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THE INTERACTIONS BETWEEN SHIELDS, GROUNDS, AND COMMON CABLE CONFIGURATIONS ARE CENTRAL TO UNDERSTANDING COMMON-MODE SIGNALS' CREATION AND THEIR SUPPRESSION.

Understanding common-mode signals

A COMMON-MODE SIGNAL is one that appears in phase and with equal amplitudes on both lines of a two-wire cable with respect to the local common or ground in phase and with equal amplitudes. A common-mode voltage is one-half the vector sum of the voltages between each conductor of a balanced circuit and the local ground. Such signals can arise from radiating signals that couple equally to both lines, a driver circuit's offset, or a ground differential between the transmitting and the receiving locations.

THE DATA-TRANSMISSION ENVIRONMENT

The principal aim of any data-transmission system is to send data from one location to another, whether within a single box or enclosure, between boxes within an enclosure, between enclosures within a building or defined area, or between buildings. For example, RS-485-signaling applications include runs between buildings with supply service derived from different power circuits (**Figure 1**).

Bonding a power-line subscriber's neutral line to a ground rod sunk in the earth at the power-entry point establishes the power-line neutral as a safety ground. From there, a bare or green-insulated wire carries the safety-ground reference throughout the premises to all electrical outlets and installed equipment. A bond between an industrial chassis frame and the safety ground at the chassis' power-input point establishes the frame ground.

System designs provide for connections between circuit common and the chassis at one or more points, but a single ground point per chassis is best. Some designs isolate the circuit common from the frame ground. Leakage currents flowing in the safety-ground wire from machine windings to the case or, more commonly, flowing between ground and earth due to ac primary or secondary neutral currents in the power-distribution system can produce a potential difference between the neutral and frame ground.

Ground differentials can vary from several volts to several tens of volts. You find the highest levels in three-phase Y-distribution or single-phase systems,

