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Management of Microwave Signals in Automated Test Systems

Robert Green, Keithley Instruments, Inc.

MINIMIZING reflections and signal losses in test systems associated with the design, characterization, and production of microwave RF products can be a complex challenge. In addition to issues such as cable and interconnect quality, engineers must consider conductor length, physical layout, and other aspects of system design that have little effect on DC circuits, yet are fundamental to the satisfactory operation of high frequency RF systems. Understanding and dealing with the mechanisms of impedance matching and signal loss are crucial to designing test systems that can evaluate the performance of wireless products.

Basic Electrical Properties of RF Test Systems

There are several electrical properties to consider when developing an RF switching or signal conditioning system. The main parameters include system bandwidth, insertion loss, isolation, power handling capability, and voltage standing wave ratio (VSWR).

Power losses are primarily a function of the resistive loss through the path and impedance mismatch losses through each path. Mismatch uncertainty, usually the largest contributor to power measurement uncertainty, can be calculated from the magnitudes of the reflection coefficients of the source and load:

$$Uncertainty = 20 \log (1 \pm |\Gamma_S \Gamma_L|) dB$$

where: Γ_S = the reflection coefficient of the source, and Γ_L = the reflection coefficient of the load.

RF Signal Conditioning and Switching Application Example

Test systems often must simulate actual application environments using complex signal paths that contain switches, other passive components, and active components. Characterizing how well a cellular phone can reject multipath interference, noise, and other RF signals is one example of such a production test.

Reconstructing the mechanism of multipath interference in a test system is a complex procedure, because it requires that noise and time-delayed signals reach the phone under test with appropriate power levels and phase relationships. ***Figure 1*** shows a typical signal conditioning/switching system application for testing mobile phones.

For mobile phone receiver testing, the output of the mobile station test set can be switched through two types of paths: 1) a path through instrumentation that simulates multipath fading and noise interference, and 2) paths than can switch in gain to simulate varying distances between the mobile phone and the base station. For phone transmitter testing, the output of the phone is directed to the mobile station test set through either an attenuated or unattenuated path. For monitoring purposes, the output of the phone or the input to the phone can be transmitted to a spectrum analyzer.

Figure 2 shows the control and signal path cabling associated with this type of system. Electromechanical switches are located in the foreground. Signal paths extend to the rear panel through banks of isolators, divider/combiners, and additional isolators. Ribbon cables supply the signals needed to control the microwave relays.

The Importance of Understanding and Managing Power Loss

Before attempting to perform any meaningful testing or calibration of products, it's critical to quantify the power losses through the RF test system to be used. Some first-time users of RF test systems may expect that such systems will be completely "invisible," implying perfect matching, zero insertion loss, and insensitivity to frequency-dependent effects. However, the use of switches, circulators, isolators, couplers, and attenuators (***Figure 1***) presents many avenues for slight impedance mismatches and power loss. The following paragraphs discuss these components. ***Tables 1–6*** show typical specifications.

Switches. Typical switch types include electromechanical and solid state devices. Generally, switch performance is judged in terms of bandwidth, insertion loss, isolation, and VSWR. Electromechanical switches

