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Optimizing a Switch System for Mixed Signal Testing

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Switching systems are often needed to automate and speed up the testing of multiple devices in a production environment, and when making mixed signal measurements during R&D and production. Mixed signal measurements on multiple devices increases the importance of switching systems as a means of achieving high test system throughput.

Still, there are a number of potential pitfalls in choosing and configuring the switch hardware and software for such a test system. These can lead to less than optimal speed, measurement errors, shortened switch life, and excessive system cost. Therefore, the test system developer needs to understand common sources of errors affecting the integrity of signals to be measured, switch configuration and cabling errors affecting throughput, and switch selection issues that can increase test system cost.

Common Sources of Error

For developers of new test systems and users having problems with an existing test system that uses a switch assembly it is a good idea to review potential sources of error. Relay contacts are a good place to start.

Open State Contact-to-Contact Resistance. In the ideal open relay or switch, the resistance between contacts is infinite. In reality, there is always some finite resistance value that has to be taken into consideration. See ***Figure 1***. The key is to find the magnitude of the open resistance and to determine if it is going to affect the signal passing through the system. There are many different types of

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switches, and each of them has a specification for insulation/isolation resistance. Review the manufacturer's specification for contact-to-contact resistance in the open state.

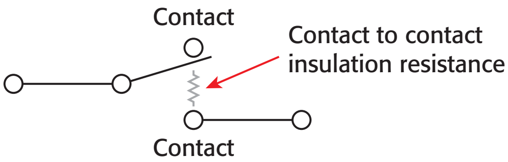

Figure 1. Representation of a switch relay's insulation resistance in the open state.

In general, the higher the resistance in the open state, the lower the leakage between contacts, and the less effect on signal integrity. Most relays have open-state resistance specifications between 1MΩ and 1GΩ, which is sufficient for most applications, especially DC measurements. For example, switching a power supply signal of 5V through a switch relay contact has little to no effect due to open-state resistance. This is because a power supply normally has low internal impedance that the high switch impedance does not affect. ***Table 1*** provides examples of different relay types with their open contact isolation resistance and other characteristics.

Table 1. Characteristics of different relay types.

Relay Type	Isolation	Speed	Power	Life at Rated Load
Electromechanical	10^7–10^{10} Ω	20–100 ms	10–100 VA	10^7 cycles
Electromechanical (high frequency)	60–130 dB	20–100 ms	1–120 W	10^6–10^7 cycles (no load)
Contactor	10^6–10^9 Ω	100–250 ms	100–4 kVA	10^5 cycles
Dry reed	10^9–10^{14} Ω	1–15 ms	10–50 VA	10^7 cycles
Mercury wetted reed	10^8–10^{12} Ω	5–10 ms	10–100 VA	10^{10} cycles
Solid state	10^6–10^9 Ω	100–500 µs	1–100 VA	10^{10}–10^{15} cycles

Closed State Contact-to-Contact Resistance. In the ideal closed relay or switch, there is no resistance between contacts. In the real world, closed switches have some small amount of contact resistance, typically on the order of a few milliohms. Depending on relay and contact design, most new relays have a closed-contact resistance specification of less than 100mΩ. This resistance usually increases with use. Most relays have an end of life specification of about 2Ω. Depending on relay type (see ***Table 1***), this typically occurs after millions of cycles of use. Even at such high resistance, a relay can still function, although it may begin to have a greater impact on the signal passing through the switch.

Contact Potential. This is a voltage produced between contact terminals due to dissimilar metals and a temperature gradient across relay contacts and contact-to-terminal junctions. The temperature gradient typically arises due to power dissipated by the energized relay coil. Contact potential can be significant when conducting low-level voltage and resistance measurements. It can range from several nanovolts to as much as 1mv, depending on contact design. For best measurement results, the contact resistance should be substantially lower than the smallest signal being measured.

Channel-to-Channel Isolation. This specification is related to leakage and crosstalk between adjacent signal paths through the switch assembly. Troubleshooting problems caused by leakage and crosstalk can be a difficult task. It's much easier to start system development with the proper switch design and specifications than to spend precious time troubleshooting an elusive problem, which applies to other potential error sources.

Most switch assemblies are printed circuit board (PCB) cards that are inserted into a switching type of measurement instrument, or into a switching mainframe used with separate instruments. Therefore, the electrical isolation between any two adjacent switches may be expressed in different ways depending on the intended use of the switch card. Normally, the switch channels on the PCB are aligned in order to achieve proper voltage isolation and accommodate the physical dimensions of the switches and other components, such as connectors. This spacing and the PCB material provide a certain level of isolation between channels. The higher the isolation, the lower the chance of crosstalk or leakage.

