Application Note

CHARACTERIZING PHASED ARRAY ANTENNAS

Products:

- R&S®FSW
- R&S®SMW
- R&S®SGS
- R&S®SGT
- R&S®SGU
- R&S®RTO
- R&S®TS6710
- R&S®NRPxxS/SN
- R&S®ZVA
- R&S®ZVAX-TRM
- R&S®ZNBT

M.Naseef, G.Lloyd, M.Reil | 1MA248 | Version 3e | 11.2021

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Contents

1 Overview

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.

The application note is directed towards Mobile Communication and RADAR industry and aims to explain test procedures and give recommendations toward characterization of the relevant parameters for active phased array antennas and their passive subsystem. This document describes transmit mode signal quality testing and introduces a new automated test methodology for 2D antenna radiation pattern measurement.

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

2 Abstract

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 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.

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**

3 Theoretical Background

3.1 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. Theses 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. Every active array comes equipped with a passive radiating element connected to each T/R module in the RF subsystem as shown in Figure 1.

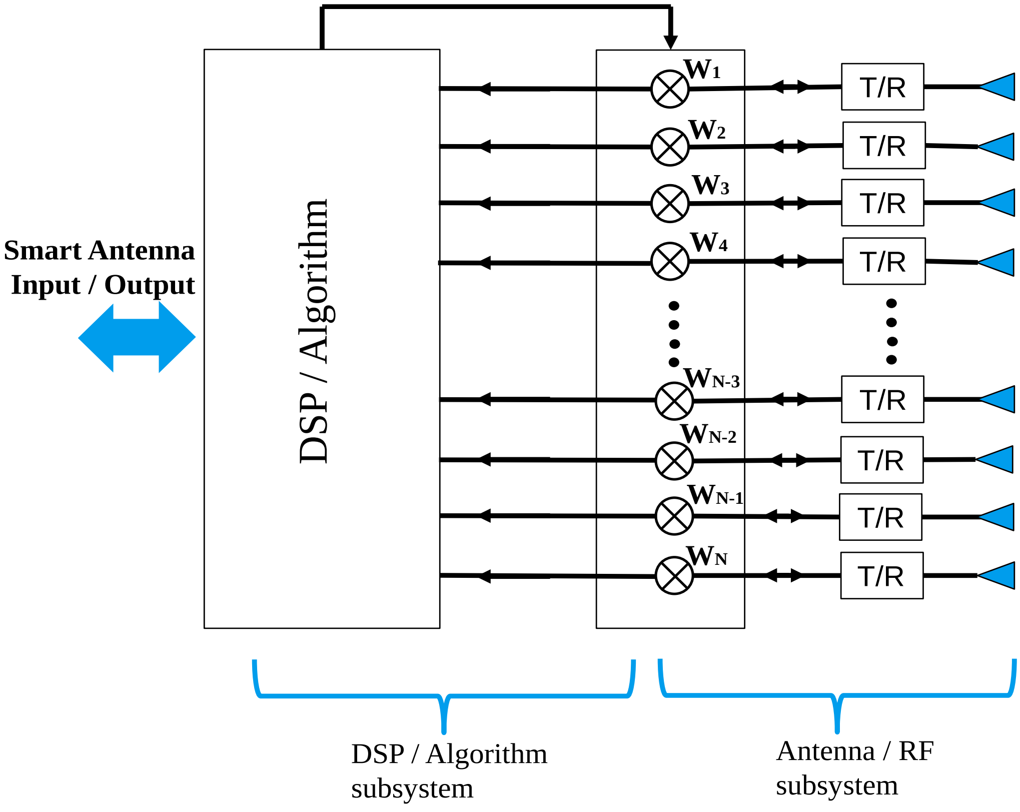


Figure 1: Block diagram of an Active Antenna Array [2]

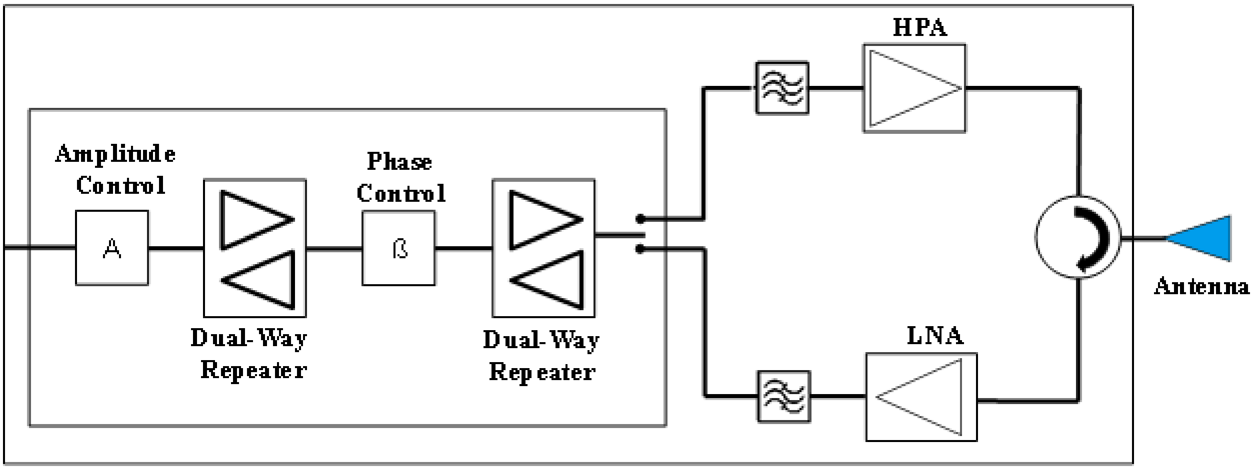


Figure 2: Simplified block diagram of a T/R-module for an Active Phased Array Antenna in Rx mode [3]

Each of these passive radiated elements need to be is fed with different antenna feeding weights. The weight is a function of amplitude and/or phase. Each of these weights are varied depending on the specific relationship with all other elements, which are configured in rows and columns, in order achieve the desired beam manipulation.

A look up table of consisting of different antenna weights and the corresponding beam manipulation (beam forming and beam steering) can be calculated or measured for each individual antenna array. The look up table is also known in the industry as a codebook. In order to instantly adapt the radiated beam, the smart antenna then uses the codebook. The application note 1MA278 describes how to measure the codebook of any passive antenna array using transmit mode measurement setup.

Active Phased Array Antennas fall under two basic categories:

- Switched Beam Antennas
- Adaptive Antenna Arrays

3.1.1 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.

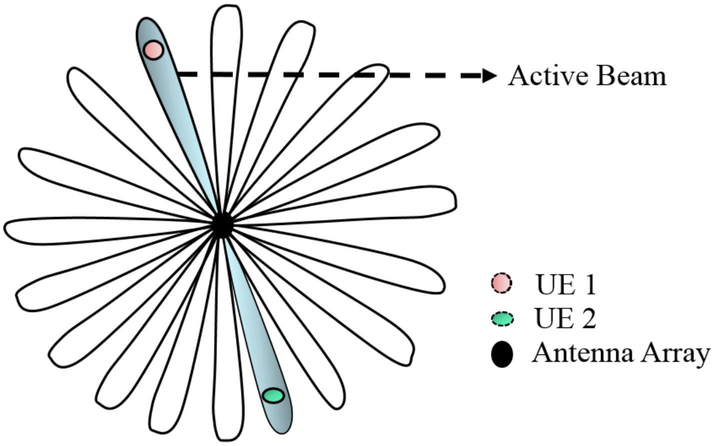


Figure 3: Switched beam antenna radiation pattern

3.1.2 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. Figure 4 shows the radiation pattern of an adaptive array antenna. UE in the figure stands for User Equipment.

