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## TUTORIAL 2045

# Understanding Common-Mode Signals

Jun 29, 2003

*Abstract: To understand how common-mode signals are created and then suppressed, you should first understand the interaction of shields and grounds in common cable configurations. The following discussion defines a common-mode signal, reviews the common cable configurations, considers shielded vs. unshielded cables, and describes typical grounding practices. The article discusses methods whereby common-mode signals are created and rejected.*

*The primary focus of this discussion is on RS-485/RS-422 cables and signals, but the discussion also applies to telephone, audio, video, and computer-network signals.*

A similar version of this article appeared in the April 17, 2003 issue of *EDN* magazine.

## Common-Mode Signals Defined

When referenced to the local common or ground, a common-mode signal appears on both lines of a 2-wire cable, in-phase and with equal amplitudes. Clearly, a common-mode signal cannot be present if one of the lines is connected to local common. Technically, a common-mode voltage is one-half the vector sum of the voltages from each conductor of a balanced circuit to local ground or common. Such signals can arise from one or more of the following sources:

- Radiated signals coupled equally to both lines,
- An offset from signal common created in the driver circuit, or
- A ground differential between the transmitting and receiving locations.

Further details about these basic conditions appear in a later section. Before examining those details, however, it is useful to understand different cable configurations, signal-grounding conventions, and shield-grounding practices.

## General Data-Transmission System

The principal aim of any data-transmission system is to send data from one location to another, whether



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within a single box or enclosure, between boxes within an enclosure, between enclosures within a building or defined area, or between buildings. **Figure 1** illustrates an RS-485 signaling situation in which the buildings are supplied from different power circuits.

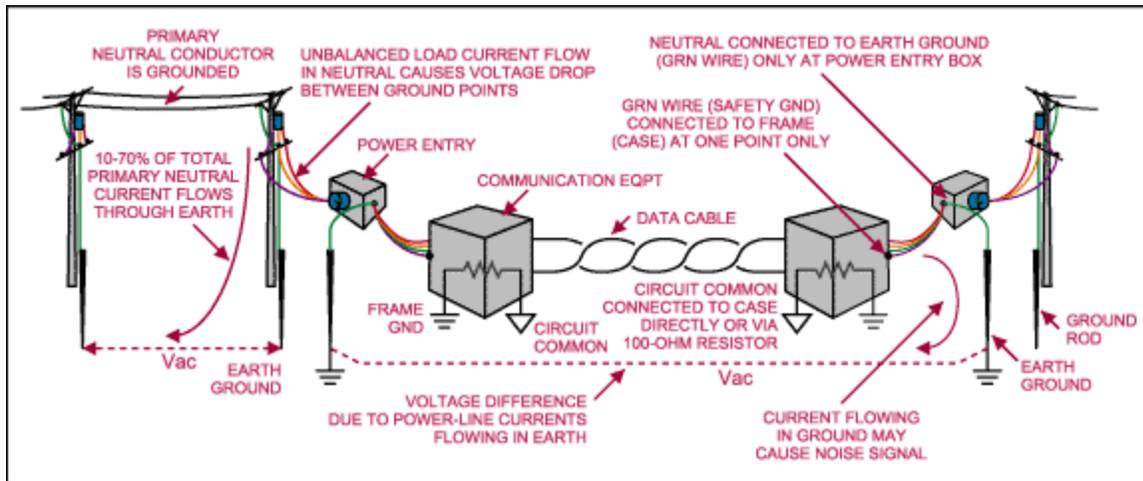


Figure 1. This generalized system transmits data between two widely separated buildings, and shows the earth currents created between ground points in a single-phase power-distribution system. Similar currents are created in 3-phase, Y-connected systems.

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 that point, a bare or green-insulated wire carries the safety-ground reference to all electrical outlets and installed equipment throughout the premises. Industrial chassis frames are bonded to the safety ground at the chassis' power-input point, where it becomes frame ground.