Typical values of channel-to-channel isolation are up to 10GΩ with capacitance of less than 100pF. ***See Figure 2***. In high-frequency applications, leakage capacitance becomes an important consideration. For these applications, isolation is usually stated in dB. For instance, 60dB would be an isolation of 1000 to 1 from channel to channel, meaning that a 1V signal on one channel could bleed over and become a 1mV signal on an adjacent channel. Keep in mind that open contact isolation resistance must also be taken into consideration when developing the switching portion of a test system. The higher the isolation between open contacts and between adjacent channels, the better the integrity of signals passing through the system.

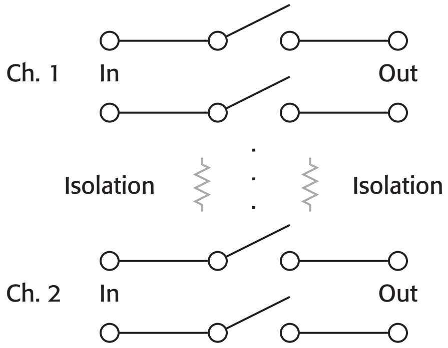

Figure 2. Representation of channel-to-channel isolation with shunt capacitance and resistance.

Offset current. This current can occur on switch cards even when no test signal is present. The largest magnitudes are due to finite coil-to-contact impedance in electromechanical relays. It is also generated by triboelectric, piezoelectric, and electrochemical phenomena on the switch card, regardless of relay type.

Offset current is important, for example, in low level and high impedance measurements taken during semiconductor parametric testing on wafers and individual devices. Low offset current becomes a critical specification when conducting leakage current measurements on semiconductor devices and materials. It is also important when doing semiconductor C-V characterization.

Depending on card design and intended usage, the offset current specification could range from less than 1pA up to 1nA. Manufacturers of cards designed for relatively high level DC current and voltage switching may not provide an offset current spec, because it is normally unimportant in those applications.

Relay Switching Speed. A relay's operating speed has a direct affect on the throughput of a switching type of test system. The system developer has to pay attention to relay speed specifications to also ensure that measurements are accurate. A typical test scenario is to apply a stimulus to the device under test (DUT), wait a short amount of time for the test system and DUT to react and settle to a final value, and then measure the DUT's response. If measurements are taken before the system has settled sufficiently, results can be inaccurate.

Relay operating speed is a measure of the rate at which its contacts can be cycled and still obtain reliable operation. This rate is limited by the relay's actuation and release times. Actuation time is measured from when power is applied to the coil until the contacts have settled. Thus, actuation time includes contact bounce time. Release time is the opposite of actuation time. It is measured from the time power is removed from the coil until the contacts have settled to their open position and includes bounce time.

A significant amount of system settling time is associated with relay bounce time, which must have settled out before a solid reliable connection is established in the signal path. Settling time varies from relay to relay with typical times in the millisecond range. Sometimes relay switching cards have a built-in delay to avoid problems associated with contact bounce. In addition, some switching equipment may even have a user programmable delay time.

Use of Solid-State Switches. Standard electromechanical relays can switch from one state to another in as little as a few milliseconds, which is fast enough for some applications. However, in production applications where test time carries a significant dollar value, this switching time may be too long. Solid-state relays (e.g. transistors, FETs) have a much faster switching time, generally below one millisecond. Going from a few milliseconds to a few hundred microseconds could shave off substantial test time and increase test throughput.

Another advantage of solid-state relays is their reliability. Solid-state relays have a switching life of almost 100 times that of electromechanical relays. This would be on the order of about 10 billion switch cycles instead of a good electromechanical relay's life of about 10 million cycles.

One disadvantage is the "on" resistance of solid-state relays, which is on the order of tens of ohms. Such a high resistance could lead to measurement inaccuracies in a two-wire resistance measurement. Trying to measure a few milliohms with upwards of 10Ω of resistance in the circuit from the "on" resistance would effectively bury the low-resistance measurement. One way around this is to use a so-called golden or standard channel. This is a channel with a short on the device side. The channel is closed, the resistance measurement is made, and the measurement is subtracted from all other channels. Therefore, the "on" resistance is essentially zeroed out. The problem is that this holds for only the golden channel and would be slightly different on each channel. Using this method would depend on the magnitude of the resistance to be measured and the accuracy required.

Another way to correct for this resistance is the four-wire (Kelvin) measurement technique, which involves using two channels instead of one. One channel is used to source the current and one to sense the voltage. This is a standard method to measure low resistance. Using an electromechanical or reed relay would only have a contact resistance of tens of milliohms, which would be more advantageous in low-resistance measurements using the two wire method.

