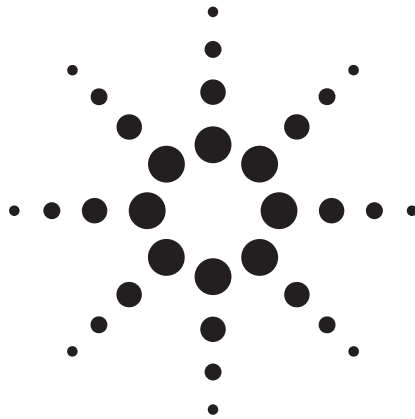


Reducing Noise in Switching for Test Systems

Application Note 1441-2



Introduction

Designing a switch system for testing electronic and electromechanical devices can present as many problems as designing the device itself. A modern test system has many signal and power lines for stimulating or measuring the DUT and a variety of switches to automatically make connections. This results in a multipoint switch system in which the interaction of stimulus, power, and other signals may create noise and interfere with the measurements.

There are only three components to a noise problem. A noise problem must have a noise source that couples to a receiver that is susceptible to the noise. To solve a noise problem, first the noise source must be identified, then the reception point must be identified, and finally the method of coupling must be identified. This is not a mysterious process but one that reliably follows the laws of physics. At times, the source and the method of coupling may be subtle, but it never breaks basic rules.

Often, an engineer will spend considerable effort designing the signal path from one system to another, but will ignore the return path. A properly designed system will have both the signal path and the return path defined, as both are required to create a working system. When the return path is neglected during design, the task of tracking down a noise problem is much more difficult. Also, a poorly designed return path may change depending upon what else is going on in the system. A changing return path can appear like an intermittent problem and create a mysterious infestation of unwanted noise.

A generic test-system architecture is shown in **Figure 1**. The switch is central to the entire system, connecting the many test points to the measuring instruments and routing signals and power to the DUT. It is also the source of many, sometimes inexplicable, measurement errors, as the many interconnections in close proximity provide ample opportunity for noise coupling.

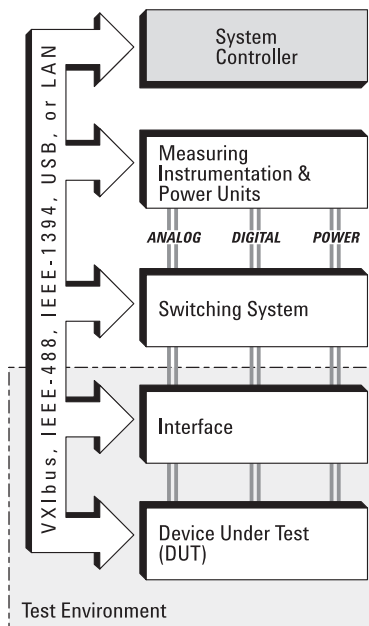


Figure 1.
A generic test-system architecture. Nearly all analog, digital, and power signals pass through the switch subsystem.



Agilent Technologies

The advent of higher-speed logic in devices requiring testing, in conjunction with more-sensitive analog circuitry, has created a situation where careful design and implementation of the switching system have become critical for reducing noise and maintaining signal integrity.

This application note is for engineers who must create test systems. It addresses the problems of reducing noise coupling when integrating commercially available switch products and measuring instrumentation into a test system.

Designing a test system demands knowing the frequency and amplitude of the test signals, and the input and output characteristics of the test instrumentation, the switching system, and the DUT. This application note covers noise reduction techniques for signal frequencies less than 300 MHz, voltages less than 250 V, currents less than 5 A, and volt-hertz products less than 10^7 . Extrapolation of these solutions to either higher amplitude or higher frequency is not recommended without additional references.

Sources of Noise in a Test System

Knowing potential sources of unwanted noise in a test system is particularly important to a test engineer. A list of design rules for reducing unwanted noise can be helpful, but an understanding of where noise might originate is also required. In electronic test systems designed for testing electronic modules, the most significant causes of noise are conductive coupling, common-impedance coupling, and electric and magnetic fields. In addition, some systems are sensitive to noise from galvanic action, thermocouple noise, electrolytic action, triboelectric effect, and conductor motion.

One of the easiest paths for noise to couple into a circuit is a conductor leading into it, resulting in conductively coupled noise. A wire running through a noisy environment has an excellent chance of picking up unwanted noise and transferring it to another circuit. The power supply leads connected to a circuit are often the cause of conductively coupled noise.

Common-impedance coupling occurs when currents from two different circuits flow through a common impedance. The ground voltage of each is affected by the other. As far as each circuit is concerned, its ground potential is modulated by the ground current flowing from the other circuit in the common ground impedance, leading to noise coupling.

Radiated magnetic and electric fields occur whenever an electric charge is moved or a potential difference exists, and can also be a cause of noise coupling. In a circuit, high-frequency interference may be rectified and appear as a DC error. Switch system circuitry is also susceptible to electromagnetic radiation from radio, TV, and other wireless broadcasts. Thus, it is imperative to shield sensitive circuitry from these fields.

The accurate measurement of low-level signals in a test-system environment can best be accomplished with careful attention to the details of grounding and shielding. Noise reduction techniques apply equally to single-point and multipoint systems.

Noise Sources in Switching Systems

The sources of noise in the switching system are those generated internally by the circuitry driving the switches, by thermal imbalance across the switches, by noise coupling from other conductors in the system, and by noise generated outside the system. Thermal imbalance can be minimized either by a mechanical design that ensures that all the contacts in the relay are subject to the same temperature gradient across the leads, or by using latching relays. With latching relays, the relay is only energized for 15 to 20ms to change the relay's state. This reduces the coil energy that is a major source of thermal generation.

