affects the value of the current-division factor, *h*. In other words, mode conversion occurs if and only if there is a change in the electrical balance.

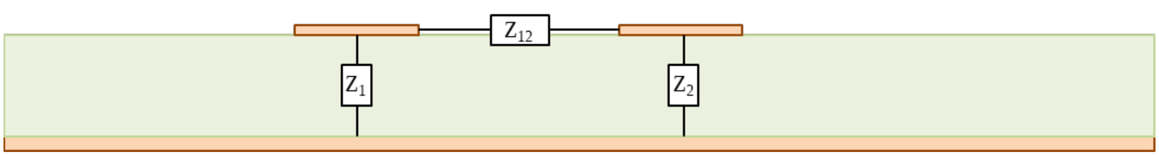

Figure 7.3. Partial impedances between each transmission line conductor pair.

Common Mode on Two-Conductor Transmission Lines

As indicated earlier, two-conductor transmission lines support only one TEM propagation mode. The current flows out on one conductor and back on the other conductor. If we consider the "ground" or zero-volt reference to be infinitely far from the conductor pair, this propagation mode is consistent with the differential-mode propagation in a three-conductor transmission line.

However, in the chapter on electromagnetic radiation, we saw that (due to displacement current) it is possible for current to flow on a conductor without returning on another conductor. This means it is possible to have a component of current that flows in the same direction on both conductors of a two-conductor transmission line. This current is a common-mode current, so it is possible to have both common-mode and differential-mode currents on a two-conductor transmission line. The differential-mode currents are due to TEM propagation on the transmission-line. The common-mode current propagation is not TEM. In fact, the common-mode current does not carry power from the source to the load, but it can be a significant source of radiated emissions and other unwanted coupling.

It is important to note that even though the common-mode current is not associated with transmission line propagation, the definitions of common-mode and differential-mode current still apply,

$$\begin{aligned} I_{CM} &= I_1 + I_2 \\ I_{DM} &= (1-h) I_1 - h I_2 \ . \end{aligned} \tag{7.4}$$

The definition of the differential-mode voltage also still applies,

$$V_{DM} = V_1 - V_2 \ . \tag{7.5}$$

However, without TEM propagation or a nearby zero-volt reference, the common-mode voltage (essentially a voltage to infinity) is no longer uniquely defined.

Nevertheless, it is still possible to calculate the relative common-mode voltage between two nearby points along the transmission line. For example, consider the two sections of parallel-wire transmission line illustrated in Figure 7.4. Both have the same characteristic impedance, however, the line on the left is balanced (h_L = 0.5) and the line on the right is unbalanced ($h_R \neq 0.5$). The differential-mode voltage is the voltage between the pair of wires at any point along the transmission line. This is $V_{DM\text{-}L}$ on the left and $V_{DM\text{-}R}$ on the right. The common-mode current is the sum of the currents on each wire.

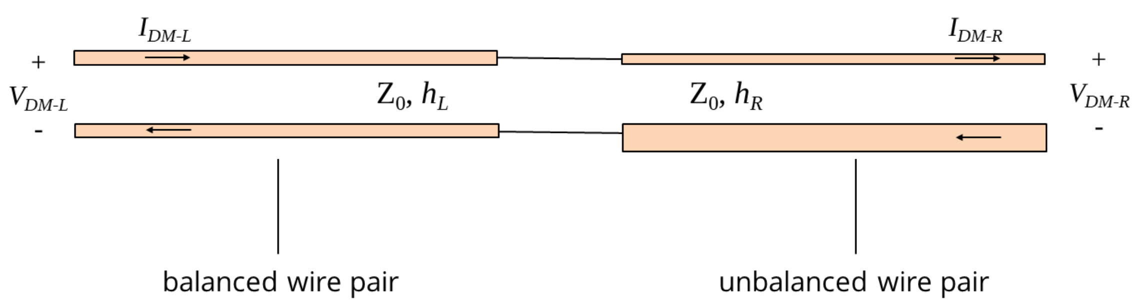

Figure 7.4. Transitioning from a balanced wire pair to an unbalanced wire pair.