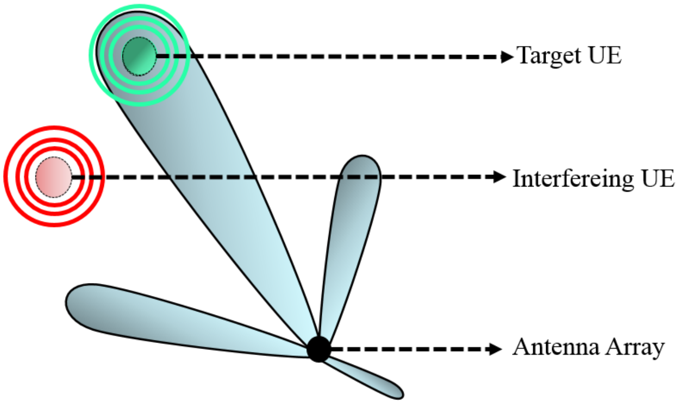


Figure 4: Adaptive array antenna radiation pattern

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

3.2 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, beamsteering and side-lobe nulling play a vital role in reducing the problems listed above.

3.3 Beamsteering and Beamforming

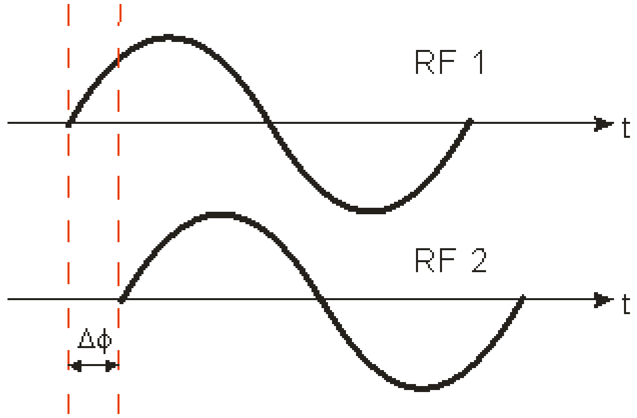
The literal definition of beamsteering is the change of direction of the main lobe of a radiation beam. The phase of the element feed signals is varied in a controlled manner to achieve beam steering.

Beamforming is used to steer and to "form" the shape of the radiation pattern of the array antenna for either signal transmission or signal reception. There are many techniques applied in the design of the antenna feeding network in order to perform beamforming but in essence the antenna feeding amplitude and phase of the signal are varied. The design of the feeding network is optimized based on the application requirements in order to conveniently achieve the final goal.

Irrespective of beamforming or beamsteering, the phase of the antenna feeds needs to be precisely controlled. Thus, phase coherent signaling is a key requirement for phased array antennas.

3.4 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 λ is 3.3 cm. An additional length of 1 mm results in a phase shift of about 11° 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 [2].

Copper has a coefficient of thermal expansion of $16.4\text{x}10^{-6}$ 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 [2].

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 [3].

4 Transmit Mode Testing for Passive Array Antenna

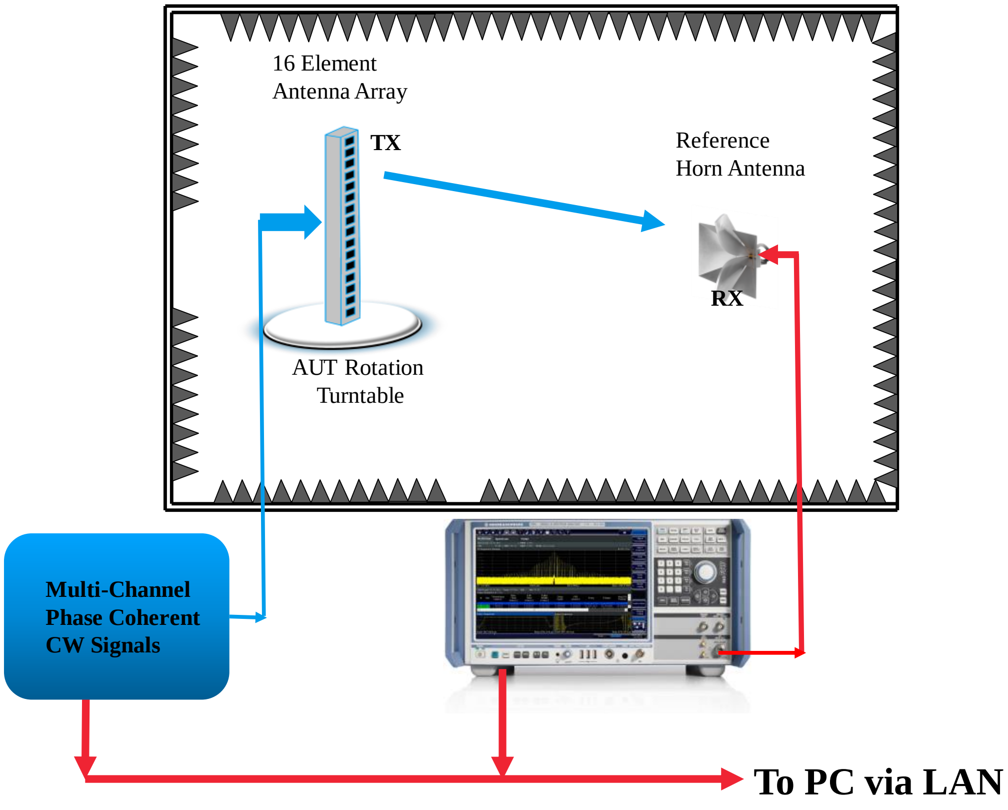


Figure 5: Test setup for Active Phased Array Antenna measurement in TX mode using FSW and TSMW

Error! Reference source not found. shows the proposed test setup for characterizing Smart Active antenna arrays. A Receive (RX) antenna is connected to a FSW spectrum analyzer.

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/j/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.

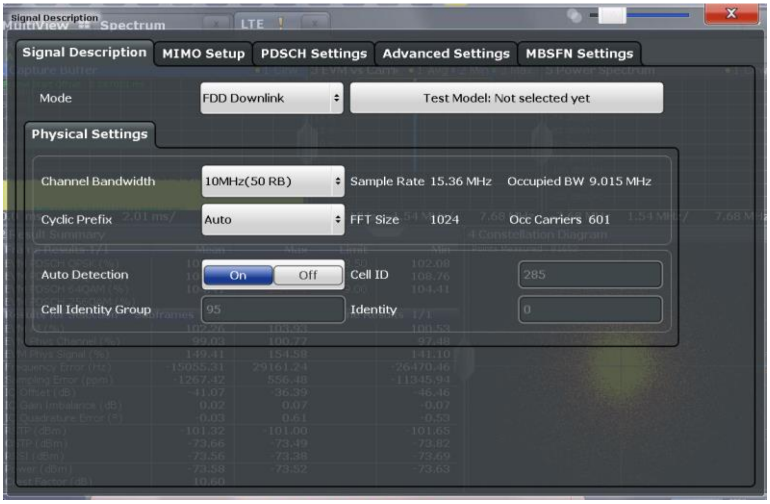
4.1 Transmit Signal Quality Measurement

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*



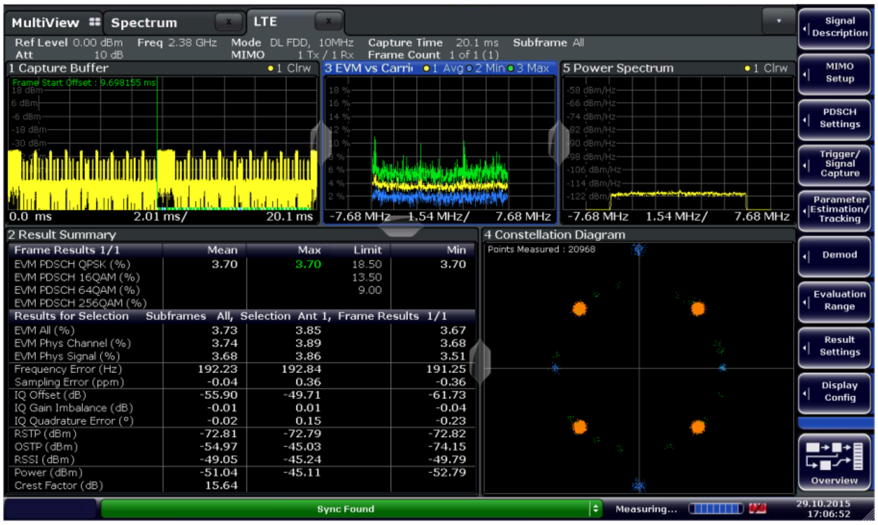
Mode: FDD Downlink
Test Model: Not selected yet