Circuit common is often connected to the chassis at one or more points, but a single ground point per chassis is best. In some cases, the circuit common might be isolated from the frame ground. Leakage currents that flow in the safety-ground wire from machine windings to the case, or more commonly, that flow between the 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. The greatest differentials are found in single-phase or 3-phase Y-distribution systems, in which the portion of neutral current flowing in the earth can be 10% to 70% of the total neutral current flowing in the primary circuit. Voltage measurements between ground points are typically  $0.2V_{RMS}$  to  $5V_{RMS}$ , and (rarely) as high as  $65V_{RMS}$  between widely separated grounds.

## Cables and Noise

Noise signals can appear in a cable for several reasons: capacitive coupling of nearby electric fields (E); inductive coupling of local magnetic fields (M); electromagnetic coupling of radio signals in space (EM); and conduction through intentional or sneak circuit paths (C). The coupled signal appears as an additional signal in series with the line or lines (**Figure 2**). **Table 2** lists the type and origin of potential noise sources in cables. Twisted-pair lines intercept coupled signals equally, so the incident signals appear only as common-mode signals. Twisted-pair lines are said to be balanced if the impedances connected from each line to the local common are identical.

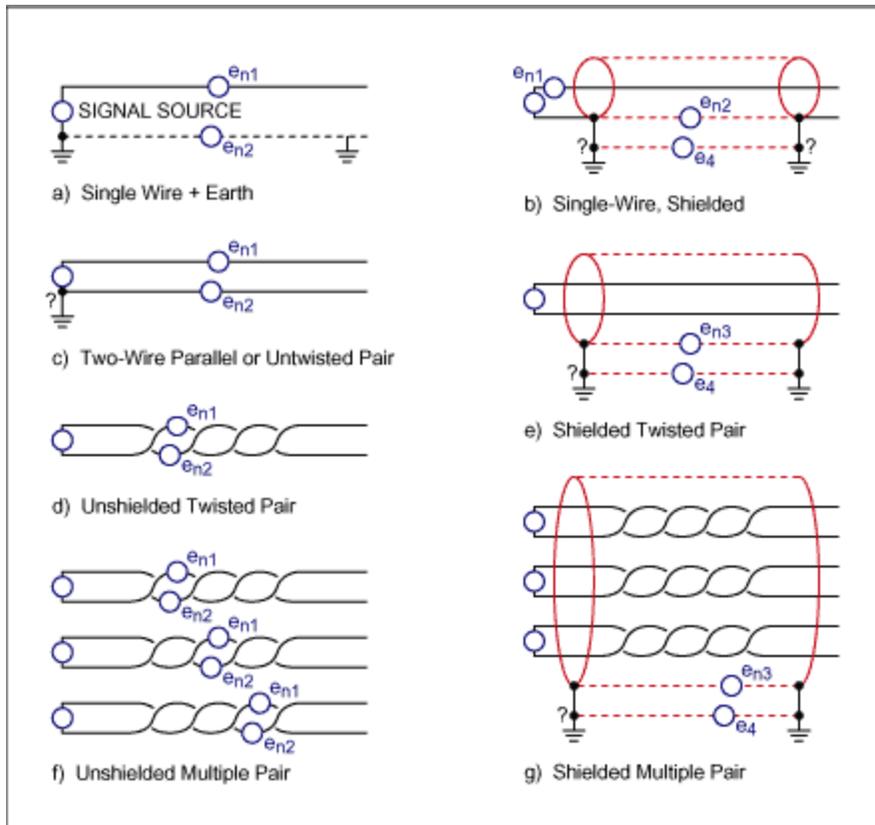


Figure 2. These transmission-cable configurations show the locations of possible noise sources.

**Table 1. Electrical Cable Types and Applications**

Description	Electrical Return Route	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 radio-frequency (RF) signals
Unshielded Parallel Pair	Second wire of the pair	Signaling or AC power distribution
Unshielded Twisted Pair (UTP)	Second wire of the pair	Single-line telephone, signaling, or data cables
Shielded Twisted Pair (STP)	Second wire of the pair	Balanced microphone cable, twin-axial RF cable, or shielded data-transmission cables
Unshielded Multiple Twisted Pair	Second wire of the pair	26-pair telephone cable and 4-pair EIA/TIA-designated Categories 1 through 6
Shielded Multiple Twisted Pair	Second wire of the pair	Intercom cable and EIA/TIA CAT 5 Class D or CAT 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 an unshielded portion of the main conductor or appears between source common and a	Radiated E, EM, or M along length of shield	–	Conduction by electrical currents flowing in external ground path if both ends of shield	Copper shield ineffective for inductively-coupled noise. $e_{n1}$ is insignificant if: inductive coupling is absent; shielding is complete from source to load; and ground points

