Improving T/R module test accuracy and throughput

White paper

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ROHDE&SCHWARZ

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Introduction

Phased arrays have been used in radar applications for many decades. Recent trends are driving their adoption into other applications such as electronic warfare (EW), satellite systems and even 5G communications. There are several new component technologies that are behind this migration: multiple T/R modules on a chip, higher performance PCB laminates and the acceptance of GaN as a power amplifier (PA) semiconductor process.

Characterizing a T/R module places high demands on a test system's performance and flexibility. The test system needs to support a variety of test modes while maintaining accuracy and constantly improving throughput. In many cases, it must measure high output power, while at the same time delivering very low, highly accurate stimulus power. The system must provide intermodulation measurements on pulsed signals, including on frequency-converting DUTs. As a rule, noise figure and/or spectral measurements are also required. T/R modules with separate TX and RX paths and an antenna connector call for three-port measurements and typically require two local oscillator (LO) signals in addition.

The flexibility of the R&S®ZVA vector network analyzer can be greatly enhanced with the addition of our R&S®ZVAX-TRM extension unit. The extension unit supports a wide range of measurements in a compact, individually configurable design that is available in 24 GHz, 40 GHz, 50 GHz and 67 GHz models. The unit allows the user to configure the vector network analyzer (VNA) for customizable signal conditioning and switching. The R&S®ZVAX-TRM allows the VNA to specifically provide a suite of measurements on active DUTs under manual or automatic system control. These measurements can be made in both the forward and reverse directions, all with a single connection to the DUT.

This white paper provides an overview of the basic building blocks of a phased array system and discusses how the nature of their design leads to a challenging test environment. It shows how the R&S®ZVAX-TRM expands the capabilities of the R&S®ZVA to perform a wide range of T/R module measurements with just a single connection. Real measurement configuration examples are shown to highlight the flexibility required for T/R module testing.

Table 1: Phased array applications

Platform trends	Enabling technologies
▪ Satellite payloads and ground stations are moving away from parabolic dish antennas for LEO systems ▪ Electronic warfare systems are moving to phased arrays for jamming and ESM ▪ 5G will use phased arrays to overcome higher frequency path losses	▪ MMIC insertion is driving the price of systems down (multiple T/R modules on a chip) ▪ GaN is maturing and becoming the semiconductor process of choice for high power density PAs ▪ Higher frequencies are allowing the use of smaller apertures and PCB printed antennas ▪ Higher performing, lower loss PCB laminates are allowing printed antennas and beamformers ▪ True multiport VNAs are allowing faster test times and higher measurement accuracy

Phased array overview

The physically stationary phased array antenna beam is steered by varying the relative amplitude and phase used to control the individual antenna elements. This steering works on both transmit and receive. By changing the relative amplitude and phase across the beam, we can steer the beam and reduce the sidelobes of the resulting beam pattern (Figure 1). On the transmit side, sidelobes are usually unwanted radiations of energy in unwanted directions. On the receive side, sidelobes allow signals into the receiver from unwanted directions when the system is in receive mode.

Figure 1: Principles of phased array beamforming and beam steering

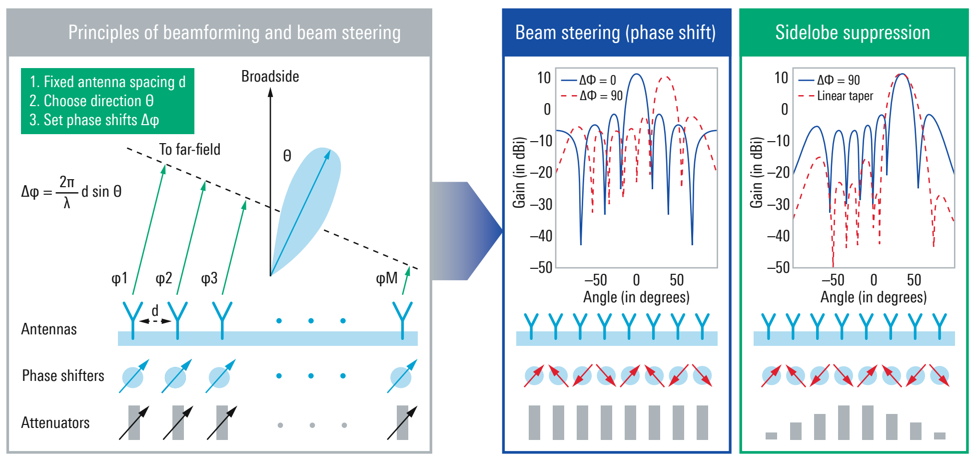
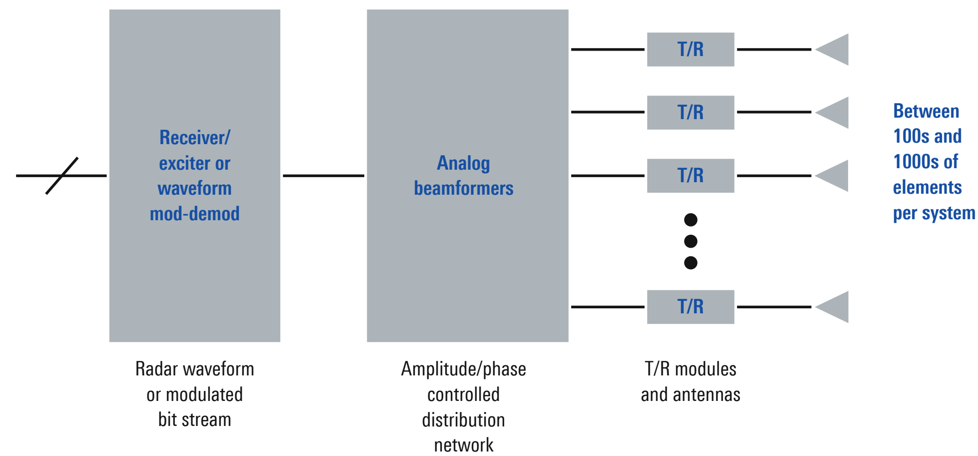


