Designing and implementing an active phased array antenna requires precise characterization of individual components and the integrated performance of the array. To ensure an accurate test of the intended adaptive nature of the active phased array antenna, the embedded algorithms need to be tested as well.

This application note aims to explain test procedures and give recommendations towards characterization of the relevant parameters for active phased array antennas and their passive subsystem, as often used in applications for Mobile Communication and RADAR. This application note describes transmit signal quality testing, multi-element amplitude and phase measurement techniques both in receive and transmit cases and introduces a new automated test methodology antenna radiation pattern measurement over frequency.

This paper also describes the test system used for transmit and receive module (TRM) characterization in active array antennas.

Note:

Please find the most up-to-date document on our homepage
https://www.rohde-schwarz.com/appnote/1MA248

This document is complemented by software. The software may be updated even if the version of the document remains unchanged.
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Abstract

Active phased array antenna systems have existed in the aerospace and defense sector for a long time. Over the last decade or more, active phased array antenna arrays have been growing in popularity in the Wireless & Cellular communication industry. However, it is only very recently that the technology has gained significant pace in commercial applications, fueled by the often-cited exponential rise in demand for voice, data and video related wireless services.

The use of an active phased array antenna increases the capacity of a cellular network. Conventional arrangements for urban terrain, with its high to very high user density, suffer from signal to interference ratio (SIR) that is often worse than signal-to-noise ratio (SNR). For network planning or optimization, this means that based on subscriber count, SIR is a bigger problem than SNR. Using active phased array antennas, adaptive beamforming algorithms can be implemented and thus make it possible to better target user groups or even individual subscribers. Narrow receive beams increase received signal strength versus level of interference. The amount of interference in the radio environment is simultaneously lowered by the narrower transmit beams. Higher spatial diversity and better frequency reuse hence are the main benefits derived from adoption of active phased array antennas. Side benefits include the fact that narrow beams may allow more precise user positioning in areas of spotty GNSS coverage such as indoors or in urban canyons, at least as long as line-of-sight conditions apply.

In rural terrain, subscriber number are much lower. The number of radios required to provide acceptable quality of service coverage can be reduced if Base Transceiver Stations (BTS) with active phased array antenna grids are installed. Higher beam directivity made possible with smart arrays allow to maintain sufficient signal power at the receiver terminal at far larger distances, while narrower receive beams increase the reverse link range of a network (1).

In the Aerospace & Defense scene, active phased array antennas remain the technology of choice in satellite tracking and surveillance. The same is true for radar applications such as detecting and tracking of aircraft, ships and missiles. Smart arrays have superior performance for radar clutter rejection, nulling of jammer signals and compensation for Doppler shift as experienced with fast-flying objects.

Broadcast satellite systems may also benefit from active phased array antennas by reducing needed transmit power or increasing communication capacity at a given amplifier output.

This application note aims to explain test procedures and give recommendations towards a general characterization strategy of the relevant parameters for active phased array antennas based on applications for mobile communication and RADAR. This application note describes transmit signal quality testing, multi-element amplitude and phase measurement techniques both in receive and transmit cases and introduces a new automated test methodology antenna radiation pattern measurement over frequency.

This paper also describes the test system used for transmit and receive module (TRM) characterization in active array antennas.
Abstract

Abbreviations

The following abbreviations are used in this application note for Rohde & Schwarz products:

- The R&S®SMW200A vector signal generator is referred to as SMW
- The R&S®SGT100A SGMA vector RF source is referred to as SGT
- The R&S®SGS100A SGMA RF source is referred to as SGS
- The R&S®SGU100A SGMA upconverter is referred to as SGU
- The R&S®SGMA-GUI PC Software is referred to as SGMA-GUI
- The R&S®FSW signal and spectrum analyzer is referred to as FSW
- The R&S®ZNBT vector network analyzer is referred to as ZNBT
- The R&S®ZVT vector network analyzer is referred to as ZVT
- The R&S®ZVA vector network analyzer is referred to as ZVA
- The R&S®RTO digital oscilloscope is referred to as RTO
- The R&S®TS6710 automatic TRM test system is referred to as TS6710
- The R&S®TSMW universal radio network analyzer is referred to as TSMW
- The R&S®ROMES4 Drive Test Software is referred to as ROMES
- The R&S®NRPxxS/SN three-path diode power sensor is referred to as NRP
- The R&S®ZVT8/20 Vector Network Analyzer is referred to as ZVT
- MATLAB® is a registered trademark of The Mathworks Inc.
1 Theoretical Background

1.1 What is an Active Phased Array Antenna?

The basic definition used in this document is that the active phased array antenna is an array of antenna elements designed to adapt and change the antenna radiation pattern in order to adjust to the radio frequency (RF) environment. These adaptations are realized by performing electrical beam tilting, beam width adjustments and possess the capability to direct beams toward particular users and tracking user movement. The active phased array antenna should also be able to steer nulls, reduce side-lobes and self-heal in case one of the elements in the array stops functioning.

The RF environment is polluted by noise, interference signal falling in the band of interest and multipath fading effect on the desired frequency. Antenna arrays by themselves are not smart. A combination of antenna array and digital signal processing (DSP) running algorithms make it possible for the antenna to transmit and receive signals, adapt, and hence perform smart beamforming measures.