Channel Bandwidth: 10MHz(50 RB)
Sample Rate 15.36 MHz
Occupied BW 9.015 MHz
Cyclic Prefix: Auto
FFT Size 1024
Occ Carriers 601

Auto Detection: On
Cell ID: 285
Cell Identity Group: 95
Identity: 0

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

Figure 6 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. Figure 7 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.

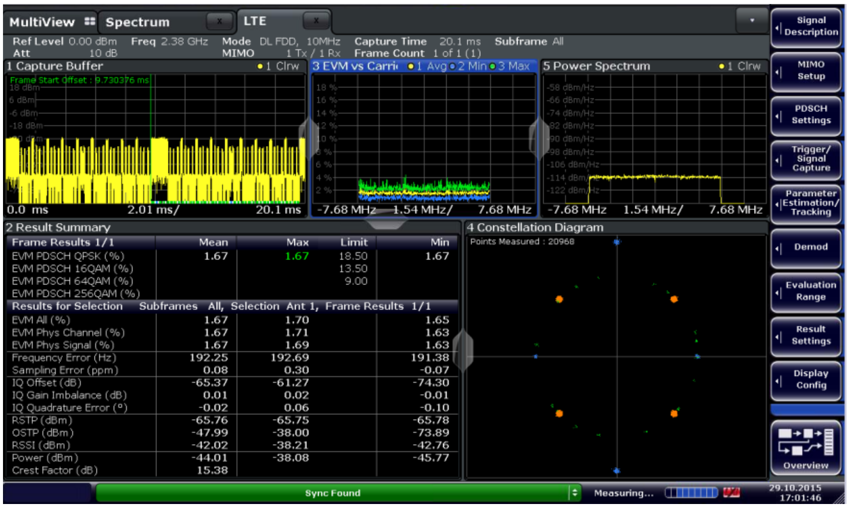


Ref Level 0.00 dBm Freq 2.38 GHz Mode DL FDD, 10MHz Capture Time 20.1 ms Subframe All
Att 10 dB MIMO 1 Tx / 1 Rx Frame Count 1 of 1 (1)

2 Result Summary

Frame Results 1/1	Mean	Max	Limit	Min
EVM PDSCH QPSK (%)	3.70	3.70	18.50	3.70
EVM PDSCH 16QAM (%)			13.50	
EVM PDSCH 64QAM (%)			9.00	
EVM PDSCH 256QAM (%)				
Results for Selection Subframes All, Selection Ant 1, Frame Results 1/1				
EVM All (%)	3.73	3.85		3.67
EVM Phys Channel (%)	3.74	3.89		3.68
EVM Phys Signal (%)	3.68	3.86		3.51
Frequency Error (Hz)	192.23	192.84		191.25
Sampling Error (ppm)	-0.04	0.36		-0.36
IQ Offset (dB)	-55.90	-49.71		-61.73
IQ Gain Imbalance (dB)	-0.01	0.01		-0.04
IQ Quadrature Error (°)	-0.02	0.15		-0.23
RSTP (dBm)	-72.81	-72.79		-72.82
OSTP (dBm)	-54.97	-45.03		-74.15
RSSI (dBm)	-49.05	-45.24		-49.79
Power (dBm)	-51.04	-45.11		-52.79
Crest Factor (dB)	15.64			

Figure 6: Measurement results on the FSW using 4-element Tx antenna without phase coherence and one receive antenna



Ref Level 0.00 dBm Freq 2.38 GHz Mode DL FDD, 10MHz Capture Time 20.1 ms Subframe All
Att 10 dB MIMO 1 Tx / 1 Rx Frame Count 1 of 1 (1)

2 Result Summary

Frame Results 1/1	Mean	Max	Limit	Min
EVM PDSCH QPSK (%)	1.67	1.67	18.50	1.67
EVM PDSCH 16QAM (%)			13.50	
EVM PDSCH 64QAM (%)			9.00	
EVM PDSCH 256QAM (%)				
Results for Selection Subframes All, Selection Ant 1, Frame Results 1/1				
EVM All (%)	1.67	1.70		1.65
EVM Phys Channel (%)	1.67	1.71		1.63
EVM Phys Signal (%)	1.67	1.69		1.63
Frequency Error (Hz)	192.25	192.69		191.38
Sampling Error (ppm)	0.08	0.30		-0.07
IQ Offset (dB)	-65.37	-61.27		-74.30
IQ Gain Imbalance (dB)	0.01	0.02		-0.01
IQ Quadrature Error (°)	-0.02	0.06		-0.10
RSTP (dBm)	-65.76	-65.75		-65.78
OSTP (dBm)	-47.99	-38.00		-73.89
RSSI (dBm)	-42.02	-38.21		-42.76
Power (dBm)	-44.01	-38.08		-45.77
Crest Factor (dB)	15.38			

Figure 7: Measurement results on the FSW using 3-element Tx antenna with phase coherence and one receive antenna

4.2 2D Radiation Pattern Measurement of Passive Array Antenna

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

4.2.1.1 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 4.2.1.2.
- Figure 8 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.

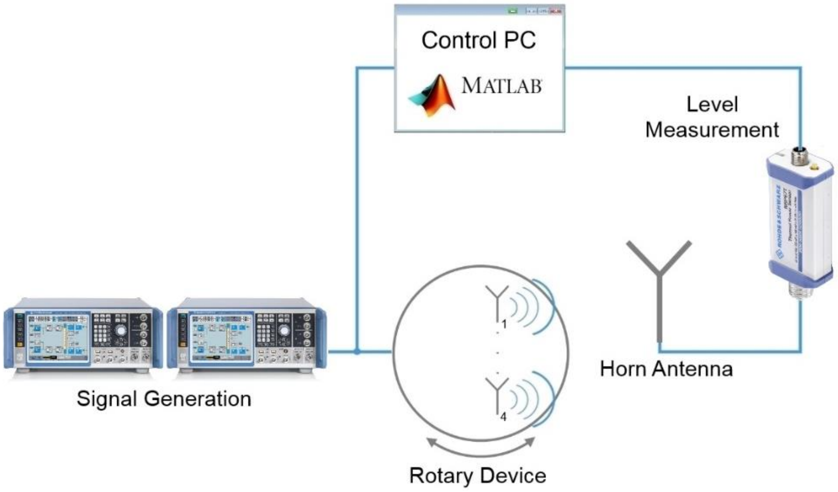


Figure 8: Test setup for 2D radiation Pattern measurement. On the measurement side, a spectrum analyzer may also be used if an increased dynamic range is required

4.2.1.2 Measurement Configuration and Setup

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

	Choice 1	Choice 2
Signal Generator	2 x SMW[1]	1 x SMW[1] + 2 x SGS / SGT
Rec. Pow. Meas.	1 x FSW / FSV / NRP/ FSVA	1 x NRP / FSW / FSV/ FSVA
Calibration	0° Phase Coherent with RTO[2] /Boresight	Boresight Cal. without additional instrument / 0° Phase Coherence Cal.
Transmit Antenna (DUT)	Patch-Antenna / Passive Antenna[3]	Patch-Antenna / Passive Antenna[4]
Receive Antenna	Horn Antenna	Horn Antenna

Table 1: A simple list of possible setups.

