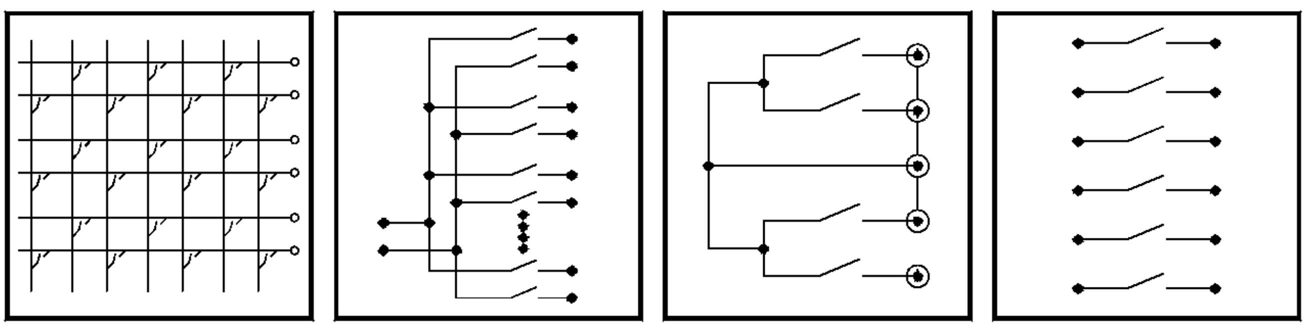
VXI Test System Signal Switching

Application Note



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Practical Test System Signal Switching

Introduction

This application note presents solutions to problems encountered when designing systems for testing electronic and electromechanical devices. With such a wide range of devices to be tested, this application note is not exhaustive in its approach, but is representative so that you can interpolate your solution from the solutions offered.

This application note covers switching topology and signal maintenance for signal frequencies less than 300 MHz, voltages less than 250 V, currents less than 5 A, and Volt-Hertz products less than 107. Extrapolation of these solutions to either higher amplitude or higher frequency is not recommended without additional references.

The system architecture, illustrated in Figure 1, is common to all test systems used to test discrete electromechanical and electronic devices. The switch is the heart of the system. It is the glue that connects the many test points to the measuring instruments. It is also the source of many inexplicable errors addressed by this application note.

Basically, the problem is that in a system there are many signal and power lines that you may want to use to measure or stimulate the device under test (DUT). Further, as far as is practical, automation is desired to reduce human error and monotony in the testing of these devices. Hence, you are confronted with the problems of a multi-point system where the interaction of test and power signals may interfere with measurements.

The configuration of the simplest test is suddenly changed when you automate. The picture must now include a test-switching device to route signals and power to the DUT. As long as the amplitude and frequency of the test signal are of moderate value and the measurement accuracy is not a stringent requirement, it is relatively easy to construct a switching system from off-the-shelf parts. The advent of higher speed logic in DUTs in conjunction with more sensitive analog circuitry, however, has created a situation where special designs in the switching system become very important for signal integrity. Further, the apparent savings in hardware costs by building your own switching device may be consumed many times over by documentation and support costs. These costs tend to make the purchase of well-specified commercial hardware desirable.

The test system configuration is a function of what you are testing, how you are testing it, and how often you change the test or tested device. It may also be dependent upon the system throughput required. For example, if the DUT is a DC resistive ladder that you are laser trimming, there is no need for short cable length. On the other hand, if you are testing receivers in the VHF frequency range, it may be desirable to keep the test leads as short as possible between the receiver and the test instruments. Moreover, if you are testing many different radios, you may want a convenient way of changing the test system interface; i.e. you might need short cable length and mass interconnection to meet both these needs.

Switching topologies, distinct from system configurations, involve the actual routing of the test signals as well as the power from the instruments to the DUT. The various topologies of simple relays, multiplexers, and matrices are discussed in the topology section.

This application note addresses the problems of maintaining optimum signal integrity when integrating commercially available switch products and measuring instrumentation into a test system. Tree switching, T-switching, isolation, insertion loss, Voltage Standing Wave Ratio (VSWR), path length, noise decoupling, shielding, and grounding in automatic systems are examined.

Before continuing, you should have a working knowledge in the use and characteristics of basic measuring instruments. The bibliography at the end of this note should help in finding additional information. Other pertinent application notes can be obtained from your local Agilent sales office.

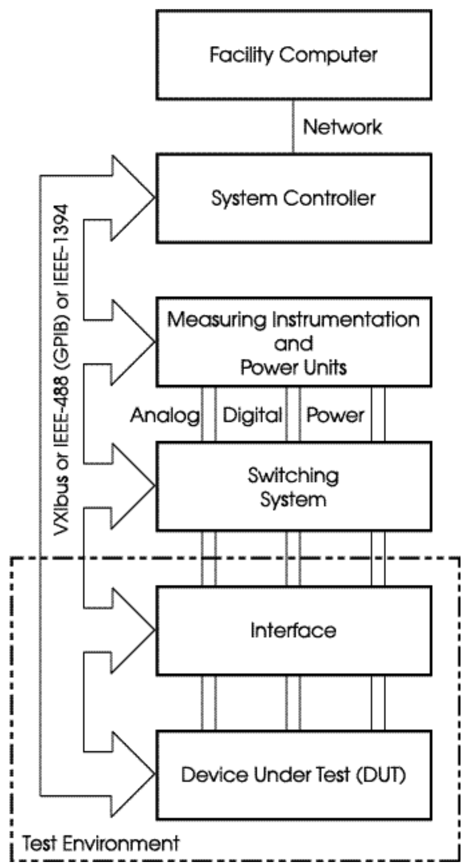


Figure 1 System Architecture.- the switching system is the heart of the test system. Nearly all the analog, digital, and power leads pass through and are routed by the switch system.

Measurement Basics

Common to all test system designs is the need to know the frequency and amplitude of the test signals and the input and output characteristics of the test instrumentation, the switching system, and the DUT.

Frequency Range

Frequency range of interest may be from DC to many GHz. Only the frequency range where lumped circuit analysis using Kirchoff's laws applies is discussed in detail. Hence, the frequencies of interest will span wavelengths that are physically large compared to the electronic circuits, (i.e., up to approximately 500 MHz). Even above this frequency useful approximations may be made using the laws of circuit analysis.

Amplitude Range

The range of amplitudes discussed is from 1 micro volt to 250 volt.

The measurement of this wide range of amplitudes requires both amplifiers and attenuators to accommodate any A-to-D conversion scheme or any human interface of practical value.

Input Characteristics

Measuring instruments can be divided into three separate categories according to their input resistance:

Very High > $10^{10}\Omega$
    Multimeters, DC semiconductor parameter analyzers

1 MΩ
    Oscilloscopes, counters waveform recorders, low frequency spectrum analyzers

50Ω or 75Ω
    High bandwidth oscilloscopes, spectrum analyzers, wave analyzers

The upper frequency limit of the instrumentation is dictated in part by the input capacitance. The reactive impedance represented by the input capacitance can be calculated from:

$$X = \frac{1}{2\pi f C}$$

As can be seen from this simple relationship, as the frequency increases the impedance decreases. For example, an oscilloscope's input impedance may be specified as 1 MΩ shunted by 30 pF. Substitution in to the above formula for a 50 MHz test signal yields 1 MΩ shunted by 106.1 Ω. If the output impedance of the test signal is a nominal 50 Ω, then the amplitude error in this measurement is 9%! The frequency dependence of the input impedance is illustrated in Figure 2, where the amplitude error relative to the DC response is plotted against input frequency for a typical oscilloscope input.

In cables capacitance is a function of length. Hence, the cabling must be kept as short as possible to keep the capacitance low. Another way of achieving low capacitance is to use a passive compensating network to reduce the overall capacitance of the cabling. The penalty is reduced sensitivity. For example, you can use passive voltage divider probes with high impedance oscilloscope and counter inputs because they tend to keep the input capacitance low while increasing the resistance to 10 MΩ (10 to 1 divider probes). However, the 10 to 1 divider probe may not leave you enough signal to measure with the resolution you require.