Noise coupling from adjacent channels into the measurement channels presents a threat to signal integrity. Proper shielding and grounding techniques can remove many of these problems in hard-wired systems, but when the signal must be selectively switched into an oscilloscope, counter, or some other measuring instrument, the problem can become acute.

In many cases the noise source is an adjacent channel in the system (crosstalk). In the simplified equivalent circuit in **Figure 2**, most of the capacitance in the switch system resides across the open switch contacts and between the adjacent conductive paths. Because noise coupling is a function of area and proximity, a simple way to reduce the coupling is to separate the switches and the conductors from each other. However, increasing the switch density is also a desirable objective; it provides more capability in a smaller package. The systems being tested today tend to be much more complex and have larger point counts than ever before. So the test engineer is faced with the dilemma of having to increase component density and the distance between channels at the same time.

Noise Reduction

Shielding and grounding are the two primary methods for reducing unwanted noise. They often work together such as when the shielding of a cable is connected to ground. In such cases it is important to understand where to ground the cable shield in order to maximize the shield's effectiveness. In some cases, the solution to one noise problem may reduce the effectiveness of the solution to a different noise problem, making it imperative that the noise source, method of coupling, and noise receiver be well understood to make the appropriate tradeoffs.

Shielding

Shielding against noise in test systems involves shielding against both capacitive (electric) and inductive (magnetic) coupling.

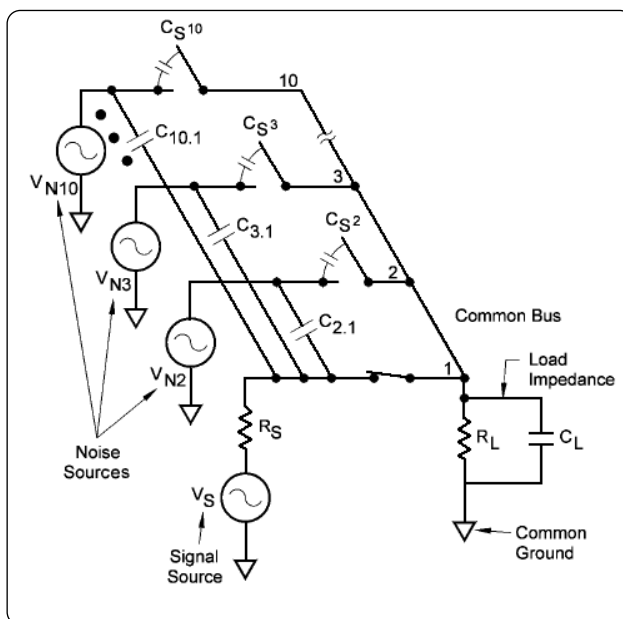


Figure 2. Often, a signal in an adjacent channel creates a noise source. The stray capacitances within the switch system provide the path to couple the noise.

Shielding Against Capacitive Coupling

Capacitive noise coupling between channels in a test system, caused by the interaction of electric fields between circuits, is the easiest to understand and also the easiest to shield against. **Figure 3** shows how the coupling of noise from one conductor to another is a result of the capacitance between the conductors (C_{12}). For a load resistance R (where, as in most practical cases, $R \ll 1/[j\omega(C_{12} + C_{2G})]$), the noise voltage is approximated by the equation $V_N \approx j\omega RC_{12}V_1$.

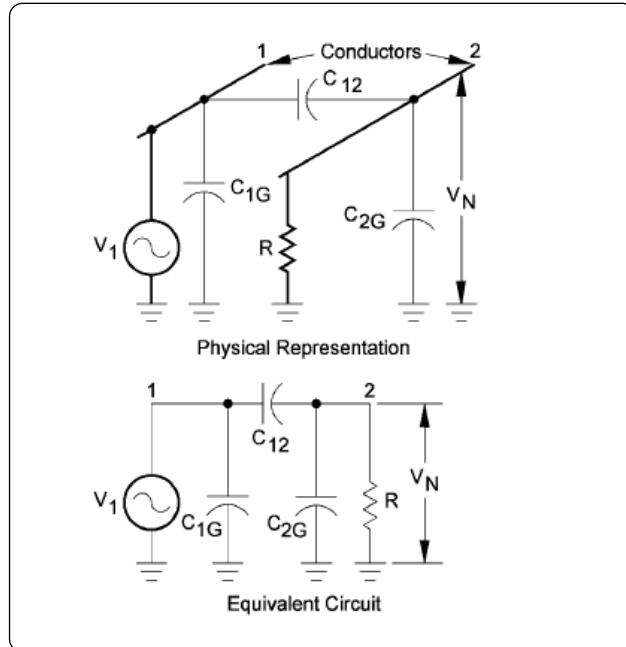


Figure 3.
Capacitive coupling between two conductors

This equation shows that the noise voltage is directly proportional to the frequency and magnitude of the noise source, resistance R , and capacitance C_{12} . Assuming the noise source has already been improved as much as possible, the only parameters that can be changed are R and C_{12} .

If the capacitance C_{12} could be reduced, then the noise voltage coupled into the affected conductor would be reduced. **Physical separation will accomplish up to about 8 dB of noise reduction for a distance of 40 times the diameter of the conductor.** More separation between the conductors has little effect. Another alternative is to operate at a lower resistance, but required circuit loading or impedance matching may make this unfeasible.

Surrounding the signal conductor with a grounded shield that has a uniform electric field (the geometry of the shield is smooth) reduces the noise voltage on the signal conductor to zero. However, at high frequencies the conductor must not extend beyond the shield. It is very important that the shield be grounded. If the shield is not grounded, then the noise voltage picked up by the center conductor is equal to the noise voltage on conductor 1; the shield merely couples the noise voltage (**Figure 4**).