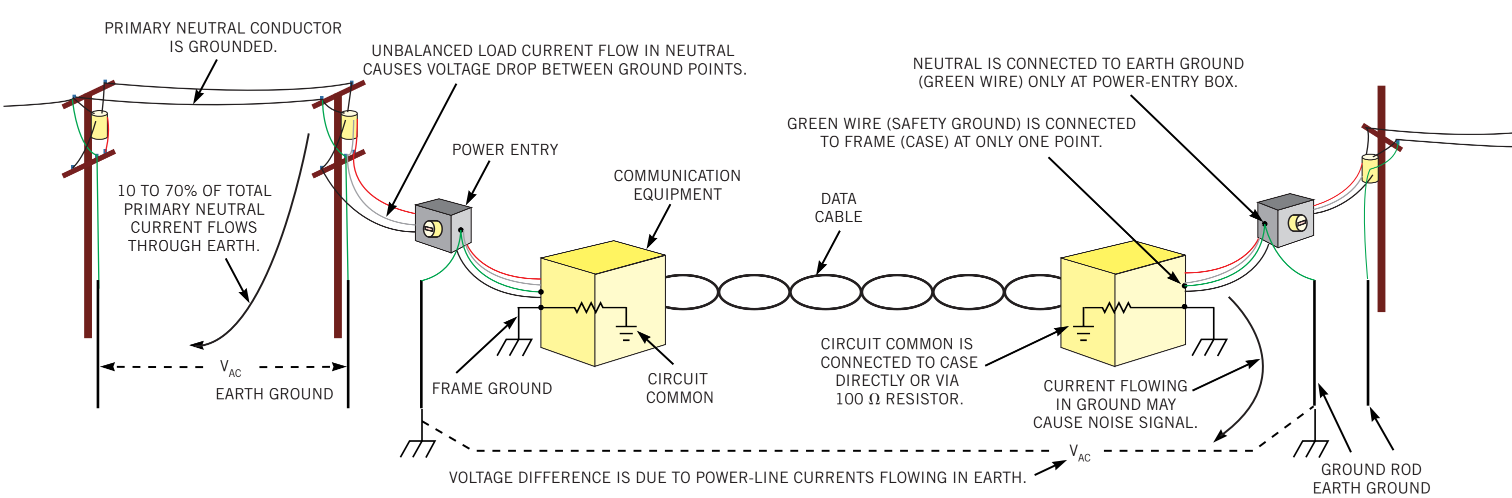


Figure 1 This generalized system transmits data between two widely separated buildings and shows the earth currents created between ground points in a single-phase power-distribution system. It also applies to three-phase, Y-connected systems.

for which the portion of neutral current flowing in the earth may be 10 to 70% of the total neutral current flowing in the primary circuit (**Reference 1**). Voltage measurements from ground point to ground point are typically 0.2 to 5V rms and, though rarely, as high as 65 V rms between widely separated grounds (**Reference 2**).

CABLES AND NOISE

Noise signals can appear in a cable as the result of capacitive coupling of nearby E (electric) fields, inductive coupling of local M (magnetic) fields, EM (electromagnetic) coupling of radio signals in space, and C (conduction) via intentional or leakage paths. The coupled signal appears as an additional signal in series with the line or lines (**Figure 2**). Depending on the cable type, the coupled signal may appear in normal or common mode (**Table 1**). **Table 2** lists typical cable configurations and the noise sources to which they are susceptible. Twisted-pairs equally intercept coupled signals, so the incident signals

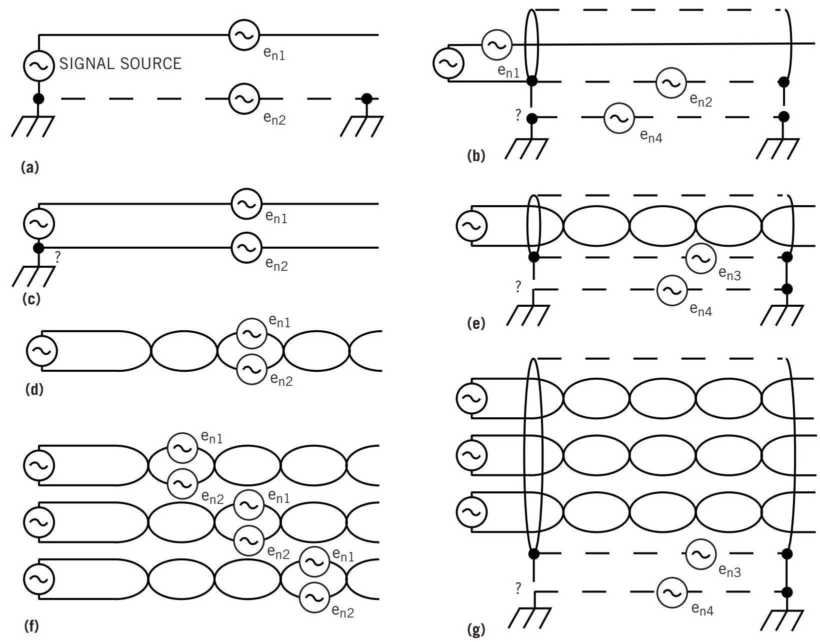


Figure 2 The transmission-cable configurations show the locations of possible noise sources. The configurations are the single-wire and earth (a), single-wire shielded (b), two-wire parallel or untwisted pair (c), unshielded twisted pair (d), shielded twisted pair (e), unshielded multiple twisted pair (f), and shielded multiple pair (g).