	ground point at cable ends			are grounded.	are connected directly to circuit common at source and load.
Unshielded Parallel Pair	Radiated E, EM, or M	Radiated E, EM, or M	–	–	$e_{n1}$ and $e_{n2}$ will partially cancel if the lines are parallel and closely spaced.
Unshielded Twisted Pair (UTP), 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 $V_{CM}$ signal.
Shielded Twisted Pair (STP), or Shielded Multiple Twisted-Pair	Radiated M	Radiated M	Radiated E, EM, or M along length of shield	Conduction by electrical currents is flowing in the external ground path if both ends of the 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. Receiving circuit must reject $V_{CM}$ signal if $e_{n1}$ and $e_{n2}$ are present.

## Circuit and Shield Grounding

**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 be connected to the earth (frame) ground.

**Single-wire shielded:** Signal current is always carried on the shield, so connections to the circuit common must be present at both source and load. **Table 3** lists the shield-grounding connections for various conditions.

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, for example, an antenna with 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. Double grounding is thus used only: within a single chassis or enclosure; or between several enclosures sharing a common iso-potential frame ground or having no frame ground at all. Audio and video cables within a home entertainment system are examples of this use.

**Two-wire parallel:** Each conductor carries an equal amount of signal current, but in opposite directions. **Table 4** lists line-grounding connections for various conditions.

Table 4. Line Grounding for Two-Wire Parallel Cables		
When	Shield Is Grounded	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 (headphones or loudspeaker). Found 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 utilizes twisted-pair cabling.
Source and Load Floating	At neither end	Found in transformer-coupled signaling systems (doorbell or other call systems). These systems are often immune to any low-level noise signals that may be present.

**Unshielded twisted pair(s):** Any driving or receiving circuit probably includes a connection to local common or frame ground, but connecting the transmission line itself to 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 10/100 Base-T Ethernet cables.

**Shielded twisted pair(s):** Grounding the shield of any shielded pair shunts to ground any unwanted

signals or noise intercepted by the shield. Typical shield materials (copper and aluminum) shield the internal conductors from signals coupled capacitively or electromagnetically, but not from those coupled inductively.

For any shielded pair(s) carrying balanced signals, you should connect the shield to ground at one end, usually the receiving end. If the transmitting-location ground carries a noise signal different from that at the receiving location, grounding the shield at both ends causes current flow along the shield. Grounding at both ends is acceptable if there is no substantial potential difference between the two ground locations. This configuration includes shielded RS-422 and RS-485 data-transmission circuits. RS-485 Application Guidelines specify connecting the shield to earth ground, either directly or through a fusible resistor at one or both ends of the cable shield.

## Signal-Mode Definitions

Electrical signals carried on cables can be described as normal mode, differential mode, or common mode.

- A **normal-mode signal** is any type (other than common mode) that appears between a pair of wires, or on a single wire referenced to (or returned through) the earth, chassis, or shield. Normal-mode signals are read between two wires in a balanced or unbalanced transmission path. (For a balanced 2-wire path, one wire is driven positive while the other is driven negative by an equal amount, both with respect to a static or no-signal condition in which both lines assume the same voltage level relative to circuit common.)
- A **differential-mode signal** appears differentially on a pair of wires in an ungrounded cable configuration.
- A **common-mode signal** appears equally (with respect to local circuit common) on both lines of a 2-wire cable not connected to earth, shield, or local common. Usually, but not always, this is an unwanted signal that should be rejected by the receiving circuit. Common-mode voltage ( $V_{CM}$ ) is expressed mathematically as 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 AC and DC. (Figure 3 represents the simplest case, a DC common-mode voltage with no AC component.)