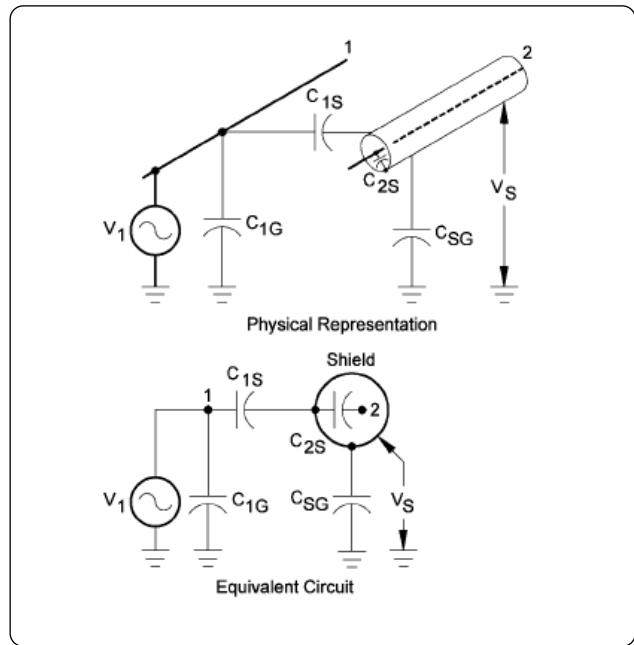


Figure 4.
Capacitive coupling with an ungrounded shield placed around the receiver conductor

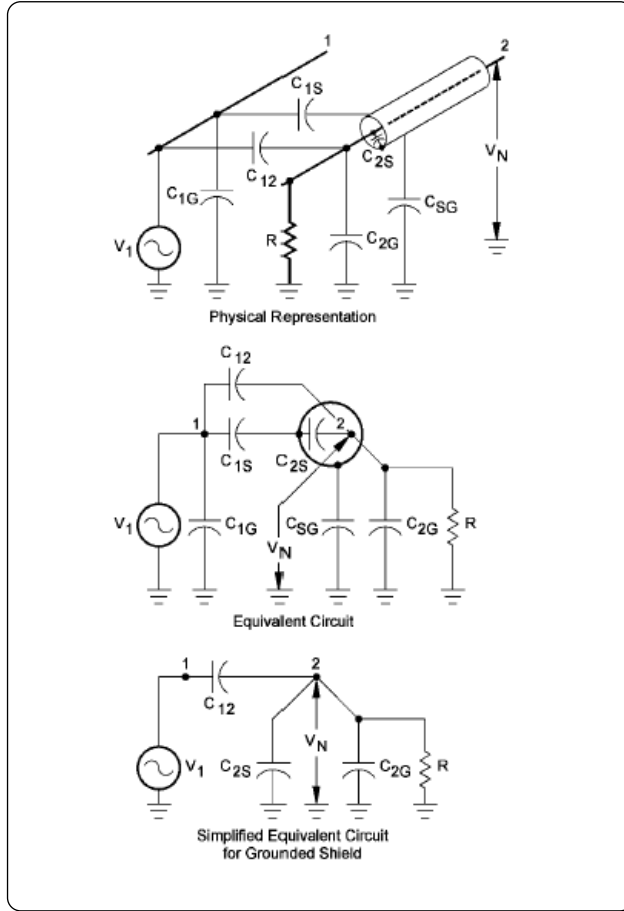


Figure 5.
Capacitive coupling when the center conductor is exposed beyond the shield

Figure 5 shows the same circuit with the center conductor (which has a finite resistance to ground) exposed beyond the confines of the shield. The noise voltage still reduces to:

$$V_N = j\omega RC_{12}V_1$$

However, C_{12} is now greatly reduced because a portion of the cable is shielded, reducing the noise coupling. But if the shield is braided or not uniform then the effect of the holes in the shield must be included in the value of C_{12} .

To summarize, for good electric field shielding it is necessary to minimize the length of the center conductor that extends beyond the shield and to provide a good ground on the shield.

Shielding Against Inductive Coupling

Inductive coupling is much more difficult to eliminate than capacitive coupling. The excellent electric-field shielding in the example described above has no effect on inductively coupled noise.

An important derivation for inductive coupling is that the mutual inductance between shield and the center conductor equals the shield inductance ($M = L_S$).

From the circuit diagram in **Figure 6** and the fact that $L_S = M$, the following relationship can be derived:

$$V_N = \frac{j\omega_{\text{Shield}}}{j\omega + R_S/L_S}$$

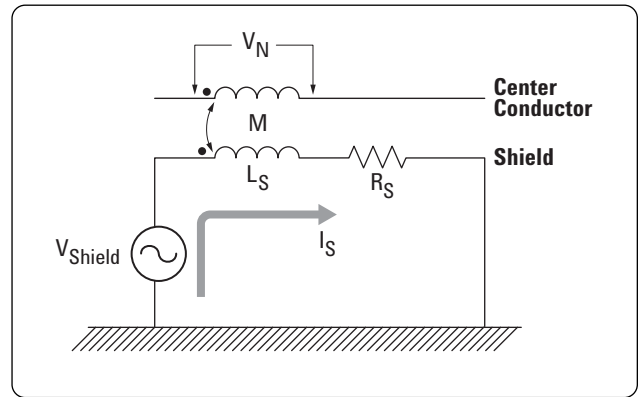


Figure 6. *Inductive coupling of a shielded conductor*

The 3-dB point on the graph of V_N versus frequency is defined as the cutoff frequency of the shield, ω_c . It can be shown that $\omega_c = R_S/L_S$. The center-conductor noise voltage is zero at DC and increases to almost V_{Shield} at five times the cutoff frequency.

