RF/Microwave Switching Systems Subtleties: Achieving the Performance You Need

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Introduction

The continuing growth of the communications industry and growing integration of wireless technology into consumer products means increased testing of communications systems components, ranging from active components like radio frequency integrated circuits (RFICs), microwave monolithic integrated circuits (MMICs), and system on chip (SOC) devices to space communication systems. Typically, these are tested at gigahertz (GHz) frequencies or higher. The main components of a typical test system may include a DC bias source, DC measurement instruments, RF power meter, network analyzer, etc. Automating the test process and improving test efficiency demands integrating RF/microwave and low frequency switching systems into the test system.

With the help of a switch, an instrument can measure multiple devices under test (DUTs) with increased efficiency, and the test process can be automated. Multiple tests with different instruments can be run on the same DUT or multiple instruments can test multiple DUTs. This article addresses several important aspects of configuring a high frequency switch system, including the system configurations and critical switch specifications.

Configuration of a Switch System

Switch systems can be very simple or quite elaborate. For example, a single pole double throw (SPDT) switch can be used to route signals to two different DUTs. It can be expanded further into a multiplexer configuration so that a single instrument can be routed to many different DUTs. Multiple instruments can be routed to multiple DUTs. In this case, the switch system is known either as a multiplexer-demultiplexer or a blocking matrix—only one signal path is active at any given time. *Figure 1* shows the application of an SPDT and a 1-to-16 multiplexer.

A switch system with a "blocking configuration" (*Figure 2*) can connect multiple instruments to multiple DUTs. Any instrument can be connected to only one output at a time. To switch any signal to any DUT at any time, a "non-blocking" configuration (sometimes called a switch matrix) can be used. Although this switch configuration has the highest flexibility, it is also the most expensive. The minimum number of interconnecting cables in a non-blocking matrix is a product of the number of inputs and outputs. Therefore, a 10×10 non-blocking matrix requires 100 cables and SP10T relays. Assembling such a system is a major challenge. Furthermore, the large number of components has the potential to reduce system reliability. *Figure 3* shows a 4×4 non-blocking switch configuration, and *Figure 4* shows an expanded 4×6 switch configuration.

Critical Switch Specifications

The use of a switch will inevitably degrade the performance of the measurement system, so it is important to consider several critical parameters that may affect system performance significantly. Two types of specifications are very important when configuring a switch: electrical and mechanical.

Electrical Specifications

Impedance Matching: The switch is positioned between the measurement instruments and the DUT, so it's critical to match the impedance levels of all three system
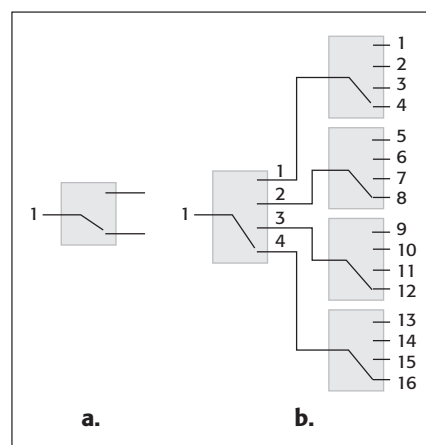

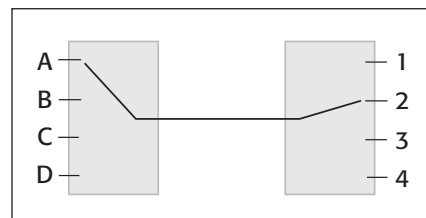*Figure 1a. SPDT. Figure 1b. 1-to-16 multiplexer.*
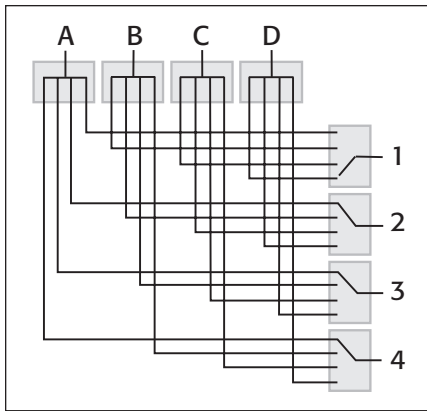