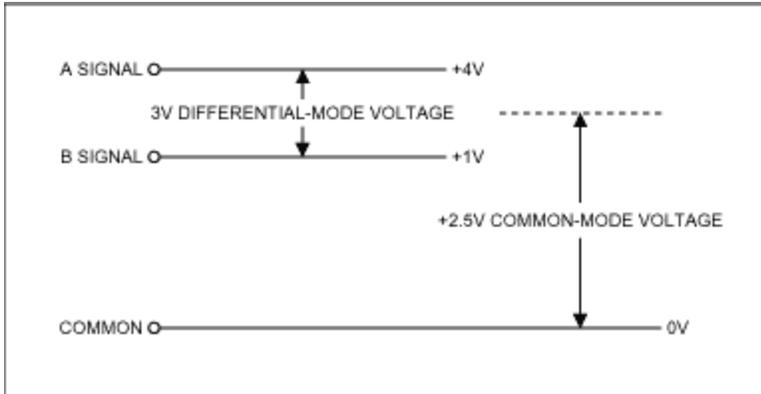


Figure 3. Typical RS-485 transmitters generate a common-mode DC offset voltage as shown.

When cables are long (as RS-485 data cables can be), the originating signal's common or ground may not have the same electrical potential as that of the receiving location. The RS-485 specification says to connect the drive-circuit common to frame ground, either directly or through a 100Ω resistor. The result is illustrated in **Figure 4**.

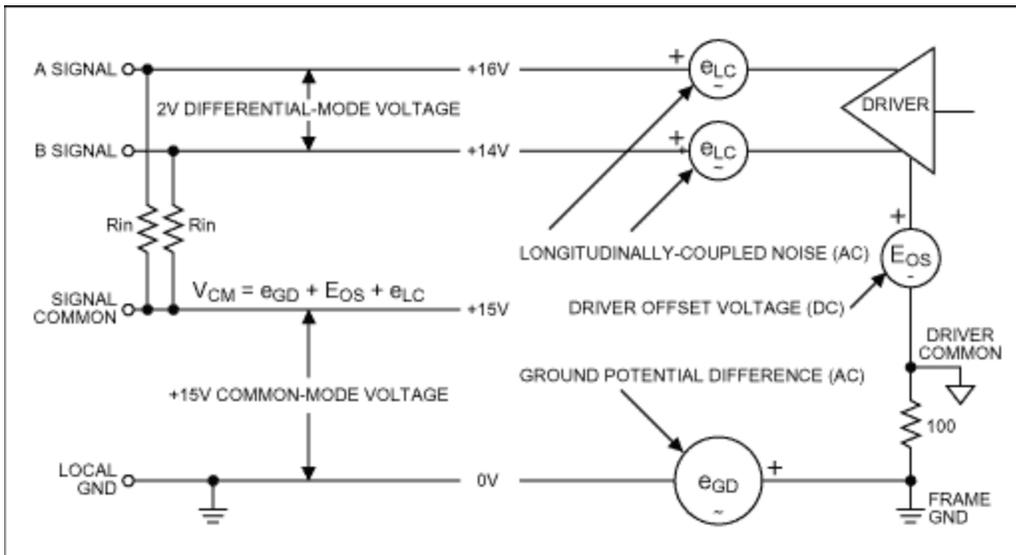


Figure 4. Three types of common-mode signal ( $e_{GD}$ ,  $e_{LC}$ , and  $E_{OS}$ ) can be present in a 2-wire data-transmission system.

Signal common can assume a common-mode voltage equal to the vector sum of the ground-potential difference, the driver-offset voltage, and any longitudinally coupled noise voltage generated along the signal path between transmitter and receiver:

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

## The Origin of Common-Mode Signals

Three sources of common-mode voltage are represented in Figure 4 as  $e_{GD}$ ,  $e_{LC}$ , and  $E_{OS}$ :

- $E_{OS}$  is typically a DC offset introduced by a differential-mode driver operating from a single supply, as represented in Figure 3.
- $e_{GD}$  is a noise signal representing the difference in ground potentials at the transmitting and receiving locations. It is usually an AC signal containing the fundamental and possibly several harmonics of the power-line frequency.
- $e_{LC}$  is a longitudinally coupled noise signal occurring equally on both transmission lines due to capacitive, electromagnetic, or inductive coupling from extraneous sources.