At the connection point between the two transmission lines, the currents on each conductor must be continuous. For a differential-mode signal traveling on the balanced wire pair, the currents on each conductor are equal and opposite. When that signal encounters the unbalanced wire pair, the boundary condition requires that the currents remain equal and opposite. However, equal and opposite currents on an unbalanced wire pair are inconsistent with differential-mode propagation. Both differential- and common-mode propagation are required. The transition from a balanced line to an unbalanced line effectively behaves like a common-mode voltage source.

Applying Equation (7.2) on both the left and right sides of the transmission lines in Figure 7.4, while enforcing the boundary conditions $I_{1\text{-}L} = I_{1\text{-}R}$, $I_{2\text{-}L} = I_{2\text{-}R}$, and $V_{DM\text{-}L} = V_{DM\text{-}R}$ yields the value for the effective common-mode voltage at the interface, $V_{CM} = \Delta h \times V_{DM}$.

This is illustrated in Figure 7.5, which shows the effective common-mode source created when a differential-mode signal encounters a change in electrical balance. The amount of common-mode current generated will depend on the input impedance seen by the common-mode source. For two-conductor transmission lines, the common-mode input impedance is effectively an antenna input impedance. It can be calculated using numerical modeling techniques, but EMC engineers are more likely to be interested in the worst-case input impedance. This is likely to be about 72 Ω for a dipole structure or 36 Ω for a monopole structure.

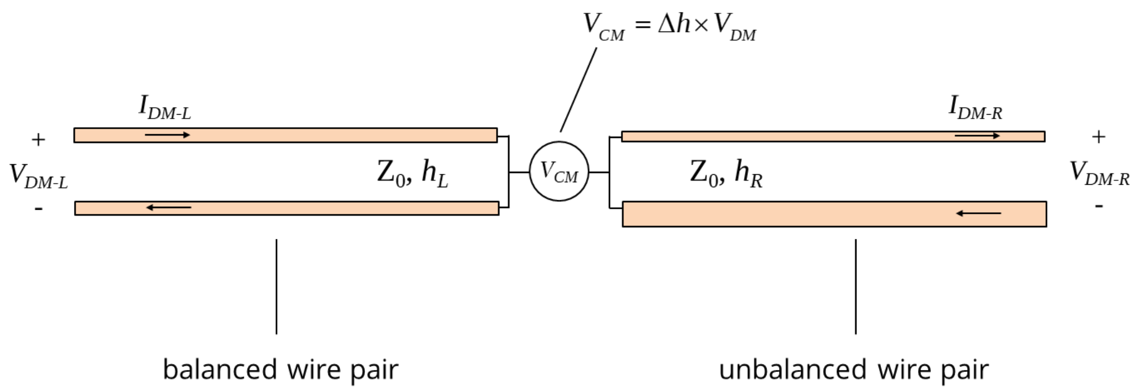

Figure 7.5. A change in the electrical balance creates a common-mode source.

The model in Figure 7.5 applies only to the common-mode. The impact that the change in electrical balance has on the differential-mode is negligible if the power converted to common-mode is a small fraction of the differential-mode power. However, in cases where the common-mode draws a significant amount of power away from a differential-mode signal, the effect of the change in electrical balance can be modeled as a shunt resistance. This is illustrated in Figure 7.6.