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.

4.2.1.2.1 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. Figure 9 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.

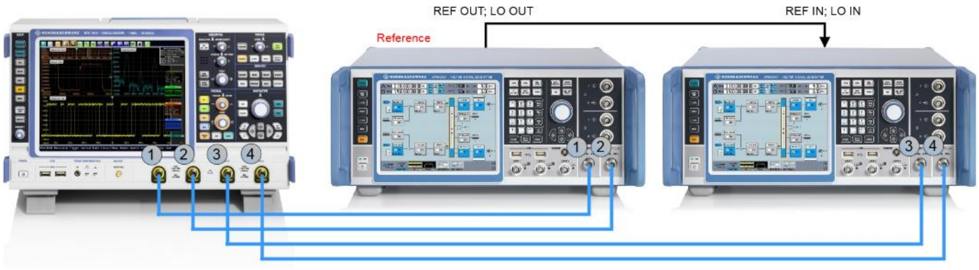


Figure 9: Measurement setup of two SMWs connected to the RTO for phase coherence calibration

Another possibility to generate four RF signals up to 4 GHz is to use one SMW and two SGT. Figure 10 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).

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[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.

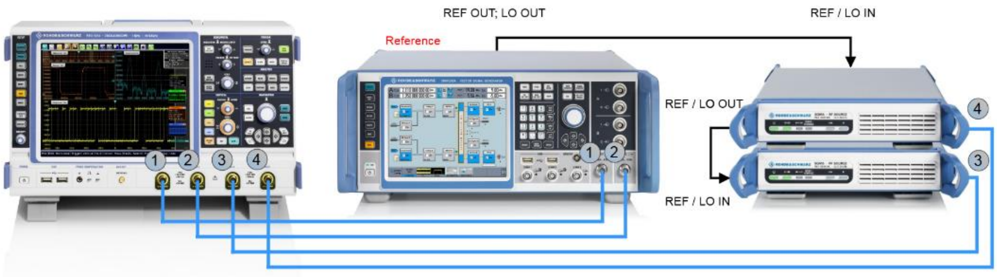


Figure 10: Connection of one SMW and two SGx with phase coherent calibration

4.2.1.2.2 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. Figure 11 and Figure 12 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 Figure 14.

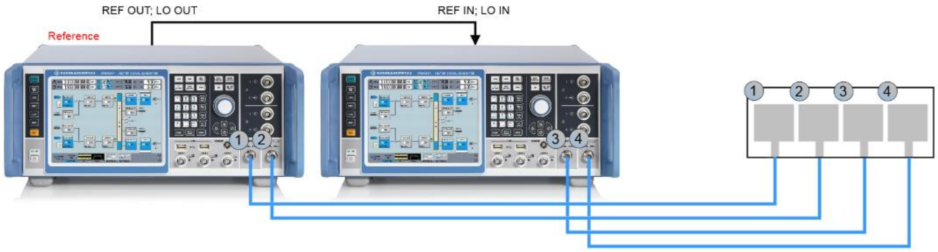


Figure 11: Connection of two SMWs while performing the measurement

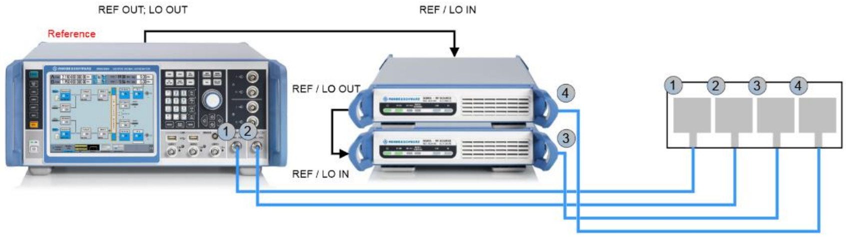
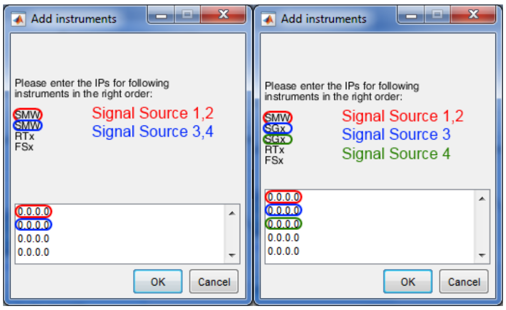


Figure 12: Connection of one SMW and two SGx while performing the measurement

This SW offers two different calibration methods that may be selected in the window shown in Figure 17 :

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 Figure 13 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.



Please enter the IPs for following instruments in the right order:

SMW Signal Source 1,2
SMW Signal Source 3,4
RTx
FSx

0.0.0.0
0.0.0.0
0.0.0.0
0.0.0.0

Please enter the IPs for following instruments in the right order:

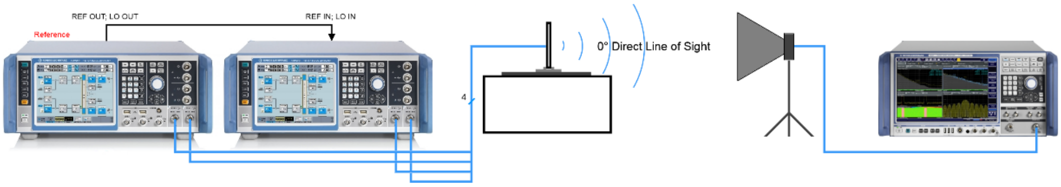
SMW Signal Source 1,2
SGx Signal Source 3
SGx Signal Source 4
RTx
FSx

0.0.0.0
0.0.0.0
0.0.0.0
0.0.0.0
0.0.0.0

Figure 13: Order of Instruments using 0° Phase Coherence Calibration

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 Figure 19.
- The receiving horn antenna is connected to the power sensor or to a spectrum analyzer. The calibration setup is shown in Figure 14.
-



-

Figure 14: Complete Setup using Boresight Calibration

4.2.1.3 Performing a measurement

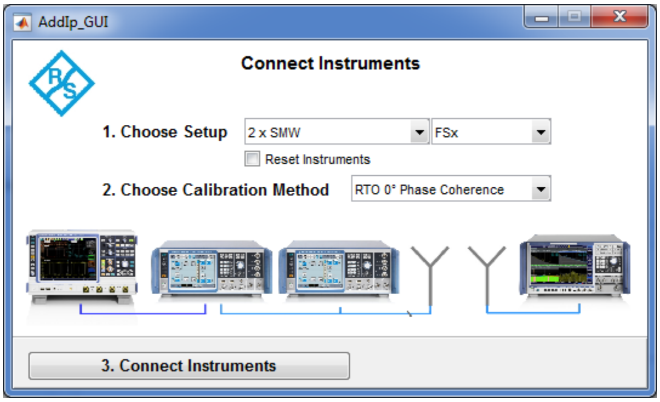
During a typical measurement, the GUI guides you through the following steps

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.

4.2.1.3.1 Selecting a Setup and Connecting the Instruments

After installing the software, start the program.