![Figure 1-1: Block diagram of an Active Antenna Array](image-url)
Active Phased Array Antennas fall under two basic categories:

- Switched Beam Antennas
- Adaptive Antenna Arrays

### 1.1.1 Switched Beam Antenna

A switched beam antenna array is a system typically intended for a cellular base transceiver station (BTS), which has multiple predefined beam pattern designed to enhance the received signal power of the UE. The arrangement of antennas at a BTS are designed to have a triangular structure. Each side of the triangle covers a 120° sector with multiple beams in each sector. Depending on the exact location of the user, the relevant beam is switched on and handed over to another relevant predefined beam having better signal strength when the user changes location. One major drawback of this technique arises when the user is not at the center of the allocated main predefined beam, the signal quality drops. Likewise, if an interference signal falls close to the center of the main beam, it is unintentionally amplified more than the intended user signal.
1.1.2 Adaptive Array Antennas

Adaptive antenna array systems have the ability to adjust and adapt their radiation pattern(s) almost in real time based on the movement of each individual user terminal. In principle, beam steering is also useful in non-line-of-sight (NLOS) channels. Simultaneously, the interferers are rejected by performing a technique called side lobe nulling and thus making the interferers fall intentionally into a direction of weak receive gain. Fig. 1-4 shows the radiation pattern of an adaptive array antenna. UE in the figure stands for User Equipment.

Essential for every type of active phased array antenna are stable phase-coherent signals.
1.2 Signal Propagation

The signals radiated from any antenna have certain basic characteristics. The signals undergo multipath fading and delay spreading. Both of these effects play a significant role in reducing the capacity of a cellular network. The co-channel interference and increased usage of the number of available channels magnify the problem of reduced capacity even further.

**Fading:** Signals add up constructively or destructively because of the shifting nature of the phase of the multipath signals. This problem associated with multipath signal propagation is fast- or Rayleigh- fading. This is the creation of small fade zones in the coverage area.

**Phase cancellation:** This phenomenon occurs when multipath signals are 180° out of phase from each other. This also causes problem in maintaining a satisfactory signal level at the user terminal. Another problem with multipath propagation is the delay spread. This causes the inter-symbol interference and causes the bit error rate (BER) to increase over the maximum limit for maintaining a predefined quality.

**Interference:** A major problem with multipath signal propagation is the co-channel interference. This occurs when the user signal interfered by another signal of the same frequency.

**Solution:** Active phased array antenna system helps to ameliorate most of these problems since the technology depends on the direct propagation of signals between the BTS and the user terminal. Depending on the time of arrival, the active phased array antenna panel at the BTS can adapt. During signal processing stage at the UE, the algorithm can ignore the signals arriving later and process the signals that arrive first. The properties of beamforming and side-lobe nulling play a vital role in reducing the problems listed above.

1.3 Antenna Beamforming

Beamforming is a signal processing technique used to steer the direction of maximum radiation pattern of the array antenna for either signal transmission or signal reception. Digital signal processing (DSP) run multiple algorithms to collect data on the surrounding RF environment and take action to estimate the direction of arrival (DOA) of signals by measuring and calculating the appropriate weights to each array element in order to steer the beam/beams radiating to or from the array. Adaptive beamforming algorithms, which are not based on DOA, use reference signals or training sequences to estimate the weights applied to each array element. Weights are functions of magnitude and phase of each signal that is fed into each individual array element.
Defense radar antennas typically use completely different techniques for implementing beamforming. Military applications make use of phase shifters for each antenna element while cellular mobile radio BTS perform phase shift in the baseband and have individual digital to analog converters (DAC) for each antenna element.

Beamforming has been used for TD-LTE for quite some years. In a Time Division Duplex (TDD) access scheme, the implementation of Multiple Input Multiple Output (MIMO) beamforming is relatively easy as the uplink (UL) and downlink (DL) channel are the same and hence channel estimation derived from the received signal is fully applicable also to the transmit side.

Beamforming will be key aspect for the 802.11ad (60 GHz) standard. In such mm-Wave (mmW) systems, beamforming is not only used for directivity tracking of the incoming/outgoing signal, but also in order to establish the extremely narrow patterns and hence high antenna gains needed to overcome the path attenuation met in mmW bands.

An important prerequisite for every beamforming architecture is a phase coherent signal generation. Beamforming is only possible if the relative phase of all source signals is constant and can be set to a defined or arbitrary value.

Usually two variables are used for beamforming: Amplitude and phase. The combination of these two factors is used to improve side lobe suppression or steering nulls. Phase and amplitude for each antenna element are combined in a complex weight $w_n$. The complex weight is then applied to the signal that is fed to the corresponding antenna (3).

### 1.3.1 Analog Beamforming

Fig. 1-5 shows a basic implementation of an analog beamforming transmitter architecture. This architecture consists of only one RF chain and multiple phase shifters that feed an antenna array.
Theoretical Background

1MA248

Rohde & Schwarz Characterizing Active Phased Array Antennas

Fig. 1-5: Analog Beamforming Architecture

This architecture is used today in high-end millimeter-wave systems as diverse as radar and short-range communication systems like IEEE 802.11ad. Analog beamforming architectures are not as expensive and complex as the other approaches described in this paper. On the other hand implementing a multi-stream transmission with analog beamforming is a highly complex and not a straight-forward task (4).

Performance of this architecture can be improved by additionally changing the magnitude of the signals. A variable gain amplifier can both compensate the insertion loss due to phase shifting and scale the magnitude of the signal. The use of delay lines instead of phase shifters mitigates frequency dependent effects.

