Supercharging a VNA with an RF Matrix Switch (VNA Port Extension)

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Introduction

The latest wireless standards for Internet-of-Things and 5G cellular telecommunication and wireless sensing technologies incorporate multi-input multi-output (MIMO) and beamforming techniques that enhance the radio performance of modern devices at the expense of drastically increasing complexity. One area this complexity is increased is during RF testing where the high port counts of these new devices and systems have laboratory and automated test designers juggling between several options to accommodate additional ports. At the same time, a far greater number of wireless devices and high-speed digital devices are being manufactured, encouraging automated test facilities to reduce test times and individual cost-per-test, often by testing a greater number of devices at a time.
To address these challenges, a test designer generally must choose either purchasing a very high ticket VNA with the required number of ports, purchasing an array of the most recent modular VNAs that reach the desired port count, or using a switch matrix, or matrix switch, to extend a VNA port count. Of these options, extending a VNA with a matrix switch can be one of the most cost effective, modular, fastest, and least resource intensive methods of reaching a desired port count, all without having to replace any VNAs that may already be on hand.

This article aims to educate readers on how switch matrices can be used to extend the port count of VNAs to meet the testing demands of the latest wireless standards and sensing technologies.

Switch Matrix Primer

In essence a switch matrix is as its name implies, a matrix of switches. The basic functionality of a switch matrix is to relay desired RF signals among the various inputs to the desired outputs. There are a variety of ways to do this and several common switch matrix configurations. This section provides insights into the various types of switch matrices, highlights key performance parameters to consider for RF switch matrices, and discusses what switch matrix solutions may be most viable for VNA port extension.

Switch Matrix Configurations

The most common switch matrix configurations are blocking, non-blocking, super non-blocking, and common highway configurations. This section provides a brief description of each configuration and discusses the merits and drawbacks of each. In this section the distinction of input and output port of a switch matrix is used. In these cases, an input port of a switch matrix is typically the set of ports that are connected to the VNA ports, where the switch matrix output ports are the ports connected to the device-under-test (DUT). In some cases a switch matrix is symmetrical, and the distinction may be arbitrary.

Blocking

A blocking switch matrix only allows one input to be relayed to a single output at a given time. This type of switch matrix is composed entirely of RF switches. In general, a blocking switch matrix exhibits lower insertion loss, higher port-to-port isolation, and can often handle higher RF input power compared to other switch matrix configurations. However, a non-blocking switch matrix has no fan-out capability, which may be limiting in some applications.

Non-blocking

A non-blocking RF switch matrix uses dividers/combiners at each input port to distribute the RF signal throughout the matrix where an RF switch selects which of the inputs to relay to specific output port(s). In this way, a non-blocking switch matrix makes the signal energy from each input available to every output, but the signal from only one input port will ultimately be relayed to the output port. A non-blocking switch matrix allows for a greater variety of connection options than a blocking switch matrix, but exhibits higher insertion loss and lower port-to-port isolation compared to a blocking configuration.

Super Non-blocking

A super non-blocking switch matrix allows for the signal energy from any input to be available at any of the outputs simultaneously. In this configuration, the input and output layers are both made up of power divider/combiners RF switches integrated to select which inputs and/or outputs are active. Super Non-blocking is the only matrix switch configuration that allows multiple inputs to be connected to multiple outputs simultaneously. A super non-blocking switch matrix offers the highest degree of connectivity and flexibility, but also exhibits the highest insertion loss and lowest port-to-port isolation due to the repeated splitting and combining of the signal.

Common Highway

A common highway switch matrix is composed of only RF switches and only allows for one active signal path at a time. That means that only one input can be connected to only one output at any given time in this configuration. A common highway RF switch matrix can be very cost effective and exhibit low insertion loss, high port-to-port isolation, and high RF power handling, especially when compared to non-blocking switch matrix types.

Switch Matrix Key Performance Parameters & Switch Types

Ultimately, the overall performance of a switch matrix from port to port depends upon the cumulative behavior of the internal components and whatever limiting behaviors some components may exhibit. For instance, the insertion loss of a switch matrix is a result of the combined losses from each component in the signal path, including connectors, interconnects, switches, and combiners/dividers when applicable. Other factors, such as frequency range, power handling, and switching speed are limiting factors that can be the contribution of a single component in the switch matrix signal path or a combination of components.