TABLE 1–ELECTRICAL-CABLE TYPES AND APPLICATIONS

Description	Electrical return via	Typical applications
Single-wire line	Earth or frame	Early telephone and telegraph signaling circuits, automotive power distribution
Single-wire shielded cable	Shield	Single-wire shielded microphone cable or coaxial cable for video or RF signals
Unshielded parallel pair	Second wire of the pair	Signaling or ac power distribution
Unshielded twisted pair	Second wire of the pair	Single-line telephone, signaling, or data cables
Shielded twisted pair	Second wire of the pair	Balanced microphone cable, twin-axial RF cable, or shielded data-transmission cables
Unshielded multiple twisted pair	Second wire of each pair	26-pair telephone cable and four-pair EIA/TIA-designated categories 1 through 6
Shielded multiple twisted pair	Second wire of each pair	Intercom cable and EIA/TIA Category 5 Class D or Category 7

TABLE 2–NOISE SOURCES FOR LISTED CABLE CONFIGURATIONS

Description	e_{n1}	e_{n2}	e_{n3}	e_{n4}	Notes
Single-wire line, earth, or frame return	Radiated E, EM, or M	Earth currents			Receiving circuit must be insensitive to the sum of $e_{n1}+e_{n2}$ at load.
Single-wire shielded cable	If radiated or conducted noise enters the unshielded portion of the main conductor or appears between source common and a ground point at cable ends.	Radiated E, EM, or M along length of shield		Conduction by electrical currents flowing in external ground path if both ends of shield are grounded.	Copper shield is ineffective for inductively coupled noise. If inductive coupling is absent, shielding is complete from the source to the load, and ground points are connected directly to circuit common at the source and the load, then, e_{n1} is insignificant.
Unshielded parallel pair	Radiated E, EM, or M	Radiated E, EM, or M			If lines are parallel and closely spaced, then e_{n1} and e_{n2} partially cancel.
Unshielded twisted pair or unshielded multiple twisted pair	Radiated E, EM, or M	Radiated E, EM, or M			Twisted lines make e_{n1} and e_{n2} equal in amplitude and phase. Receiving circuit must reject the VCM signal.
Shielded twisted pair or shielded multiple twisted pair	Radiated M	Radiated M	Radiated E, EM, or M along length of shield	Conduction by electrical currents flowing in external ground path if both ends of shield are grounded.	Neither e_{n3} nor e_{n4} appear in the signal path but could cause circulating current if both ends of the shield are grounded. The receiving circuit must reject VCM signal if e_{n1} and e_{n2} are present.

appear only in common mode. Pairs with identical impedances to the local common are *balanced*.

CIRCUIT AND SHIELD GROUNDING

Different combinations of feed lines, shields, and ground leads are appropriate for different source and load grounding arrangements (**tables 3** and **4**). They include:

- Single line with earth return: The signal common line connects to earth ground at the source and load by the earth (frame) return path. Circuit commons must also connect to earth (frame) ground.
- Single-wire shielded: Signal current flows through the shield, so both the source and the load require connections to the circuit common.
- Two-wire parallel: Each conductor carries an equal amount of signal current but in opposite directions.
- Unshielded twisted pairs**:** Any driving or receiving circuit probably includes a connection to a local common or frame ground, but connecting the transmission line to the frame ground is unnecessary and undesirable. A differential-mode or balanced-signal source, such as unshielded RS-422 and RS-485 data-transmission circuits, transmits data signals to a remote location where source and load circuits are both referenced to local ground or common. Transformer-coupled applications include 10/100BaseT Ethernet cables.
- Shielded twisted pairs**:** Grounding the shield of any shielded pair shunts unwanted signals or noise that the shield intercepts to ground. Typical shield materials, copper and aluminum, shield the internal conductors from signals coupled capacitively or electromagnetically but not from those coupled inductively.

You should connect the shield to ground at only one end of the cable—usually, the receiving end. If the transmitting-location ground carries a different noise signal from that at the receiving location, grounding the shield at both ends causes current flow through the shield. Grounding at both ends is acceptable if no substantial potential difference exists between the two ground locations. This configuration includes shielded RS-422 and RS-485 data-transmission circuits. RS-485 Application Guidelines call for connecting the shield to earth ground—either directly or through a fusible resistor—at one or both ends of the cable (**Reference 3**).