Figure 2 shows the major blocks in a phased array system. These blocks are similar in communications systems and radar/EW systems. The left block shows the receiver/exciter if the system is a radar, or a modem if it is a communications system. This block generates the signals used for transmitting and houses the receivers in receive mode.

The next block represents the beamforming network. This network is responsible for routing the transmitted and received signals to the many T/R modules and radiators in the system. The beamforming network has a small number of (or one) input signals and many output signals. The beamformer drives the next block – the system's T/R modules. These modules are responsible for controlling the amplitude and phase of the signals transmitted to and received by the individual antenna elements.

Figure 2: Generic phased array block diagram



Drilling down to the individual building blocks of the system, let us start with the analog beamforming network (Figure 3). These are usually made of passive structures such as splitters and combiners. The structures are configured as a distribution network by combining these into the desired topology for the specific system. The structures are usually manufactured out of a multilayer PCB, where the individual passive structures can be printed and interconnected using strip-line and micro-strip structures.

The beamforming networks need to be tested for insertion loss and insertion phase across their many paths. The performance requirements are usually quite strict, typically measurement tolerances of 0.1 dB and a few degrees. It becomes difficult to maintain this uncertainty as the frequency increases and becomes very difficult as the frequencies increase above 8 GHz. Multiport VNAs (like the R&S®ZNBT series) are the measurement tool of choice to characterize these networks.

Figure 3: Analog beamforming networks (RF manifolds)

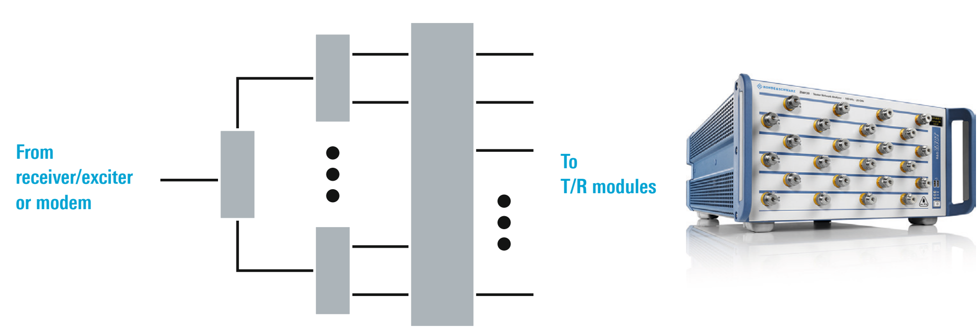
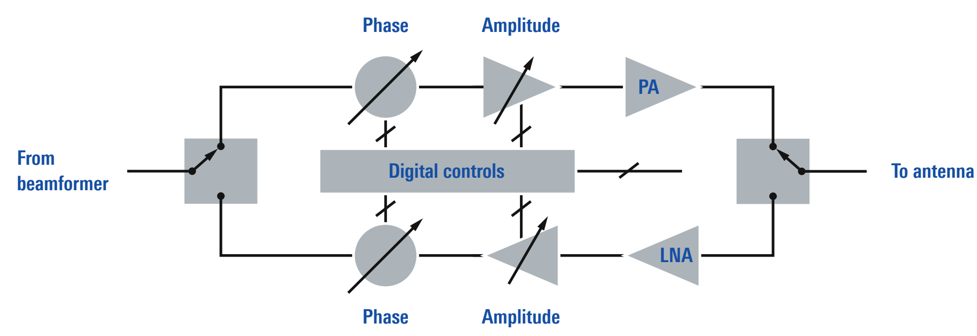


Figure 4 shows an example block diagram of a T/R module. The upper leg is used for transmitting, while the lower leg is for receiving. There are input and output switches to change from transmit to receive mode. The amplitude weighting and phase shifting is done using the variable gain amplifiers and phase shifters in each leg. These are controlled digitally and can be varied over a large value of states. There is also a PA used to transmit and an LNA used to receive. These components also need to be characterized for noise figure, compression, intermodulation and linearity. In R&D, each of these characteristics needs to be tested over all the T/R module states of gain and phase settings. For many designs, each T/R module may also require testing in production. Combining the large number of T/R modules with many potential gain/phase states drives the need to improve test throughput times.