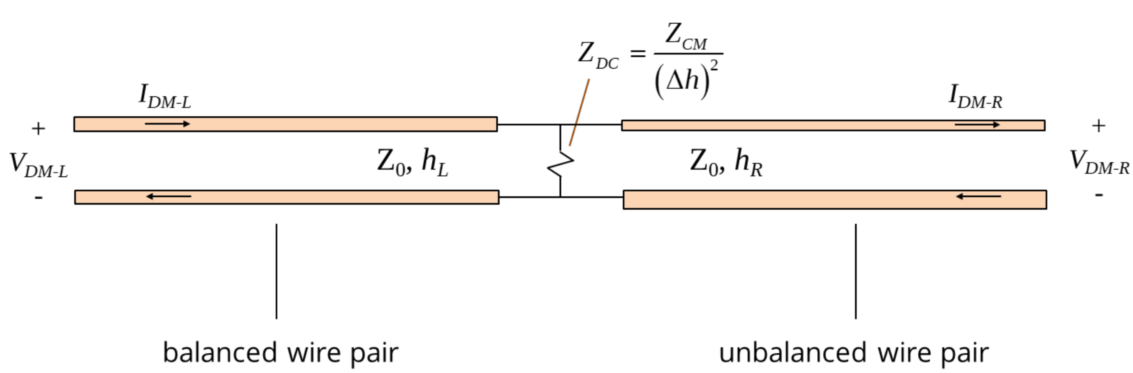

Figure 7.6. Modeling the impact of the imbalance change on the differential-mode signal.

Note that for two-conductor transmission lines, the common-mode and differential-mode currents are still independent. Anywhere the electrical balance does not change, the common-mode current does not affect the differential-mode signal, and the differential-mode signal does not contribute to the common-mode current. Mode conversion occurs only at places where there is a change in the electrical balance.

Electrical Balance

Many electromagnetic interference problems are the direct result of an unintentional mode conversion. And because of this, electrical balance is one of the most fundamental and important concepts in EMC.

Signals are typically conveyed using two closely-spaced conductors. The signal current flows in one direction on one conductor and the opposite direction on the other conductor. This is differential-mode propagation. For differential signaling, the signal conductors are balanced. For single-ended signaling, the conductors are unbalanced.[1]

Any component of the current on a pair of signal conductors that flows in the same direction (i.e., common-mode) is generally associated with noise. Energy unintentionally coupled to or from a signal conductor pair tends to be primarily common-mode.

Mode conversion can only occur when there is a change in the electrical balance of a transmission line. Therefore, to maintain the integrity of a signal, it is important to maintain the same level of electrical balance from the signal source to the signal termination. The general rule for signal transmission is: *If you're balanced, stay balanced; and if you're unbalanced, stay unbalanced*. In other words, if the signal source is balanced, the transmission line and the signal termination should also be balanced. If the signal source is unbalanced, the transmission line and the signal termination should be equally unbalanced.

Digital signal sources generally fall into one of three categories: single-ended, differential, and pseudo-differential. These are illustrated in Figure 7.7. Single-ended sources drive signal current onto a signal conductor such as a trace or wire and the current returns to the source on a current-return conductor that is often labeled "ground". Different single-ended sources typically share the same current-return conductor. Differential signal sources drive a signal current on one conductor and return that current on another conductor with the same impedance to ground. For digital signals, a *balun*[2] is typically used to convert a single-ended signal to a differential signal as illustrated in Figure 7.7.

Pseudo-differential signals are generated by driving two identical signal conductors relative to the same ground. When one side transitions from low-to-high the other side transitions from high-to-low. This puts a common-mode voltage on the signal pair at DC that is half the signal voltage. However, ideally, the voltage at all other frequencies is purely differential.

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[1] Single-ended signaling is always unbalanced because one of the signal conductors is the ground reference and the other is not. Therefore, the two conductors do not have the same impedance to ground.

[2] A balun is a device for connecting a <u>ba</u>lanced circuit to an <u>un</u>balanced circuit without causing a mode conversion. An isolation transformer with one terminal connected to ground is an example of a balun that has a relatively wide bandwidth.