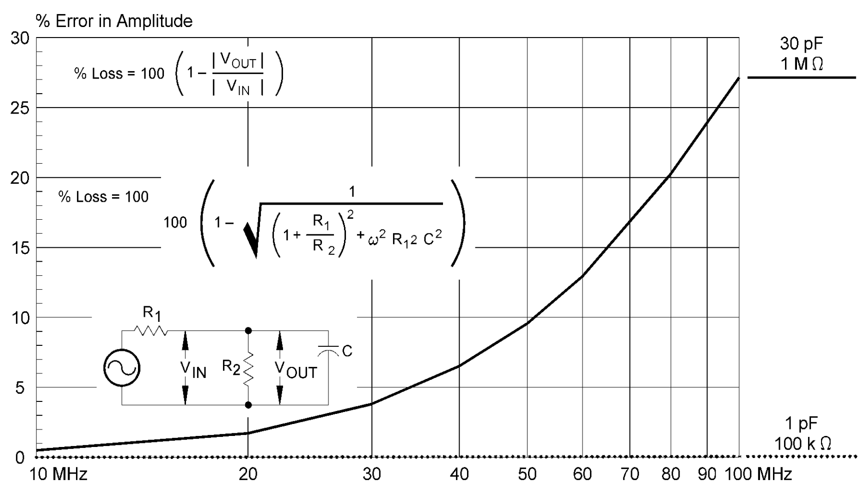


Figure 2 Amplitude error caused by capacitive loading. Assumes that R1 is 50 Ω

Terminated instruments tend to reduce the problems of capacitance over their operating range. The trade-off, however, is a loss of general purpose capability by terminating in low impedance (generally 50 or 75Ω). The solution to this problem is to use a passive divider probe or an active probe designed for 50Ω input impedances. Passive divider probes can offer up to 5kΩ of resistive impedance to the DUT but they can also reduce the amplitude of the input signal 100 to 1. The active probe uses active circuitry to produce input impedances of 100kΩ shunted by 1 pF. When examining the test signal of 50 MHz and 50Ω output impedance, we find that with this active probe the input reactance is 3183Ω. The amplitude error relative to the DC response is only 0.05% - all resistive loss.

In addition to the frequency dependence of input impedance, signal amplitude may change the input impedance of the instrument. For example, if a multimeter is measuring 100 V, it may have an input impedance of 10MΩ; if it were measuring 10 V its input impedance could be 10,000MΩ. This is not significant unless you are designing a system to work with a constant input impedance. Some high frequency peak detector probes are designed to work only with 10MΩ instrument input impedances; a higher input impedance becomes detrimental to the measurement.

Of further significance is the input impedance when the instrument is in an overload or overrange condition. A high speed voltmeter may be connected in parallel with a multimeter. Ordinarily, this connection causes no problem. The high impedance of 1MΩ of the system voltmeter doesn't cause too much degradation of the test signal. If, however, the test signal should exceed the input amplitude range of either of the meters they will change their input impedance. This is a design feature intended to protect the voltmeter from damage. To the unsuspecting user, it could cause unexplainable measurement errors. **The instrument is designed to operate within the specified input range, not beyond it.**

Of equal importance to the concept of input impedance is the input isolation offered by the various input terminal configurations. Measurements made with minimal need for amplitude accuracy or sensitivity can be accomplished with single ended connections-connections that only need to have a signal "high" terminal and a common return. The BNC connectors found on oscilloscopes and counters fill this criteria.

Lower frequency, high sensitivity measurements are subject to common mode noise of an inductive nature. Commonly, this noise is avoided by breaking the ground loop with a floating input; where even the low terminal of the measuring instrument is connected to source low. Typical multimeter configurations display this type input. The signal low is actually, floating above chassis low by tens of mega-ohms in the typical configuration. The high input is isolated from low by the specified instrument input impedance. More is covered on grounding in the section on maintaining signal integrity.

Other measurements may call for still more isolation. For example, a picoammeter capable of measuring small currents in the neighborhood of 10^{-12} a commonly uses a triaxial input to achieve sufficient isolation. In this same vein, some LCR meters employ 4 terminal pair measurements to give them more signal isolation.

Output Characteristics

In a system it is important to know the output impedance of both the instrument and DUT signal sources. Ideal voltage sources are defined to have zero source impedance and current sources are defined to have infinite source impedance. A nearly perfect voltage source is the automobile battery, but it still has some series source impedance. If it did not, then a dead short across it would cause an infinitely large current to flow. Real current sources, likewise, have a finite parallel impedance. The object of a current source is to provide a constant current no matter what the load impedance might be. The object of a voltage source is to provide a constant voltage no matter what the load impedance might be. Since neither of these objectives is realizable, the concept of source compliance comes into play. Source compliance is encountered when the output voltage (current) is no longer constant with a change in load impedance. In some cases, with autoranging power supplies for example, your system can be informed via a service request that such an area in the operation of the power supply has been reached.

The output impedance of most signal sources is 50 or 75Ω. Programmable sources expect to be terminated in 50 or 75Ω to be amplitude calibrated. High impedance inputs, like voltmeters and oscilloscopes read the amplitude as twice the programmed amplitude.

In network analysis the signal source and the analyzer work together as a stimulus/response unit. Typically, these are 50 or 75 ohm systems; hence, it is important to maintain this characteristic impedance through any switching network in a system.

Switching Topologies

Switching topologies can be divided into simple switches, multiplexers, and matrices. Let's examine each of these in this order.

Simple Relay Configurations

Simple relay configurations may be used in applications from switching the power to the DUT to forming a complex matrix topology for measurements. Some of the most common configurations consist of form A, form B, and form C configurations which can be linked together to form binary switching networks that guarantee that only one point can be connected to any other point at a time. Similarly, these points can be configured to form measurement buses for the connection of many points to one point at a time. For the most part, this configuration is used for simple on-off switching of power rather than for signals. See Figures 3 and 4.

Multiplexer Configurations

The multiplexer configuration is most commonly used for signal switching into instrumentation. Generally, in this signal switching configuration, only one signal is connected at a time to the measuring device and the switching is break-before-make; i.e., the input is disconnected before a new input is connected. An enhancement, T-switching, reduces unwanted signal coupling into the measurement channels. In T-switching another relay is connected to ground via a low impedance path. Hence, unwanted signals, which would be capacitively coupled to the measurement, are shunted to ground. T-switching is discussed in more detail in Noise Reduction Techniques in Switching Systems on page 16.

Multiplexing configurations are used primarily to connect multiple signals to a single output such as a number of thermocouples to a voltmeter or a number of test points to an oscilloscope. The main advantage of this configuration is economy. Single wire configurations are useful for high frequency applications for two reasons:

1. Most measuring instruments for higher frequency signals are single ended (common ground or low with all the inputs).
2. At high frequency it is difficult to design a switch where both "high" and "low" are switched without affecting the characteristic impedance through the switch. See Figure 5.

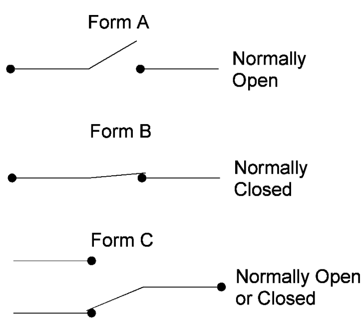


Figure 3 Simple relays configurations: form A, form B, and form C relays.

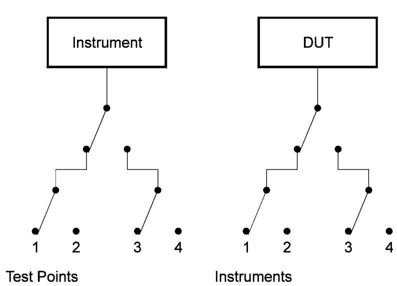


Figure 4 The Binary Switching Ladder. This is an excellent switching configuration to assure that only one device at a time is connected to the test point and that no two test points are connected together – a major safety consideration. The construction uses form C relays.

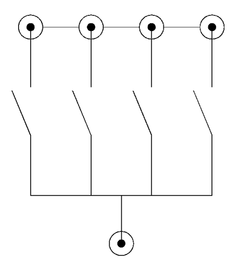


Figure 5 Single ended multiplexing topologies used at higher frequencies: Only the signal conductor is switched; the shield is common to all signals.

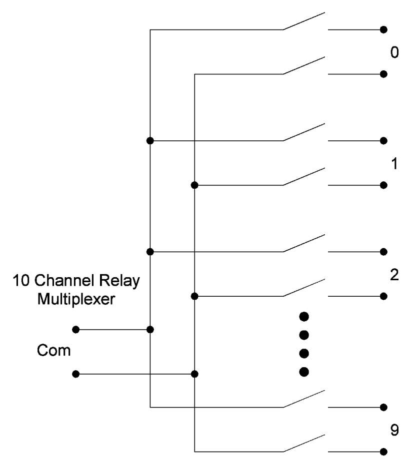


Figure 6 2 - Wire Multiplexing Topologies: a 10 channel relay multiplexer can be used for floating measurements since both conductors, the signal and the ground return, are connected to the common bus at the same time.