Figure 4: Typical T/R module block diagram



Test systems

The comprehensive characterization of T/R modules and active DUTs requires test equipment that supports diverse test scenarios. For example, test equipment must be able to provide and handle both very high and very low powers without any modifications to the test setup and perform intermodulation and group delay measurements on converters with an embedded local oscillator (LO).

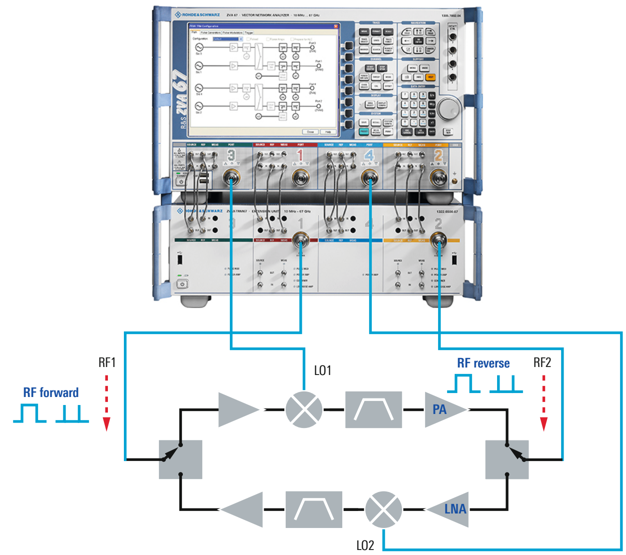
Rohde & Schwarz offers the configurable R&S®ZVAX-TRM extension unit, which can be used together with an R&S®ZVA/R&S®ZVT network analyzer to provide signal conditioning for a wide variety of demanding measurements up to 67 GHz (Figure 5). In addition to normal S-parameter measurements, it supports a full suite of measurements (Table 2).

The extension unit adds additional signal conditioning to the network analyzer. This provides several economic and technical benefits. If several network analyzers are available to perform various tasks, not all analyzers need to be equipped with all options. This means that fewer options are needed for the network analyzer itself, thus reducing investment costs. Another advantage of the extension is that is offers additional protection for the network analyzer during measurements, as its high-power frontend may be used instead of the VNA ports.

Adding signal conditioning to the network analyzer provides yet another benefit: measurements requiring no signal conditioning can be carried out using just the standalone VNA. This enables uncompromised network analyzer performance thanks to the instrument's superior dynamic range, sensitivity and stability.

Since the R&S®ZVA vector network analyzer is available with up to four sources, these can be used with the extension unit to characterize T/R modules with the frequency converting capability. This capability allows you to make measurements under multitone (and pulsed multitone) stimulus while providing coherent LO signals to the T/R module. This four-source, four-port configuration is the only high-end VNA available on the market with this unique capability.

Figure 5: Single-connection measurements up to 67 GHz



Combining the configurable R&S®ZVAX-TRM extension unit with the R&S®ZVA/R&S®ZVT vector network analyzer enables signal conditioning for a wide variety of demanding single-connection measurements up to 67 GHz

Table 2: Versatile measurement capability

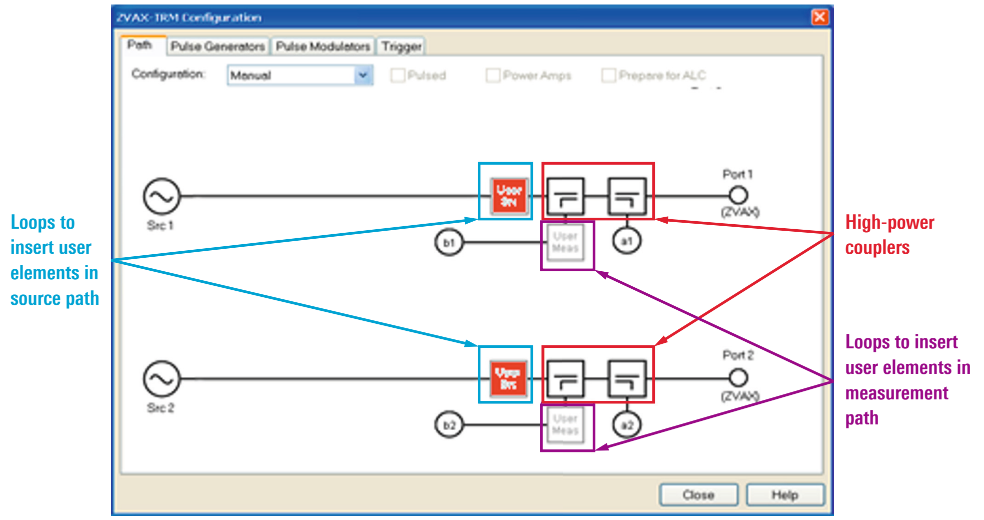
Measurement suite	Featured flexibility
Intermodulation	Combiners switched in/out as needed
Linearity	LNA up to 50 GHz (with HPF)
Frequency translated measurements	Booster amplifiers
Group delay with embedded LO	Pulsed modulators up to 60 GHz
Noise figure	User-selectable reference point
Two-port S-parameters	User-selectable external devices
Pulsed S-parameters	User-selectable routing of signals
Pulsed intermodulation	Loops to insert user elements in source path
Hot S-parameters	Loops to insert user elements in measurement path
Provide one or two LO sources	