In order to calculate the phase relations, a uniformly spaced linear array with element spacing $d$ is assumed. Referring to the receive scenario shown in Fig. 1-6, the antenna array must be in the far field of the incoming signal so that the arriving wavefront is approximately planar. If the signal arrives at an angle $\theta$ off the antenna boresight, the wave must travel an additional distance $d \cdot \sin \theta$ to arrive at each successive element as illustrated in Fig. 1-6. This translates to an element specific delay which can be converted to a frequency dependent phase shift of the signal (5):

$$\Delta \phi = \frac{2 \pi d \sin \theta}{\lambda}$$

(1)

Fig. 1-6: Additional Travel Distance when Signal arrives off boresight
1.3.2 Digital Beamforming

While analog beamforming is generally restricted to one RF chain even when using a large-number antenna array, digital beamforming in theory support as many RF chains as there are antenna elements. If suitable precoding is done in the digital baseband, this yields higher flexibility regarding the transmission / reception. This additional degree of freedom can be leveraged to perform advanced techniques like multi-beam MIMO. These advantages result in the highest theoretical performance possible compared to other beamforming architectures (6).

Fig. 1-7 illustrates the general digital beamforming transmitter architecture with multiple RF chains.

![Digital Beamforming Architecture](image)

Nonetheless, digital beamforming may not always be ideally suited for practical implementations regarding 5G applications. The very high complexity and requirements regarding the hardware may significantly increase cost, energy consumption and complicate integration in mobile devices. Digital beamforming is perhaps more attractive for use in base stations, since performance outweighs mobility in this case.

1.3.3 Hybrid Beamforming

Hybrid beamforming has been proposed as a possible solution that is able to combine the advantages of both analog and digital beamforming architectures. First results from implementations featuring this architecture have been presented in prototype level, i.e. in (7).

A significant cost reduction can be achieved by reducing the number of complete RF chains. This does also lead to lower overall power consumption. Since the number of
converters is significantly lower than the number of antennas, there are less degrees of freedom for digital baseband processing. Thus, the number of simultaneously supported streams is reduced compared to full-blown digital beamforming. The resulting performance gap is expected to be considerably low due to the specific channel characteristics in millimeter-wave bands (4).

1.4 Phase-Coherent Signal

Phase coherence of two RF signals means that there is a defined and stable phase relationship between two (or more) RF carriers, i.e. there is a fixed delta phase between the carriers. Phase coherence is only defined for carriers derived from the same source.

If two signal generators are coupled via a common 10 MHz (or 100 MHz) reference, they generate exactly the same output frequency but only judged from a more long-term perspective. A closer inspection of the instantaneous differential phase (“delta phase”) of these two RF signals, shows instability due to:

- phase noise of the two synthesizers
- “weak” coupling at 10 MHz and a long synthesis chain up to the RF output
- temperature differences which cause a change in the effective electrical length of some synthesizer components

Most critical for a stable delta phase is the thermal RF phase drift between multiple RF synthesizers. Temperature differences leading to thermal expansion of conducting paths or cables change the electrical length of the signal path. In a conventional PTFE loaded coaxial cable, a signal with a frequency of 6 GHz, the wavelength $\lambda$ is 3.3 cm. An additional length of 1 mm results in a phase shift of about $11^\circ$ if calculated for coaxial cables where the velocity of propagation is approximately two-thirds that of free space. Consequently, the wavelength will be approximately two-thirds of that in free space and the electrical length approximately 1.5 times the physical length (8).
Copper has a coefficient of thermal expansion of 16.4 × 10^{-6} K^{-1}. Using a copper cable of 1 m and changing the temperature by 10 K will lead to a change in mechanical length of 164 μm, which means approx. 2° phase drift (8).

This drift can be reduced to 0.1° by use of a common synthesizer, i.e. a common local oscillator (=LO) signal, for all RF carriers. Only when this LO signal (which is internally used for up converting the baseband signal to the RF) is common to all carriers, can a stable phase between the RF signals be achieved.

A detailed description of phase coherence and phase coherent signal generation is provided in AN 1GP108 (9).
1.5 Active Phased Array Antenna Measurement Algorithm Test-Bed

The measurement modes for characterization are described below:

1.5.1 Vertical Sectorization

The process of vertical sectorization brings about a capacitive boost in a cellular network. The base station using AAS (Active Antenna System) can adjust the beam pattern, introducing two sectors inside the existing larger cell sector. This is implemented by adjusting the down tilt of the beam electronically at the AAS. In addition to the conventional horizontal sectoring, having two beams with different tilt angle within each horizontal sector, increase the network performance.

1.5.2 Antenna / RF Testing System

For the characterization of conventional or passive antenna, the antenna under test (AUT) is assumed reciprocal. However, the same rules do not apply for the characterization of active phased array antennas. This is because an active antenna module has Transmitter / Receiver (T/R) module installed with each individual element in the active phased antenna array as shown in Fig. 1-1. An active phased array antenna can be operated in both transmit mode as well as in the receive mode. Fig. 1-2 shows a simplified T/R-module block diagram. When the antenna is in receive mode, the signal has to flow through a low noise amplifier (LNA) and when the antenna is in the transmit mode, the signal has to travel through the high power amplifier (HPA).

Because of the non-reciprocal nature of the active phased array antenna, the characterization process involves stepping out of the conventional antenna testing methodology and instead testing both receive and transmit operation of the AUT. However, over-the-air (OTA) testing of antennas is still relevant for active phased array antenna characterization.
The tests that are of interest are:

- Directivity
- Boresight direction
- Peak sidelobe level distribution
- RMS sidelobe level
- Spurious signal radiation
- Half power beamwidth
- 3D radiation pattern

It is also important to test functionality of the power amplifiers in the T/R-module.