Other Settling Time Issues. In addition to mechanical issues, there are electrical issues associated with the opening and closing of switches. When a mechanical relay opens or closes its contacts, there is a charge transfer on the order of picocoulombs that causes a current pulse in the test circuit. This charge transfer is due to the mechanical release or closure of the contacts, the contact-to-contact capacitance, and the stray capacitance between signal and relay drive lines. This phenomenon can affect both the signal settling time and signal integrity.

The nature of the signals must also be considered. Some signals originating from a DUT take longer to settle than others. As a general rule, the rise time of a DUT output signal is defined as the time for it to rise from 10% to 90% of its final value when the stimulus rises instantaneously from zero to some fixed value. If the signal originates from an extremely high impedance (producing a very low current), then it may require several seconds or even minutes to settle. The settle time is directly related to the small current charging the cable or stray capacitance in the circuit. The higher the impedance the lower the current and the more time it takes to settle out.

Making sure a test system has settled sufficiently is the key to good measurements. Specifications listing relay actuation time are only the starting point in determining the total test time for a measurement sequence. The mainframe or switching instrument holding the switch card also contributes some overhead time, which is a function of its command to connect times in a test sequence. This varies according to the test sequence design, but some switching instruments and mainframes have displays that depict when a relay has closed, providing some indication of how fast a sequence is progressing. However, keep in mind that test system design always involves tradeoffs between throughput and accuracy issues.

Cabling and Switching Issues

Evaluating the nature of the DUT signal, test circuit, and switch system can help ensure the signal will pass with minimal degradation and without added noise that could generate false readings. Still, inappropriate cabling and design of a test sequence can introduce errors, or affect switch contact life.

Cabling Practices. Each type of signal has some unique unwanted characteristics that can be reduced or eliminated by choosing the appropriate cabling. Not using the appropriate cabling for switching the DUT signals can degrade signal quality. For example, in a high-frequency test system, using a 75Ω coax cable in a 50Ω characteristic impedance system would cause signal reflections and excessive VSWR (Voltage Standing Wave Ratio), resulting in signal attenuation. Also, using a coax cable in a high magnetic field can help reduce the magnetic field effect, but not as much as using a shielded twisted-pair cable, ***Table 2*** gives some examples of signals and appropriate cables.

Table 2. Cable selection for different types of test signals.

Signal Type	Unique Parameter	Cable Type
High frequency	Impedance match	e.g. 50Ω to 50Ω
Magnetic field	Magnetic flux	Shielded twisted pair
Low current	Triboelectric effect	Low noise cable (graphite on shield braid)
Low current	Leakage currents	Low noise coax or triax with driven guard
Low voltage	Thermal effect	Copper wires
Electrostatic field	Noise	Shielded cable (coax or triax)

Special consideration must be given to the cabling required for semiconductor wafer probing applications where DC I-V (current-voltage), C-V (capacitance-voltage) and pulsed I-V measurements are all required. ***Table 3*** lists the types of cables that can be used for these applications. However, switching between different types of semiconductor measurement gets messy and time consuming when different types of cables are used. To solve this problem, Keithley Instruments developed a line of triaxial cables that can be used for all these measurements. They eliminate the need for recabling when you change from one type of measurement to another. This avoids common cabling mistakes and the measurement errors they often produce.

Table 3. Different cable requirements for semiconductor wafer I-V, C-V, and Pulsed I-V measurements.

DC I-V	• Triaxial cables • Kelvin connection • Isolated, driven guards
LCR/C-V	• Coaxial cables • Kelvin connection • Shields connected at the probe tips
Pulsed I-V	• Coaxial cables • Non-Kelvin connection (single cable) • Shields connected at the probe tips • Shield optionally connected to a probe tip

Switching Practices. A significant test system issue is hot versus cold switching. Cold switching is defined as opening and closing the switch when no current is flowing. Using cold switching lengthens the contact life of the switch. The carry current is the maximum current the switch can tolerate once the contacts have been closed and is limited by the cross-sectional area of the path through the switch contacts.

Hot switching is defined as opening and closing relay contacts when the test signal is applied, which results in immediate current flow and may cause arcing across the contacts. Depending on switch specifications and the signal passing through, contact life is usually reduced when using hot switching. Switched current is the maximum current that can be handled reliably while opening and closing contacts. Contact material and plating are the primary factors that determine this specification and the life of the switch. If the switched current is too high, the resulting temperature increase and contact arcing will degrade the relay and shorten contact life. In extreme instances, the contacts may weld together.