Shielding Against Magnetic Radiation

Shielding may be used to prevent radiation from one signal path from inductively coupling into another path. **Figure 7a** shows both the electric and magnetic fields surrounding a conductor. If a shield that is grounded at one point is placed around the conductor, the electric field lines are controlled but the shield has no effect on the magnetic field (**Figure 7b**). On the other hand, if a current flows through the shield that is equal and opposite to the current flowing in the center conductor, the generated magnetic fields will be canceled (**Figure 7c**).

Figure 7a.
The fields of a bare current-carrying conductor

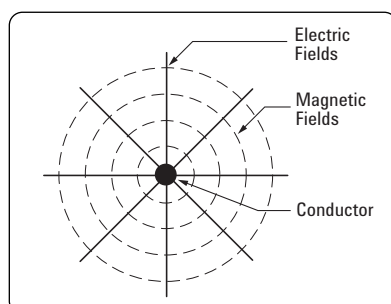


Figure 7b.
Fields with a shield grounded at one point

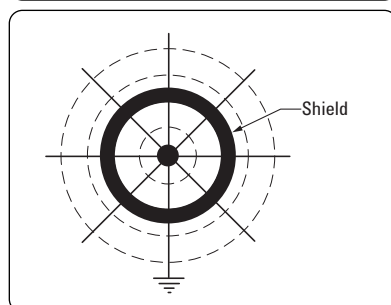
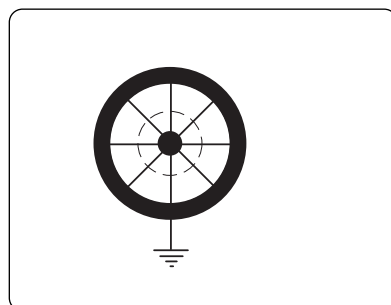


Figure 7c.
Fields with a grounded shield that is carrying current equal to the conductor but in the opposite direction



For a circuit grounded at both ends of a shielded cable, the shield must also be grounded at both ends to prevent magnetic radiation. This is true for frequencies well above the shield cutoff frequency because the mutual inductance between the shield and the center conductor provides a lower-impedance path than the ground plane. Below this frequency the ground plane carries most of the noise current and the shield is not as effective in containing it.

If the circuit is grounded at only one end, then the shield should be grounded at the same end. This ensures that the induced signal will have equal and opposite currents in the center conductor and the shield. Grounding both ends reduces the effectiveness of the shield because some of the induced current will flow via the ground path. Grounding just one end of the shield is effective at frequencies below the shield cutoff frequency.

Shielding Against Magnetic Reception

Because magnetic noise coupling is proportional to the loop area cutting the magnetic flux of the noise, circuits receiving noise can most effectively be protected against magnetic fields by decreasing the area of the receiver loop. The receiver loop is the total area enclosed by current flow in the receiver circuit, including the path of the current returning to the source. Often, this return path is not carefully considered, and it may even change during the course of a test, causing the loop area to change. This can be especially difficult to debug.

Figure 8a, pg. 7, shows a receiver with no shielding and large loop area that is very susceptible to magnetic reception. The shield added in **Figure 8b** and grounded at both ends reduces the loop area. This provides some protection against magnetic fields due to the reduced loop area, not to any magnetic shielding properties of the shield. In **Figure 8c**, a shield placed around the conductor and grounded only at one end does not change the loop area and therefore provides no magnetic shielding.

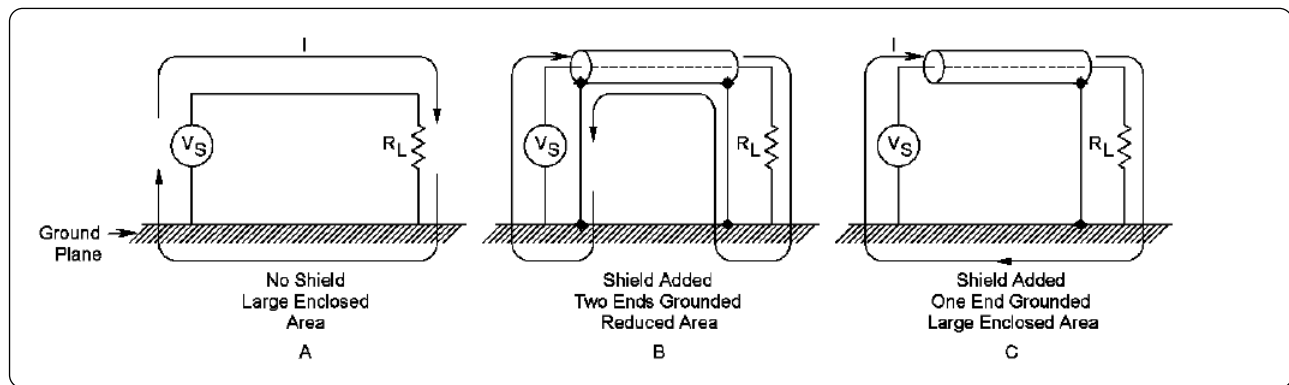


Figure 8. *The size of the enclosed receiver loop area with different grounding methods*

At frequencies below the cutoff frequency of the shield, most of the current returns through the ground plane instead of the shield even when both ends are grounded. In the lower frequency case of **Figure 8b**, the shield does not protect against magnetic fields. This circuit should be avoided for two reasons. First, because the shield is one of the conductors, any noise current in it will produce an IR drop in the shield and appear in the circuit as a noise voltage. And second, any difference in ground potential between the two points in the ground plane will also produce noise voltage in the circuit. Whenever a shield is used in a circuit and is grounded at both ends of the circuit, only limited low-frequency magnetic field protection is possible because of large noise currents induced in the ground loop. For maximum protection against induced noise at low frequencies, the shield must not be one of the signal conductors and one end of the circuit must be isolated from ground.