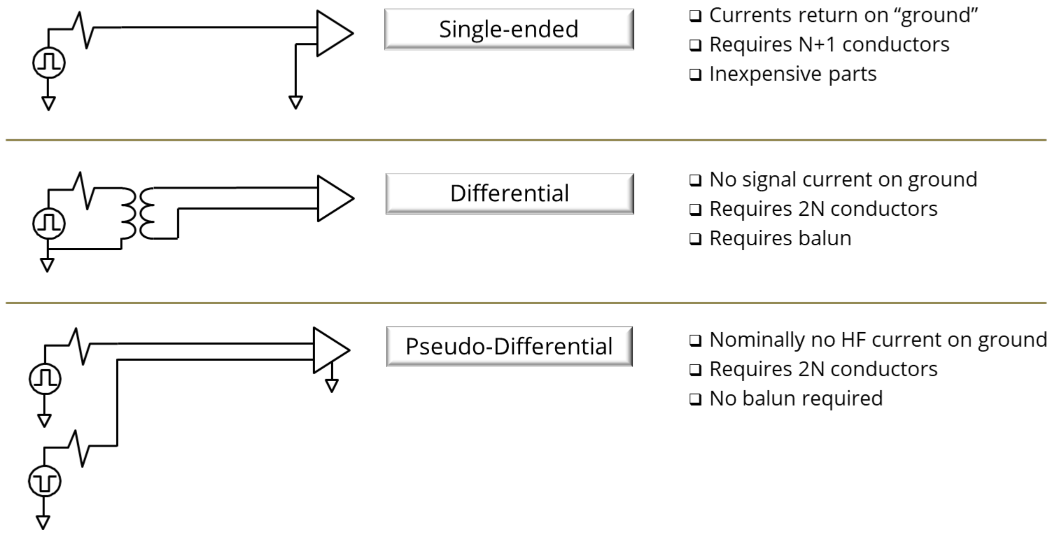


Figure 7.7. Single-ended, differential, and pseudo-differential sources.

Pseudo-differential drivers do not require a balun, which allows them to be smaller and more cost-effective than differential drivers. Many high-speed digital interfaces, including CAN, LVDS, USB and HDMI typically employ pseudo-differential signaling[3]. Unfortunately, due to problems with matching the rising and falling edges in both sides, virtually all pseudo-differential sources produce a significant common-mode voltage spike with every transition. This generally has no impact on the signal integrity, but it can be a significant source of radiated emissions in designs that do not properly account for this common-mode voltage.

Single-ended sources should drive unbalanced transmission lines that are terminated with unbalanced loads. Differential sources should drive balanced transmission lines terminated with balanced loads. Examples of unbalanced and balanced transmission lines are illustrated in Figure 7.8.

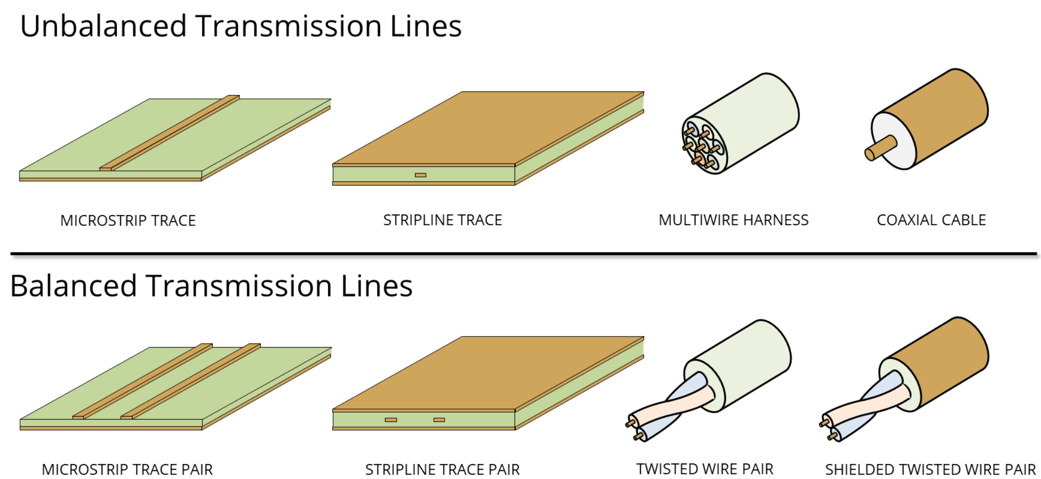


Figure 7.8. Examples of unbalanced and balanced transmission lines.