## Minimizing Common-Mode Signals

$E_{OS}$  can be made quite small, or even zero, by operating a differential-mode driver from balanced supplies. In contrast,  $e_{GD}$  can be minimized only by maintaining a relatively short distance between the transmitting and receiving locations.  $e_{LC}$  can be minimized by using a shielded twisted pair: noise introduced within the cable arises equally on each of two tightly twisted wires. Otherwise, a normal-mode signal would be present due to the line's asymmetry with respect to disturbing fields.

The load must also be symmetrical; the resistive and capacitive load impedances on both lines of the twisted pair must be matched. Inductively coupled signals can be prevented only by using magnetic shielding. (Note that any wire carrying signal current is a source of magnetic radiation.)

## Suppressing Common-Mode Signals

Common-mode signals ( $V_{CM}$ ) must be rejected in the receiving circuit. That rejection is easily accomplished when the receiving circuit is passive (headphones or loudspeaker), transformer coupled, isolated and battery operated, or otherwise not referenced in any way to the transmitting-circuit common (either capacitively or resistively connected). The configurations noted here are inherently immune to common-mode signals, but receiving circuits referenced to the transmitting-circuit common must be designed to accept the full range of  $V_{CM}$  presented to them. All such designs involve differential receivers with high common-mode-rejection (CMR). If the  $V_{CM}$  is of relatively low amplitude, a high-CMR receiver alone may be adequate.

## How High-CMR Receivers Work

All high-CMR receivers employ either some form of differential pair, or a traditional instrumentation amplifier consisting of three amplifiers, as indicated in **Figure 5**. Each amplifier accepts a differential input in the presence of a limited common-mode voltage, with an acceptable  $V_{CM}$  limited to somewhat less than the supply voltages. Such circuits can handle analog and digital signals.

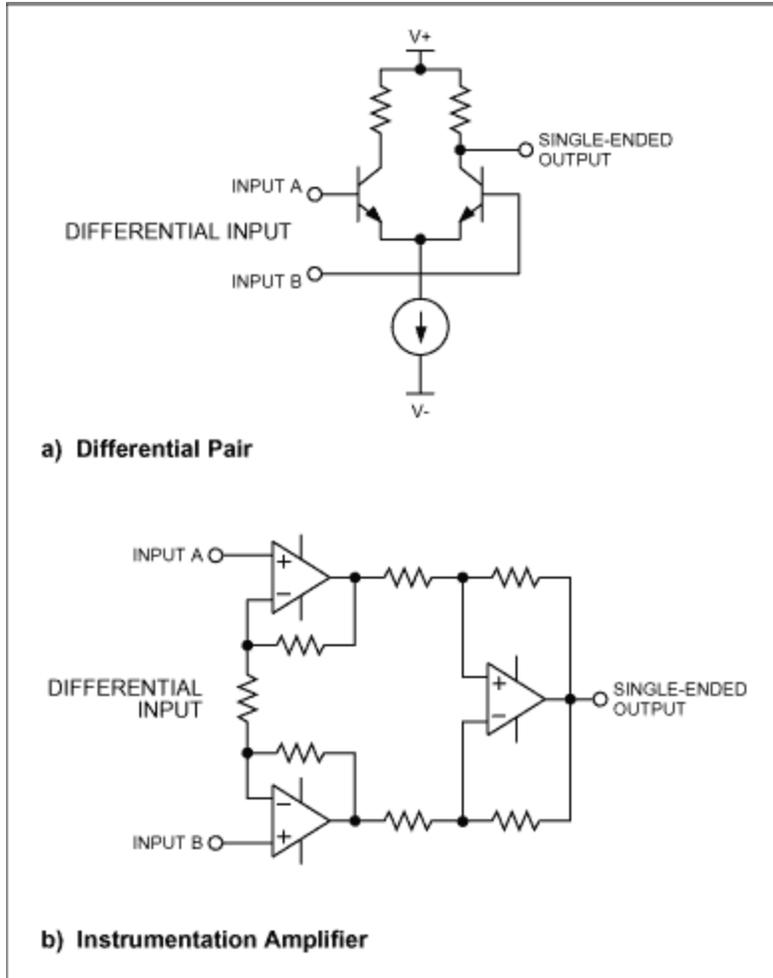


Figure 5. These differential-amplifier circuits exhibit high common-mode rejection.