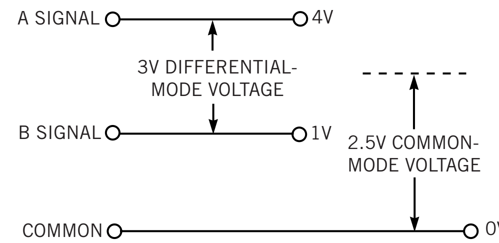


Figure 3 Typical RS-485 transmitters generate a common-mode dc offset voltage.

SIGNAL-MODE DEFINITIONS

Electrical signals can have normal-, differential-, or common-mode components. A normal-mode signal is any type—other than common mode—that appears between a pair of wires or on a single wire with respect to ground. Normal-mode signals are read between two

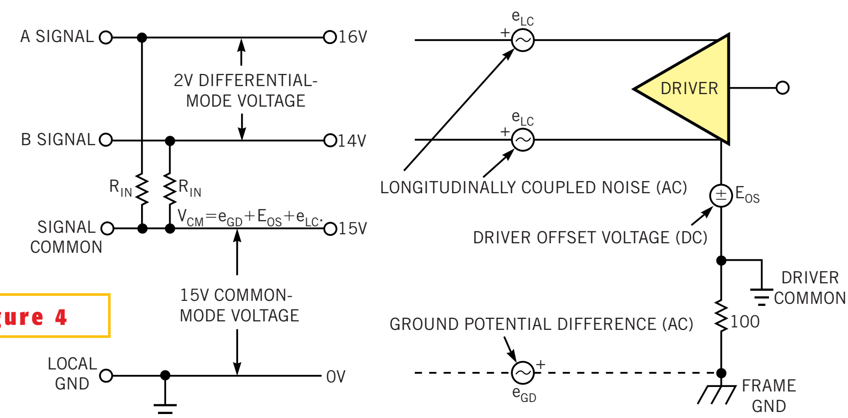


Figure 4 Three types of common-mode signal, e_{GD}, e_{LC}, and E_{OS}, can be present in a two-wire data-transmission system.

TABLE 3–SHIELD GROUNDING FOR SINGLE-WIRE SHIELDED CABLES

When	Shield is grounded	Conditions
Source floats	At load only	Source is battery-powered or is an unpowered transducer, such as a microphone, although the microphone case may be connected to the shield.
Load floats	At source only	Load is isolated, such as a battery-powered device. Such a line may be used to transmit signals to a remote ungrounded load as in, for example, an antenna with an isolated ground plane.
Source and load grounded	At both ends	Source and load grounds are at equal voltages. Otherwise, circulating currents in the shield create a noise source in the signal path. You thus use double grounding only within a single chassis or enclosure or between several enclosures sharing a common isopotential frame ground or having no frame ground at all. Audio and video cables within a home-entertainment system are examples of this use.

TABLE 4–LINE GROUNDING FOR TWO-WIRE PARALLEL CABLES

When	Grounding	Conditions
Source floats	At load only	Source is battery-powered.
Load floats	At source only	Source is electronic and the load is passive or nonelectronic, as in headphones or loudspeakers. You find these conditions in ac power-distribution systems, where the power enters a user's premises.
Source and load grounded	At both ends	Electronic signaling systems, such as RS-232. Note, however, that RS-232 commonly uses twisted-pair cabling.
Source and load floating	At neither end	Transformer-coupled signaling systems, such as doorbells and other call systems. These systems are often immune to any low-level noise signals that may be present.

wires in a balanced or unbalanced transmission path. A balanced source drives one wire of a two-wire path positive while driving the other negative an equal amount—both with respect to a static or a no-signal condition in which both lines assume the same voltage level relative to circuit common under no signal conditions.

A differential-mode signal appears differentially on a pair of wires in an ungrounded cable configuration.