Key Switch Matrix Performance Parameters

- Frequency Range
- Voltage Standing Wave Ratio (VSWR) or Return Loss
- Isolation
- Insertion Loss
- Power Handling
- Switching Speed
- Group Delay
- Rated Switching Cycles or Lifetime
- Off-State Impedance

The performance of a switch matrix is mostly determined by the switches used, with the exception of loss, VSWR, and in some cases, port-to-port isolation (these are characteristics related to the power divider/combiners). There are two main switch types used in RF switch matrices, namely electromechanical switches and solid-state switches. Electromechanical RF switches use electrical actuation means to make or break a mechanical switch connection. Where, a solid-state RF switch employs semiconductor devices to make and break the electrical connection based on their electrical states. Hence, both types of switches can be controlled somewhat similarly by applying a switching control signals, the switching function and fundamental aspects of the connection are very different between the two switch types.

In general, solid-state RF switches can operate at higher switching speeds, shorter settling times, are smaller, may be lower cost, and exhibit higher life cycles delivering greater repeatability compared to electromechanical switches.

On the other hand, electromechanical switches exceed solid-state switches in power handling, low-end frequency range, insertion loss, isolation across the frequency range, and ESD immunity. In some cases, an electromechanical switch may also be more susceptible to shock and vibration than a solid state-switch. However, solid-state switches may exhibit greater sensitivity to external temperatures and performance variation at high RF power levels.

Another important aspect to consider is the off-state impedance or unused port condition of a switch matrix. When a switch matrix port is in the off-state it may present an open/shorted (reflective) port condition or a matched port impedance with the interconnect impedance (absorptive). This means that for a reflective unused port condition, all of the signals delivered to that port will be reflected back to the transmitter, where an absorptive unused port condition acts as a termination in the impedance of the overall test system.

Do's and Don'ts of VNA Port Extension

Optimizing a VNA test setup for accurate and repeatable multi-port testing is now critical for minimizing the cost of testing in modern systems. Important factors in achieving this are reducing the amount of operator intervention in testing, interconnect cycling, calibration cycles/times, and reconfiguration between tests. Though in some cases an extensive natively multiport VNA may be able to objectively help achieve these aims, these units generally come with massive upfront capital expense. Moreover, modern MIMO/beamforming antennas and RF Front-Ends (RFFEs) designed for the latest wireless standards that use spatial multiplexing and beamforming, may have more ports than non-custom VNA units can offer. Modular VNA solutions that can be setup to accommodate high port counts are also relatively expensive, but also may not be able to achieve the same level of performance of a switch matrix-extended VNA at the same price point.

Hence, the extension of VNA ports using RF switch matrices are becoming increasingly necessary for many test houses and laboratories exploring the latest wireless technologies or attempting to more efficiently test massive numbers of IOT devices. By adding a switch matrix to a VNA, there is necessarily some additional loss and mismatch introduced into the system, and ensuring accurate calibration is more complex than without a switch matrix.

To keep test times as low as possible, switch matrices that allow for programmable switching are extremely valuable. In order to properly control programmable switch matrices, a physical interface and programming interface is needed. This does lead to an additional layer of complexity to multiport testing with switch matrices compared to true multi-port VNAs, but is not an uncommon situation for many automated test applications. This makes the control interface another critical factor to consider when choosing a matrix.

Next, we will explore parameters and functionality of switch matrices used as VNA port extension and provide some guidance/best practices in selecting switch matrix solutions for this application.

RF Switch Matrix Solutions Best Suited For VNA Port Extension

The most optimal switch matrix solution is unique to each test application and the dynamics of the device-under-test (DUTs). It is important to note that for many applications the number of switch matrix ports may not be symmetric. Moreover, VNAs commonly come with an even number of ports, generally 2, 4, 8, or 16. VNAs with 2 or 4 ports are the most commonly available and the most economically affordable.

Depending on the number of input ports to output ports of the network-under-test (NUT), which may not be symmetric to the number of ports on the VNA, a switch matrix can often be readily designed/constructed from a combination of RF switches alone. For devices that have multiple paths that nominally don't interact, such as a multiplexer, a simple common highway or blocking switch matrix may be adequate. In this example, testing between multiple ports of the switch matrix input ports, or between any of the output ports simultaneously isn't necessary.