Additional isolation must be employed if  $V_{CM}$  is to exceed the receiver's common-mode range. Most such circuits employ a transformer-coupled isolated supply, plus any one of the following:

- Optically coupled circuits
- Capacitively coupled differential circuits
- Inductively coupled circuits
- Resistively coupled differential circuits

All the techniques shown in **Figure 6** can couple a signal across the isolation barrier in the presence of high values of  $V_{CM}$ . Each depends on the use of an isolated power supply, which is usually transformer coupled. Isolation voltage limits are determined by the transformer and by the type of isolation chosen. Isolation to 2500V or more is practical with transformer-, optical-, and capacitive-coupling techniques; resistive coupling is usually limited to the range of 50V to 100V.

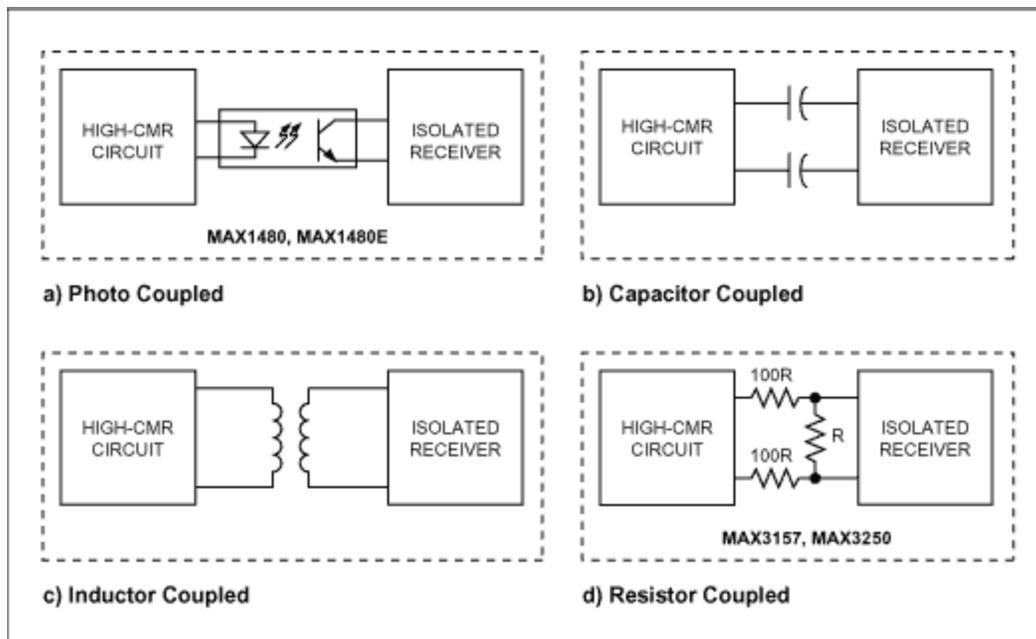


Figure 6. The isolation techniques and typical components shown achieve high common-mode-signal rejection.

Resistive coupling involves transferring data across 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 can be accommodated by the receiving circuit, while reliably detecting a small fraction of the original data signal.

In Figure 6, the various isolation drivers treat the requirement for isolated power in different ways. 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 they require external transformers. Maxim's [MAX3157](#) and [MAX3250](#) drivers contain isolated supplies and require external, low-profile, ceramic charge-pump capacitors. Members of the [MAX1480](#) and [MAX1480E](#) families, however, contain fully isolated supplies including transformers.

Thus, you can choose the cable type and isolation technology intelligently, once the source and magnitude of an intruding common-mode signal is known. 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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## Related Parts

<a href="#">MAX1480E</a>	±15kV ESD-Protected, Isolated RS-485/RS-422 Data Interfaces	<a href="#">Free Samples</a>
<a href="#">MAX3157</a>	High CMRR RS-485 Transceiver with ±50V Isolation	<a href="#">Free Samples</a>
<a href="#">MAX3250</a>	±50V Isolated, 3.0V to 5.5V, 250kbps, 2 Tx/2 Rx, RS-232 Transceiver	<a href="#">Free Samples</a>

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