- From the window shown in Figure 15, choose the relevant signal source configuration and the relevant power measurement instrument from the drop down menu


AddIp_GUI

Connect Instruments

1. Choose Setup: 2 x SMW, FSx

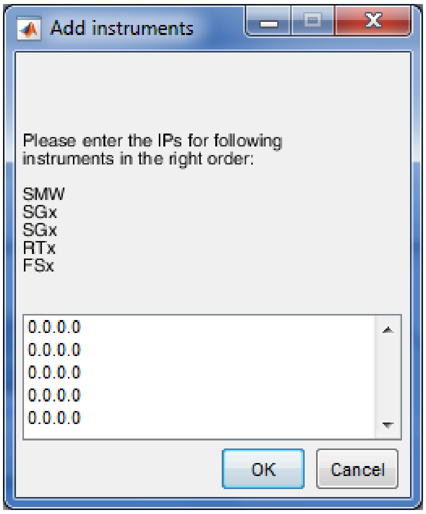
☐ Reset Instruments

2. Choose Calibration Method: RTO 0° Phase Coherence

3. Connect Instruments

Figure 15: Choosing a Setup

- 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 Figure 16. Insert the IP address of all the instrument 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.*


Add instruments

Please enter the IPs for following instruments in the right order:

SMW
SGx
SGx
RTx
FSx

0.0.0.0
0.0.0.0
0.0.0.0
0.0.0.0
0.0.0.0

OK Cancel

Figure 16: Input Dialog for IP Addresses

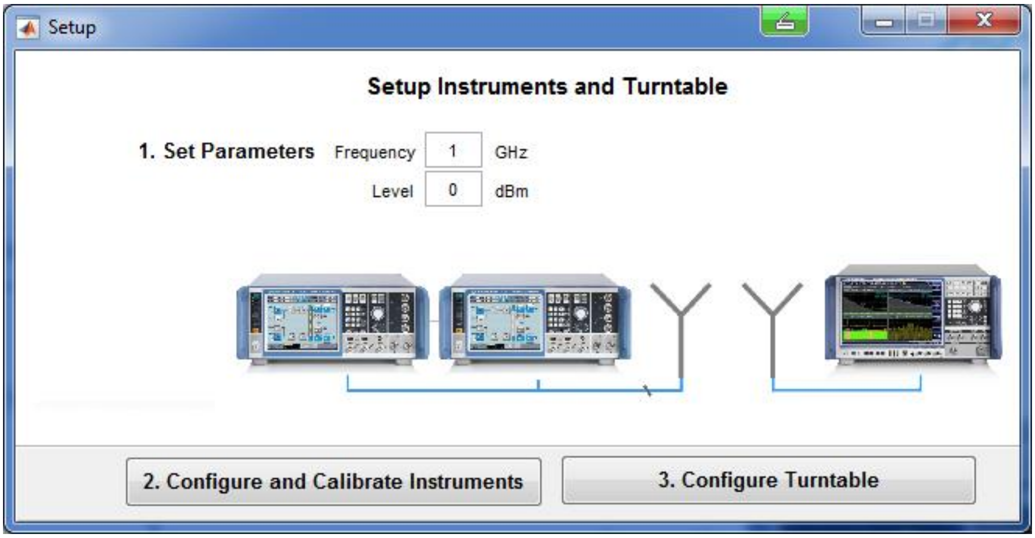
- Press the OK button, the connection with the instruments will be established.
-

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 Error! Reference source not found. **corresponds to the setup shown in** Figure 12**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** Figure 12**.**

4.2.1.3.2 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.

- Click the button *Setup Instruments*. It opens a new window shown in Figure 17.



Frequency 1 GHz

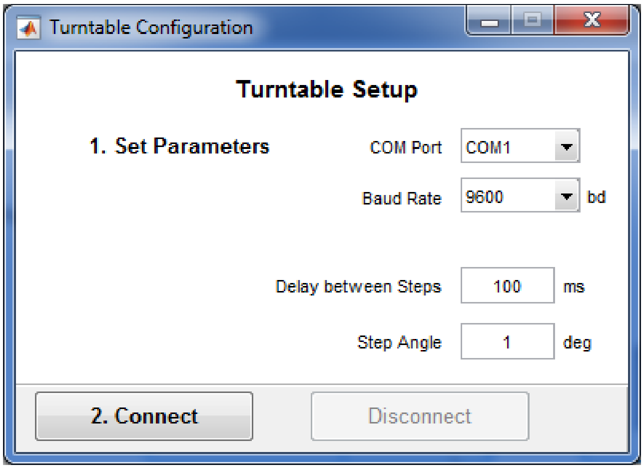
Level 0 dBm

Figure 17: Calibration Setup

- **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.

- Click on *Configure Turntable* to connect to the turntable device. A new window shown Figure 18 in will open.



COM Port COM1

Baud Rate 9600 bd

Delay between Steps 100 ms

Step Angle 1 deg

Figure 18: Turntable Setup

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 Figure 17
  - – 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.

4.2.1.3.3 Measurement

After the setup has been calibrated, a measurement can be started. The main window shown in Figure 19 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)[5]. The results are applied to the signal sources.**

$$\vartheta = \arcsin \frac{\lambda}{2\pi * d} * \Delta\varphi \tag{1}$$

Where ϑ **is the steered beam angle / rad**

λ **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. $0 * \Delta\varphi, 1 * \Delta\varphi$**, …)**

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

③ **These controls allow to set a user defined 0° value to the rotary device with the transmit antenna attached.**

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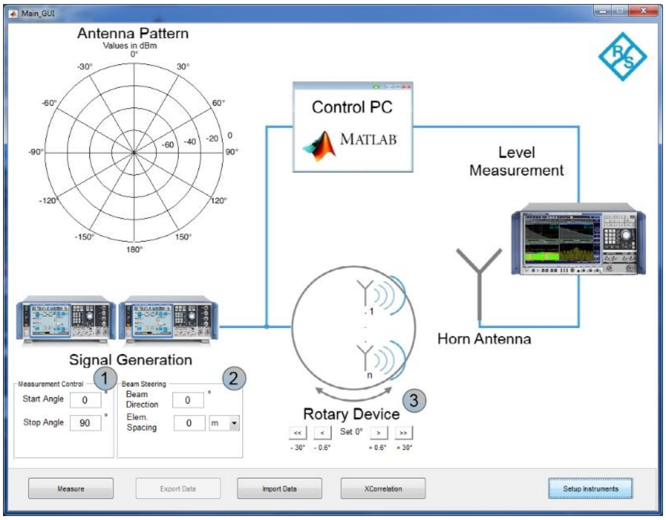
[5] See [7], page 56.



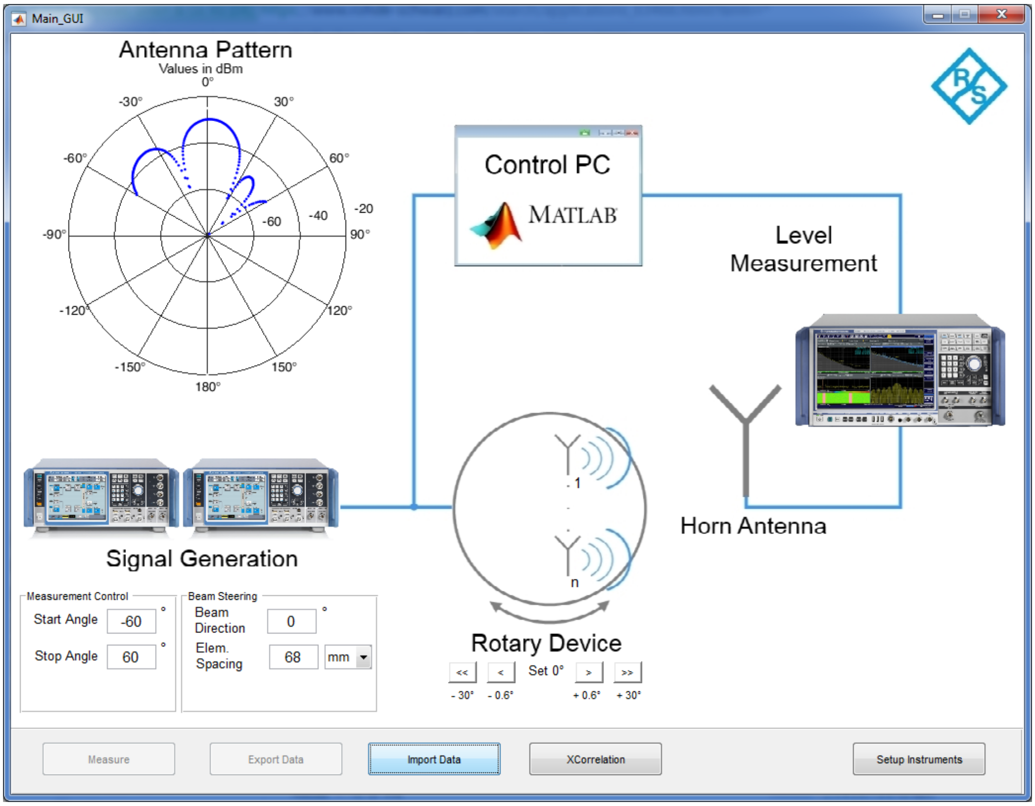
Measurement Control
Start Angle 0 °
Stop Angle 90 °