Routing signals

The stimulus and measured signals from the network analyzer are fed to the extension unit via the network analyzer's direct generator/receiver inputs. The signals are modified via the extension unit and either output through its ports or fed through the network analyzer ports. The unit includes a high-power test set with access to the network analyzer's generator and receiver paths.

The extension unit allows test engineers to add user-supplied components to both the source and measurement paths. By inserting amplifiers, attenuators or even other test instruments into the measurement path, you can expand your measurement capabilities. The internal hardware and switching allows this capability to be used while keeping the DUT connected. The base R&S®ZVAX-TRM extension module with no optional hardware is shown in Figure 6. These elements may be software controlled and switched in as required.

Figure 6: Extension unit

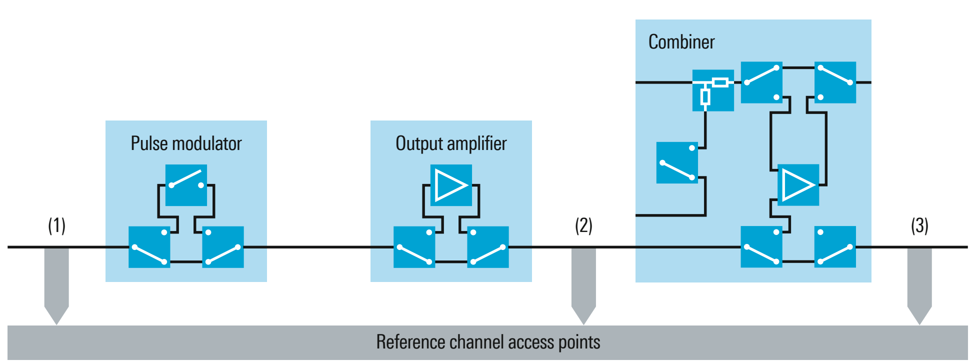


The extension unit allows test engineers to add user-supplied components and instruments to both the source and measurement paths

The extension unit contains two high-power couplers behind its test ports. These couplers allow measurements in the reference and measurement paths up to +43 dBm. The extension unit also allows the user to insert an element into its two source paths. This creates flexibility in a system's set-up and enables power amplifiers to be inserted for high-power testing. This feature in conjunction with the high-power couplers allows the measurement of high-power S-parameters as well as hot S_{22} measurements on active DUTs. Often it is convenient to be able to insert elements into the measurement paths. The extension unit also allows the insertion of user-provided attenuators or preamplifiers right upstream of the network analyzer's measurement receivers.

The extension unit allows the reference signal to be accessed at several points in the signal chain to maximize system performance. This mainly serves to optimize the ALC function of the network analyzer in applications that call for precise output powers. Figure 7 shows the three reference access points.

Figure 7: Access points



The extension unit offers three access points for the reference signal

Signal conditioning

In addition to the standard features, the extension unit also offers optional pulse modulators, combiners, output amplifiers and low-noise preamplifiers (LNAs). The individual components are activated via mechanical switches as required for a given measurement setup (Figure 8).