The rate of repetitive open-and-close cycles also affects switch life. If the switch cycles ten times a second for 24 hours a day, seven days a week, then it's apt to reach the end of its life rather quickly. For example, if a relay life specification is 100,000,000 cycles, which is typical, then at ten cycles per second it would reach its end-of-life cycle total in about four months. For many applications, ten cycles per second would be considered a medium to slow speed. It's not uncommon for production test systems to operate at much higher speeds. So be aware of switching rate and pay attention to the cycle life spec when selecting a switch for the test system. In addition, consider designing the test sequence to accommodate cold switching if the signal current is high in relation to the switched current rating of the relay contacts. Observing these precautions will improve switch performance and contact life.

Switch System Architecture and Topology

Major test system design issues are the type of instrumentation and switch architecture to use, and the topology used on each switch card.

Instrumentation Architecture. Broadly speaking, there are two choices in the selection of instrumentation for a switching type of test system. One option is measurement instruments with built-in switching capabilities. The other option is a switching mainframe used with separate measuring instruments. If an instrument with integrated switching has the capabilities needed for your mixed signal application, then it tends to result in a more compact test system for either benchtop use or rack mounting and is relatively easy to configure and operate. The main considerations are instrument measurement capabilities, test sequence programming, number of switch channels available, the types of switch cards available, and switch specifications as described above.

On the other hand, a switch mainframe generally provides maximum flexibility in a mixed signal environment because it is used with separate instruments that can be selected precisely to meet measurement needs. In addition, a switch mainframe may have greater channel capacity than a measuring instrument with integrated switching and possibly a greater variety of switch cards available.

Switching Topologies. The three basic types of switch cards are isolated switches, switch scanners, and matrix switches. Depending on application complexities, more than one card type could be used in a test system. Regardless of the switch topology, different relay contact configurations are possible. These are shown in ***Figure 3***.

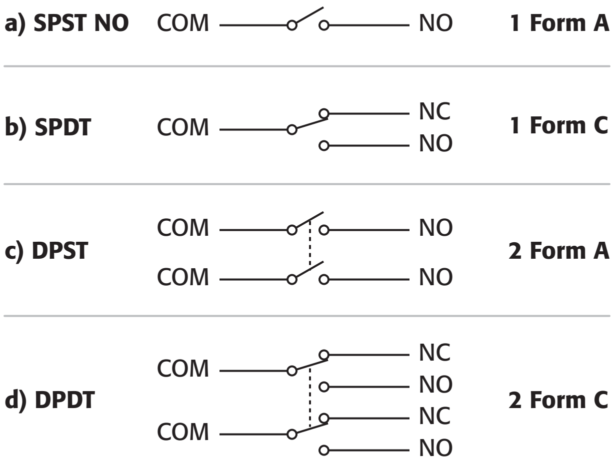

Figure 3. Relay contact schematics.

Isolated switch cards have independent relays with no connections between them, and each relay may have multiple poles, such as the DPST and DPDT configurations in ***Figure 3***. They are commonly used in power and control applications to open and close different parts of a circuit that are at substantially different voltage levels. Typical applications include controlling power supplies, turning on motors and lamps, and actuating pneumatic or hydraulic valves. Since each isolated relay is not connected to any other circuit, the addition of some external wiring allows the test system designer to build flexible combinations of input/output configurations.

Scanner cards come in two varieties: sequential scanners and non-sequential multiplexers. A scan topology can be thought of as a sequential selector, switching one instrument to multiple DUTs (1:N), or multiple instruments to a single DUT (N:1). Only one set of contacts at a time is closed, and, in the most basic form, relay closure proceeds from the first channel to the last. Some scanner systems can be programmed to skip channels. Nevertheless, since relays operate sequentially, this limits test system throughput. The larger the number of outputs (channels), the longer it takes to complete a test sequence. Typical applications, where speed is not an overriding consideration, are burn-in testing of components, monitoring time and temperature drift in circuits, and acquiring data on system variables such as pressure, temperature, and flow.

A multiplexer can do the same things a scanner does but is more flexible in that it can make multiple simultaneous connections non-sequentially. One example is routing DUT output to multiple instruments, such as an AC voltmeter and frequency counter. Typical applications include QA testing of capacitor leakage during production, contact resistance for multiple devices, and the insulation resistance of multipin connectors. In the latter application, the multiplexer would be used to connect a voltage source between any one pin and all other pins of the connector and route the resulting current from each set of connections through a picoammeter that calculates resistance from R=V/I. Multiple simultaneous connections can substantially speed up testing.

A matrix card is the most versatile topology in that it can connect multiple inputs to multiple outputs. This type of crosspoint switching is very useful when connections must be made between multiple instruments and a multipin device, such as an integrated circuit or resistor network (***Figure 3***). The matrix configuration is described by its number of rows and columns, such as 3×6, 4×10, 6×32, etc. Typically, matrix relay contacts are SPST or DPST.