Beam Steering
Beam Direction 0 °
Elem. Spacing 0 m

Figure 19: The Main Window

- ► Clicking on the Measure button starts the measurement.
- ► **A live plot in the top left corner displays the results. Generally, a 360° measurement swipe takes around 10-11 mins.**

Figure 20 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 Control
Start Angle -60 °
Stop Angle 60 °

Beam Steering
Beam Direction 0 °
Elem. Spacing 68 mm

Figure 20: Measurement Example

4.2.1.3.4 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.

4.2.1.3.5 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).

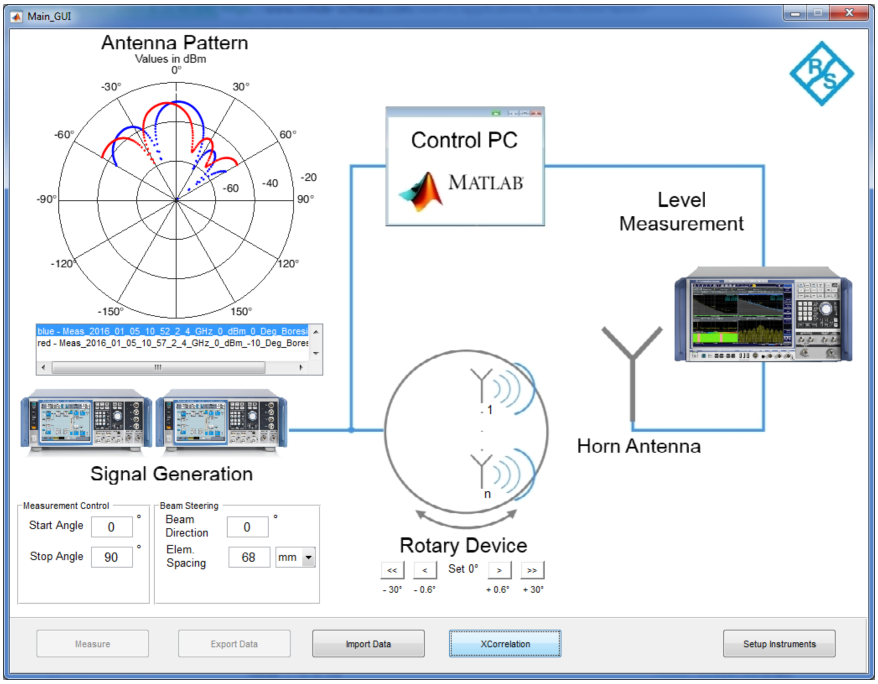
The trace data with n points is saved in a 2 x n matrix. The first row contains the level measurement results in dBm while the second row stores the angle in rad.

4.2.1.3.6 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.

Figure 21 shows the import of two traces. Trace one (blue) is not steered while trace two (red) is steered at -10°.



blue - Meas_2016_01_05_10_52_2_4_GHz_0_dBm_0_Deg_Boresi
red - Meas_2016_01_05_10_57_2_4_GHz_0_dBm_-10_Deg_Bores

Measurement Control
Start Angle 0 °
Stop Angle 90 °

Beam Steering
Beam Direction 0 °
Elem. Spacing 68 mm

Figure 21: Import of multiple traces

4.2.1.3.7 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. Figure 22 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.

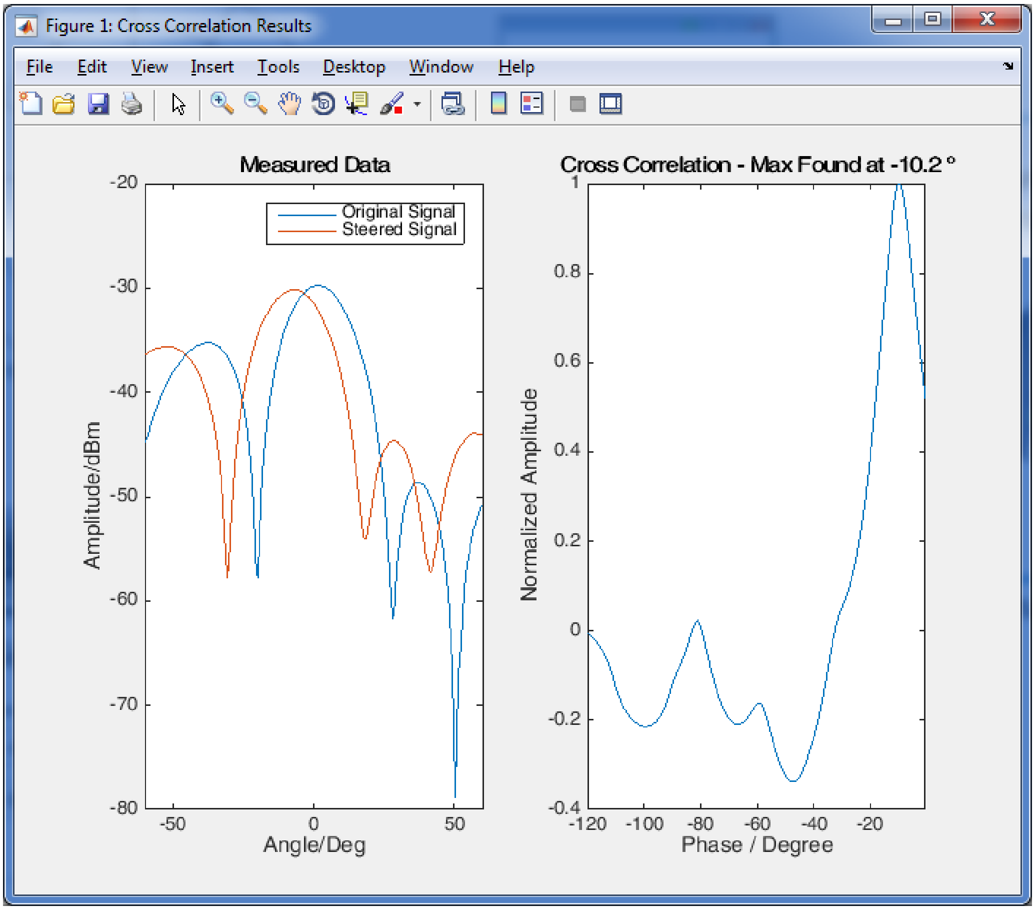


Figure 22: Cross Correlation two signals

5 Transmit-Receive-Module Testing of Active Array Antenna

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 5.1.1 and 5.1.2 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.