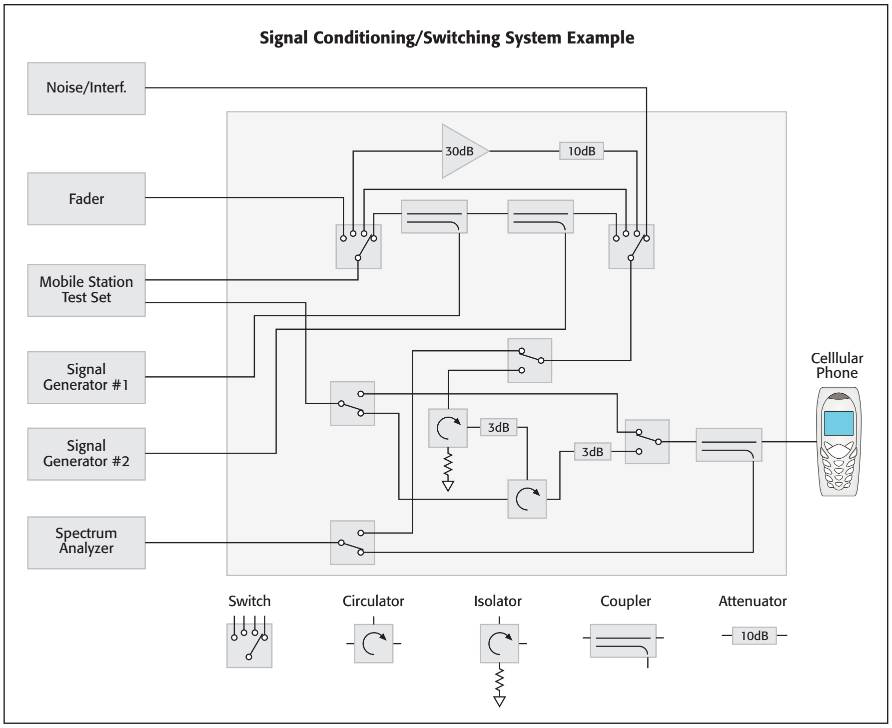


Figure 1. Signal Conditioning/Switching System Example

typically offer wider bandwidth, lower insertion loss, higher isolation, and lower VSWR specifications than solid-state switches. However, they provide a smaller number of cycles in the life of the switch—typically 2 million cycles for electromechanical switches as opposed to 10 million for solid-state switches. Electromechanical switches also require switching times on the order of 25ms, as compared to 25ns for solid state switches.

Table 1. Electromechanical Switches

Frequency Range (GHz)	DC – 3	3 – 8	8 – 12.4	12.4 – 18
VSWR (max)	1.2:1	1.3:1	1.4:1	1.5:1
Insertion Loss (max dB)	0.2	0.3	0.4	0.5
Isolation (min dB)	80	70	60	60

Directional Couplers. Directional couplers extract a specific amount of RF energy from a wave traveling in one direction through a transmission line. Directivity is the difference between the coupled port's output with power flowing in the forward direction as compared to its output with power flowing in the reverse direction. Often, the insertion loss specification of a coupler does not include the loss represented by coupled power. This power loss must also be budgeted for when estimating total system insertion loss.

Table 2. Directional Couplers

Frequency Range (GHz)	1.7 – 2.1
Coupling (max dB)	10 ± 1.0
Directivity (min dB)	10
Insertion Loss (max dB)	0.1
VSWR (max)	1.15:1

Table 3. Power Dividers/Combiners

***N*-Way**	2
Frequency Range (MHz)	800–2500
Amplitude Balance (max dB)	0.2
Phase Balance (max degrees)	3
Isolation (min dB)	22
VSWR (max)	1.3:1
Insertion Loss (max dB)	0.4

Power Dividers and Combiners. *N*-way strip line power dividers/combiners divide an input into *N* separate paths or combine *N* inputs into one output with a specified amount of isolation between inputs. These devices are band limited. Often, the insertion loss specification of dividers/combiners does not include the split loss. Just as with couplers, the total insertion loss for a divider must be taken into account when estimating total system insertion loss.

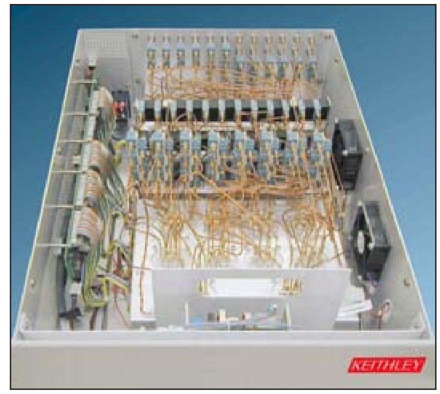


Figure 2. The internal construction of a microwave switching system must take into consideration the layout of components, as well as the quality and routing of signal-carrying conductors.

Circulators and Isolators. A circulator is a multi-port device that allows power to travel sequentially from one port to the next port. Each port can be used as an input or output. An isolator is a circulator containing a terminated port. Power input to the port immediately upstream from the terminated port will be absorbed in the termination.