Figure 2. 4×4 blocking switch.
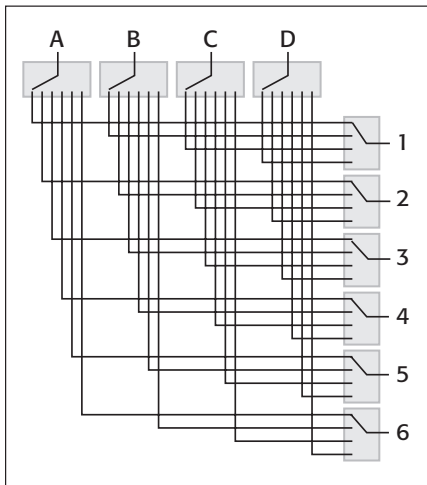
Figure 3. 4×4 non-blocking switch.

Figure 4. 4×6 non-blocking switch.

elements. For optimal signal transfer, the impedance of the source has to be equal to that of the switch and the DUT. In RF testing, different impedance levels are used to achieve different purposes. The most commonly used impedance level is 30Ω, and all RF/microwave relay manufacturers make 50Ω characteristic impedance relays. This value is a trade-off between maximum power transfer (at 30Ω) and minimized attenuation (at 75Ω).

Insertion Loss: Any component added to the signal path will cause some degree of loss, but the amount of loss is especially severe at higher or resonant frequencies. When the signal level is low or noise is high, insertion loss is particularly important. The insertion loss is reflected as a decrease in the available power on the DUT as compared to the test instrument source value. Normally, it is specified as the ratio of output power over the input power in dB at a certain frequency or over a frequency range.

$$\text{Insertion Loss (dB)} = -10 \log \left[\frac{P_{out}}{P_{in}} \right]$$

Path Isolation: At higher frequencies, signals traveling on different paths can interfere with each other or create "crosstalk" due to capacitive coupling between the paths or through electromagnetic radiation. This is especially severe when signal paths are not properly shielded or de-coupled from each other. Crosstalk is particularly problematic when a weak signal is physically adjacent to a very strong signal. Additional isolation measures are necessary when maintaining signal path isolation is critical.

Voltage Standing Wave Ratio (VSWR): Any component added to the high frequency signal path will not only cause insertion loss, but will cause an increase in the standing wave in the signal path. This standing wave is formed by the interference of the transmitting electromagnetic wave with the reflected wave. This interference is often the result of mismatched impedances in different parts of the system or connecting points in the system, such as connectors. VSWR is specified as the ratio of the standing wave's highest voltage amplitude to the lowest voltage amplitude in the signal. VSWR is often also expressed as Return Loss:

$$\text{Return Loss (dB)} = -20 \log \left[\frac{(VSWR-1)}{(VSWR+1)} \right]$$

Signal Filter: Signal filters can be useful in a number of circumstances, such as when spurious noise is inadvertently added to the signal as it travels through the switch. They can also be helpful if the original signal frequency exceeds the DUT testing frequency. In these cases, filters can be added to the switch to modify the signal frequency bandwidth or spurious signals at unwanted frequencies can be eliminated from the signal to the DUT.

Phase Distortion: As the size of a test system is expanded, signals from the same source may travel to the DUT via different paths of different lengths. This specification is often referred to as propagation delay. For a given conducting medium, the delay is proportional to the length of the signal path. Different signal path lengths will cause the signal phase to shift. This phase shift may cause erroneous measurement results. Therefore, techniques to ensure the same

phase or path length can be used to compensate for such effects.

Reliability and Repeatability: Typically, a switch relay should provide a lifetime of at least one million closures; many relays offer rated lifetimes of five million closures or greater. The repeatability of the switch performance is an equally important issue. Repeatability is the measure of the changes in the insertion loss or phase change from repeated use of the switch system. In RF measurement, it is not easy to eliminate the effects from the cycle-to-cycle change in the switch relay closure.

In some applications, particularly when low power is being switched, solid-state, pin diodes can be used. They offer a much longer life than electro-mechanical switches. Where high volume testing is being performed, and test tolerances are not that tight, then solid-state switches can be very cost-effective. Their disadvantages are much higher insertion loss (more than one decibel versus an electromechanical switch with a few tenths of a decibel of insertion loss). Isolation in solid-state switches is much lower than in electromechanical RF relays. Electromechanical relays can have a minimum isolation of 100dB out to 6GHz. Solid-state switches can have isolation levels down to less than 30dB at less than 3GHz. Electromechanical relays are a superior choice for high performance test systems.