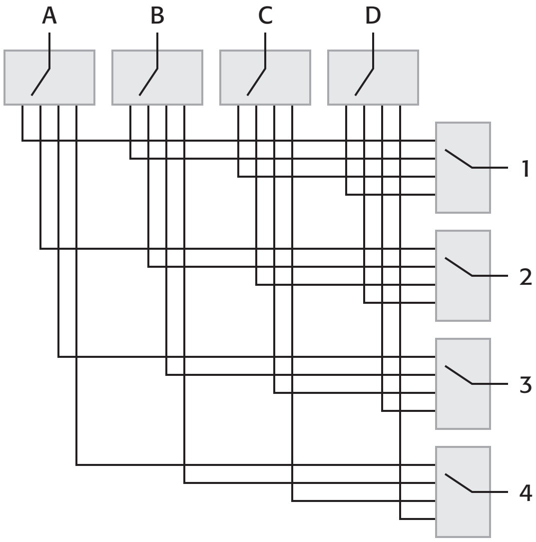

Figure 4. Non-blocking matrix used to connect multiple instruments (A–D) to multiple DUT pins (1–4).

When choosing a matrix card for mixed signals, some compromises may be required. For instance, if both high frequency and low current signals must be switched, review card specifications carefully. The card chosen must have wide bandwidth as well as good isolation and low offset current. A single matrix card may not satisfy both requirements completely, so decide which switched signal is more critical. In a system with multiple cards, card types should not be mixed if their outputs are connected together. For example, a general-purpose matrix card with its output connected in parallel with a low current matrix card will degrade the performance of the latter.

Matrix Considerations in RF Measurements. Given the fast growth of mobile voice and data communications, a large amount of testing is required on the different components of a communications system. These components range from active devices such as RFICs (Radio Frequency Integrated Circuits) to complete communication systems. RF test system instrumentation includes a DC bias source, DC meter, RF source, RF power meter, network analyzer, and other instruments. Automating the test process to improve test efficiency and throughput requires the integration of RF/Microwave and low-frequency switching into the test system.

To ensure signal integrity, an RF type of matrix is typically used for most or all of the switching in a communications test system, even when routing low frequency and DC signals between multiple instruments and DUTs. The number of DUTs and pieces of test equipment (i.e., number of inputs and outputs) normally determines the size of the matrix. There are three basic types of RF matrix that might be considered, but their characteristics should be fully understood before making a selection. These characteristics affect the size of the matrix, its cost, and signal integrity.

- Non-blocking matrix – This type of matrix (***Figure 4***) allows simultaneous connections of multiple input/output single paths up to the full number of matrix inputs. This is the most flexible and most expensive matrix. Although it is possible to close multiple paths, this is only practical in DC testing such as applying a continuous bias voltage to a number of DUTs. Impedance considerations preclude closing multiple paths in RF and microwave switching. Given that a switch system is positioned between the measurement instrument and the DUT, matching the impedance levels of all elements in the system is critical for maintaining signal integrity. For optimum signal transfer, the output impedance of the source should be equal to characteristic impedance of the switch, cables, and DUT.
- Blocking matrix – This matrix (***Figure 5***) allows the connection of a single input to any single output. Therefore, only one signal path is active at any given time. This is somewhat restrictive, but when working with RF and microwave signals, the paths must have impedance matching. Closing several paths at one time could cause reflections, poor VSWRs, loss of signal power, and other effects on signal integrity. So while a blocking matrix may be restrictive, most of the time it's necessary to maintain signal quality.

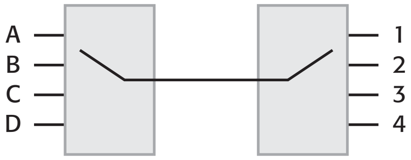

Figure 5. Blocking matrix.

- Full or partial matrix – A full access matrix allows simultaneous connection of an input to multiple outputs, as shown in ***Figure 6***. Using a switch mainframe, as typically required for communication test systems, will probably involve switch cards that have a modular switch design. These switch cards are normally designed in 1×4 building blocks, meaning one card may have three or four 1×4 switch matrixes on them. These can be configured together as a partial matrix to gain access to just the number of rows and columns needed, or configured for full access to all rows and columns. Still, using this approach to building the switch matrix requires a power divider at each input and a multiple position switch at the outputs. Again, impedance matching is important. The advantage of these configurations includes the absence of unterminated stubs, access to all channels, and similar path characteristics. Disadvantages include the need for extensive cabling and the use of many coaxial relays.