Two-wire multiplexers are useful for floating measurements. Inductive coupling can cause the generation of ground loops in the low lead. To break these loops it is necessary to switch the "low" as well as the "high". This is particularly useful for capacitance and inductance measurements at frequencies below 1 MHz. Devices such as thermocouples and other DC transducers can also be connected to voltmeters with good common mode noise rejection. See Figure 6.

The three-wire multiplexer is designed for the guarded voltmeter. This additional connection can shunt noise current away from the input measurement terminals and give the user up to 120 dB of common mode noise rejection, almost 1000 times more than the two-wire measurement. Four-wire multiplexers can be used for 4-wire ohms measurements. Five and six-wire switching can be useful for simultaneous application of driven grounds for in-circuit component isolation and measurements.

Matrix Configurations

The matrix switch is the easiest to specify for any system use, but for the most part it offers the least performance for switching in your system. In addition, the matrix configuration, which requires at least the number of relays equal to the number of inputs times the number of outputs, is generally the most expensive way to approach any system problem. The trade-offs are flexibility versus price and performance.

If you need to have more than one instrument connected to the same test point at the same time though, you may need a matrix topology.

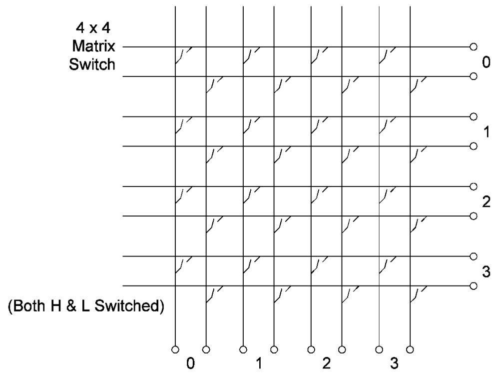


Figure 7 The Full Crossbar Matrix.- this matrix card allows 2-wire connection from any point to any point. This configuration can be expanded to much larger systems but the switch capacitance increases dramatically as the system increases in size.

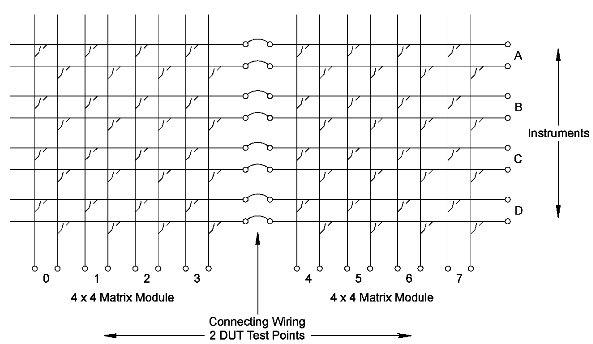


Figure 8 Multiple matrix cards can be added together to increase the size of the switching system. By using 5 matrix modules, 4 instruments could be simultaneously connected to any one of 20 test points. Since the inter-channel capacitance has increased due to longer conductor paths, the overall capacitance increases more than just the sum of the additional switch capacitances. This makes high frequency signal integrity difficult to maintain for large matrix configurations.

In theory, by using a matrix switch topology anything can be connected to anything else in the system at the same time. These are the trade-offs for this configuration:

1. Reflections: Reflections can be a problem in actual practice above a few MHz in frequency. Particularly, digital systems can have many reflections and isolation problems that may be unsuspected because of relatively low repetition rates coupled with fast transition times on digital signals. Reflections caused by impedance mismatches on the open channels can cause erroneous behavior in the DUT, which can cause poor measurements and also interfere with the unit tested.

2. Signal Integrity. It is very difficult to maintain crosstalk isolation, insertion loss, and good VSWR. Hence, bandwidth is typically reduced in a matrix configuration when compared to a multiplexed configuration for the same type of switches and cabling. Further, there is generally a limitation on the amount of voltage and current switched through the system because of the physical density of the switches in a matrix configuration.

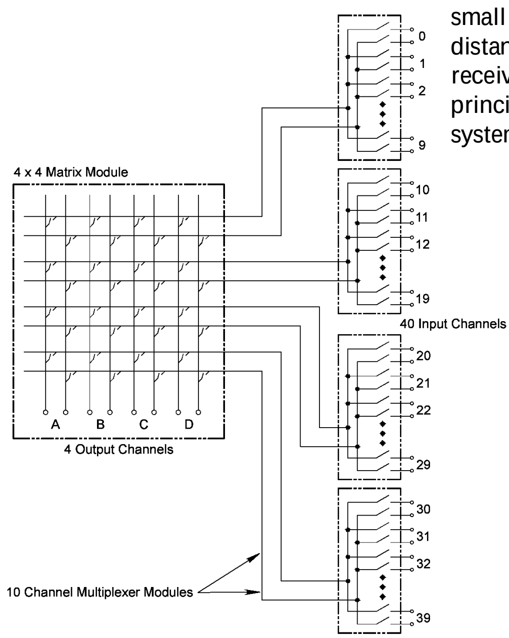


Figure 9 - Use multiplexers to effectively expand the number of inputs or outputs of a matrix. This arrangement is not a true complete crossbar matrix because any combination of inputs cannot be connected to any combination of outputs. (For example, you can't connect channel A to channel 2 while also connecting channel C to channel 1.) But this "4 x 40" topology can be an economical way to achieve a configuration that provides flexible multiple channel closures for 4 different signals.

3. Cost. The cost of relays has to be considered in designing a system. To switch n items to n items ("lines" and "trunks" in communication terminology) requires at least n x m relays for arbitrary connections.

4. May not be necessary. Most test systems do not require simultaneous closure of more than a few channels to individual instruments or test points for complete testing. Hence, a complete matrix is not necessary for most testing applications. Even the most common full crossbar matrix application, the telephone system, is only designed around a finite number of trunk lines and these tend to be connected via a small number of pathways as the distance between the originating and receiving call is increased. This same principle can be applied to a test system.

5. Safety. Because one can connect any point to any other point in the system, there is a greater burden on the system designer to build software that prevents the user from connecting things together that shouldn't be connected. In the case of a hardware failure, the potential is much greater for such a catastrophe.

The result is that unless arbitrary connections are absolutely necessary, the full crossbar matrix should be avoided. In most cases it can be sidestepped by a judicious selection of multiple multiplexing schemes.

Only limited matrixing is required in most test applications. In many applications there is a need to matrix a limited number of signals to a fixed set of instrumentation simultaneously. However, there is seldom a need to connect all of these instruments together to the same signal. With matrixed multiplexers, the number of relays needed is reduced from $n \times m$ *to* $n \times p + p \times m$ where p is the number paths between the instruments and the DUT, and n *and* m are equal to the number of rows and columns in the matrix.

Before departing from switching topologies, a quick look at some typical switches used to construct these topologies is in order.

The trade-off between solid-state and mechanical relays is complex. For low level measurements the electromechanical relay is best for overall measurement performance. If speed or the number of switch closures in a controlled environment is the issue, then the FET switch offers a better solution. Typically, the FET will change the input impedance of the signal to the measuring instrument from a low impedance to a moderately high impedance. As discussed earlier, this fact alone can be a source of error. A summary of switch performance is in Table 1.

Switch Performance							
Type	**Switch**	**Agilent Instrument**	**Switch Speed**	**Thermal offset**	**Bandwidth (-3 dB)**	**Current Rating**	**Max Input**
Power	General Purpose	E1463A	>7ms	7µV	10MHz	5A	125 V
Signal	Matrix	E1361A	>7ms	14µV	10MHz	1A	250V
	Microwave	E1368A	30ms		18GHz		
	RF Multiplexer	E1472A	>7ms	6µV	1.3GHz	1A	42
	FET	E1351A	>0.16ms	25µV	500kHz	1mA	16V

Table 1. This table lists characteristics of some of instrumentation switches manufactured by Agilent. They are listed by the type of signal they switch (power or signal), the type of switch, where they are found, the maximum switching speed, thermal offset, bandwidth and the maximum voltage and current switchable

Maintaining Signal Integrity

Sources of Electronic Noise

The measurement of low level signals in a test system environment can best be accomplished with careful attention to the details of grounding and shielding. The following are major offenders of noise coupling into these systems:

1. Conductively coupled noise
2. Coupling through a common impedance
3. Electric and magnetic fields

Besides these sources of noise, some systems are sensitive to noise from galvanic action, thermocouple noise, electrolytic action, triboelectric effect, and conductor motion. In electronic test systems designed for the testing of electronic modules, the important noise sources are generally the following:

Conductively Coupled Noise

The easiest way to couple noise into the circuit is on the conductor leading into the circuit. A wire running through a noisy environment has an excellent chance of picking up unwanted noise and transferring it to the circuit. Major offenders are often the power supply leads connected to the circuit.