Mechanical Specifications

Physical Form Factor: Depending on the application involved, the switch's physical form factor may limit the choice of the switch system. For a switch system with a medium number of signal pathways, a system such as the Model S46 RF/Microwave Switch System can offer numerous flexible configurations with up to 32 control ports. For a large-scale switch system, the System 41 RF/Microwave Signal Routing System offers dual 1×36 or a single 1×72 multiplexer. The System 41 also can be configured as a 6×6 or a 10×10 non-blocking multiplexer. When both low frequency and microwave switching are required, the Keithley Model 7116-MWS combines a 1×16 microwave multiplexer with 40 channels of DC low frequency switching and control capability. Connectors and Cables: Many different types of connectors and cables can be used

in RF/microwave switch systems. The signal frequency, the system impedance, power rating, and test fixture/handler compatibility, etc. should all be taken into consideration when choosing connectors and cables.

Relay Status Visual Feedback: Switch mainframes that provide an LED display to indicate the open/closed status of the switch relays are very useful during system setup and troubleshooting.

Considerations When Specifying an RF/Microwave Switch System

Several other factors must be considered carefully because they can easily degrade system performance even when high quality components are used.

Termination: At high frequencies, unless all signals are properly terminated, unacceptable amounts of power will be reflected from the terminating point. This is seen as an increase in VSWR. It may even cause damage in the source if the reflected portion is large enough. Switching paths must maintain the characteristic impedance, either 50Ω or 75Ω, and the path needs to terminate in the characteristic impedance. Unlike at low frequencies, where relay contacts can be connected in parallel or connected in matrix crosspoints, microwave switches cannot be connected in parallel because the characteristic impedance would not match the standard characteristic impedance of the system. This requirement to maintain the same impedance throughout the system is why non-blocking microwave matrices are such large systems.

Bandwidth: Most switch system users would like to have a switch with as wide and as flat a bandwidth as possible. However, wide-bandwidth switches are costly. If it is not absolutely needed, a narrow band switch can achieve the same objectives at a significantly lower cost. Another factor to consider is that when higher frequency is used, the bandwidth will depend on the type of connectors and cables used. More expensive types of these products are typically needed to ensure adequate system performance.

Power Transmission: Another important consideration is the system's ability to transfer the RF power from instrument to DUT. Due to insertion loss, the signal may require amplification. In some applications, it may be necessary to reduce the signal power to the DUT. An amplifier or attenuator may be needed to ensure the accurate level of power is transmitted through the switch.

Testing Digital Circuits and Devices

Anyone testing, characterizing, or performing environmental studies on multiple digital devices that are driven with pulses at gigahertz rates or higher will need a high frequency, microwave switch system to transfer undistorted pulses. Because the devices are being driven by digital pulses rather than sinusoidal-based signals, the switch system must be capable of switching the DC component of the pulses as well as the higher frequency components of the excitation pulses. That means the frequency response of the switch must cover DC to the maximum frequency for the required bandwidth of the test system. Coaxial microwave, electromechanical switches are specified to operate down to DC. Users may assume that the specified life of the relay is the same at all frequencies, but not all switches perform as repeatably at DC as they do at RF frequencies.

Figure 5 shows a plot of a microwave coaxial relay's performance at the mid-point of its warranted 1,000,000-cycle life. The relay's DC contact resistance is plotted versus switch closure activations. Note how the contact resistance varies. Particularly note that the DC contact resistance does not fail, exceed its specification of 100mΩ, and then remain in a failed state. It actually recovers and operates within specification, and then it fails again. Variations like this can significantly affect test data. For applications that require switching high frequency pulsed signals, ask your switch system manufacturer to provide test data to ensure that the relay will remain repeatable over its specified life for DC signals as well as microwave signals.
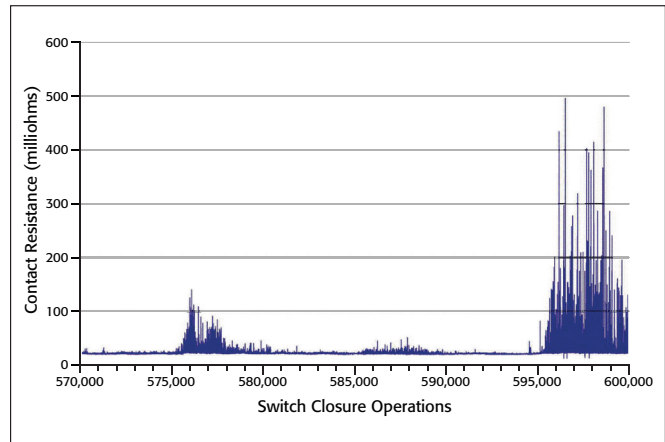