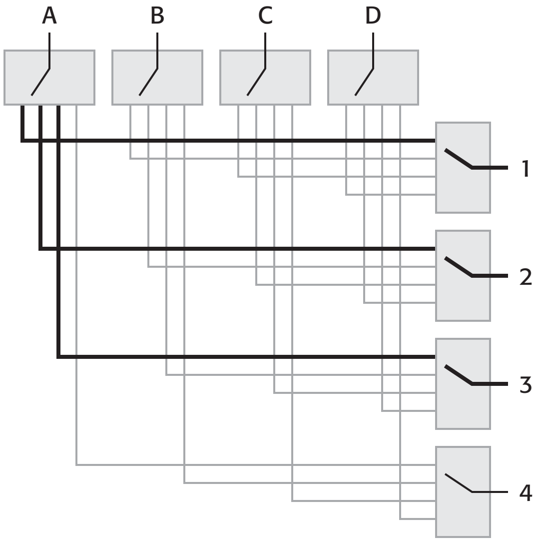

Figure 6. Full access matrix.

Matrix vs. Multiplexing in Four-wire Measurements. As mentioned earlier, a four-wire (Kelvin) measurement is the standard technique used to overcome high "on" resistance of solid-state switches. Using the four-wire technique eliminates both lead wire and switch contact resistance. This may be required in applications such as contact resistance, isolation resistance, and cable continuity testing, which typically involves low resistance (<100Ω). Switching signals associated with these measurements requires two channels instead of one, where each channel is a two-pole channel.

Normally, these two channels are paired in the four-wire or four-pole mode, which eliminates all the trace and test-lead resistance from the measurement. A matrix switch topology is not required for four-wire low resistance measurement applications; only a multiplexer is required for the switching portion of the test system. A multiplexer can use both the current source and voltage sense channels in a single four-pole switch. While a matrix can connect all of the rows to all of the columns, it is not required in low-resistance applications. Refer to ***Figure 7***.

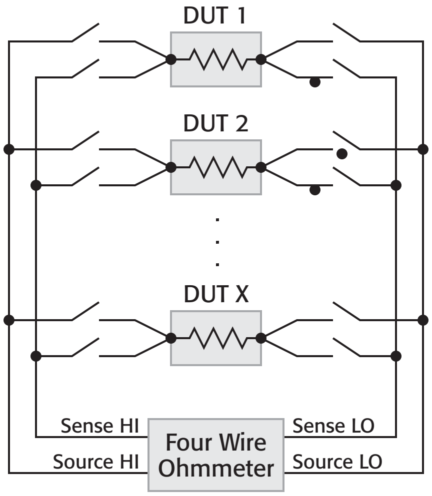

Figure 7. Multiplexed four-wire switching.

Design Tradeoffs

In a mixed signal testing environment there are a number of tradeoffs in switch mainframe and switch card selection that can have a major impact on test system performance and cost. Many of the performance considerations for matrix cards and their switch relays have already been described. Some examples of switch card and mainframe features currently available to test system developers follow.

Switch Card Considerations. As alluded to earlier, system integration may be simplified by using an RF type switch card, such as the Keithley Model 7173-50 4×12 matrix, for high frequency, low frequency, and DC signal switching. This card provides 200MHz bandwidth, offset voltage less than 15µV per crosspoint, and offset current less than 200pA, making it suitable for a wide range of mixed signal applications. A card with this kind of versatility may be a good tradeoff instead of using multiple cards designed specifically for either high or low frequency signals. Besides hardware costs, using different types of cards may make test system programming a bit more complicated.

Similarly, when characterizing semiconductor devices in R&D and production environments, a huge amount of data must be collected quickly in I-V and C-V measurements. This means that a matrix card must combine low-level measurement capabilities with fast switching and settling times. Such applications call for both low offset current and low parasitic capacitance, which are characteristics of the Keithley Model 7174A 8×12 matrix card. This card has offset current of less than 100fA on all pathways, along with low leakage and minimal dielectric absorption to allow measurements many times faster than other switching technologies.

Another type of matrix design that can be cost effective is one that has multiple signal paths with different characteristics for different signals. For example, the Keithley 7072-HV matrix card is designed to switch low-level, high-voltage, and high-impedance signals for semiconductor parametric tests. This unique design provides two signal paths capable of switching 1300V with less than 1pA of offset current. Another two paths can be used for C-V measurements from DC to 1MHz or for switching low currents with a common ground. Four additional high quality signal paths with less than 20pA offset current provide for signal switching to 200V.