Coupling Through a Common Impedance

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, the ground potential is modulated by the ground current flowing from the other circuit in the common ground impedance.

Electric and Magnetic Fields

Radiated magnetic and electric fields occur whenever an electric charge is moved or a potential difference exists. In a circuit, high frequency interference may be rectified and appear as a DC error. Particularly, radio and TV broadcasts in close proximity to the circuit of interest will tend to cause this kind of problem. Extremely strong fields can cause non-linear behavior of active circuitry without being suspected. Hence, it is imperative to shield sensitive circuitry from these fields.

Sources of Noise in an Automatic System

Of particular importance to the test engineer is knowing the source of the unwanted noise in his system. A simple list of rules may be helpful in reducing unwanted noise, but it is seldom enough for an understanding of where the noise is coming from.

In many cases the noise culprit is the adjacent channel in the system. A look at the simplified equivalent circuit in Figure 10 shows that most of the capacitance in the switch system resides across the switch contacts and between the adjacent conductive paths. Since 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. This is not practical in many cases. Increasing the switch density is a desirable objective; it gives you more capability in a smaller package. Further, the systems being tested today tend to be much more complex and have larger point counts than ever before. Hence, you are faced with a dilemma of having to increase component density and the distance between channels at the same time.

One solution to this problem is to connect the large amplitude signals as far away as possible from the low-level signal leads. In addition, ground leads should be placed between the signal leads to provide a convenient path for the interfering noise.

Noise Coupling

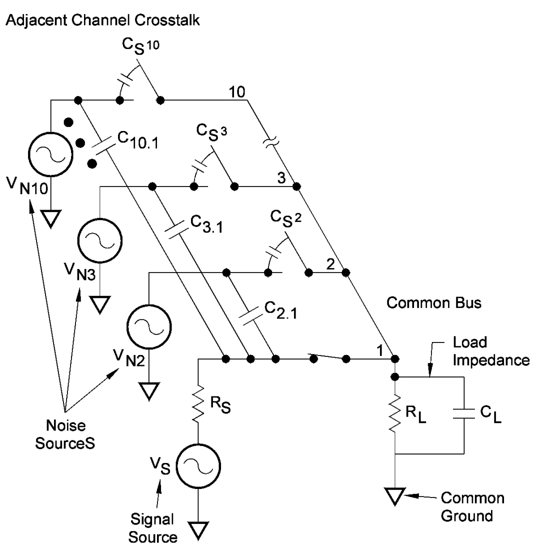


Figure 10 - The noise is coupled onto RL by the capacitance between leads $C_{2,1}$, $C_{3,1}$ and the capacitance across the switches, C_{S3}, and C_{S2}.

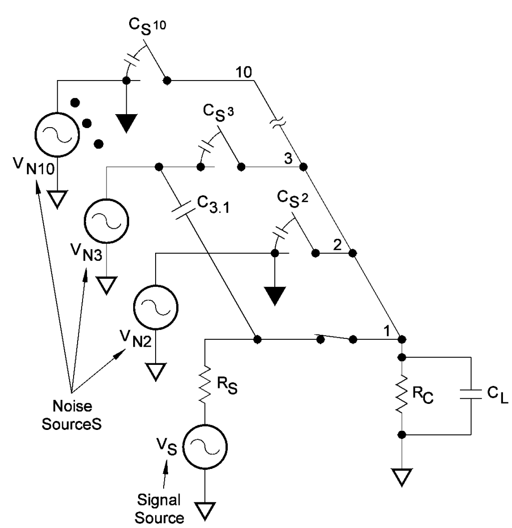


Figure 11 - A short placed on every other signal conductor reduces the conductor capacitance and provides a low inductance path to ground.

Noise Reduction

Noise reduction techniques apply equally to single point systems and multi-point systems. Let's look at the following topics:

1. Shielding
2. Grounding
3. Balancing
4. Isolation

Shielding

Shielding Against Capacitive Coupling

Shielding against noise in systems involves shielding against both capacitive (electric) and inductive (magnetic) coupling in the system. Capacitive noise coupling between channels is both the easiest to understand and shield against in a test system. As Figure 12 shows, the coupling of noise from one conductor to the other is a result of the capacitance between the conductors. For a load resistance R, much less than the impedance (because of lower frequency) formed by the parallel combination of the capacitance to ground of the signal conductor and the capacitance between the conductors, the noise voltage is:

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

C_{1G} does not couple noise into the signal conductor #2. Implied here that:

$R < 1/[j\omega(C_{12} + C_{2G})]$

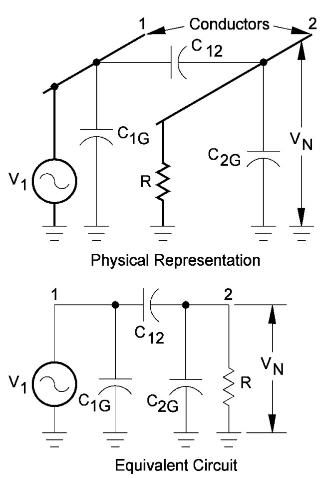


Figure 12[†] - Capacitive coupling between two conductors.

If you could reduce the capacitance, C_{12}, then the noise voltage coupled into the 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. Loading or mismatching may make this unfeasible.

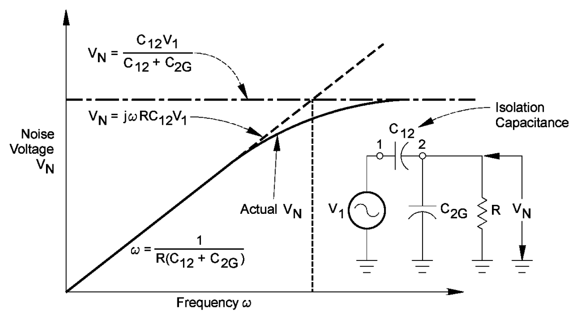


Figure 13[†] - Frequency response of capacitive coupled noise voltage.

Surrounding the signal conductor with a grounded shield with a uniform electric field (the geometry of the shield is smooth) reduces the noise voltage on the signal conductor to zero provided the conductor does not extend beyond the shield at high frequency. 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 as shown in Figure 14.

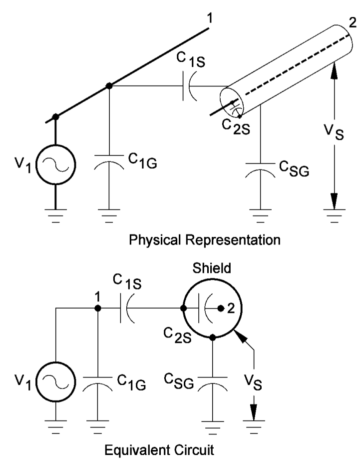


Figure 14[†]- Capacitive coupling with unguarded shield placed around receiver conductor.

[†] Ott, H., "Noise Reduction Techniques in Electronic System", John Wiley and Sons, 1988.

If the center conductor is exposed beyond the confines of the shield. and it has a finite resistance to ground, then the circuit is as shown in Figure 15. Again the noise voltage reduces to

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

Now however, C_{12} is greatly reduced because of the shield. If the shield is braided or not uniform then the effect of the holes in the shield must be included in C_{12}.

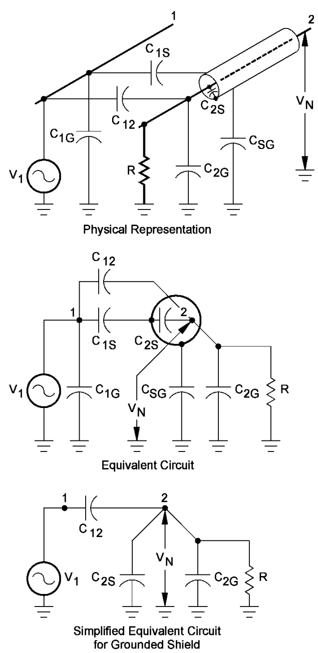


Figure 15† - Capacitive coupling when receiving conductor has resistance to ground.