When the active phased array antenna is in transmit mode, the behavior of the high power amplifier is characterized by testing the T/R-module for the following parameters:

- Effective Radiated Power (ERP)
- Transmitted pulse shape

When the active phased array antenna is in receive mode, behavior of the low noise amplifier is characterized by testing the T/R-module for the following parameters:

- Antenna noise figure
- Input saturation level
- 1-dB compression level (at antenna output)
- Third-order intermodulation distortion

In production, each antenna element needs characterization before integrating the complete active phased array antenna.
2 Active Phased Array Antenna Measurement

2.1 Transmit Mode Testing for Array Antennas

2.1.1 Transmit Signal Quality Measurement

Fig. 2-1: Test setup for Active Phased Array Antenna measurement in TX mode using FSW and TSMW
Fig. 2-1 shows the proposed test setup for characterizing Smart Active antenna arrays. A Receive (RX) antenna is connected to a FSW spectrum analyzer or a TSMW Drive Test Scanner, depending on the test parameter.

Active phased array antenna algorithm testing, beamforming algorithm testing, modulated signal analysis (User defined digital modulated signal, GSM, CDMA2000®, WCDMA, LTE and TETRA systems) and electric field pattern measurement can be performed using the FSW.

Single beam measurement applications for algorithm testing are maximum radiation testing, side lobe reduction testing, side lobe reduction testing with null filling, RF fair beam, Nulling beam, self-healing measurement. For all these measurements, the FSW is connected to the Rx antenna. The measurements are carried out in the spectrum analyzer mode.

In measurements where the CW signal is replaced with a modulated signal, FSW-K70 is the general-purpose vector signal analyzer (VSA) for single carrier modulation. The features that the FSW-K70 offers are:

- User defined modulation formats
- Equalizer
- Support of 2-ASK and 4-ASK, 16QAM up to 4096QAM
- Support of the FSW user interface, sequencer and MSRA (Multi Standard Radio Analyzer)
- EVM and BER measurements

IEEE 802.11 a/b/g/p/n/ac measurements

- The FSW-K91x application firmware covers standard-related tests as well as further evaluations for in-depth analysis in development for signals in line with the WLAN IEEE 802.11 a/b/g/p/n/ac standard.

EUTRA/LTE and LTE- Advanced Signal Analysis Measurements

- The FS-K10xPC software is used for transmitter measurements on 3GPP long-term evolution (LTE) and LTE-Advanced base stations and user equipment. Analysis of MIMO transmitters provides detailed insight into the performance of the complete system.

OFDM Vector Signal Analysis Measurements

- The FS-K96 OFDM analysis software extends the capability of the FSW signal and spectrum analyzers and the FSUP signal source analyzer to include modulation measurements on general OFDM signals. The OFDM demodulator is user-configurable and standard-independent.
In this section, two measurement examples are shown (e.g. four TX non-coherent carriers versus three TX coherent carriers). A 4-element passive antenna array is used to transmit LTE signal for this measurement purpose.

**Transmit signal settings**

- Set transmit signal frequency at 2.38 GHz

**Signal receive and analysis Settings on the FSW**

- On the FSW hard keys, press **FREQ**
  - **Center** = 2.38 GHz, **Span** = 10 MHz
- On the FSW hard keys, Press **BW** and set **Resolution Bandwidth** at 100 KHz
- On the FSW hard keys, press **Mode** and then select **LTE**
- Perform **signal description settings as shown below**

![Screen capture of FSW settings](image)

- Point the receive antenna in the direction of the transmit antenna beam, the FSW will automatically sync with the transmit LTE signal

**Fig. 2-2** shows the LTE measurement results on the FSW using four element passive array antenna transmitting (Tx) non-phase coherence signals in a certain direction. On the receive side only one receive antenna is pointing in the direction of transmitting antenna maximum boresight. The FSW synchronizes automatically with the Tx signal with an Error Vector Magnitude (EVM) of 3.73%. At this point, perform the phase coherence calibration. **Fig. 2-3** shows the measured value of the LTE signal for the same setup as before. The EVM performance improves to 1.67% with only using three elements.
Fig. 2-2: Measurement results on the FSW using 4-element Tx antenna without phase coherence and one receive antenna

Fig. 2-3: Measurement results on the FSW using 3-element Tx antenna with phase coherence and one receive antenna
The **TSMW** is a broadband Drive Test Scanner. It is capable of handling any band in the range of 30MHz to 6 GHz and thus detects all LTE signals.

In addition to LTE, the R&S®TSMW will also perform GSM, WCDMA, CDMA2000 1x EVDO and mobile WiMAX measurements in parallel. The TSMW offers two separate RF paths with adaptive pre-selection to cover the frequency range with highest signal quality and lowest possible intermodulation. With 20 MHz bandwidth in each path, the R&S®TSMW allows maximum flexibility in respect of upcoming communication standards and resource distribution. Up to two technologies may be measured simultaneously without sharing the same scanner resources. This provides outstanding measurement performance.

The TSMW Universal Radio Network Analyzer is designed to measure all kind of digital signals via real-time IQ streaming in a mobile or lab environment. The option TSMW-Gigabit LAN I/Q Interface uses MATLAB or C++ as an industry standard tool, so detailed analysis of the captured signals is possible.

- From *Hardware Configuration* in the ROMES software, select **TSMW LTE**

![Hardware Configuration](image)

- Fig. 2-4 shows a sample measurement using the TSMW and ROMES software

![Sample Measurement](image)

**Fig. 2-4**: LTE signal measurement using the ROMES in combination of the TSMW
2.1.2 Automated Antenna Radiation Pattern Measurement vs Frequency

In this section, a convenient measurement setup and a MATLAB-based software is introduced. The example MATLAB sequence offered for download can perform the generator setting for electronic beamforming and electronic beam steering. Using this software, it is possible to perform 2D antenna radiation pattern measurements. The automated configuration and measurement routine in parallel to an easy-to-use GUI interface help to obtain quick and accurate test results.