In the case where a NUT/DUT needs to have several paths active at the same time, a non-blocking or even super non-blocking switch matrix may be required. If only one port at the input and one port at the output needs to be connected at a time, then only a non-blocking switch matrix will be needed. This could be the case if multiple devices are being tested simultaneously, but having a connection between every port doesn't benefit the test and having slightly less insertion loss is desirable. However, for maximum flexibility of test, a super-non blocking switch matrix is the best option. This solution can allow for large port count multiport devices to be measured with full S-parameter frequency sweeps where the source energy from a given port can be received by every other port, albeit attenuated somewhat by the switch losses and that of the power divider/combiners.

For the most optimal test setup with a VNA port extension, the switches and power dividers/combiners place a limitation on the available output power, trace noise, and sensitivity. The insertion loss of the extension system impacts the temperature stability and longevity of a calibration. Hence, higher performance switch matrix solutions will result in longer calibration intervals, improved dynamic range, and better measurement noise performance.

VNA Port Extension Best Practices

One of the intrinsic drawbacks of VNA port extension is the addition of components and interconnect that degrades the signal conditions from the VNA test ports to the DUT/NUT. Hence, depending on the desired dynamic range of a test setup, it may be desirable to choose a switch matrix solution that allows for an adequate amount of signal energy to be received at the test ports. This calculation involves including the total losses of the switch matrices, as well as any coaxial cables or adapters needed to connect the switch matrix to the VNA and the DUTs.

It is important to note that placing any components between a DUT and the VNA ports contributes to measurement instability. Calibration helps to correct for this instability. However, active semiconductor components in switches tend to be less stable with temperature variations, and depending on the device and laboratory temperature stability may require frequency-specific calibrations to minimize measurement inaccuracy.

Some types of VNAs have ports that provide direct access to the transmitter (stimulus or source) and receiver (incident/reflected receiver) ports within the VNA that bypass the directional couplers (measurement bridge or test port coupler). The type of VNA port extension possible with direct access to stimulus and receiver ports can be different from that with VNAs that only have external ports available. Part of the reasoning for this is that direct receiver ports may allow for bypassing the VNA bridge (directional couplers) at the front of the port, which generally add a significant amount of insertion loss to the receiver ports. Bypassing the VNA bridge could allow for switch matrix solutions that would otherwise result in insertion loss that is beyond a threshold for viably testing signals from certain devices. With direct receiver access a different VNA bridge could be employed that has a higher coupling value that is a better fit for a given test application, though no overall benefit to dynamic range is achievable this way.

Furthering this concept, a full extension test set can be made by adding VNA bridges (directional couplers) to the output of a switch matrix configured to allow for switching of both the source and receiver ports of a VNA. In effect, this approach enables a full multiport extension of a VNA with full calibration capability. A full calibration of each port can correct for the load match inaccuracies for every port and path. This approach provides much more enhanced measurement stability and performance than others, as the switching is performed "behind" the measurement bridges. Though the dynamic range is reduced via this approach, the switch losses do not impact measurement stability and offer the best performing VNA port extension method short of having a true multiport VNA with enough ports to accommodate complete testing. These VNA port extension units are also sometimes referred to as full crossbar switching test sets.

Tackling Calibration and Other VNA Port Extension Considerations

A typical VNA calibration involves connecting various calibrated loads to the ports of the VNA to account for every port combination. This produces a single calibration state that is used to calculate corrections to measurements either during measurement or after capture.

By adding a switch matrix to the ports of a VNA additional corrections need to be calculated for each different switch position to offset the inevitable errors added to the measurements. Hence, a calibration must be performed for each switch position of the matrix, which can be time consuming and potentially error prone if the process isn't automated.

If the switch isolation is inferior to the measurement noise floor, then it may be desirable to include an isolation calibration stage in addition to the standard short-open-load-thru (SOLT) calibration procedure. This is generally performed by terminating the open ports with precision loads so that the ports are as isolated as possible and only the internal isolation is included in the calibration correction.

A limitation of calibrating high port count VNAs and VNAs with port count extensions is that there may not be calibration units or sets available that match the port count of the test setup. This means that there will intrinsically be multiple manual steps of connecting various ports to achieve a full multi-port calibration.

Conclusion

There are many considerations to take into account when tackling high port count measurement scenarios. Though there are now true multiport VNAs and modular VNAs that can be expanded to accommodate a large number of ports, using a switch matrix to extend the ports of a VNA is still one of the most cost effective and time efficient methods of meeting the needs of modern multiport testing. As with any test and measurement application, having an understanding of the nuances of each test instrument and metrology science helps to ensure an optimal test setup and smooth operation.

Resources

1. RF Matrix Switch Types & Functionality
2. When Choosing Test Equipment, Don't Forget the Interface