Inductive coupling is much more difficult to eliminate than capacitive coupling. In fact, the above illustration for excellent electric field shielding 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 = Ls

In this case, the two conductors, the shield and the center conductor, do not even have to be coaxial.

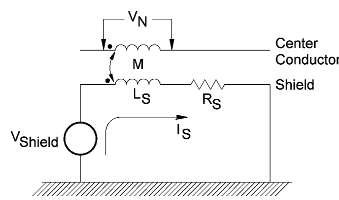


Figure 16† - Equivalent circuit of shielded conductor.

From the circuit diagram in Figure 16 and the fact that Ls = M.

We can derive the following relationship:

$$V_N = \frac{j\omega V_{shield}}{j\omega + R_S/L_S}$$

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 this frequency is $\omega_C = R_S/L_S$

Shielding Against Inductive Radiation

If current is allowed to flow in the shield by connecting both ends of the shield to ground, at 5 times above the cutoff frequency, ω_C, most of the noise current flows in the shield and cancels the noise current flowing in the center conductor. Below this frequency the ground plane carries most of the noise current and the shield is not effective in containing the noise. Hence, for audio and higher frequency applications the shield should be grounded at both ends. The noise reduction is a result of the field generated by the current in the shield that cancels the conductor's field and has little to do with the magnetic properties of the shield material.

Shielding Against Magnetic Reception

Since inductive noise coupling is proportional to the loop area cutting the magnetic flux of the noise, receiver circuits can be best protected against magnetic fields by decreasing the area of the receiver loop.

Referring to Figure 17C, a shield placed around the conductor does not change the loop area and therefore provides no magnetic shielding. In Figure 17B, above the cutoff frequency, wc the circuit provides excellent magnetic field protection; however, below cutoff frequency most of the current will return through the ground plane and not through the shield. Since 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. If there is a difference in ground potential between the two points in the ground plane, this too will 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.

†Ott. H., "Noise Reduction Techniques in Electronic Systems", John Wiley and Sons, 1988.

For maximum protection against induced noise at low frequencies, the shield should not be one of the signal conductors and one end of the circuit must be isolated from ground.

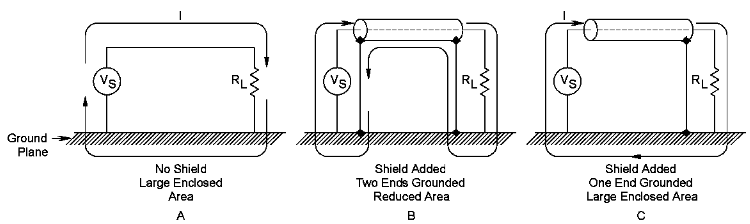


Figure 17† - Effect of shield on receiver loop area.

Coaxial Cable Versus Twisted Pairs

Twisted pairs, where the wires are twisted together to reduce the loop area, and shielded twisted pairs should be used for applications up to a few hundred kHz. Above this frequency these cables are prone to signal loss. By contrast, the impedance of coax cable is relatively uniform from DC to VHF (30 MHz to 300 MHz) frequencies.

A coaxial cable with its shield grounded at one point provides a substantial amount of protection from capacitive pickup. A double shielded or triaxial cable with insulation between the two shields provides the maximum protection against noise coupling. Since 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 for noise coupling. Fortunately (since triaxial cables are expensive and awkward to use), above 1 MHz skin effect on the shield of coaxial cable tends to simulate 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.

Up to a few hundred kilohertz the shielded twisted pair cable has performance comparable to triaxial cable without the expense and awkwardness. An unshielded twisted pair, unless it is used in a balanced circuit, offers little protection against capacitive pick-up but has good noise immunity from magnetic pickup.

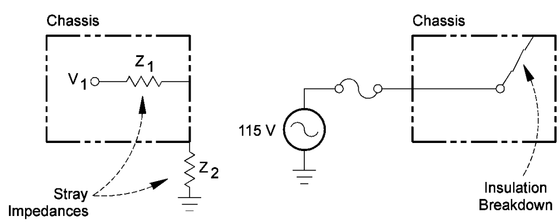


Figure 18† - Instrument chassis should be grounded for safety. Otherwise, it may reach a dangerous voltage level through stray impedances (left) or insulation breakdown (right).

†Ott. H., "Noise Reduction Techniques in Electronic Systems", John Wiley and Sons, 1988.

Grounding

There are two definitions of ground:

1. A signal ground is an equipotential circuit reference point for a circuit or a system.
2. A signal ground is 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.

The design objectives of a grounding system are:

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

Improper Grounding can be a Primary Noise Source

Grounds can be divided into two parts; safety and signal grounds. 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. See Figures 18 and 19.

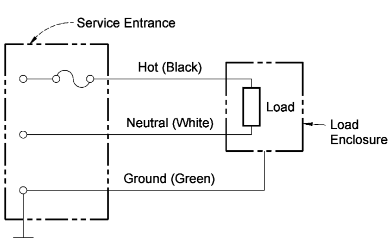


Figure 19†- Standard 115 V AC power distribution circuit has three leads.

Single Point Ground Systems

Signal grounds are either single point or multi-point grounds. Single point grounds can be connected in series or parallel in systems. For noise coupling the least desirable grounding scheme is the series ground, but it is also the least expensive and the easiest to wire. It is therefore the most widely used. For non-critical applications the series ground may work satisfactorily. The most critical circuits should be placed nearest to primary ground point. See Figure 20.

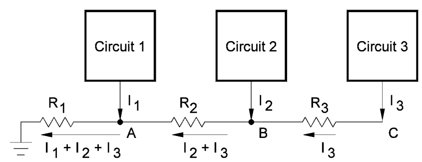


Figure 20†- Common ground system is a series ground connection and is undesirable from a noise standpoint but has the advantage of simple wiring.

†Ott, H., "Noise Reduction Techniques in Electronic Systems", John Wiley and Sons, 1988.

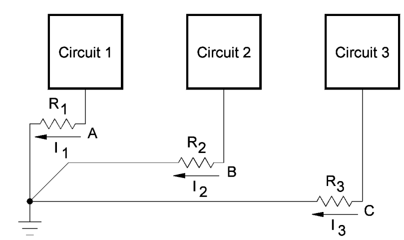


Figure 21† - Separate ground system is a parallel ground connection and provides good low-frequency grounding, but is mechanically cumbersome.

The parallel ground shown in Figure 21 is the most desirable configuration for frequencies in the audio range. This configuration eliminates cross coupling between ground currents through different circuits. The scheme, which is not as simple as the series connections, is awkward to wire and use.

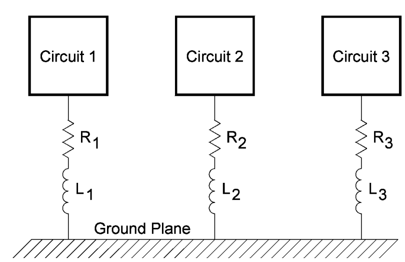
At high frequencies the parallel single point connection is very limited. It is here that the inductance of the ground conductors increases the ground impedance and also produces capacitive coupling between the ground leads. This situation worsens as the frequency increases to the extent that the ground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

† Ott, H., "Noise Reduction Techniques in Electronic Systems" -, John Wiley and Sons, 1988.

Multipoint Ground Systems

For high frequency applications the multi-point grounding system should be used. Typically, the circuits are connected to the nearest available low impedance ground plane, normally the system chassis. However, just as parallel single point configurations are not effective for high frequencies, multi-point ground systems should be avoided at low frequencies.
In multi-point ground systems all the ground currents from all the circuits flow through a common ground impedance -the ground plane, as shown in Figure 22.

Figure 22† - Multi-point ground system is a good choice at frequencies above 10 MHz. Impedances R, - R3, and L1 - L3 should be minimized.



Grounding Summary

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

For practical reasons, most systems require three separate ground returns. 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, as shown in Figure 23.

A single ground reference system should always be used for low level work. If it is not used, any differences in ground potential will show up as noise on the signal path. As shown in Figure 24, a measurement system with a return path through two grounds will produce a noise voltage across the measurement terminals of the instrument. Disconnecting this path on the instrument side and allowing the instrument to float its low terminal above ground breaks the low frequency connection and prevents the common mode voltage from coupling into the circuit. (See Hewlett-Packard Application Note #123, "Floating Measurements and Guarding".)