[3] CAN (Controller Area Network), LVDS (Low Voltage Differential Signaling), USB (Universal Serial Bus), HDMI (High-Definition Multimedia Interface)

Signal terminations are balanced if both terminals have the same impedance to ground. Most two-terminal passive components can be either balanced or unbalanced depending on how they are connected. Differential signal receivers are inherently balanced, but most can be unbalanced simply by connecting one side to ground.

Two Definitions of Common Mode

Two signal conductors are balanced if they have the same impedance to ground. This means that the definition of electrical balance requires that "ground" be identified. For a two-conductor transmission line, "ground" is defined as the potential infinitely far from the conductors and the common-mode conduction current has no defined return path. For the three-conductor transmission line, "ground" is defined as the third (i.e., the non-signal) conductor. This third conductor serves as the return path for the common-mode current.

The common-mode current in the two-conductor transmission line is potentially a significant source of radiated emissions, while the common-mode current in the three-conductor transmission line is not. However, it is possible to have a component of current that flows in the same direction on all the conductors in a three-conductor transmission line as illustrated in Figure 7.9.

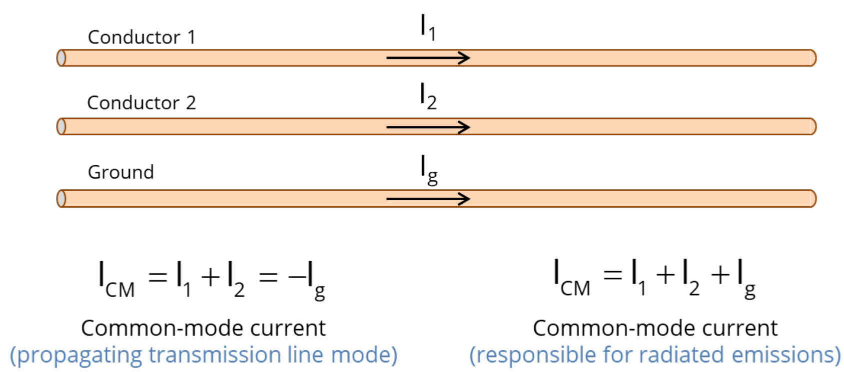


Figure 7.9. Two definitions of common-mode current in a three-conductor transmission line.

In general, a transmission line with N conductors will support N-1 independent TEM propagation modes plus one non-propagating mode[4] whose current is the vector sum of all the currents flowing in the same direction. From a radiated emissions perspective, the TEM propagation modes are usually insignificant. The important current is the current in the non-propagating mode (i.e., the vector sum of the currents on all conductors). This is the current that would be measured with a common-mode current probe.

The fact that the term *common-mode* has different meanings depending on the situation can be confusing. However, whether we are referring to the TEM common-mode (with current returning on a conductor) or the non-propagating common-mode (with no conducted return path), mode conversion is the result of changes in electrical balance. For TEM propagation, electrical balance is defined in terms of the impedances to the ground conductor. For the non-propagating (or radiating) common-mode, electrical balance is defined in terms of the impedances to infinity.

[4] This mode is non-propagating in the sense that it doesn't carry any power from the source to the load. However, it can be responsible for radiated emissions that carry power away from the transmission line.

High-Speed Digital Interface Example

Consider the high-speed digital interface illustrated in Figure 7.10. A differential driver on one circuit board drives a balanced, differential receiver on another board. The signal initially travels on a matched pair of traces over a ground plane. Then it is carried on two wires in a ribbon cable to the second board where it is terminated. Since the differential signal propagates on a balanced trace pair and then a balanced wire pair in the ribbon cable, it never experiences a change in electrical balance, and there is no differential to common-mode conversion.