The measurement setup consists of signal generators, receiving (Rx) antenna and transmitting (Tx) antenna, a power meter and a turntable. In this setup, the Tx antenna is always used as the Device Under Test (DUT). In the case where a high measurement dynamic range is required, the power meter can be replaced with a spectrum analyzer. The setup requirements are as flexible as possible in order to ensure compatibility with a wide range of Rohde & Schwarz equipment. After conducting a measurement, the user is presented the results for evaluation.

The SW includes the following features:

- automated signal phase coherence calibration (up to 4 channels)
- antenna boresight calibration (up to 4 elements)
- signal generator configuration
- 2D azimuth antenna radiation pattern measurement
- beamforming and beam steering
- importing and exporting measurement data
- measurement data correlation

Software can be downloaded from http://www.rohde-schwarz.com/appnote/1MA248

2.1.2.1 Prerequisites

In order to perform a measurement, several prerequisites have to be met:

- A supported ARDUINO based DIY turntable device is mandatory
- The software supports T&M instruments only from Rohde & Schwarz
- Minimum configuration of instruments for at least one of the possible setups listed in 2.1.2.2.

Fig. 2-5 shows the proposed setup that can be used for a measurement consisting of two SMW signal generators and a FSW signal analyzer.
The software is supplied in an installation package. The installation wizard automatically installs the necessary free MATLAB Runtime if it is not already present on the host computer.

Fig. 2-5: Test setup for 2D radiation Pattern measurement. On the measurement side, a spectrum analyzer may also be used if an increased dynamic range is required.

### 2.1.2.2 Measurement Configuration and Setup

It is possible to choose from a range of setups. Each row in Table 2-1 can be combined with all rows of the other columns. Thus for every device one of the presented choices can be arbitrarily selected.

<table>
<thead>
<tr>
<th>Choice 1</th>
<th>Choice 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal Generator</strong></td>
<td>2 x SMW$^1$</td>
</tr>
<tr>
<td><strong>Rec. Pow. Meas.</strong></td>
<td>1 x FSW / FSV / NRP / FSVA</td>
</tr>
<tr>
<td><strong>Calibration</strong></td>
<td>0° Phase Coherent with RTO$^2$ / Boresight</td>
</tr>
<tr>
<td><strong>Transmit Antenna (DUT)</strong></td>
<td>Patch-Antenna / Passive Antenna$^3$</td>
</tr>
<tr>
<td><strong>Receive Antenna</strong></td>
<td>Horn Antenna</td>
</tr>
</tbody>
</table>

Table 2-1: A simple list of possible setups.

---

$^1$ Each R&S®SMW has to be equipped with two RF outputs.

$^2$ 4 channel variant required.

$^3$ 4 signal inputs required.

$^4$ 4 signal inputs required.
However, the setup and the corresponding required T&M equipment is dependent on the operating frequency and number of elements on the DUT. Ensure that all the instruments are capable of operating in the selected frequency range.

In order for the remote operation to work properly, the devices have to be connected in a specific predefined order described in the following chapters.

**Phase Coherence Calibration Setup**

A master / reference generator provides the reference and the LO signal to all other signal generators in the measurement setup. The first SMW that is connected takes over this task. The RF output A of this reference SMW is considered as signal no. 1 and output B as signal no. 2. The RF path A and path B of the second SMW is considered as signal no. 3 and 4 respectively. Fig. 2-6 shows the test setup using two SMWs connected to the RTO for performing phase coherence calibration. The highest possible frequency of the RTO determines the maximum frequency up to which this calibration can be performed.

![Fig. 2-6: Measurement setup of two SMWs connected to the RTO for phase coherence calibration](image)

Another possibility to generate four RF signals up to 4 GHz is to use one SMW and two SGT. Fig. 2-7 shows the test setup. The reference / LO signal comes from the SMW and is forwarded to the other two signal sources (SGT / SGS / SGS+SGU).

![Fig. 2-7: Connection of one SMW and two SGx with phase coherent calibration](image)

**Boresight Calibration Setup**

In case of boresight calibration, no RTO is required. The instrument order and signal labeling is the same as for the phase coherent calibration setup. Fig. 2-8 and Fig. 2-9 show two possible setups of the signal generators and the array antenna. A complete
representation of the setup including the receiving side is shown in Fig. 2-11.

This SW offers two different calibration methods that may be selected in the window shown in Fig. 2-12:

1. **First Method: 0° Phase Coherence Calibration**

   Using an RTO oscilloscope, the four signal sources are set to produce phase coherent signals with 0° phase shift with regard to signal no. 1. Please ensure that the signal sources are connected to the corresponding oscilloscope channels. The correct way to configure the signal sources is shown in Fig. 2-10. The highest possible frequency of the RTO determines the maximum frequency up to which this calibration can be performed. In this case, up to 4 GHz.

   A visual inspection is possible on the RTO after the calibration is done. After the calibration is finished, connect the antenna ports to the signal sources.

---

**Fig. 2-8: Connection of two SMWs while performing the measurement**

**Fig. 2-9: Connection of one SMW and two SGx while performing the measurement**

**Fig. 2-10: Order of Instruments using 0° Phase Coherence Calibration**


1. **Second Method: Boresight Calibration**

   The boresight calibration aims to maximize the received signal level when the antennas directly face each other. When the calibration is performed, the optimum phase for every channel is determined. No additional instrument is necessary.

   **In order for this calibration to work properly, transmit and receive antenna must directly face each other.** If this is not the case, you can adjust the transmit antenna azimuth using the controls in the main window shown in Fig. 2-16.