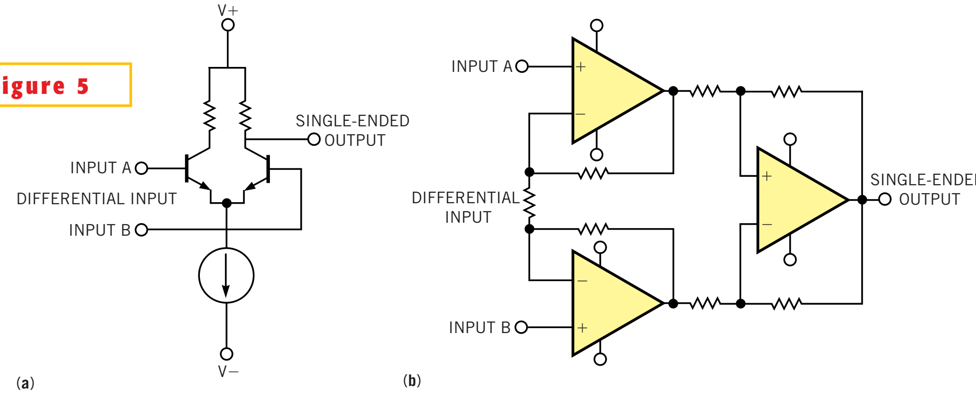
A common-mode signal appears equally on both lines of a two-wire cable with respect to local circuit common. Most applications call for receivers that reject the common-mode signal, which rarely contains useful information. The common-mode voltage, V_{CM}, is the average of the two signal voltages with respect to local ground or common:

$$V_{CM} = \frac{\vec{V}_A + \vec{V}_B}{2}.$$

Figure 3 shows a 3V differential-mode signal riding on a 2.5V common-mode signal. The dc offset is typical of differential-mode data transmitters operating from a single supply. The common-mode voltage can be ac, dc, or a combination of the two. **Figure 3** represents the simplest case—a common-mode voltage with no ac component.

With long cables, such as are common on many RS-485 runs, the originating signal's common or ground may have a different electrical potential from that of the receiving location. The RS-485 specification calls for connecting the drive-circuit common to frame ground, either directly or through a 100Ω resistor (**Reference 4, Figure 4**).

Figure 5



A differential pair (a) and an instrumentation amplifier (b) exhibit high common-mode rejection.

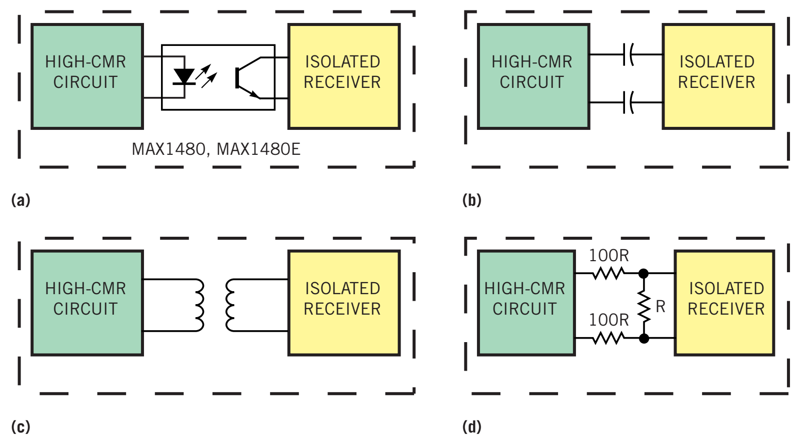


Figure 6

Photo-, capacitor-, inductor-, and resistor-coupled components (a, b, c, and d, respectively) achieve high common-mode-signal rejection.