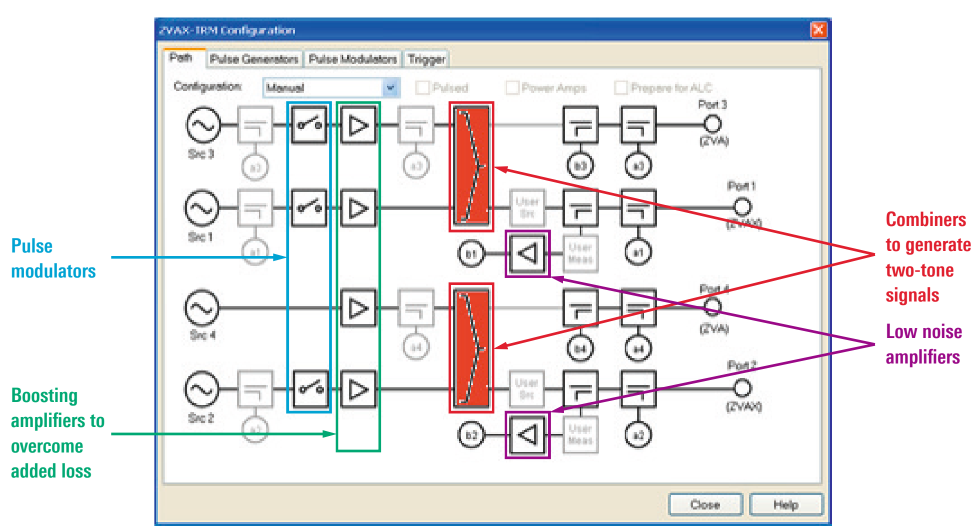
The optional combiners can be switched in to allow the signals from the VNA source 1 and 3 and/or source 2 and 4 to be combined. Having multiple sources to deliver stimulus signals allows the system to test intermodulation distortion, as well as third-order intercept points on active DUTs. This can be done in both the forward and reverse direction of the DUTs.

There are also three optional pulse modulators available for sources 1, 2 and 3. This allows you to output pulsed stimulus signals to perform pulsed S-parameter measurements. Adding this capability with the optional combiners allows pulsed intermodulation distortion measurements.

Optional amplifiers may be switched in on the source paths. They may be used to overcome any additional loss in the signal path and increase the output power at the test ports of the extension unit, as well as the test ports of the R&S®ZVA vector network analyzer. This allows output power at the ports to be between +5 dBm and +15 dBm depending on installed options and frequency.

Optional LNAs may be added to the extension unit. This has the net result of lowering the noise figure for the b1 and b2 measurement receivers. The LNAs may also act as a preamp for noise figure measurements on active DUTs.

Figure 8: Extension unit



The extension unit also offers options to include pulse modulators, combiners, low-noise preamplifiers (LNAs) in the receiver paths and output amplifiers

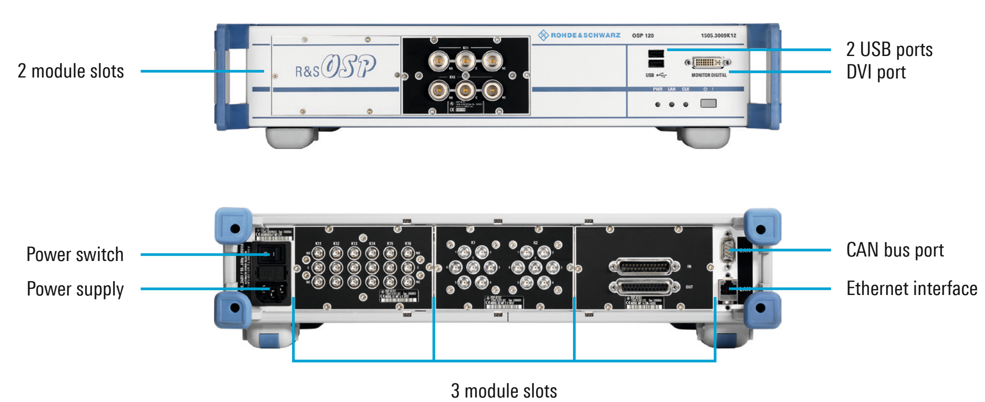
Additional switching

The ability to implement complex signal routing by means of a single switch and control platform is another option. In addition to the extension unit, Rohde & Schwarz also offers the modular R&S®OSP open switch and control platform (Figure 9). This allows a test system to perform even more RF switch and control tasks. We will discuss some applications and benefits of this capability in the next section.

The R&S®OSP RF switch and control platform base unit can be a manually operated instrument or it can be controlled via an Ethernet interface. This interface allows connection to a PC for automatic and manual control via a software application. Rohde & Schwarz offers multiple switch/relay modules configurations:

- Electromechanical switching to 67 GHz
- Solid state switching to 10 GHz
- Terminated 50 Ω modules
- SPST, SPDT, DPDT, DP3T, SP6T modules
- Multiple modules per extension unit
- Architecture supports multiple extension modules

Figure 9: R&S®OSP



The modular R&S®OSP open switch and control platform allows a test system to perform even more RF switch and control tasks