   - The receiving horn antenna is connected to the power sensor or to a spectrum analyzer. The calibration setup is shown in Fig. 2-11.

   ![Fig. 2-11: Complete Setup using Boresight Calibration](image)

   **2.1.2.3 Performing a measurement**

   During a typical measurement, the GUI guides you through the following steps

   1. Selecting a setup and connecting the instruments
   2. Configuration and calibration
   3. Measurement
   4. Results
   5. These steps will be explained in the following chapters.

   **Selecting a Setup and Connecting the Instruments**

   After installing the software, start the program.

   - From the window shown in Fig. 2-12, choose the relevant signal source configuration and the relevant power measurement instrument from the drop down menu.
Next select one of the two calibration methods i.e. phase coherence or boresight.

Next click on Connect Instrument.

- This opens a new window shown in Fig. 2-13. Insert the IP address of all the instruments to be used for this measurement. The IP of the SMW that is listed first will be set as the master instrument providing the reference signals.

Press the OK button, the connection with the instruments will be established.

In order to obtain correct results during calibration and measurement, it is important that the order given in the dialog is strictly followed. The prompt in Fig. 2-13 corresponds to the setup shown in Fig. 2-9. The first IP belongs to the SMW, the second entered IP should be the SGS whose output is labeled 3 while the third IP refers to the SGS labeled 4 in Fig. 2-9.
Configuration and Calibration

The main window is displayed after all instruments are connected. In order to perform measurements, all the equipment needs to be calibrated.

1. Click the button *Setup Instruments*. It opens a new window shown in Fig. 2-14.

![Fig. 2-14: Calibration Setup](image)

Turntable Configuration

The MATLAB program works only in conjunction with a DIY ARDUINO based turntable device. The ARDUINO board has to be connected via a USB cable to the host computer.

1. Click on *Configure Turntable* to connect to the turntable device. A new window shown Fig. 2-15 in will open.

![Fig. 2-15: Turntable Setup](image)
COM Port allows selecting one of all currently available serial ports. Please control if any other application is currently occupying the interface if the port where the ARDUINO board is attached is not shown.

Baud Rate sets the baud rate for the communication. Beware that 9600 bd is hardcoded in the ARDUINO software. Any changes to this setting may require the software to be changed.

Delay between Steps is used to set a minimum time interval between the single motor steps. Steps may be skipped resulting in an unknown position if the interval is too short.

Step Angle can be used to allow for different turntable constructions resulting in a varying step angle.

By clicking on Connect, the tool tries to establish a connection to the ARDUINO board at the chosen COM port.

After a connection is established if any settings are changed the board must first be disconnected and then connected again for the changes to take effect.

Instrument Configuration and Calibration

- Next in the window shown in Fig. 2-14
  - Enter the desired frequency and signal level for the calibration.
  - Next click on Configure and Calibrate Instruments to start the calibration.

If no calibration is selected, then this step is used to simply configure the instruments.
**Measurement**

After the setup has been calibrated, a measurement can be started. The main window shown in Fig. 2-16 allows setting all relevant parameters. The controls are explained below:

1. The Start Angle and Stop Angle values can be set from -180° to 180°, e.g. -60° for start and 60° for stop angle.

2. **Beam Direction** defines the angle where the beam will be steered to. The best results are obtained with angles ranging from -20° to 20°. All necessary parameters are automatically calculated using formula (1). The results are applied to the signal sources.

   \[ \theta = \arcsin \left( \frac{\lambda}{2w \cdot d} + \Delta \varphi \right) \]  
   
   Where \( \theta \) is the steered beam angle / rad
   \( \lambda \) is the wavelength / m
   \( d \) is the element spacing
   \( \Delta \varphi \) is the phase delta that has to be added to each antenna patches multiplied by its number (e.g. 0 \( \cdot \Delta \varphi \), 1 \( \cdot \Delta \varphi \), …)

3. **Elem. Spacing** is the distance between the equidistant antenna patches. Values can be entered in m, mm or inch.

4. These controls allow to set a user defined 0° value to the rotary device with the transmit antenna attached.

![Fig. 2-16: The Main Window](image)

- Clicking on the **Measure** button starts the measurement.

---

5 See (5), page 56.
A live plot in the top left corner displays the results. Generally, a 360° measurement swipe takes around 10-11 mins.

Fig. 2-17 shows an example measurement from -60° to 60° with 0 dBm output level. The main lobe was centered at 0°. A boresight calibration was performed for this example. The DUT in this case is a 4-element passive array antenna with 68 mm equal spacing between elements.

![Measurement Example](image)

**Fig. 2-17: Measurement Example**

**Results**

At the end of a measurement, the GUI becomes responsive again. The results can be exported or compared to other measurements by importing multiple traces. A cross correlation function between two steered beam plots allows the verification of the results.
Export

To export Measurement data to current directory, click the button Export Data. The name is automatically composed by the following pattern:

'Meas_yyyy_mm_dd_hh_mm_frequency_GHz_level_dBm_angle_Deg_calibration.mat'

Where

- frequency = measurement frequency in GHz
- level = source level in dBm
- angle = angle of the steered pattern in degree and 
- calibration = calibration method used (Boresight / Oscilloscope).

The trace data with n points is saved in a 2 x n matrix. The first row contains the level measurement results in dBm while the second row stores the angle in rad.

Import

All exported data can be re-imported later. Only the file format described in section, Export, is supported. A maximum of seven traces can be imported at a time.

After the traces have been imported, the legend is displayed below the plot area.

Fig. 2-18 shows the import of two traces. Trace one (blue) is not steered while trace two (red) is steered at -10°.