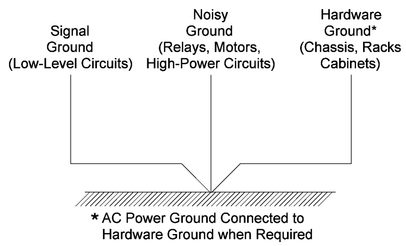


Figure 23† - These three classes of grounding connections should be kept separate to reduce noise coupling.

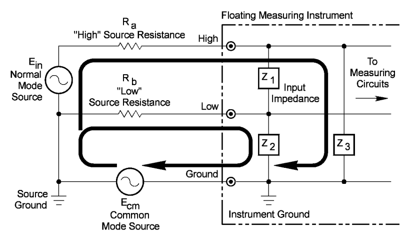


Figure 24 - Inside the ideal floating voltmeter the impedance between low and ground is extremely high at DC. The insertion of Z_2 in the ground loop creates a voltage divider on the noise presented to the measurement terminals. The common mode noise is attenuated by a factor of R_B/Z_2.

Grounding Shield Cable and Connectors

Shields on cables used at frequencies less than 1 MHz should only be connected to a ground at one point. In the case of shielded twisted pair, to connect ground at more than one point may inductively couple unequal voltages into the signal cable and be a source of noise. The IR drop in the shield of a coaxial cable will couple into the signal conductor, and is a problem if the shield is connected to ground at more than one point.

Since we must connect ground somewhere, where should that be?

1. For a grounded amplifier and an ungrounded source, the shield should always be connected to the amplifier common terminal even if this point is not earth ground.
2. For an ungrounded amplifier and grounded source, the shield should be connected to the source common terminal, even if it is not at earth ground.

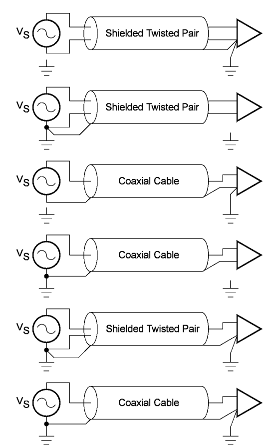


Figure 25† - Preferred grounded schemes for shielded twisted pairs and coaxial cable at low frequency. The grounds may have large potential differences that can cause ground loops and couple noise into the circuits.

3. If both source and amplifier are grounded, we have no choice but to ground the shield at both ends. This is the least desirable of all circuit con-figurations for noise reduction. Figure 25 shows the proper connections for shielded twisted pair and coaxial cables at low frequency.

† Ott, H.,"Noise Reduction Techniques in Electronic Systems", John Wiley and Sons, 1988

Other Methods of Reducing Ground Coupled Noise

Ground loops in very noisy environments can be broken by the use of isolation transformers as shown in Figure 26. In cases where a DC path must be maintained a longitudinal choke can be used to suppress higher frequency loops. Optical isolation likewise can be used to break ground loops.

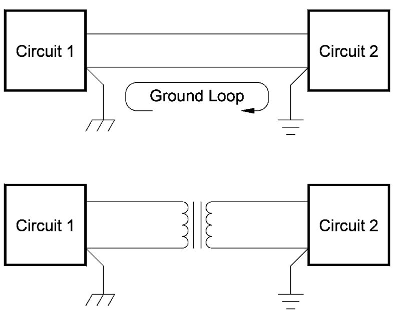


Figure 26† - A ground loop between two circuits can be broken by inserting an isolation transformer.

Other methods of 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. Even more noise rejection can be obtained at low frequency with a guard shield around the amplifier.

Up to this point we have discussed shielding only at low 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. Besides, capacitive coupling between the shield and ground plane tends to complete the circuit at high frequency and makes the shield isolation difficult to impossible.

At high frequency it is common practice to ground the shield at every 1/10th wavelength to assure good grounding.

If there is any question about the ground in a system, it is better to isolate the questionable ground and find some other way of making a good ground connection.

A hybrid ground formed by inserting small capacitors every 1/10th wavelength provides a single ground at DC and multiple grounds at high frequency. Further, its performance can be characterized reliably.

Noise Coupling in Switching Systems

The interface between your DUT and switching system provides an excellent opportunity for inadvertently introducing noise to your system. Follow these simple rules for the cable harness:

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.

For connectors follow these guidelines:

1. High and low level leads should be separated on the connector.
2. Ground leads should be placed between the signal leads where possible.
4. Any unused connector pins should remain between the signal leads and be grounded.
5. Cable shields should each have their own connector pin through the connector.

The sources of noise in the switching system are those generated internally by the circuitry driving the switches, by thermal unbalance across the switches, by noise coupling from other conductors in the system, and by noise generated outside the system. Thermal unbalance can either be minimized by a mechanical design that assures that all the contacts in the relay are subject to the same temperature gradient across the leads or by using latching relays. In this case the major source of thermal generation, the coil energy, is removed so that the relays are always in thermal equilibrium.

Noise coupling from adjacent channels into the measurement channel(s) presents a great danger 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.

Noise Reduction Techniques in Switching Systems

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 20-channel multiplexer this series switch effectively reduces the stray capacitance seen by the measuring circuit to 1/20th the value without the tree switch. The result is less crosstalk and faster measurement settling time for the system. This is shown in Figure27.

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. Figure 28 illustrated the concept of T-switching. The result is excellent channel-to-channel signal isolation at high frequency on the same multplexer. As shown in Figure 29.

† Ott, H., "Noise Reduction Techniques in Electronic Systems", John Wiley and Sons, 1988.

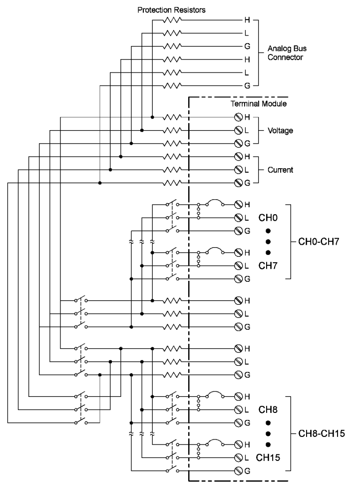


Figure 27 - 3- Wire multiplexing and tree switching are shown in this illustration of a 20 channel multiplexer card. By placing the tree switch in series with the input channels the effective capacitance of the unused cards in the system is reduced to 1/20th of the normal shunt capacitance in the system. This is very useful for large system configurations.

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

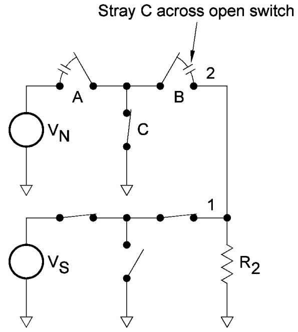


Figure 28 - T-Switching.- this is a simplified circuit diagram of how T-switching works. Conductor 2 is open in this diagram; hence, its 'C' switch is closed prodding a low impedance path to ground.

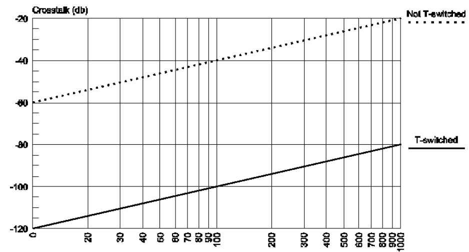


Figure 29 - The effect of T-switching on Crosstalk. The effective capacitance between signal paths is minimized to the extent that up to 60 dB of crosstalk isolation is realized through T-switching.

Impedance Mismatching

Impedance mismatching in switching systems can cause many unpredictable measurements results, if the signal is either a high frequency cw waveform or is a digital signal with fast transition times. Basically, the reflected wave at the point of the impedance mismatch adds algebraically with the incident waveform creating a standing wave on the transmission line. The ratio of the sum of the peaks of these waves to the difference (the Voltage Standing Wave Ratio, VSWR) can be calculated from the differences in the characteristic impedance of the system and the switch.

For $Z_O > Z_L$: $$VSWR = \left(\frac{Z_L}{Z_O}\right)$$

For $Z_L > Z_O$: $$VSWR = \left(\frac{Z_O}{Z_L}\right)$$

For lossless systems, Z_O is the characteristic impedance of the transmission line. Z_L is the load impedance.