Table 4. Isolators

Frequency Range (GHz)	1.7 – 2.0
Isolation (min dB)	20
Insertion loss (max dB)	0.4
VSWR (max)	1.25:1

Table 5. Terminations and Attenuators

Frequency Range (GHz)	DC – 3
VSWR (max)	1.2:1
Attenuation (dB) (attenuators, only)	3 ± 0.3

Terminations and Attenuators. A termination (also called a "load") is an RF device that, ideally, absorbs all RF energy flowing into it and reflects no energy back to the transmission line. An attenuator is similar, except that it reduces the RF power in the path by a specified amount and passes the remainder to an output port. Attenuators can be fixed or adjustable.

Cabling. Interconnecting cables are sometimes ignored when designing an RF test system, but they can be a critical element in system performance. In addition to electrical parameters such as characteristic impedance and insulation properties, physical attributes such as diameter, length, conductor and shielding design, and plating can strongly affect bandwidth, loss, and VSWR. Generally, larger diameter cables offer lower insertion loss and higher power handling capability, but decreased bandwidth and flexibility when compared to smaller diameter cables.

Table 6. Cable (10 inch, 0.141 Inch Diameter SMA)

Frequency Range (GHz)	DC – 1	1 – 2	2 – 4	4 – 6	6 – 12	12 - 18
VSWR (max)	1.06:1	1.10:1	1.14:1	1.17:1	1.20:1	1.30:1
Insertion Loss (max dB)	0.17	0.23	0.34	0.42	0.62	0.82

Quantifying the Performance of a System

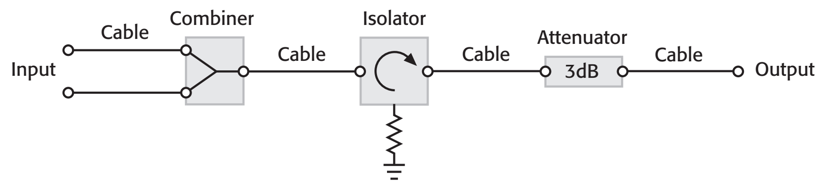
Calculating the root sum square of the reflection coefficients of each of the components in the system produces an excellent approximation of system VSWR performance. *Table 7* shows a simple RF path consisting of a combiner, an isolator, an attenuator and cables, and the corresponding calculations using some typical specifications. *Tables 7* and 8 contain the formulas employed in estimating final circuit VSWR.

To estimate the VSWR at the input of a system, start at the output port. The reflection coefficients of the components in the path are root summed squared to yield the estimate of VSWR at the input port. In this case, VSWR can be calculated as 1.389:1.

The best case input-to-output insertion loss would be no worse than the summation of the individual components' insertion loss specifications. In this case, that would be four cables at 0.4dB each, the combiner at 0.4dB, the isolator at 0.4dB, and the highest value of attenuation of 3.3dB, adding up to a maximum of 5.7dB of insertion loss through the system.

The worst case output to input isolation can be estimated by the lowest value of attenuation of 2.7dB, 20dB from the isolator, and 3dB for the power split in the combiner, adding up to at least 25.7dB in output to input isolation for the system. The input 1 to input 2 isolation should be no worse than the isolation specification of the combiner, which is 22dB.

Table 7. Example signal path and calculations for determining VSWR



Component	VSWR	Reflection Coefficient	Insertion Loss	Isolation
Cable	1.10:1 max.	0.048	0.40dB max.	
Combiner	1.30:1 max.	0.130	0.40dB max.	22dB min.
Isolator	1.25:1 max.	0.111	0.40dB max.	20dB min.
Attenuator	1.20:1 max.	0.091	3 ±0.3dB	