Fig. 2-18: Import of multiple traces
Cross Correlation

A cross correlation between two measurements can be performed. The step angle used during the measurements is automatically calculated. If the two step angles differ by more than 5 % the calculation is aborted.

The result shows the actual phase shift and a comparison of the two traces. Fig. 2-19 shows a cross correlation between a signal with 0° and one with -10° phase shift. When the results are evaluated, the resolution of the turntable should be kept in mind.

![Cross Correlation Results](image)

Fig. 2-19: Cross Correlation two signals
2.2 Receive Mode Testing for Array Antenna

Performing receive power level measurement for each element in an active phased array antenna in receive mode is of key importance for characterizing. Active phased array antennas. The multi-port ZNBT is a powerful and cost-effective equipment for performing antenna characterization measurements.

Alternatively, the **ZVA** is considered for measurement of the frequencies up to 67 GHz. A 4-port ZVA is used to measure the received power level of up to eight individual element of an array antenna. Fig. 2-20 shows test setup for performing over the air (OTA) measurement an antenna array in receive mode.

![Test setup for characterizing array antenna in receive mode](image)

**Fig. 2-20: Measurement setup for characterizing array antenna in receive mode**

To perform the receive power level measurements, the **REF** and **MEAS** ports of ZVA need to be calibrated at first. The receive antenna (antenna under test) is a 4-element array antenna. On the TX side, the HF907 (horn antenna) is transmitting a CW signal generated from the SMW.

**Calibrating the ZVA**

- **Source power calibration using power sensor NRP-Z55**
  - Preset the ZVA
  - Connect NRP-Z55 via USB to the ZVA
  - Connect NRP-Z55 directly to Port 3 of the ZVA
  - Select Channel > Stimulus > Center = 2.38 GHz, Span = 2 MHz
  - Select Channel > Power Bandwidth Average > Meas Bandwidth = 1 KHz
Select Channel > Mode > Port Config and click Freq Conv Off and OK

Channel > Calibration > Start Power Cal > Source Power Cal > Modify Settings

Press Ok and Take Cal Sweep
Disconnect power sensor from the ZVA and connect the source from Port 3 to Ref IN of Port 1 (Test ports are the cable endings referred to as calibration plane in Fig. 2-20)

- Trace > Measure > Wave Quantity > More Wave Quantity
  - **Ref IN** for Port 1 is a1, Port 2 is a2, Port 3 is a3 and Port 4 is a4
  - **Meas IN** for Port 1 is b1, Port 2 is b2, Port 3 is b3 and Port 4 is b4

Select Trace > Scale > scale/Div = 1dB , Ref Value = -10 dBm

Channel > Calibration > Start Power Cal > Receiver Power Cal

Parameter setting: a1 on Take Cal Sweep

After sweep is completed, Click close to save calibration of a1(P3)

Perform the same steps for all other REF and MEAS IN ports
2.2.1 Amplitude measurement for antenna arrays up to 8 elements

After performing the Calibration Process, perform the instrumental setup as shown in Fig. 2-20. Over-The-Air (OTA) received power measurements can now be performed.

In this example, only 4-element array is used. However, the measurement can be performed for up to eight elements using a four port ZVA.

For every trace i.e. $a_1, b_1, a_2, b_2, a_3, b_3, a_4, b_4$

- Trace > Format > dB Mag
- Select Channel > Stimulus > Center = 2.38 GHz, Span = 2 MHz
- Select Trace > Scale > Autoscale All
- Channel > Power Bandwidth Average > RF Off (All Chans)
- **Signal Generator** > Freq = 2.38 GHz, Power = 0 dBm, CW signal

![Graph](image-url)

Fig. 2-21: Parallel measurement for received power on a 4-element array antenna using the ZVA
2.2.2 Phase measurement for antenna arrays up to 8 elements

After performing the Calibration Process, perform the instrumental setup as shown in Fig. 2-20. Received phase difference measurement between the elements can be performed now, e.g. in order to characterize the Direction of Arrival (DoA).

In this example, only 3-element array is used. However, the measurement can be performed for up to eight elements using a four port ZVA

For every trace i.e. a1, b1, a2, b2, a3, b3, a4, b4

- Trace > Format > Phase
- Select Channel > Stimulus > Center = 2.4 GHz, Span = 1 Hz
- Select Trace > Scale > Autoscale All
- Channel > Sweep > Trigger > Periodic > 2 sec
- Channel > Power Bandwidth Average > RF Off (All Chans)
- Signal Generator > Freq = 2.4 GHz, Power =0 dBm, CW signal

![Fig. 2-22: Phase difference at boresight on a 3-element array antenna using the ZVA](image)

![Fig. 2-23: Phase difference between elements on a 3-element array antenna using the ZVA](image)
2.3 Transmit-Receive-Module Testing

There are two different approaches to characterize Transmit-Receive-Module especially for Active Phased Array Antennas, manual characterization or automated characterization. Each of the two approaches offers a different set of tradeoffs in terms of test time versus test flexibility.

In the research and development phase, the manual characterization offers greater test flexibility but at the cost of greater testing time.

For the manufacturing phase, faster characterizations are possible using an automated T/R-Module Test System. The following sub sections 2.3.1 and 2.3.2 introduce the possibility of T/R-module characterization for both manual and automated approaches, using Rohde & Schwarz equipment and test system.

In the example described in the following sections, the T/R-modules are tested using pulsed signals. This characterization technology is more commonly used in radar applications.