As long as the wavelength of the input waveform is large compared to the cable length, these effects are minimal and can largely be ignored. For example, for coaxial airline, signals less than 10 MHz will generally cause no problems with reflections. To gain an understanding of this, simple calculation of the wavelength versus frequency can be made from the relationship:

$$r \times f = C,$$

where r = wavelength
f = frequency
C = speed of light in the media

	Frequency	Wavelength
	1 MHz	300 m
	10 MHz	30 m
	100 MHz	3 m

Many times high frequency cw signals are not common in systems, but there are many encounters with pulsed signals and pulsed signal routing. Fast transition time digital pulses will cause double triggering, double counting, and race conditions in the test system if there is a mismatch through the system.

Hence, it is important to know what signals are going to cause a problem and how to estimate the size of the problem.

The relative amplitude of the reflected waveform can be calculated from the VSWR specification for the switch from the relationships:

Where BW = Frequency

$$BW \times t_r = .35 \text{ and } E_r = E_i\left(\frac{V-1}{V+1}\right)$$

t_r = pulse risetime

E_r = amplitude of the reflected wave.

E_i = amplitude of the incident wave.

V = the specified VSWR.

For example, let's look at the reflections of a 5 volt signal being routed through a switch with a VSWR of 2.0 at 100 MHz.

First, let's calculate the risetime of the signal from:

$$t_r = \frac{.35}{100 \times 10^6} \quad t_r = 3.5 \text{ ns.,}$$

We can calculate the amplitude of the reflected wave from

$$Er = 5\left(\frac{2-1}{2+1}\right) = 1.67V,$$

which for the sample case is equal to 33% of the amplitude of the incident waveform. In the case of a 5 volt signal, this amplitude could cause even TTL with risetimes of 3.5 ns to indicate a false state.

A Noise Reduction Check List†

When designing your system the following check list will be helpful in reducing noise.

A. Suppressing Noise At Source:

- ☐ Enclose noise sources in a shielded enclosure.
- ☐ Filter all leads leaving a noisy environment.
- ☐ Limit pulse risetimes.
- ☐ Relay coils should be provided with some form of surge damping.
- ☐ Twist noisy leads together.*
- ☐ Shield and twist noisy leads.
- ☐ Ground both ends of shields used to suppress radiated interference (shield does not need to be insulated).*

B. Eliminating Noise Coupling:

- ☐ Twist low level signal leads.*
- ☐ Place low level leads near chassis (especially if the circuit impedance is high).
- ☐ Twist and shield signal leads (coaxial cable may be used at high frequencies).
- ☐ Shielded cables used to protect low level signal leads should be grounded at one end only (coaxial cable may be used at high frequencies with shield grounded at both ends).*
- ☐ Insulate shield on signal leads.
- ☐ When low level signal leads and noisy leads are in the same connector, separate them and place the ground leads between them.*
- ☐ Carry shield on signal leads through connectors on a separate pin.
- ☐ Avoid common ground leads between high and low level equipment.*
- ☐ Keep hardware grounds separate from circuit grounds.
- ☐ Keep ground leads as short as possible.*
- ☐ Use conductive coatings in place of nonconductive coatings for protection of metallic surfaces.
- ☐ Separate noisy and quiet leads.*
- ☐ Ground circuits at one point only (except at high frequencies). *
- ☐ Avoid questionable or accidental grounds.
- ☐ For sensitive applications, operate source and load balanced to ground.
- ☐ Place sensitive equipment in shielded enclosures.
- ☐ Filter or de-couple any leads entering enclosures containing sensitive equipment.
- ☐ Keep the length of sensitive leads as short as possible.*
- ☐ Keep the length of leads extending beyond cable shields as short as possible.*
- ☐ Use low impedance power distribution lines.
- ☐ Avoid ground loops.*
- ☐ Consider using the following devices for breaking ground loops:
  - Isolation transformers
  - Neutralizing transformers
  - Optical couplers
  - Differential amplifiers
  - Guarded amplifiers
  - Balanced circuits

C. Reducing Noise at Receiver.

- ☐ Use only necessary bandwidth.
- ☐ Use frequency selective filters when applicable.
- ☐ Provide proper power supply decoupling.
- ☐ Bypass electrolytic capacitors with small high frequency capacitors.
- ☐ Separate signal, noisy, and hardware grounds.*
- ☐ Use shielded enclosures.
- ☐ With tubular capacitors, connect outside foil end to ground.*

*Low cost noise reduction.

† Ott, H., ."Noise Reduction Techniques in Electronic Systems", John Wilyand Sons, 1988.

A Systematic Approach to System Configuration

A systematic approach to configuring your system lets you organize the connections, the switching scheme, and the instrumentation needed to test your DUT. The following is a check list for system configuration:

1. Know what you want to test.
   Be sure that you're not overtesting the DUT. Overtesting is time consuming and costly.
2. Know your instrumentation.
3. Know the commercially available remedies for your testing problems.
4. Keep the number of crossbar matrix configurations to a minimum. The flexibility offered by the matrix configuration must be weighed against its increased switch capacitance, signal conductor to signal conductor capacitance, insertion loss, impedance mismatching, and cost. Generally, a different approach to the testing philosophy is needed if many matrices seem to be needed in the system.
5. Isolate signals that could interfere with low level signals and keep them physically separate in the system.
6. Maintain the shield integrity throughout your interface design. Ground shields at either the source or the receiver but not at both for lower frequency signal integrity. Ground shields at both ends for high frequency signal integrity. If both high and low frequencies are used in the system, a single point ground is usually best.

The approach to construct the test system is to list all the inputs and outputs to the DUT, to evaluate the type of switch needed to maintain the signal integrity for each input and output, to evaluate the test instrumentation needed, and to devise the smallest switching system possible consistent with the switching needs of the test system.

If you can set up the test instrumentation on the bench without the system interface and switching network connected, so much the better. Even manually running the test through the switching system is an aid to debugging the hardware and software for the later automation of the system.

A Sample System

Let's look at a sample system that could be used to functionally test signal generators up to a repetition rate of 50 MHz (Figures 30 and 31). The DUT is powered by the power supply and stimulated by the function generator. The DUT signal outputs are dependent upon the input frequency of the function generator. The measurements of these outputs are accomplished with the DMM, the oscilloscope, and the counter.

Test Points	The DUT Pinout	Instruments
1.	ground	System oscilloscope (Agilent E1428A)
2.	+ 5 volts DC	Dual power supply (E3620A)
3.	- 12 volts DC	Counter (E1333B)
4.	clock input (DC to 5 MHz)	System DMM (E1411A)
5.	30 mV sinusoid with 4 times the clock frequency	Programmable Function Generator (E1445A)
6.	DC level proportional to clock frequency (1 V/MHz)	Matrix Switch (E1361A)
7.	Trigger signal #1	RF Multiplexer (E1472A)
8.	Trigger signal #2	Controller
9.	5 volt sinusoid with 10 times the clock frequency	Any GPIB interfaced computer with instrument control
10.	Pulse burst outputcapability	

The Testing Tasks

1. Measure and set the power supplies to within 0.1% of their nominal values.
2. Measure the clock frequency of the function generator with the counter.
3. Measure the signal on TP5 with the counter.
4. Measure the DC signal on TP6 with the DMM.
5. Use the trigger signals on TP7 and TP8 to capture the pulse burst on TP10 with the oscilloscope.
6. Measure the propagation delay between the two trigger signals.
7. Measure risetime of the pulses on TP10.
8. Measure the frequency of TP9 with the counter.

The sequence of switch closures necessary to accomplish the testing tasks is listed in Table 2.

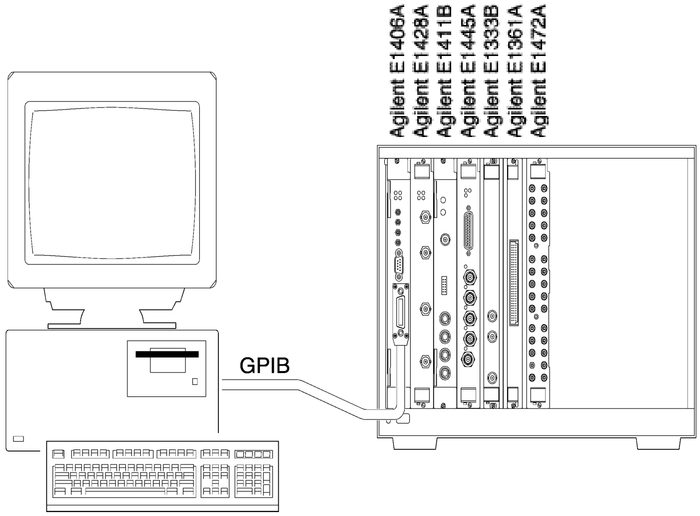


Figure 30 - A typical small testing system consisting of an automatic oscilloscope (Agilent E1428A), a digital voltmeter (Agilent E1411B), a frequency counter (Agilent E 1333B), a signal source (Agilent E 1445A), and a switching system (Agilent E1361A).