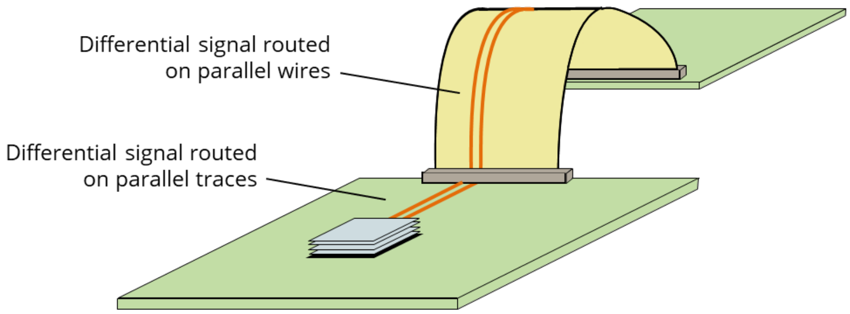


Figure 7.10. High-speed digital interface between two circuit boards.

Suppose, however, that the signal source was pseudo-differential and produced a common-mode voltage spike on the trace pair with every transition. This would put a common-mode current on the trace pair, but the common-mode return current would be on the plane below the traces. This TEM common-mode propagation would not present a radiated emissions problem. In terms of the ground at infinity, this current can be viewed as a differential current on an unbalanced transmission line. One conductor is the trace pair, while the return conductor is the circuit board plane.

The amount of imbalance in this transmission line, where one conductor is the trace pair and the other conductor is the plane, could be calculated using 2D electrostatic modeling software. By bringing all three conductors to the same potential (relative to infinity), we could calculate the charge density on the trace pair, Q_{traces} , and the charge density on the plane, Q_{plane}. The imbalance factor for this transmission line would then be given by,

$$h_{traces} = \frac{Q_{traces}}{Q_{traces} + Q_{plane}} . \tag{7.6}$$

Clearly, the wide plane would hold much more of the charge than the two narrow traces, so the imbalance factor would be a very small number (close to zero).

As the current spike reaches the ribbon cable connection, the ground plane is lost. If there are no other wires in the ribbon cable, the imbalance factor changes dramatically. All the charge in our 2D model would be on the wire pair. This transmission line is also unbalanced, but in the other direction. The imbalance factor is,

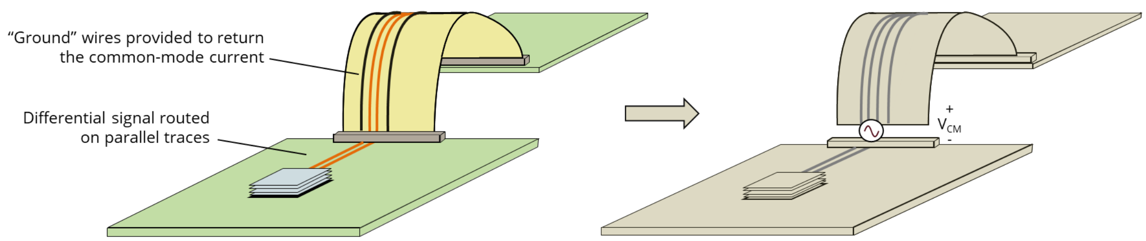
$$h_{ribbon} = \frac{Q_{ribbon}}{Q_{ribbon} + 0} = 1 . \tag{7.7}$$

The change in electrical balance results in a non-propagating common-mode voltage that drives the two wires in the ribbon cable relative to the circuit board. The amplitude of this common-mode voltage is,

$$V_{CM} = (\Delta h) V_{DM} = (h_{ribbon} - h_{trace}) V_{CM-spike} \approx V_{CM-spike} . \quad (7.8)$$

In other words, the entire common-mode spike voltage from the digital source drives the ribbon cable relative to the circuit board.