2.3.1 Manual T/R-Module Testing in Pulsed Mode

![Diagram of ZVA67 and ZVAX-TRM67](image)

Fig. 2-24: Combination of a ZVA67 and ZVAX-TRM67 to characterize T/R-modules
Complex active devices for radar or communication systems, such as transmit-receive modules or complete frontends, require comprehensive measurements during design and production. Large amounts of data are generated but only such extensive evaluation with various test parameters ensures compliance with specifications and the reliability of the entire system. Ideally, all measurements are performed with a single connection of the DUT.

The combination of a ZVA and ZVAX-TRMxx is a compact, configurable setup for pulsed measurement of active devices for a full specification with a single connection. At the same time, it is an open platform allowing inclusion of further instruments, like spectrum analyzer or power meter, or auxiliary components such as boost-amplifiers or attenuators. Without reconnection, parameters like compression, intermodulation, noise figure, embedded LO group delay, or pulse distortion can be evaluated even on a 3-port T/R-module (with antenna and RX, TX ports).

A special advantage arises when a ZVA 4-port with four sources is used. The test setup for T/R-module requiring several tones, e.g. 2-tone intermodulation test stimulus and two LO signals is shown in Fig. 2-24. For requirement, a test setup based on ZVA with four sources is a unique, flexible and compact solution, because external signal generators are not required. RF1/RF2, LO1, LO2 are provided by the VNA, and the internal sources can be configured to all operation modes of the ZVA, e.g. power sweeps.

The capability of bi-directional pulsed and intermodulation measurements allow investigating both, the RX and TX path without re-connection.

Fig. 2-25: ZVT20 Vector Network Analyzer with six port from 300 KHz up to 20 GHz
With a ZVT8/20 as show in Fig. 2-25, the signals of four ports can be routed through the ZVAX-TRM; the remaining ports can still be used for further analysis. This way, systems with up to 6/8 ports and 3/4 sources can be built, as shown in Fig. 2-26.

**Fig. 2-26: Parallel test configuration for three T/R-Modules**

For active phased array antenna arrays with relatively low T/R module count, the described way of characterization is the most cost-effective. However, testing time per T/R-module during the development phase proves prohibitive in the production phase.

To address manufacturing time for DUTs with high number T/R-modules, it is therefore important to re-address the testing procedure as in 2.3.2.
2.3.2 Automated T/R-Module Testing in Pulsed Mode

Rohde & Schwarz offers the **TS6710 Automatic TRM Test System**. The main system components are ZVaxx vector network analyzer, CompactTSVP and OSP-TRM for RF signal conditioning and DUT multiplexing (Fig. 2-27). The standard frequency range is 1 GHz to 24 GHz. Other frequency ranges can be offered on request.

Main characteristics of the TS6710 are:

- Production: test time can be decreased to about 8 sec per module.
- Full characterization: test time can be decreased to about 4 min per module.
- Multiplexing of up to 12 DUTs.
- Max. T/R-module output power: 50W CW or 100W at 35% duty cycle, max pulse width 2.5ms.
- Harmonic filter.
- Max. T/R-module input power: 15dBm at < 8GHz, 10dBm at < 18 GHz, -10dBm at < 24GHz.
- Digital T/R-module control with programmable voltage levels.
- Automatic system calibration with algorithm for minimizing operator interactions.

Fig. 2-27: TS6710 TRM Test System with extension for multiplexing of up to 12 T/R-Modules

The TS6710 includes ready-made test cases for common T/R-module tests. These preconfigured tests are designed for high measurement speed and accuracy.
- **RX mode**: S-parameters for attenuation and phase combinations, noise figure, intermodulation, compression point, harmonics, out of band rejection, phase shifter switching time, spurious emissions.

- **TX mode**: S-parameters for attenuation and phase combinations, output power, intermodulation, compression point, harmonics, phase shifter switching time, Pout versus Pin, power added efficiency, pulse profile, spurious emissions.

Optimum test performance is achieved by specifically adapting the test cases based on the supplied source code, either by Rohde & Schwarz or by the customer. Since the customer can adapt test details, it is easy for the user to protect their intellectual property rights. Thus making the test system efficient and flexible.
3 References

(1) "Smart Antenna Systems for Mobile Communications", Ivica Stevanović, Anja Skrivervik and Juan R. Mosig, Ecole Polytechnique Fédérale de Lausanne

(2) "Toward a generalized methodology for smart antenna measurements", A. Alexandridis, F. Lazaraki, T. Zervos, K. Dangakis, M. Sierra Castaner

(3) "1GP106: Multi-Channel Signal Generation Applications with SMW200A", Application Note, Rohde & Schwarz


(8) "1GP67: Phase Adjustment of Two MIMO Signal Sources with Option B90 (Phase Coherence) ", Application Note, Rohde and Schwarz

(9) "1GP108: Generating Multiple Phase Coherent Signal- Aligned in Phase and Time", Application Note, Rohde & Schwarz
## 4 Ordering Information

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*peripheral equipment offered at additional charge for Rohde & Schwarz test systems*
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### Ordering Information

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<td>ROMES4T1W</td>
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Other configurations of vector network analyzer ZVA, signal analyzer FSW, digital oscilloscope RTO, vector signal generators SMW, SGU, SGS, SGT, and Power Sensors / Power Meters in the NRP series are suitable as well. A few possible instrument configurations for this application are shown in the table. Please ask your local representative for a suitable configuration according to your specific needs.
About Rohde & Schwarz

The Rohde & Schwarz electronics group is a leading supplier of solutions in the fields of test and measurement, broadcasting, secure communications, and radiomonitoring and radiolocation. Founded more than 80 years ago, this independent global company has an extensive sales network and is present in more than 70 countries. The company is headquartered in Munich, Germany.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 | +86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

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