5.1.1 Manual T/R-Module Testing in Pulsed Mode

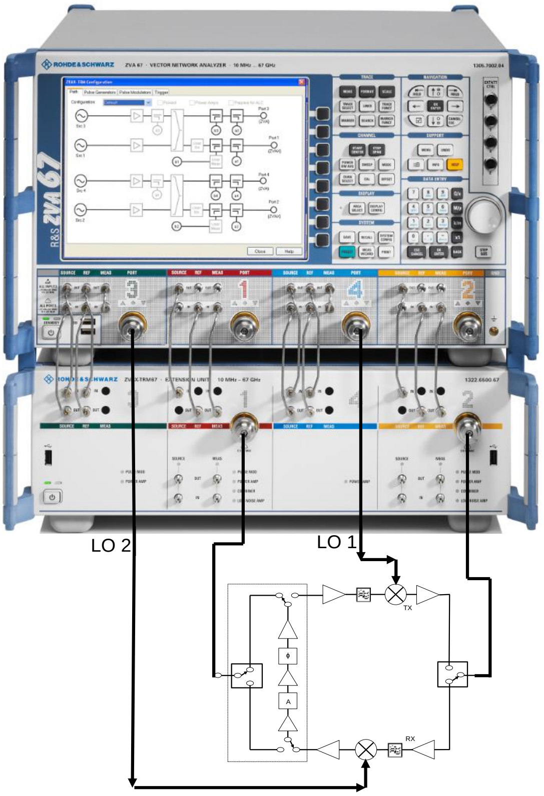


Figure 23: Combination of a ZVA67 and ZVAX-TRM67 to characterize T/R-modules

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 Figure 23. 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.

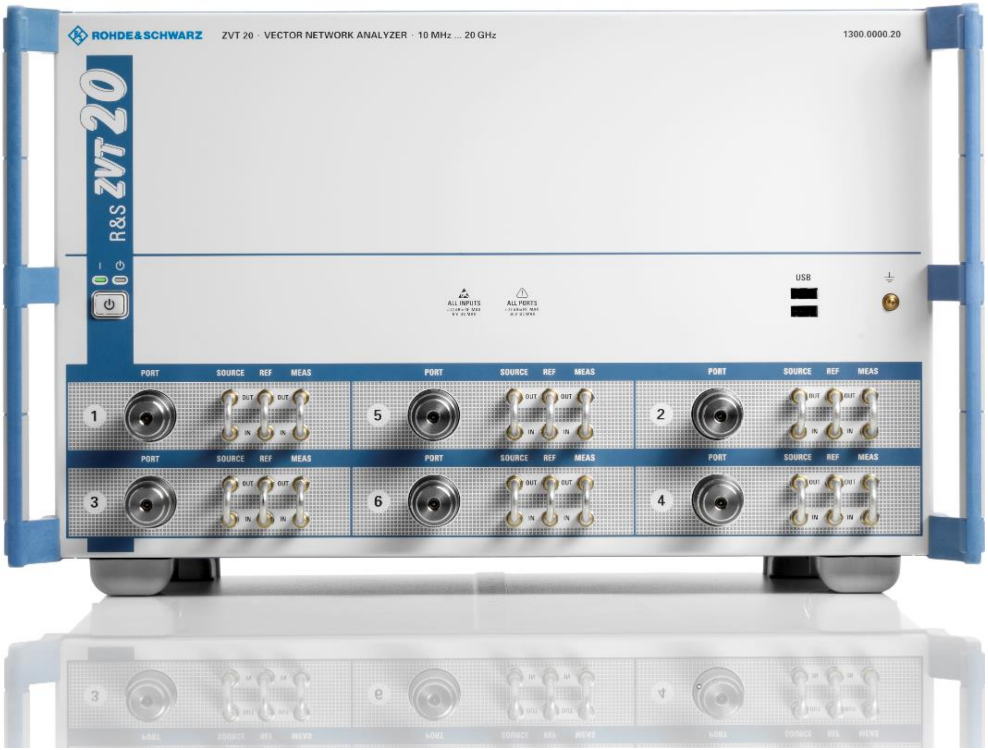


Figure 24: ZVT20 Vector Network Analyzer with six port from 300 KHz up to 20 GHz

With a ZVT8/20 as show in Figure 24, 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 Figure 25.

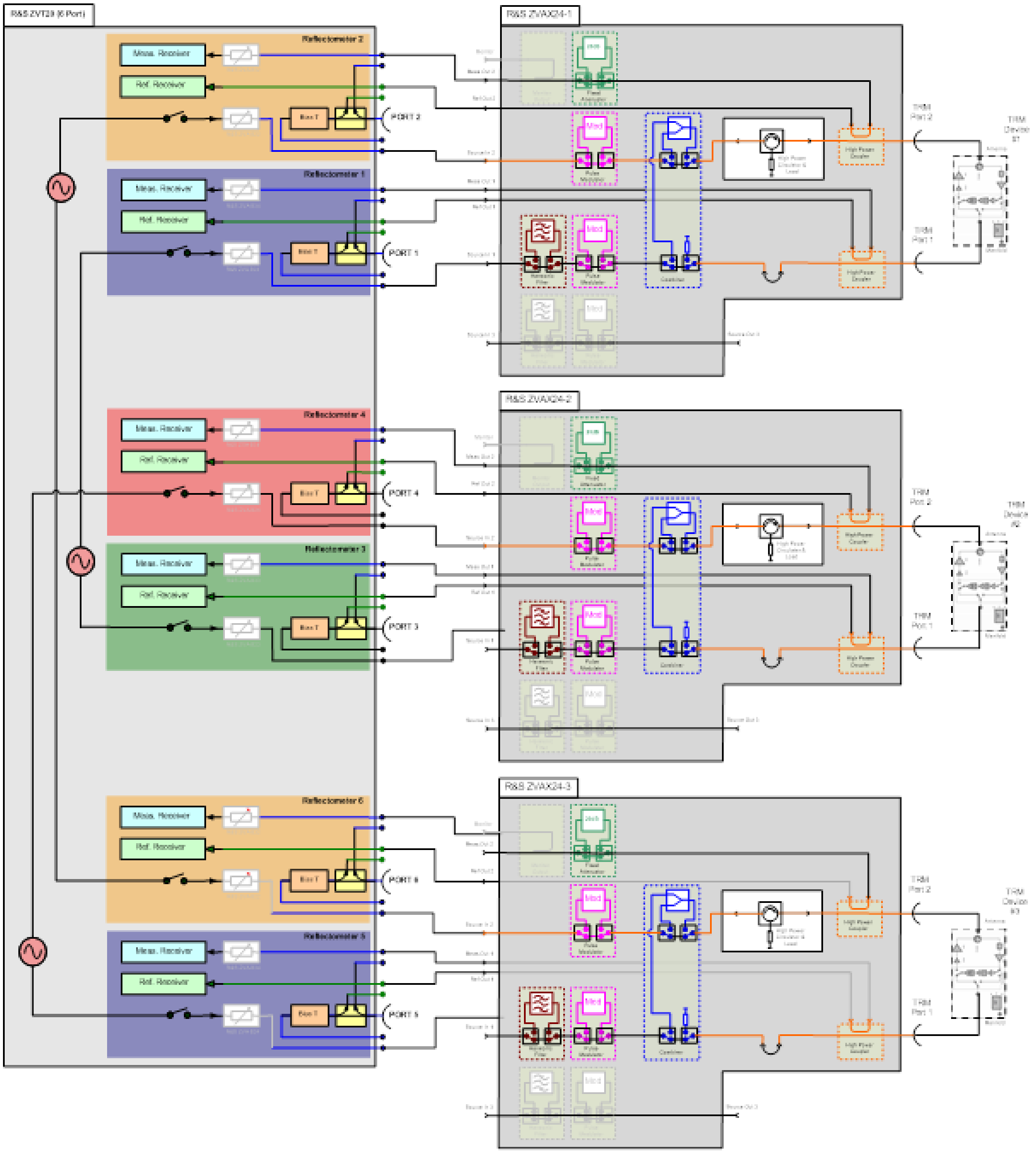


Figure 25: Parallel test configuration for three T/R-Modules

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.