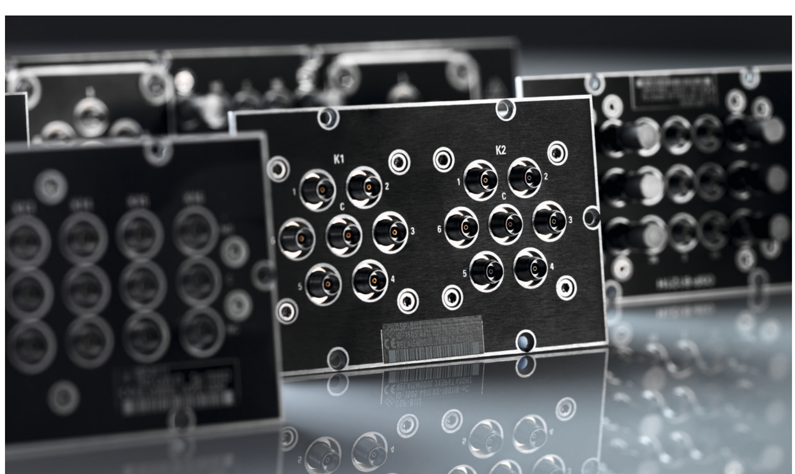


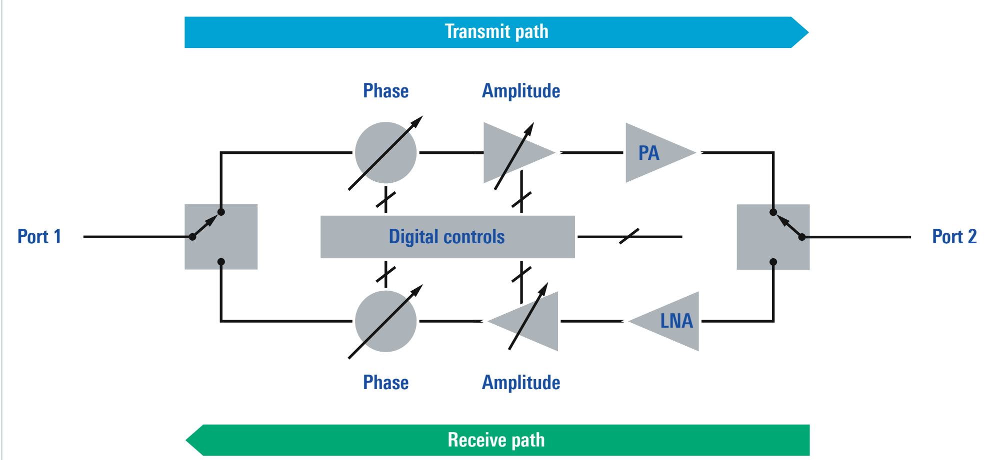
Figure 10: R&S®OSP switch modules

Example configurations

Figure 11 shows a generic block diagram of a T/R module with all its functional blocks. The transmit (TX) side is shown in the upper path and the receive (RX) side is shown in the lower path. There are input and output switches that control whether the module is in transmit or receive mode. The amplitude and phase of the TX and RX signals are adjusted by the variable phase shifters and variable gain amplifiers on their respective paths. These adjustments are usually controlled digitally, and they allow the beam to be steered across the face of the array. Typical systems have hundreds to thousands of these T/R modules in each phased array.

The TX path uses a power amplifier (PA) for transmitting, while the RX path uses a low-noise amplifier (LNA). Typically, test engineers want to look at the TX S-parameters from port 1 to 2 as shown on the diagram, as well as the RX S-parameters from port 2 to 1. The S-parameters are used to characterize all amplitude and phase settings of the digitally controlled components. The LNA and PA are also characterized for noise figure, intermodulation, third-order intercept (3OIP) and compression. The input and output matches are also important. Since T/R modules are often used in radar systems that operate in a pulsed mode, pulsed measurements are typically a requirement.

Figure 11: Generic block diagram of a T/R module



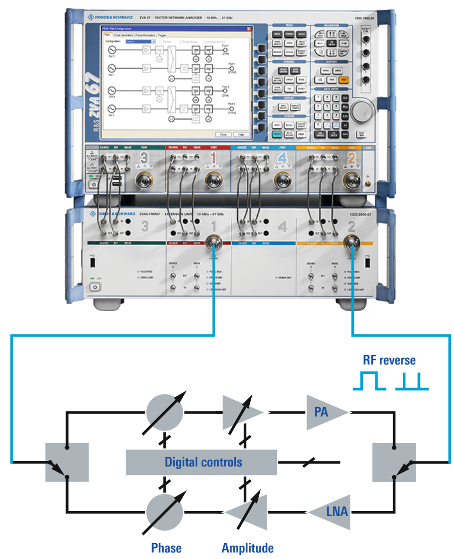
Single-connection characterization

Figure 12 shows an example of the R&S®ZVA with the R&S®ZVAX-TRM extension unit for performing measurements on a T/R module. With a single connection, the system can measure and characterize both the forward (TX) and reverse (RX) directions. The receiver characteristics such as gain, noise figure and linearity are measured, along with the transmitter characteristics such as output power, compression and intermodulation distortion. Measurements may be performed in either direction under swept, CW, multitone or pulsed stimulus. Data is typically collected over all the T/R module states of gain and phase settings. Since the VNA has an embedded PC, it can be used to control the T/R module directly. This simplifies your test setups and reduces your test time. Hardware handshaking also allows buffered data transfer while acquiring data, reducing test time further.