Figure 5. Microwave coaxial relay's performance at the mid-point of its warranted 1,000,000-cycle life.

Microwave Switch System Performance over a Device's Operating Range

Although microwave relay manufacturers provide specifications over the frequency range of the relay, they usually provide insertion loss, isolation, and VSWR data at only a few points. A microwave switch system may have paths that include multiple relays, cables, and other components that complicate determining the insertion loss or return loss at specific frequencies important to a particular test. If signal magnitudes are a critical aspect of the test results, request data from the switch system manufacturer data or test the system yourself.

Figure 6 is a vector network analyzer plot of insertion loss vs. frequency for seven paths of a 4GHz multi-path, switch system. Note that the insertion loss changes by about a factor of eight over the frequency range of the switch system. Also note that the insertion losses can vary significantly depending upon the path. In this case, the insertion loss variation between paths can be as much as a factor of three. If accurate determination of power levels is required, this characterization data is essential. If equal insertion loss paths are necessary, either fixed or variable attenuators can be added to the paths to achieve this. In cases where small differences exist between paths, cable lengths can be adjusted to equalize the insertion losses.

The VSWR plot in *Figure 7* shows how the VSWR varies over frequency, which has an impact on the amount of power delivered through the system. Complex switch systems with multiple components in a pathway may require the addition of isolators to protect input devices such as instruments or DUTs from excessive amounts
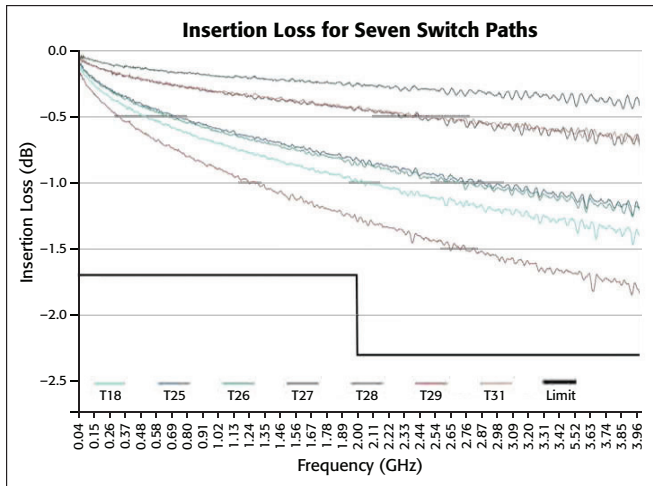
Figure 6. Vector network analyzer plot of insertion loss vs. frequency.

of reflected power. (Refer to the sidebar for information on estimating VSWR and return loss.)

To minimize VSWR, use these recommended construction techniques:

- Minimize kinks in cables.
- Ensure that the cable shields are free of holes or discontinuities.
- Confirm that all connectors are properly torqued. SMA connectors should be torqued to 7 in-lbs to 10 in-lbs.[1] Proper torquing of connectors minimizes the insertion loss through the interface of the two connections and minimizes VSWR degradation. Proper torquing ensures that the connections are stable and helps to maintain repeatable results through each switch pathway.
- Keep connectors clean. Oils and salts from the skin can contaminate insulation and reduce component isolation properties.
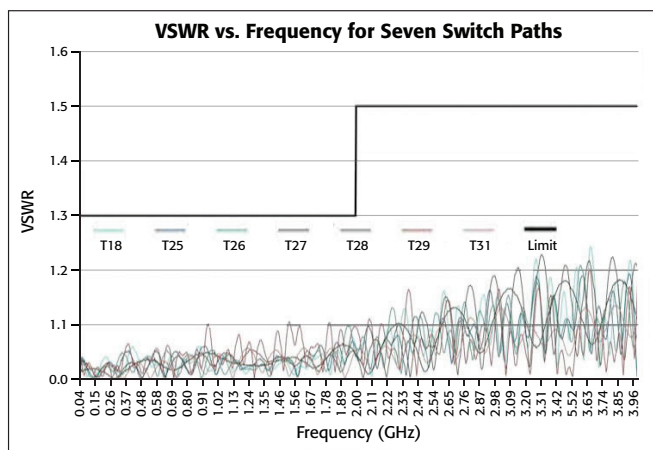
Figure 7. How VSWR varies over frequency.