ELIMINATING THE COMMON MODE

Figure 4 represents three sources of common-mode voltage as e_{GD}, e_{LC}, and E_{OS}. E_{OS} is typically a dc offset that a differential-mode driver operating from a single supply introduces (**Figure 3**). The e_{GD} noise signal arises from the difference in ground potentials at the transmitting and receiving locations. It is usually an ac signal containing the fundamental and several harmonics of the power-line frequency. Longitudinally coupled noise, e_{LC}, occurs equally on both transmission lines due to capacitive, electromagnetic, or inductive coupling from extraneous sources. The net common-mode voltage equals the vector sum of the three terms:

$$V_{CM} = \vec{e}_{GD} + \vec{E}_{OS} + \vec{e}_{LC} = e_{GD}(t) + E_{OS} + e_{LC}(t).$$

You can make E_{OS} small or even zero by operating a differential-mode driver from balanced supplies. In contrast, minimizing e_{GD} depends on maintaining a relatively short distance between the transmitting and the receiving locations. Shielded twisted-pair cable helps minimize e_{LC} by interrupting the offending fields. To the extent that the shield is not 100% effective, the residual term couples equally on the two tightly twisted wires. Asymmetries in poorly constructed cables allow the residual fields to develop normal-mode signals, which appear to the receiver as signal noise. Similarly, the load must also be symmetrical, meaning that the resistive and capacitive elements of both lines' load impedance must match. Only magnetically shielded cables can prevent inductively coupled signals, reinforcing the importance of cable and load symmetries to prevent coupled signals from converting to normal mode.

The receiving circuit must reject common-mode signals, an easy task if the receiving circuit is passive, such as in headphones and loudspeakers; transformer-coupled; isolated; battery-operated; or otherwise not referenced to the transmitting-circuit common. Those configurations are inherently immune to common-mode signals, but receiving circuits that reference the transmitting-circuit common must accept the full range of common-mode voltage appearing at their inputs. All such designs involve differential receivers with high CMR (common-mode rejection). If the V_{CM} is of relatively low amplitude, a high-CMR receiver alone may be adequate.

All high-CMR receivers employ either some form of differential pair or a traditional instrumentation amplifier (**Figure 5**). Each amplifier accepts a differential input in the presence of a limited common-mode voltage, which is limited to somewhat less than the supply voltages.

If the common-mode voltage can exceed the receiver's common-mode range, the receiver must employ additional isolation. Most such circuits use a transformer-coupled isolated supply, plus signal coupling that you can implement using optics, transformers, capacitors, or resistors (**Figure 6**).

The power transformer and the type of signal coupling you choose determine isolation-voltage limits. Isolation to 2500V or more is practical with transformer-, optical-, and capacitive-coupling techniques, whereas resistive coupling is usually limited to 50 to 100V.

Resistive coupling involves transferring data through a resistive attenuator, which attenuates both the data and the common-mode signals. Thus, resistive isolation is limited by the fraction of V_{CM} that by the receiving circuit can accommodate, while reliably detecting a small fraction of the original data signal.

In **Figure 6**, the various isolation drivers treat the requirement for isolated power differently. Today's inductively coupled devices make no provision for the power supply and, therefore, require external, isolated supplies. Some capacitor-coupled devices include transformer drivers but require external transformers. Other drivers contain isolated supplies and require external, low-profile, ceramic charge-pump capacitors. Yet others contain fully isolated supplies, including transformers.

Thus, you can intelligently choose the cable type and isolation technology, once you know the source and magnitude of an intruding common-mode signal. You need only measure or calculate the magnitude of the disturbing signals and then select your components to meet the overall requirements of the system.□

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Author's biography

Jim Sherwin is a senior strategic applications engineer with Maxim Integrated Products (Sunnyvale, CA). His background includes instrumentation, data-transmission, analog-circuit, and switching-power-supply design. He has bachelor's and master's degrees in electronic engineering from the University of California—Berkeley, where he specialized in network and circuit design and analysis. He has authored dozens of design articles, professional-society papers, and application notes. He has been a member of the ISA (Instrument Society of America), ARS (American Rocket Society), AIEE, and AES (Audio Engineering Society).