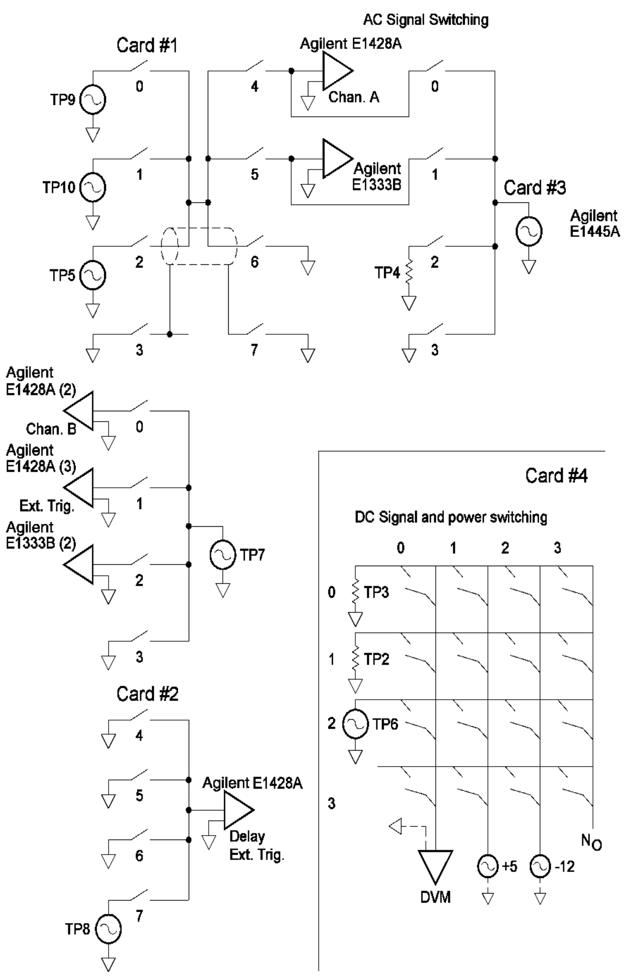


Figure 31 - The switching topology for the test system consists of 3 VHF cards and 1 matrix card. The signal ground for the voltmeter can be at the source. Without the isolation provided by T-switching, the digital signals would have to be switched on a different card than the analog signals.

Task #	Module #	Channel	Close	Open
1	4	30*	X	
		32	X	
		32		X
		31	X	
		31		X
		02	X	
		00	X	
		00		X
		11	X	
		10	X	
		10		X
2	3	1	X	
		1		X
3	3	2	X	
	1	2	X	
	1	5	X	
	3	2		X
	1	2		X
	1	5		X
4	4	20	X	
		20		X
5	1	1	X	
	1	4	X	
	2	1	X	
	2	7	X	
	1	1		X
	1	4		X
6	2	0	X	
	2	7	X	
	2	0		X
	2	7		X
7	1	1	X	
	1	5	X	
	1	1		X
	1	5		X
8	1	0	X	
		5	X	
		0		X
		5		X

Task schedule for switch closure assumed that all channels are open at power up.
All relays are reset open to test another device.
Modules #1, 2, 3 = Agilent E1472A
Module #4 = Agilent E1361A

*30 = row 3 connected to column 0.

Table 2

Input and Output Considerations

Let's apply a systematic approach to the sample system by looking at our testing tools and the DUT. The test instrumentation presents a variety of input and output impedances. First, the oscilloscope has a choice of two impedances on each of its signal inputs, either 50Ω or 1 MΩ shunted by 16 pF. The oscilloscope trigger inputs are 1 MΩ shunted by 30 pF. The counter's input impedance is 1 MΩ shunted by 30 pF. Both the counter and the oscilloscope are single ended instruments. i.e., they have grounded amplifiers. The grounding scheme used with these instruments at high frequency is multipoint. The input impedance to the voltmeter is 10^{10}Ω for DC measurements. The DMM is floating, i.e., it is an ungrounded amplifier. Its input is DC isolated from the chassis.

The output impedance of the function generator is 50Ω. To remain amplitude calibrated, the function generator must be terminated with 50Ω. The function generator is a grounded source. The output impedance of the power supply is a few milliohms. It is a floating source in which the output low is DC isolated from chassis.

Frequency Considerations

To maintain the signal integrity of the function generator with 5 ns risetime, the frequency range of the switch has to accommodate a frequency of 70 MHz. This follows from the risetime-bandwidth relationship for Gaussian rolloff:

$$BW = \frac{.35}{T_r}$$

Hence, the frequency of the clock, even if constrained to be less than 10 MHz, requires at least a 70 MHz switch frequency range to avoid undue signal degradation. This leads directly to the consideration of VHF switching to perform this task.

Topology Considerations

To measure the power supplies both under load and open circuit, the DMM has to interface to the circuit at the same time the power supplies are connected to the DUT. This forces us to use a matrix configuration.
The ground connection to the power supply and DMM is referenced to the DUT to keep the ground at one point. If we were to connect the ground at the power supply to the DMM low, then we would create a ground loop that could cause noise coupling not only into the measurement circuits but also into the DUT.

Switch Consideration

The VHF cards in the switching system have a characteristic impedance of 50Ω for each group of 1 x 4 VHF multiplexers. If two switch groups have channels closed in parallel, their characteristic impedance is a nominal 25Ω. The frequency range of the VHF switches is 300 MHz for a single switch closure. The frequency range of the matrix switch is 10 MHz for a single switch closure. The matrix switch is a floating two conductor 4 x 4 matrix.

Timing Measurements and the DUT

The digital signals of the DUT have TTL compatible logic levels and the output impedance is a nominal 150Ω. The output impedance of the cw and low level DC outputs is 50Ω. The signal low of all output and input signals is referenced to the chassis low of the DUT.

The TTL compatibility of the digital input and output signals specifies the maximum fanout and the voltage levels necessary for operation of the DUT. If we used the 50 ohm oscilloscope input for transition time measurements, we could load the TTL output to the extent that the DUT circuit would stop functioning. We must select the high input impedance for oscilloscope measurements and compromise the transition time measurements. Fortunately, since we know the measurement effect of the input impedance on the transition time, it is easy to correct the measurement.

$$t_{unk} = \sqrt{t^2_{mea}, - t^2_{2.2Rch}C - t^2_{scope}}$$

where t_{unk} = the unknown risetime

t_{mea} = the measured risetime

t_{scope} = the oscilloscope's risetime

$t_{2.2Rch}C$ = the charging risetime of the parallel resistance of the generator and the oscilloscope and the oscilloscope's input capacitance

Grounding

The high frequency circuits require multi-point grounding to reduce noise in the signal path. The low frequency signals require single point grounding to assure ground loop interruption. Also important to this application is the separation of the high frequency digital signals from the low level AC signal. This separation should extend to the switching and cabling used in the system.

Conclusion

In conclusion, there is a need to have two separate switching configurations to handle the test and power signals in this application. One is a coaxial VHF, common low, multiplexer configuration; the other is a floating, two conductor, matrix configuration. This allows the low level DC signals to be separated from the noisy digital signals. Further, ground loops can be avoided by interrupting them with the floating, two-conductor matrix.

Amplitude and risetime measurements are affected by the input and output impedances of the DUT and instruments. The amplitude calibration of the function generator and the signal loading of the TTL outputs are important. Care must be taken not to load the TTL outputs with the 50Ω input impedance of the oscilloscope. As a result, risetime measurements may require capacitance compensating circuitry or calculations for their correct determination.

Summary

While the examples have not been exhaustive, they should give the systems engineer some insight into system switching. Signal integrity is only maintained through careful attention to the input and output characteristics of the DUT and the testing instrumentation, including the switch. 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 assure signal integrity in the system.

For further discussion of cabling and connections, refer to Henry W. Ott's "Noise Reduction Techniques in Electronic Systems".

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