$$\text{Cable reflection coefficient} = \frac{1.1 - 1}{1.1 + 1}$$

Cable reflection coefficient = 0.048

$$\text{Isolator reflection coefficient} = \frac{1.25 - 1}{1.25 + 1}$$

Isolator reflection coefficient = 0.111

$$\text{Combiner reflection coefficient} = \frac{1.3 - 1}{1.3 + 1}$$

Combiner reflection coefficient = 0.13

$$\text{Attenuator reflection coefficient} = \frac{1.2 - 1}{1.2 + 1}$$

Attenuator reflection coefficient = 0.091

$$\text{Return loss from reflection coefficient} = 20 \log\left(\frac{1}{\text{reflection coefficient}}\right)$$

$$\text{Return coefficient from return loss} = \frac{1}{\exp\left(\frac{1}{20} \cdot \text{Return Loss} \cdot \ln(10)\right)}$$

$$\text{VSWR from reflection coefficient} = \frac{1 + \text{reflection coefficient}}{1 - \text{reflection coefficient}}$$

Table 8. VSWR Estimate for Example Signal Path

Input VSWR Estimate:

$20 \log \left(\frac{1}{.048}\right) + 2 \cdot 3 = 32.375$	Convert reflection coefficient of cable to return loss and lower the return loss by twice the value of the attenuator.
$\frac{1}{\exp\left(\frac{1}{20} \cdot 32.375 \ln(10)\right)} = 0.024$	Reflection coefficient of above return loss.
$\sqrt{0.024^2 + .091^2 + .048^2} = 0.106$	RSS of reduced cable reflection coefficient with coefficients of attenuator and another cable.
$20 \log \left(\frac{1}{.106}\right) + 20 = 39.494$	Convert above reflection coefficient to return loss and lower the return loss by the value of the isolation specification of the isolator.
$\frac{1}{\exp\left(\frac{1}{20} \cdot 39.494 \ln(10)\right)} = 0.011$	Reflection coefficient of above return loss.
$\sqrt{0.011^2 + .111^2 + .048^2} = 0.121$	RSS of above component's reflection coefficients with reflection coefficients of isolator and cable.
$20 \log \left(\frac{1}{.121}\right) + 3 = 21.344$	Convert above reflection coefficient to return loss and reduce the return loss by 3 dB due to the reflected power being split by the splitter/combiner.
$\frac{1}{\exp\left(\frac{1}{20} \cdot 21.344 \ln(10)\right)} = 0.086$	Reflection coefficient of above return loss.
$\sqrt{0.086^2 + .13^2 + .048^2} = 0.163$	RSS of above component's reflection coefficients with reflection coefficients of combiner and cable.
$\frac{1 + .163}{1 - .163} = 1.389$	Estimated Input VSWR of signal path.

About the Author

Robert Green is a Senior Market Development Manager at Keithley Instruments. He has seven years of experience in the wireless market providing manufacturers with fast transient power supplies, source-measure units, switching systems, and RF power analyzers. He has a B.S. in Electrical Engineering from Cornell University and a M.S. in Electrical Engineering from Washington University, St. Louis. He can be reached at 440-248-0400, or at bgreen@keithley.com

Conclusions & Recommendations

Understanding power losses and how to determine their magnitude is essential for estimating actual circuit performance, for factoring the information into the stimulus levels applied to the DUT, and for interpreting the results read back by test instrumentation. Considerable power can be lost throughout a system as a result of impedance mismatches and resistive losses.

The complexity of today's high frequency RF test systems is such that these losses can be substantial. As the example outlined here shows, even a simple signal path with only three components can attenuate a signal by 5.7dB. The mismatch error due to the path's VSWR of 1.389:1 (compared to an ideal VSWR of 1.0:1) adds further uncertainty to the total power delivered through the path.

The more realistic signal conditioning/switching system shown in ***Figure 1*** can have as many as ten components (not including cabling) in a single path. Therefore, minimizing the number of components in a pathway is essential. Whenever possible, use components with the lowest available insertion loss and the lowest available VSWR.

The purpose of this article has been to acquaint the reader with some of the considerations that go into this process. Admittedly, a complete presentation of the related theory and calculations are beyond the scope of a short article. For more information, contact the authors for a detailed version of the calculations. KEITHLEY

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Keithley Instruments, Inc. 28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
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