When measuring the RX side of the module, the four VNA sources allow two-tone stimulation using the internal combiners of the extension unit. This allows IMD and 3OIP testing to be done on the LNA. For these receiver tests, the internal preamp can be used to measure the noise figure of the LNA. This set-up can be customized with the addition of switched user components in the source or measurement loops. The stimulus to the module can be either stepped CW, pulsed or two-tone. Pulsed and two-tone stimulus signals are usually stepped across the frequency range of the module. Swept input power can also be used as a stimulus.

On the transmit side, the four sources also allow IMD and 3OIP testing to be done on the PA. The high-power couplers are useful when making high-power PA measurements. As with the RX tests, this set-up can be customized with the addition of user-inserted components in the source or measurement loops. The transmitter stimulus may also be either stepped CW, pulsed or two-tone.

Figure 12: R&S®ZVA with the R&S®ZVAX-TRM



The R&S®ZVA with the R&S®ZVAX-TRM extension unit enables single-connection characterization of T/R modules

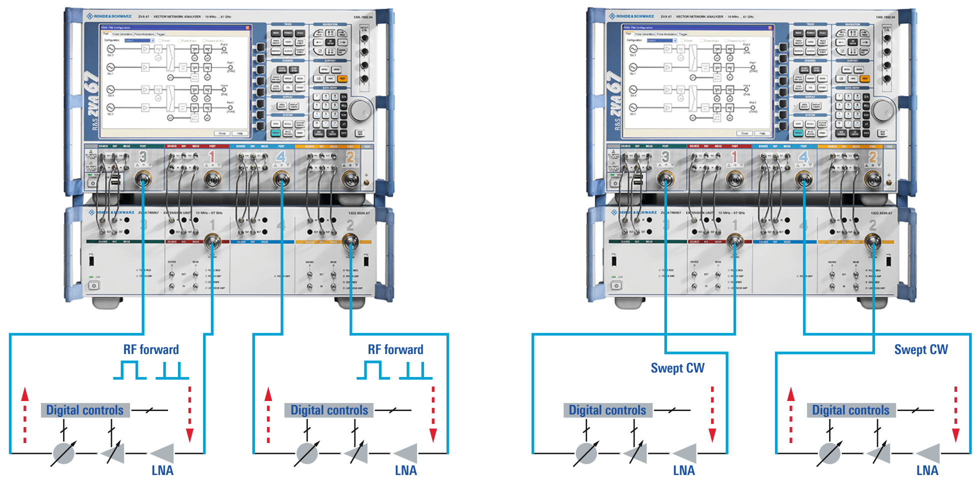
Parallel module testing

Testing parallel modules or partial modules can be a great way to speed up measurement throughput and reduce the cost of testing. Figure 13a shows an example of performing measurements on two parallel receive chains by using all the available ports. The stimulus is coming from the R&S®ZVAX-TRM ports 1 and 2 and is using the combiners and pulse modulator option. With this setup, the stimulus can be either CW, multitone or pulsed. The multitone stimulus uses all four internal sources of the R&S®ZVA in pairs for the parallel measurement. The measurement ports are ports 3 and 4 of the R&S®ZVA. This allows the VNA to measure all of the RX characteristics for both chains simultaneously.

If the R&S®ZVA ports are used as the stimulus for the receiver chains, one can sweep the receiver in frequency or power (or both) with a CW signal (Figure 13b). By using the R&S®ZVAX-TRM ports as the measurement path, the extension unit's internal preamp may be used to measure the noise figure of both receiver chains as well as all the typical single-tone swept RX measurements.

If we were to use a simple external switch matrix to switch the stimulus and measurement ports, we could do all of the RX tests on two parallel receiver chains with a single connection. This includes the pulsed, multitone as well as swept CW measurement suites shown in Figure 13a. We will discuss this further in the next section.