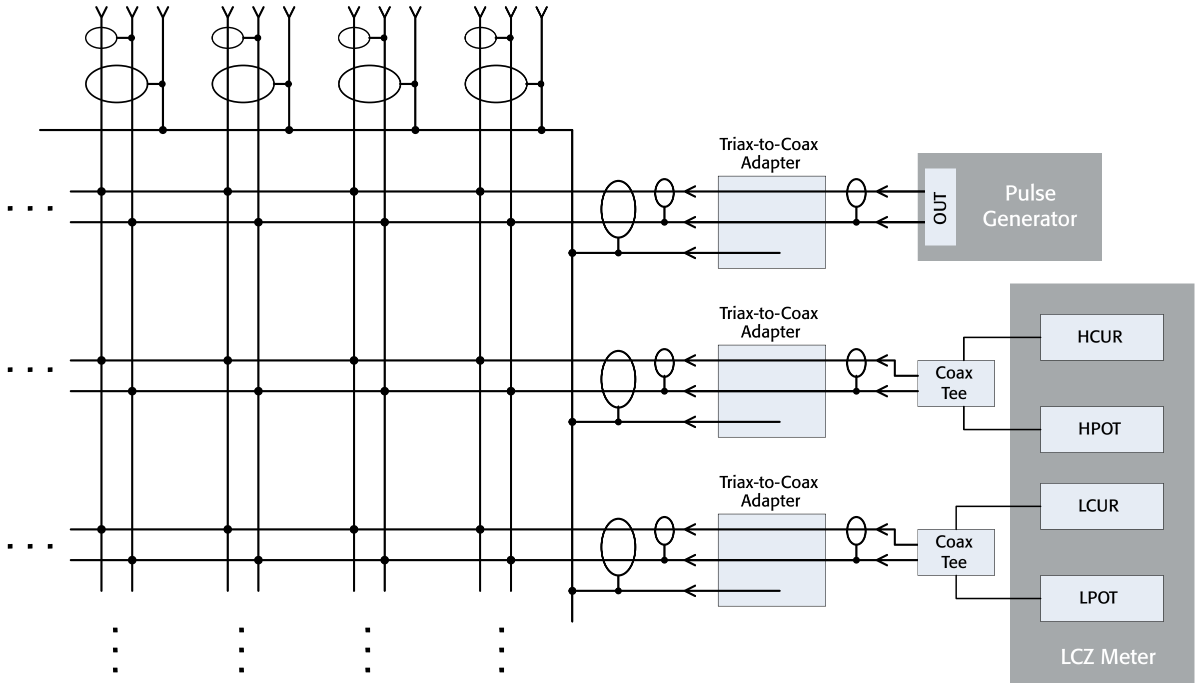

Figure 8. Example of a semiconductor test configuration with switch matrix card triaxial connections. Usually these cards have the outer shields of all triaxial connections shorted together to ground. For AC measurements, select adapters to convert from coaxial to triaxial connections carefully in order to preserve measurement quality.

Switch Mainframe Interfacing. In addition to switch card features, the mainframe's card interface must be considered. In complex test systems there is a need for a large number of matrix crosspoints. In addition to using multiple cards, it may be advantageous to have the capability to expand a particular type of matrix with jumper cables between cards in adjacent slots of the mainframe. This can be done, for example, with the Keithley 7174A cards in its Model 707B mainframe. Up to six 7174A cards can be interconnected in a single 707B mainframe to form an 8×72 or 12×48 matrix. Moreover, triax cables can be used for these connections, which provide impedance matching and allows guard connections to minimize the effects of leakage and parasitic capacitance. Coax to triax adapters may be needed between the instrumentation and the switch matrix (***Figure 8)***.

Another mainframe interfacing issue is the ease of integrating different instruments to obtain the required test system functions. This interfacing should facilitate signal routing between sources and measuring instruments, trigger connections, data communications, and digital I/O for control purposes. Modern switch mainframes, such as Keithley's Models 707B and 708B, offer the flexibility of ports for IEEE-488 (GPIB), USB 2.0, digital I/O via 25-pin D connector, LXI-compliant 10/100BaseT Ethernet (RJ-45) connectivity, and TSP-Link® connection for instruments with embedded TSP® processors.

Having a variety of connectivity options makes it easier to integrate the different instruments needed for a mixed signal test system. Developing the test system is even easier when the switch mainframe and instrumentation, such as source-measure units, parametric analyzers, etc. have all been designed to work together seamlessly. That's the case when, for example, a Keithley 707B/708B is combined with one of the company's Series 2600 SourceMeter® instruments. All these products have embedded TSP processors and a TSP-Link interface that make it easy to create a high-speed, self-contained tester that can be used with or without a PC. The 707B/708B also integrates seamlessly with the Keithley Model 4200-SCS semiconductor parametric analyzer through its matrix driver and GPIB interface, and thereby provides switching functions for I-V and C-V measurement protocols.

Test Sequence Programming and Execution. The benefits of pairing a switch mainframe and source-measure instruments, all with embedded TSP processors, are substantial. These benefits fall into two broad areas: sequence programming and execution, which are closely intertwined.