Cable Comparisons

Selecting the proper type of cable is also an important system design function. A double-shielded or triaxial cable with insulation between the two shields provides the maximum protection against noise coupling. Because the noise current flows through the outer shield and the signal return current flows

through the inner shield, the two currents do not flow through a common impedance and produce noise coupling. A coaxial cable with its shield grounded at one point provides a substantial amount of protection from capacitive pickup. Above 1 MHz, skin effect on the shield of coaxial cable tends to simulate triaxial cable, providing comparable performance without the expense and awkwardness of triaxial cable. The noise current will flow on the exterior of the shield and the signal return current will flow on the interior of the shield.

The impedance of coax cable is relatively uniform from DC to VHF (30 MHz to 300 MHz) frequencies. Twisted pairs (in which the wires are twisted together to reduce the loop area) and shielded twisted pairs should be used for applications up to a few hundred kilohertz. Above this frequency these cables are prone to signal loss, but below it the shielded twisted-pair cable has performance comparable to triaxial cable. An unshielded twisted pair, unless it is used in a balanced circuit, offers little protection against capacitive pickup but has good noise immunity from magnetic pickup.

Grounding

Appropriate grounding and shielding can solve most noise problems if designed with the same care as the rest of the system. Improper grounding can be a primary noise source. The design objectives of a

grounding system are to minimize the noise voltage generated by currents from two or more circuits flowing through a common ground impedance, and to avoid creating ground loops that are susceptible to magnetic fields and differences in ground potential.

Though there are many possible reasons for grounding a circuit, the two most common are for safety and to provide an equipotential reference for signal voltages. Safety grounds are provided so that a breakdown in impedance between the equipment chassis and the high-voltage line of the power line will result in a low-impedance path to ground, and are always at earth potential.

Signal grounds may or may not be at earth ground, and can be considered either an equipotential circuit reference point for a circuit or system or a low-impedance path for current to return to the source. The first definition is the classical interpretation of the idealized ground. The second emphasizes the realities of the IR drops that can occur in the ground plane and couple noise into the signal conductor.

For practical reasons, most systems require separate ground returns for various components of the system. Low-level signal grounds should be separate from hardware grounds and noisy grounds like relay and motor grounds. In sensitive systems, for example, separating the signal grounds into low-level and digital grounds prevents the higher level, much noisier digital signals from coupling into the low-level leads. If AC power is distributed throughout the system, the power ground should be connected to the chassis or hardware ground.

A single ground reference point should always be used for low-level work. Otherwise, any differences in ground potential will appear as noise in the signal path. As shown in **Figure 9**, if the instrument low terminal is grounded ($Z_2=0$), then E_{cm} appears directly across R_b , which is in series with the input signal. Floating the instrument low terminal, however,

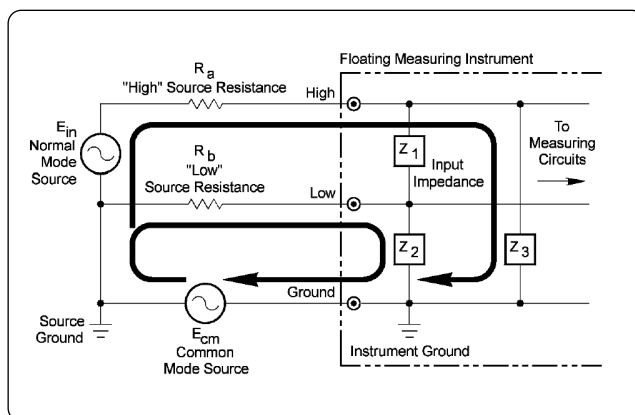


Figure 9. Equivalent circuit of a floating instrument

increases Z_2 to a large value and creates a voltage divider that reduces the noise in the measurement path by a factor of approximately R_b/Z_2 .

Single-Point Ground Systems

Signal grounds are either single point or multipoint. Single-point grounds can be connected in series or parallel. To prevent noise coupling, the least desirable grounding scheme is the series ground, but it is also the least expensive and the easiest to wire, so it is the most widely used. For noncritical applications the series ground may work satisfactorily. The most critical circuits should be placed nearest to the primary ground point. **Figure 10** shows a series ground connection; circuit 1 should be the most critical one.

The parallel ground configuration shown in **Figure 11**, pg. 9, is the most desirable configuration for low frequencies. This configuration eliminates cross-coupling between ground currents through different circuits, but is awkward to wire and use.