Equalizing the Delay through Multiple Switch Paths

In some cases, such as testing some types of communication systems and testing radar sub-systems, all switch paths must have

1 For a discussion of the installation torque requirements for creating and maintaining good radio frequency connections, see "Connector Torque Requirements," by Ted Prema, Times Microwave Systems, Wallingford, CT. Available online at: http://www.mwjournal.com/Journal/article.asp?HH_ID=AR_586&tite=Connector%20Torque%20Requirements.

near-identical time delays. There are limitations to how small the differential can be between multiple switch paths. Even the relays have some slight variation in phase. *Figure 8* shows the phase variation through a number of SP6T relays. The phase angle differential is a maximum of about a degree. The red circles highlight the phase angle delays for two of the relays.
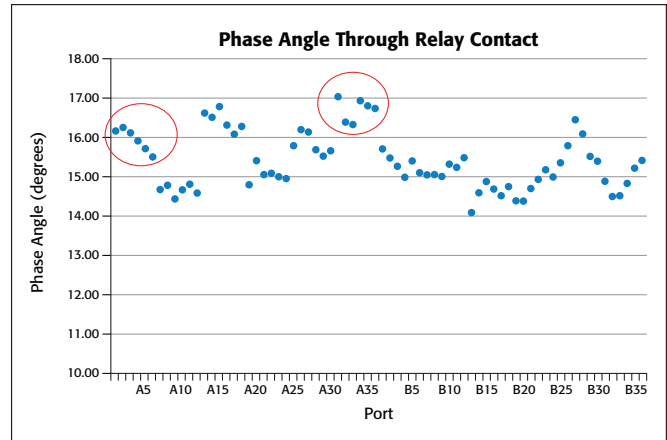

Figure 8. Phase variation through a number of SP6T relays.

Using cables that have identical electrical lengths is key to achieving a phase-matched switch system. Rigid or semi-rigid cables are recommended because they can be specified with delays of ±1ps or better. However, remember that the tighter the tolerance, the higher the cost of the cables will be.

Figure 9 shows the variation in delay times through an actual switch system. In this case, delay times through the individual paths were held to within 4ps of each other. The system required phase matched cables. To get even a more narrow variation, adjustable phase delay elements can be added to the switch system. However, it's important to weigh the benefit vs. the substantial added cost involved.
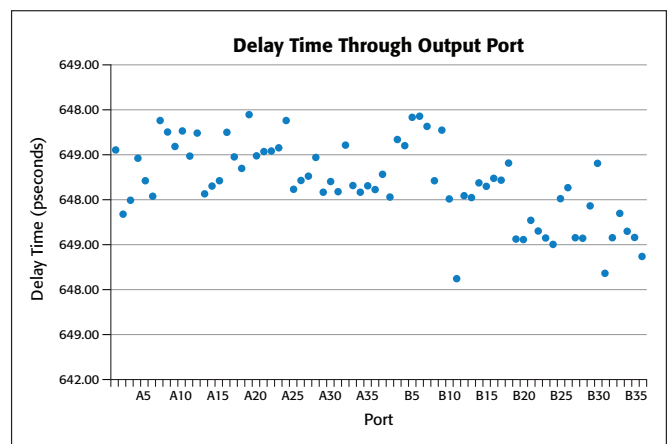

Figure 9. Variation in delay times through an actual switch system.