This is not a surprising result. It doesn't take imbalance difference theory to see that any common-mode voltage from the signal source drives the ribbon cable relative to the circuit board plane. However, suppose the ribbon cable has wires that can return the common-mode current as illustrated in Figure 7.11(a). Now the common-mode spike current can return on nearby conductors. If we define ground at infinity, it is all differential-mode current. But there is still a common-mode voltage driving the ribbon cable. The amplitude of this common-mode voltage is readily determined by performing imbalance difference calculations.



(a) (b)

Figure 7.11. Differential interface with wires provided for returning common-mode current.

Adding the pair of return wires to the ribbon cable did not change the imbalance factor of the trace pair/plane. It is still nearly zero. However, the imbalance factor in the ribbon cable is different. A 2D simulation would show that charging all four wires to the same potential would put nearly the same charge density on each wire. The outer two wires would hold slightly more charge depending on the wire diameters and spacing, but the imbalance factor would be close to 0.5,

$$h_{ribbon} = \frac{Q_{center-wires}}{Q_{center-wires} + Q_{outer-wires}} \approx 0.5 . \quad (7.9)$$

So, the common-mode voltage driving the ribbon cable relative to the circuit board, as illustrated in Figure 7.11(b), would be,

$$V_{CM} = (\Delta h) V_{DM} = (h_{ribbon} - h_{trace}) V_{CM-spike} \approx 0.5\, V_{CM-spike} . \quad (7.10)$$

In other words, almost half the common-mode spike voltage drives the ribbon cable relative to the circuit board even when we provide nearby wires to return the spike currents.

To avoid driving the ribbon cable relative to the board, we could either reduce the common-mode spike voltage or we could match the imbalance of the ribbon cable to the imbalance of the trace/plane structure.

Microstrip to Twisted Pair Example

Another common example of common-mode voltage created by a change in electrical balance is illustrated in Figure 7.12(a). A single-ended source puts a signal on a microstrip trace. The signal then passes through a connector and is transmitted on a twisted wire pair. The microstrip trace is nearly perfectly unbalanced ($h \approx 0$). The twisted pair is nearly perfectly balanced ($h \approx 0.5$). The transition from an unbalanced transmission line to a balanced transmission line generates a common-mode voltage that drives the wire pair relative to the circuit board, as illustrated in Figure 7.12(b).

At low frequencies, this common-mode voltage may not be important. However, at high frequencies (e.g., MHz or higher), the common-mode current on the wire pair can be high enough to present a significant radiated emissions problem.

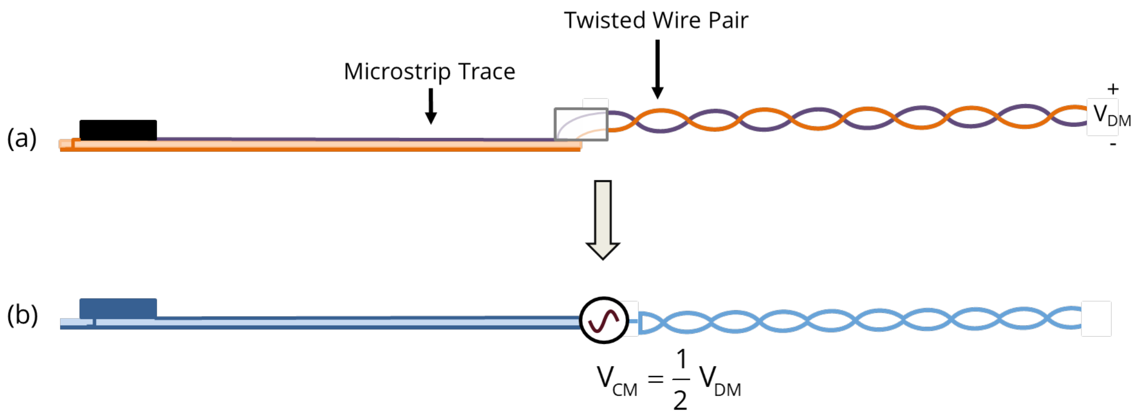


Figure 7.12. Interface between a microstrip trace and a twisted wire pair.