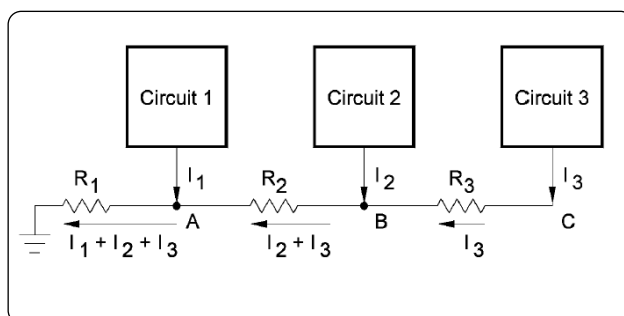


Figure 10. Series ground connection

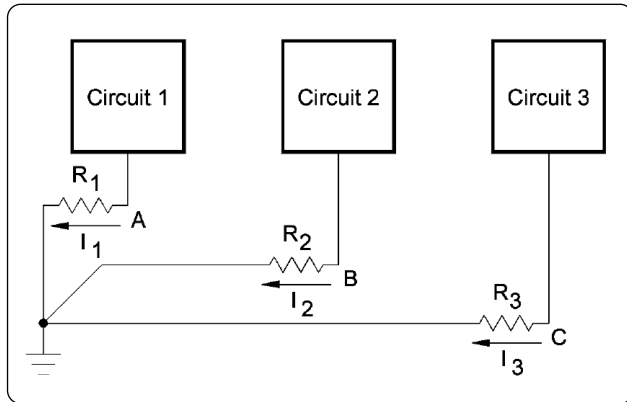


Figure 11. Parallel ground connection

At high frequencies the parallel single-point connection is of limited usefulness, as the inductance of the ground conductors increases the ground impedance and also produces capacitive coupling between the ground leads. This situation worsens as the frequency increases, and at sufficiently high frequencies the ground leads begin to act like antennas and radiate noise. As a rule, the length of the ground leads should be less than 1/20th of a wavelength to prevent radiation and maintain low impedance.

Multipoint Ground Systems

At high frequencies, the multipoint ground system is used. In multipoint ground systems all the ground currents from all the circuits flow through a common ground impedance, as shown in Figure 12. Typically, the circuits are connected to the nearest available low-impedance ground plane, normally the system chassis. The low impedance of the ground plane is due to its lower inductance, and connections to the ground plane must be as short as possible to minimize the impedance between the circuit and the ground.

Normally, at frequencies below 1 MHz a single-point ground system is preferable; above 10 MHz the multipoint ground is best. From 1 to 10 MHz, a single-point ground system can be used if the length of the longest ground return is less than 1/20th of a wavelength. If this is not possible, then a multipoint ground system should be used.

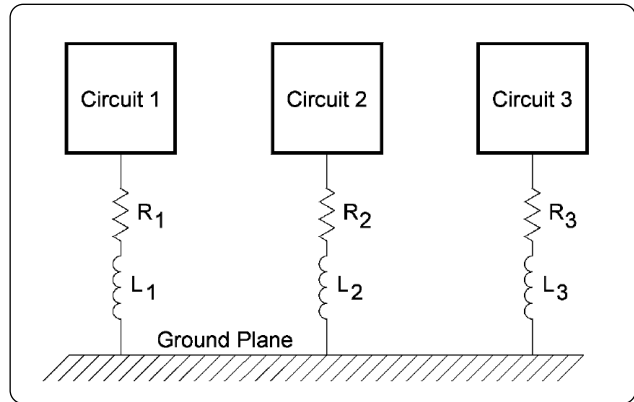


Figure 12. Multipoint ground system

Grounding Cable and Connector Shields

To minimize noise current in the shield, shields on cables used at low frequencies should only be connected to a ground at one point when the signal circuit has a single ground point. If a coaxial cable is connected to more than one ground point, the IR drop caused by the noise in the shield will couple noise into the signal conductor. For shielded twisted-pair cables, noise may inductively couple unequal voltages into the signal cable, resulting in noise there.

The single ground point must be chosen with care. If only the source is grounded (Figure 13) then the cable shield should be connected only to the source common, even if this point is not at earth ground.

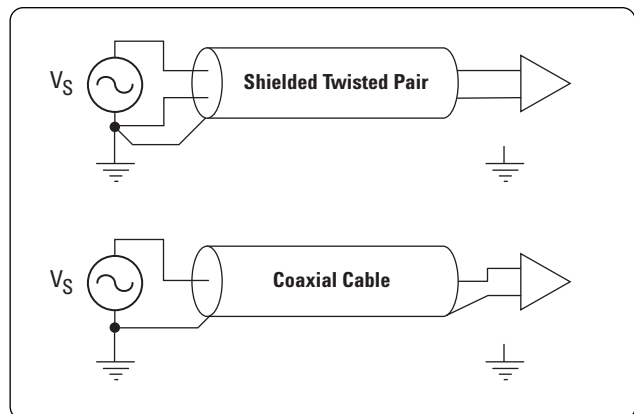


Figure 13. Recommended shield ground point when only the source is grounded

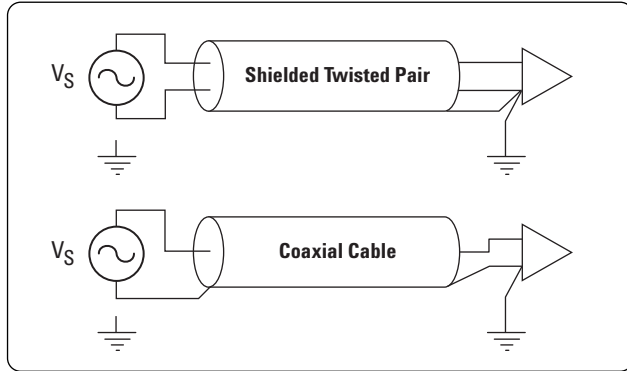


Figure 14. Recommended shield ground point when only the load is grounded

On the other hand, if the load is grounded (Figure 14), the cable shield should be connected only to the load common, again, even if the point is not at earth common.

When the signal circuit is grounded at both ends (Figure 15), only limited noise reduction is possible. Grounding both ends of the shield will allow some of the ground loop current to flow in the shield instead of all of it flowing in the signal lead. If additional noise reduction is required, the ground loop created by grounding both the source and the load must be broken. This can be done by using a transformer or other isolation device.