Figure 13: Parallel testing receiver paths increases throughput rates



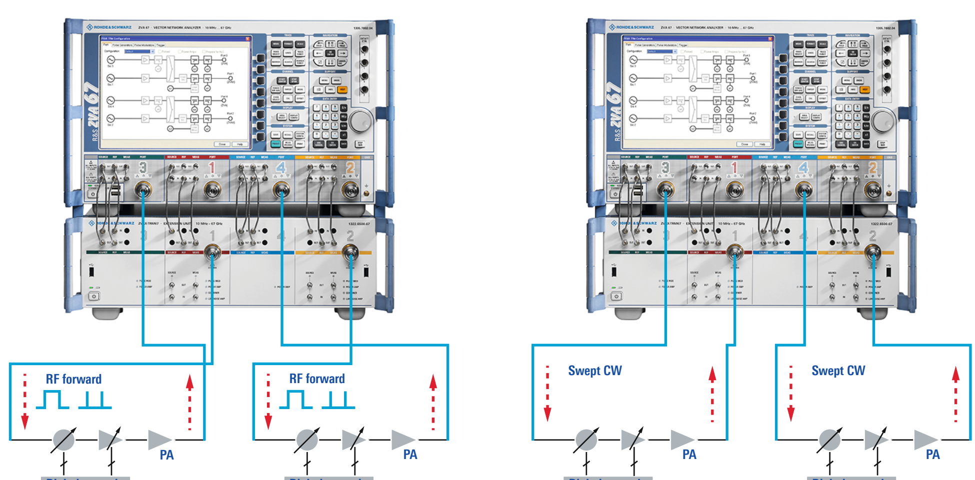
(a) Pulsed/multitone RX test

(b) Swept CW RX test

Similar to what was shown on the RX path, the same is possible for testing transmitter paths in parallel. Figure 14a shows the R&S®ZVAX-TRM ports to be used as the stimulus with either a pulsed or multitone signal. The measurement ports are on the R&S®ZVA and allow the characterization of both TX chains in parallel. An attenuator might be required for this setup to ensure that the ports and receivers of the R&S®ZVA remain uncompressed and in the linear region.

Figure 14b shows how to configure the stimulus from the R&S®ZVA ports to perform swept CW and swept power measurements. By using the R&S®ZVAX-TRM ports for the measurement, we can make use of the internal high-power couplers to execute the higher-powered TX measurement suite.

Figure 14: Parallel testing transmitter paths increases throughput rates



(a) Pulsed/multi-tone RX test

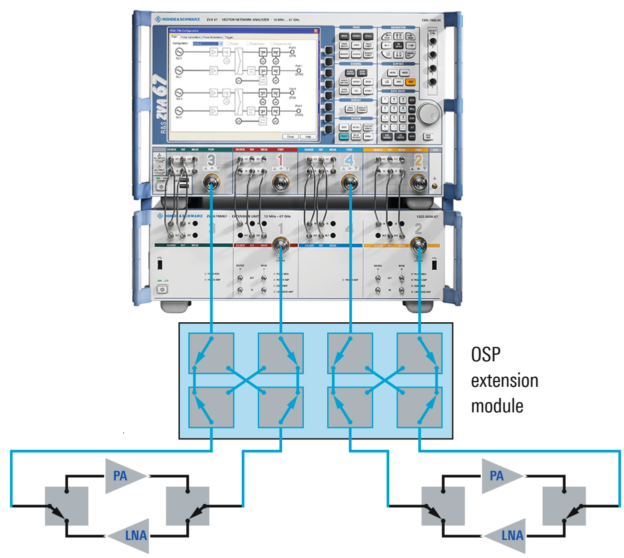
(b) Swept CW RX test

Parallel testing with external switching

Adding a simple switch matrix allows multiple T/R module bidirectional testing. With a single connection, the system can measure the entire suite of T/R module measurements in both transmit and receive mode. Figure 15 shows the system configuration with the R&S®OSP150 extension unit added to the test setup.

In this example, there is a simple external 2×2 crossbar switch for each T/R module. This allows the R&S®ZVA and R&S®ZVAX-TRM module to measure two T/R modules in parallel (in TX and RX modes), which significantly reduces test time and cost. The combination of the external crossbar and T/R module switching allows complete characterization of the two T/R modules and utilizes the benefits of the R&S®ZVAX-TRM module's combiners, pulse modulators, high-power couplers and noise figure preamplifiers to perform PA tests, multitone analysis, pulsed and noise figure measurements. It also retains the flexibility to add switched user components to the source and measurement paths.

Figure 15: R&S®OSP150 extension unit switching



The combination of the R&S®ZVAX-TRM with the R&S®OSP150 extension unit switching allows the complete characterization of two T/R modules with a single connection

Summary

As phased arrays spread into more applications, the need for improved test solutions is increasing. Accurately characterizing T/R modules at a high throughput rate can challenge a test system's performance and flexibility. The flexibility of the R&S®ZVA vector network analyzer can be enhanced with the addition of the R&S®ZVAX-TRM and R&S®OSP150 extension units. The combined solution allows the VNA to specifically provide a suite of measurements on active DUTs with a single connection. The configuration examples shown in this paper reflect just a few of the options for testing T/R modules. Adding user-supplied accessories and instruments allows almost any combination of tests to be performed.

For more information about the R&S®ZVAX-TRM extension unit, visit our website.

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, monitoring and network testing. Founded more than 80 years ago, the independent company which is headquartered in Munich, Germany, has an extensive sales and service network with locations in more than 70 countries.

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