Conclusion

In this article, we briefly discussed some typical applications of switching in communication testing. When specifying a switch system, the first step is to consider the system configuration. In order to achieve an optimal, yet cost-effective system, system designers must weigh a variety of electrical and mechanical parameters. Understanding

these parameters makes it possible to make informed tradeoffs between switch flexibility and system cost. Furthermore, the subtleties associated with achieving a high level of system performance require a significant level of detail including system characterization and well-defined specifications for items like relays and cables. KEITHLEY

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Quantifying System Performance

Estimating system VSWR requires identifying sources of reflected power and giving consideration to the effects of reflected power on components in the signal path. *Figure 10* shows a simple RF path consisting of a combiner, an isolator, an attenuator, and cables.
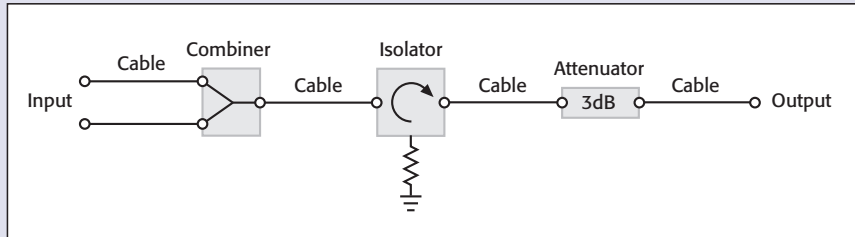
Figure 10. Example RF circuit path.

Table 1 lists specifications for the components in *Figure 10*. The reflection coefficients in the table have been determined by using Equation 5.

Table 1. Characteristics of Components in Figure 10 @ 2GHz

Component	VSWR	Reflection Coefficient (Γ)	Insertion Loss	Isolation
Cable	1.10:1 max	0.048	0.40 dB max	
Combiner	1.30:1 max	0.13	0.40 dB max	22 dB min
Isolator	1.25:1 max	0.111	0.40 dB max	20 dB min
Attenuator	1.20:1 max	0.091	3 ±0.3 dB	

To estimate the VSWR at the input of the system, start at the output port. The reflection coefficients of the components in the path are added in an rms sum to yield the VSWR value at the input port. In this case, VSWR is calculated to be 1.389:1. The steps taken to arrive at this conclusion are detailed in *Table 2*.

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

$$\text{Uncertainty} = 20 \log (1 \pm \Gamma_S \Gamma_L) \text{dB} \tag{1}$$

where: Γ_S = the reflection coefficient of the source
Γ_L = the reflection coefficient of the load

$$\text{Return Loss} = 20 \log \left(\frac{1}{\Gamma} \right) \text{dB} \tag{2}$$

$$\text{VSWR} = \frac{1 + \Gamma}{1 - \Gamma} \tag{3}$$

The reflection coefficient can be determined from the Return Loss by

$$\Gamma = \frac{1}{10^{\left(\frac{\text{Return Loss}}{20} \right)}} \tag{4}$$

Similarly, the reflection coefficient can be calculated from the VSWR by

$$\Gamma = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \tag{5}$$

Table 2. Input VSWR Estimate.

Step 1 $\text{Return Loss} = 20 \log\left(\dfrac{1}{0.048}\right) + 2 \cdot 3 = 32.375$	Convert reflection coefficient of cable to return loss and lower the return loss by twice the value of the attenuator.
Step 2 $\Gamma = \dfrac{1}{10^{\left(\frac{32.375}{20}\right)}} = 0.024$	Calculate the reflection coefficient corresponding to the above return loss.
Step 3 $\sqrt{0.0242^2 + 0.091^2 + 0.048^2} = 0.016$	rms sum of reduced cable reflection coefficient with coefficients of attenuator and another cable.
Repeat Step 1 using $\Gamma = 0.106$.	Convert this reflection coefficient representing two cables and the attenuator, to a return loss, 39.494dB.
Repeat Step 2 using Return Loss = 39.494dB	Find the reflection coefficient corresponding to the combined return loss.
Repeat Step 3 to include three cables, the attenuator, and the isolator.	The equivalent reflection coefficient is 0.121.
Repeat steps 1, 2, and 3 to arrive at an overall reflection coefficient = 0.163.	
Use equation 3 to determine the VSWR = 1.389.	

The best-case input-to-output insertion loss would be no worse than the summation of the components' insertion loss specifications. In this case, that would be four cables at 0.4dB each, the combiner at 0.4 dB, 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.