There are several options for reducing this common-mode current including:

- Reduce the high-frequency content of the differential signal voltage by limiting the bandwidth of the signal.
- Use an unbalanced cable (e.g., coax or flex cable with a ground plane) instead of the wire pair.
- Use a differential source and two traces to convey the signal on the circuit board.
- Shield the twisted wire pair and return the common-mode current on inside of the shield.

Of these options, shielding the wire pair may be the least desirable. Shielding tends to be more expensive, and this configuration would put a significant amount of current on the shield requiring the shield to make a low-inductance connection to the board ground.

Differential Signal on Coaxial Cable Example

Figure 7.13 shows a single-ended signal routed on a balanced trace pair. This example was observed in an actual product that was failing radiated emissions. An analog video signal was conveyed from one circuit board to another on a long coaxial cable. The system designers were under the impression that analog grounds should always be isolated from digital grounds. So, they returned the analog video current on a trace above the circuit board's ground plane and connected it to the plane at a single point.

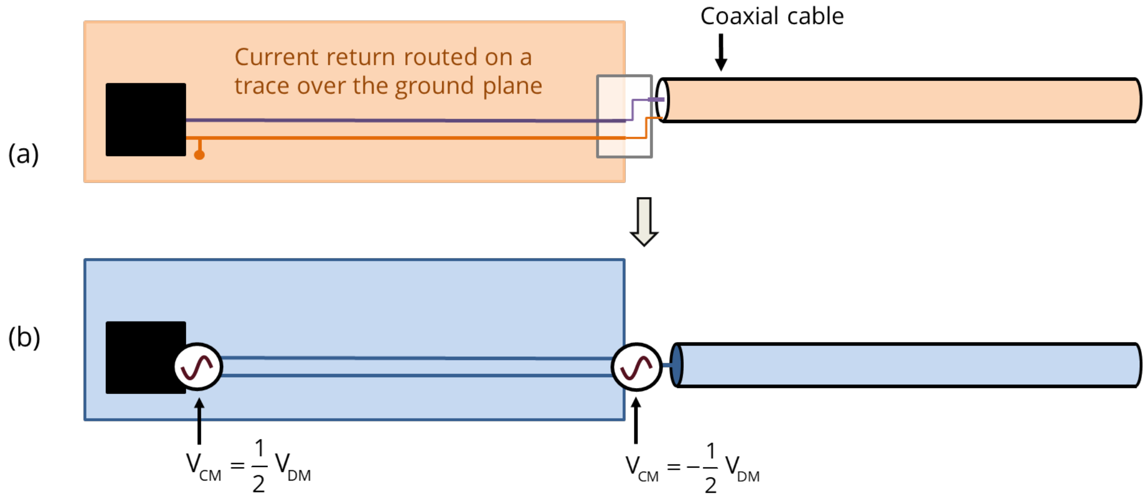


Figure 7.13. Single-ended signal routed on a balanced trace pair.

This resulted in two abrupt changes in the electrical balance; one at the video driver where a single-ended source drove a balanced trace pair, and another at the connector where a balanced trace pair drove an unbalanced coaxial cable.

The two effective common-mode voltages are out of phase, but the one near the video driver produces very little common-mode current because it is near the edge of the board. On the other hand, the common-mode source at the connector drove the entire board relative to the coaxial cable and produced significant common-mode current.

The solution, in this case, was to simply connect the cable shield to the circuit board ground plane at the connector and eliminate the isolated ground trace. With this change, the unbalanced source drove an unbalanced microstrip trace, which drove an unbalanced coaxial cable. With everything (nearly) equally unbalanced, there was no significant common-mode voltage to drive the cable.

As stated earlier, a good rule to follow to avoid converting signal voltages to common-mode sources is: *If you're balanced, stay balanced; and if you're unbalanced, stay unbalanced.* In other words, single-ended sources should drive unbalanced transmission lines terminated in unbalanced loads. Differential sources should drive balanced transmission lines terminated in balanced loads.