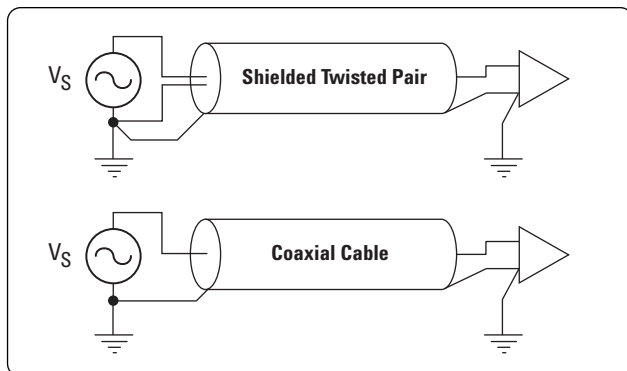


Figure 15. When the signal circuit is grounded at both ends, only limited noise reduction is possible.

Isolating Ground Loops

Ground loops are created when both ends of a circuit are grounded (Figure 16a). Ground loops in noisy environments can be broken by the use of isolation transformers (Figure 16b). For cases in which a DC path must be maintained, a transformer can be used as a longitudinal choke to suppress only the higher-frequency loops (Figure 16c). Optical isolation also can be used to break ground loops.

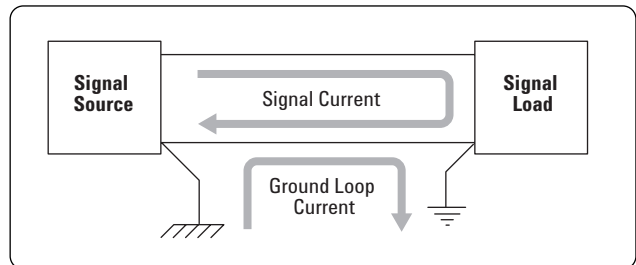


Figure 16a. Ground loops are created when both ends of a circuit are grounded.

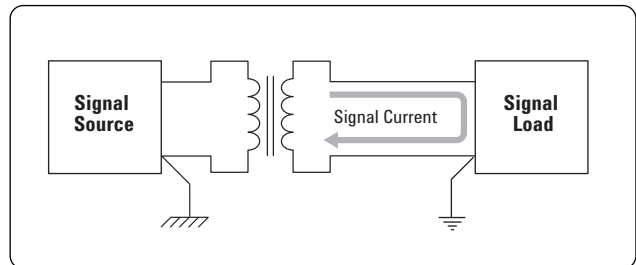


Figure 16b. They can be broken with a transformer.

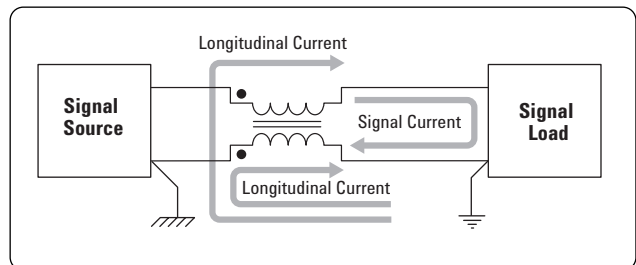


Figure 16c. When a DC path must be maintained, they can be broken with a longitudinal choke.

Other methods for reducing the effects of ground-loop noise apply directly to the measuring receiver amplifier. The receiver can be configured to minimize the effect of ground loops by using a balanced input. A guard shield around the amplifier provides even more noise rejection at low frequency.

Shield Grounding at High Frequencies

Shield grounding at high frequencies, above 1 MHz, requires more than one connection to ground to guarantee that the shield remains at ground potential. Further, capacitive coupling between the shield and ground plane tends to complete the ground-loop circuit at high frequency and makes isolation at the ungrounded end difficult to impossible. At these high frequencies, both ends of the shield are normally grounded.

To ensure good grounding for long cables at high frequencies, it is common practice to ground the shield at every 1/10th wavelength. A hybrid ground formed by connecting small capacitors to ground at every 1/10th wavelength provides a single ground at DC and multiple grounds at high frequency. An added advantage is that its performance can be characterized reliably.

Maintaining Signal Integrity through Connectors

Whenever possible, the signal and its shield should be maintained through connectors. The isolated BNC connector is an example of a nearly ideal connector in that the shield is maintained and isolated and the impedance of the cable is also maintained.

Such connectors are often not practical in a test system, and higher-density connectors are required. In these cases, high- and low-level signals should run through separate connectors. If they must run through the same connector, they should be placed as far apart as possible and ground leads should be placed between them.

Shielding must be maintained through a connector on separate pins and not connected to a single pin. Connecting all of the shields to a single pin or the connector case creates ground loops and allows shield currents to flow between individual shields.

Noise Reduction Techniques in Switching Systems

The interface between the DUT and switching system provides an easy pathway for noise to enter a test system. To prevent this problem, several guidelines should be followed.

Guidelines for the cable harness are:

1. High- and low-level leads should not share the same cable harness.
2. Shield integrity should not be broken through the system. For low frequencies, the shield must be insulated to avoid grounding at some other point in the system.

Guidelines for connectors are:

1. High- and low-level leads should be separated on the connector.
2. Ground leads should be placed between the signal leads where possible.
3. Any unused connector pins should remain between the signal leads and be grounded.
4. Each cable shield should have its own connector pin through the connector.