TSP is a full-featured test sequence engine that can store a user-defined test script or sequence in memory and execute it on command. Test scripts are complete test programs based on Lua, an easy-to-use but highly efficient and compact scripting language. Because test scripts can contain any sequence of routines that are executable by conventional programming languages (including decision-making and control of digital I/O), the switch mainframe can manage the operation of entire tests. Thus, scanning eliminates the need for a PC controller to send individual close/open commands for every switch path selection. That reduces software and communication overhead times, minimizes command processing time, and eliminates command parsing time.

In other words, Keithley's switch mainframes and SourceMeter instruments can operate autonomously in a distributed processing and control architecture. TSP can even access the mainframe's 14-bit digital I/O on the fly, increasing throughput by allowing instrument and binning equipment such as handlers to run without PC interference. This eliminates delays due to GPIB traffic congestion and greatly improves overall test times. However, when a host computer is used, a rear panel universal serial bus (USB) port allows the PC to communicate with and control the 707B/708B through the USB interface.

An integral part of the TSP architecture is TSP-Link, an ultra-fast inter-unit data bus for communications and triggering. It provides a high-speed, low-latency interface for TSP-based instrumentation, enabling simple multi-box and multi-instrument software control, as well as simplified test systems that can be easily scaled up as new requirements evolve. With TSP-Link there's no need to add external triggers and remote communication cables to individual units, because all TSP-Link connected devices can be controlled from a single master unit.

Another aspect of test programming and execution to consider is whether or not the instrumentation is LXI (LAN eXtensions for Instrumentation) compliant. LXI-enabled instruments have software that includes a built-in Web page that is accessible via any standard Web browser. In conjunction with a 10/100M Base-T Ethernet connection and LAN-based triggering, this Web interface offers a quick and easy method to program and control test sequences and perform basic troubleshooting and diagnostics. In the case of the 707B/708B mainframes, this includes interactive schematics of each mainframe switch card, which supports point-and-click control for opening and closing switches. For more advanced applications, a scan list builder is provided to guide users through the requirements of a scan list (such as trigger and looping definitions).

Often, test system development proceeds in segments, with the developer verifying proper switching sequences as each segment is completed. In addition to remote programming methods mentioned above, the 707B/708B mainframes facilitate development and troubleshooting with a variety of manual operations from the front panel.

For instance, local control from the front panel interface allows labeling switch card rows (instruments) and columns (pins) alphanumerically, which simplifies keeping track of what's connected to each crosspoint. An LED crosspoint display makes it easy to identify whether a specific channel is open or closed, as well as determine which slots are occupied and which cards are currently in use. A two-line display shows both error messages and user-defined messages and displays control menus and open/closed channel messages. An intuitive navigation/control knob allows scrolling through and opening/closing channels. Key pad controls support scrolling through menus, changing host interface settings, saving and restoring instrument setups, and loading and running factory and user-defined test scripts, etc.

Mainframe Command Structure. Overall test system throughput can be improved by taking advantage of certain features in a switch mainframe's sequence command structure to eliminate unnecessary relay closures. For each switch path change, the switch system requires time to actuate relays and stabilize. Avoid unnecessary relay actuation commands to optimize throughput. For example, Models 707B/708B maintain state information and do not unnecessarily toggle relays that are already closed. Additional relay control is available through channel connect rule programming:

Value 0 = NONE: system will close relays as it is able to without adhering to a rule

Value 1 = BREAK_BEFORE_MAKE (BBM)

Value 2 = MAKE_BEFORE_BREAK (MBB)

In typical BBM contact closure operations, the actuation time is imposed each time the mainframe processes a command to close or open a relay. The mainframe waits for the actuation time to elapse before recognizing the relay as closed. Thus, the system timing for moving from one closed path to another includes the actuation time for two relays. One way to optimize switch system timing is to turn the channel connect rule off (i.e., value = 0), so the switch mainframe attempts to open the first relay at the same time it closes the second relay, potentially reducing the total time impact to a single relay actuation period. However, given that the order of closure and opening cannot be guaranteed when the channel connect rule is off, users must implement cold switching.

In a similar vein, some mainframes may require separate open and close commands for every switch path selection. To reduce sequence time, the Models 707B/708B offer a variety of commands that combine close and open operations to minimize communication traffic, command parsing, and processing times. Some example commands include:

- CLOSE: Only closes specified relay without opening any other relay.
- EXCLUSIVE CLOSE: Opens all other mainframe relays and closes only the specified relay.
- EXCLUSIVE SLOT CLOSE: Opens all other relays on the same card and closes only the specified relay.

Conclusions

Integrating switching into a test system can greatly increase throughput when there are many devices to test or types of measurements to be made. Avoiding pitfalls in selecting and programming the switch system will help ensure signal quality and measurement accuracy while gaining throughput advantages.

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