Tree switching is often used to reduce the stray open-switch capacitance seen in large systems as a result of connecting the unused relays in parallel in the system. This capacitance is reduced by introducing a relay in series with the input relays. For a 16-channel multiplexer this series switch effectively reduces the stray capacitance seen by the measuring circuit to

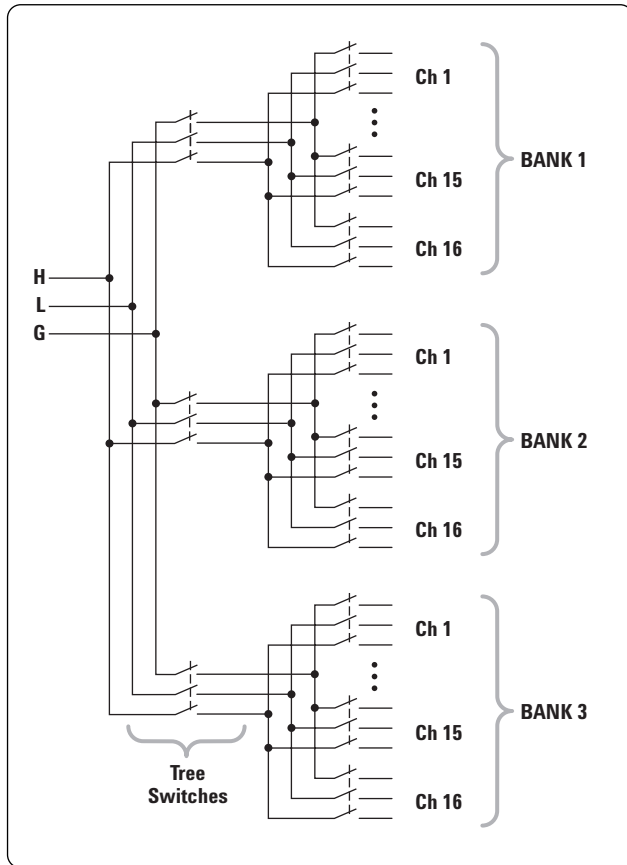


Figure 17. The tree switches separate the banks of switches from each other. If each bank has 16 channels, the tree switch can reduce unwanted coupling from one bank to another by as much as 16:1.

1/16th what it would be without the tree switch. The result is less crosstalk and faster measurement settling time for the system. A tree-switching scheme is shown in **Figure 17**.

T-switching is a method by which all of the unused channels are isolated from the measurement bus by a low-inductance path to ground. This isolation can be accomplished on a single conductor by inserting two additional contacts in the signal path. The result is excellent channel-to-channel signal isolation at high frequency on the same multiplexer. **Figure 18** illustrates the concept of T-switching, and **Figure 19** shows the effect of T-switching on crosstalk.

Other ways of reducing switch capacitance, and therefore coupled noise, are either to make the switch and the switch contact gap large or to make the contact area extremely small. For example, the Agilent 8762A coaxial SPDT switch employs a very long throw in its switching action and is housed in a precisely milled enclosure to ensure signal integrity to 18 GHz and beyond.

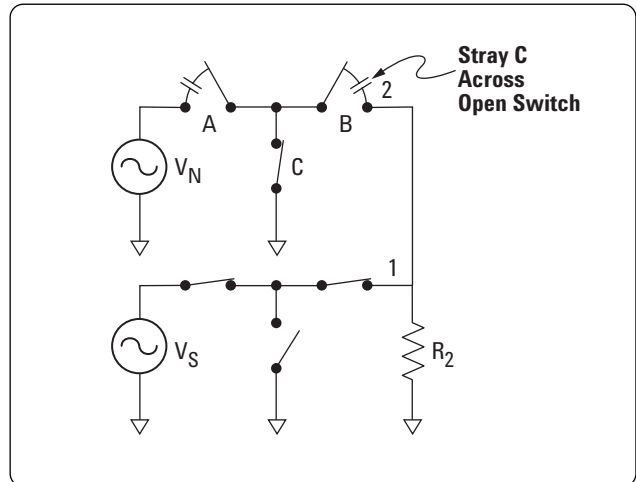


Figure 18. Simplified schematic of T-switching

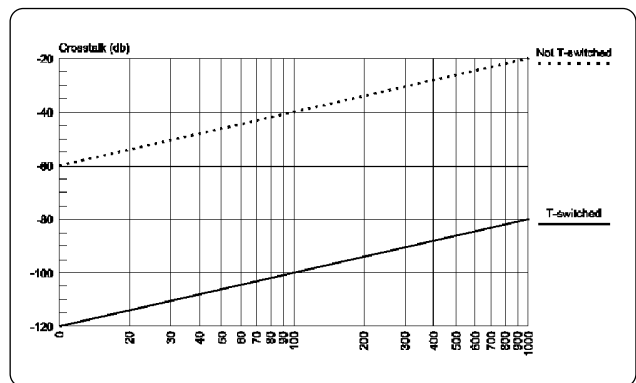


Figure 19. The effect of T-switching on crosstalk

Summary

Signal integrity is vital in a test system in order to obtain accurate measurements. Signal integrity can best be maintained by suppressing noise at its source and keeping noise coupling to a minimum. This can be accomplished by careful attention to proper grounding and shielding based on the input and output characteristics of the DUT, the test instrumentation, the switch, and other components and connectors.

With today's high-performance systems, small errors can result in significant noise. Moderate frequencies and amplitudes are fairly easy to route and measure, although care must be taken to avoid ground loops. Higher-frequency or low-level signals require special attention to the type of switch and the configuration of the switch to maintain signal integrity in the system.

For further discussion of cabling and connections, refer to Henry W. Ott's excellent book "Noise Reduction Techniques in Electronic Systems", John Wiley & Sons, 1988. This book should be on the desk of every engineer.



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