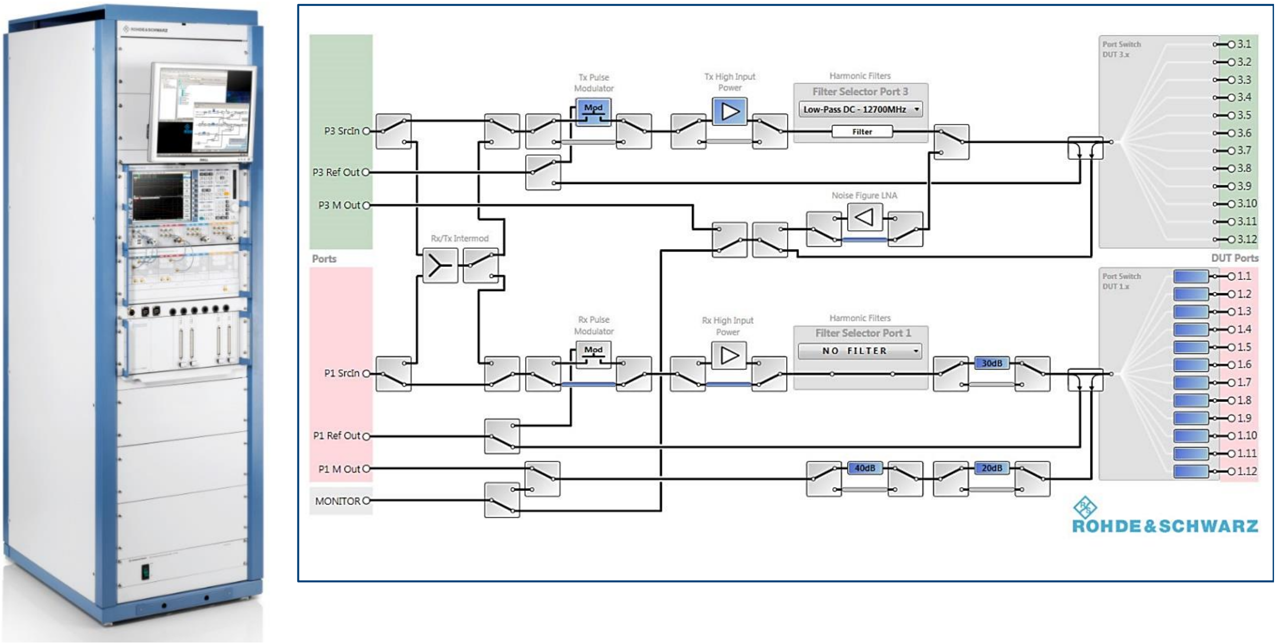
To address manufacturing time for DUTs with high number T/R-modules, it is therefore important to re-address the testing procedure as in 5.1.2.

5.1.2 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 (Figure 26). 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.



Filter Selector Port 3: Low-Pass DC - 12700MHz

Filter Selector Port 1: NO FILTER

Figure 26: 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.

6 Literature

[1] A. S. a. J. R. M. Ivica Stevanovi´c, *Smart Antenna Systems for Mobile Communications,* Ecole Polytechnique F´ed´erale de Lausanne.

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[5] Rohde & Schwarz , "Phase Adjustment of Two MIMO Signal Sources with Option B90 (Phase Coherence)," [Online]. Available: http://www.rohde-schwarz.com/appnote/1GP67.

[6] J. M. N. G.-P. a. H. R. W. J. A. Alkhateeb, *MIMO Precoding and Combining Solutions for Millimeter-Wave Systems,* IEEE, 2014.

[7] M. Longbrake, *True Time-Delay Beamsteering for Radar,* Dayton, USA: IEEE, 2014.

[8] R. W. e. al, *Millimeter-Wave Beamforming as an Enabling Technology for 5G Cellular Communications: Theoretical Feasibility and Prototype Results,* 2014: IEEE 52.

[9] X. G. e. al, *W-Band Scalable Phased Arrays for Imaging and Communications,* IEEE 53, 2015.

7 Ordering Information

Vector Network Analyzer*

Designation	Type	Order No.
Vector Network Analyzer, 10MHz to 40GHz, Four ports, four generators / sources	R&S®ZVA40	1145.1110.48
Direct generator/receiver access for 4 port ZVA40	R&S®ZVA40-B16	1164.0209.42
Frequency Conversion	R&S®ZVA-K4	1164.1863.02
5 MHz Receiver Bandwidth	R&S®ZVA-K17	1164.1070.02
Two internal pulse generators	R&S®ZVA-K27	1164.1892.02
Noise Figure Measurements	R&S®ZVA-K30	1164.1828.02
Oven Quartz (OCXO)	R&S®ZVA-B4	1164.1757.02
Universal Interface	R&S®ZVA-B14	1305.6306.02
Pulsed Measurements (25ms recording time)	R&S®ZVA-B7	1164.1492.03
Receiver Step Attenuator, Port 1	R&S®ZVA40-B31	1302.5444.02
Receiver Step Attenuator, Port 2	R&S®ZVA40-B32	1302.5450.02
Receiver Step Attenuator, Port 3	R&S®ZVA40-B33	1302.5467.02
Receiver Step Attenuator, Port 4	R&S®ZVA40-B34	1302.5473.02
Generator Step Attenuator, Port 1	R&S®ZVA40-B21	1302.5409.02
Generator Step Attenuator, Port 2	R&S®ZVA40-B22	1302.5415.02
Generator Step Attenuator, Port 3	R&S®ZVA40-B23	1302.5421.02
Generator Step Attenuator, Port 4	R&S®ZVA40-B24	1302.5438.02
Set of cables for the R&S®ZVA-K9	R&S®ZVA-B9	1305.6541.03
Network analysis with up to 24 test ports 9 kHz to 8.5 GHz	R&S®ZNBT8	1318.7006.24
Ports 5 to 8	R&S®ZNBT8-B108	1319.4200.02
Ports 9 to 12	R&S®ZNBT8-B112	1319.4217.02
Ports 13 to 16	R&S®ZNBT8-B116	1319.4223.02
Ports 17 to 20	R&S®ZNBT8-B120	1319.4230.02
Ports 21 to 24	R&S®ZNBT8-B124	1319.4246.02
Precision Frequency Reference	R&S®ZNBT8-B4	1319.4023.02
Device Control	R&S®ZNBT8-B12	1319.3956.02
Receiver Step Attenuators	R&S®ZNBT8-B361	1319.4317.02
Receiver Step Attenuators Ports 5 to 8	R&S®ZNBT8-B362	1319.4323.02
Receiver Step Attenuators Ports 9 to 12	R&S®ZNBT8-B363	1319.4330.02
Receiver Step Attenuators Ports 13 to 16	R&S®ZNBT8-B364	1319.4346.02
Receiver Step Attenuators Ports 17 to 20	R&S®ZNBT8-B365	1319.4352.02
Receiver Step Attenuators Ports 21 to 24	R&S®ZNBT8-B366	1319.4369.02
Extended Power Range for Ports 1 to 4	R&S®ZNBT8-B21	1319.4252.02

Designation	Type	Order No.
Extended Power Range for Ports 5 to 8	R&S®ZNBT8-B22	1319.4269.02
Extended Power Range for Ports 9 to 12	R&S®ZNBT8-B23	1319.4275.02
Extended Power Range for Ports 13 to 16	R&S®ZNBT8-B24	1319.4281.02
Extended Power Range for Ports 17 to 20	R&S®ZNBT8-B25	1319.4298.02
Extended Power Range for Ports 21 to 24	R&S®ZNBT8-B26	1319.4300.02
Time Domain Analysis (TDR)	R&S®ZNBT-K2	1318.8425.02
10 MHz Receiver Bandwidth	R&S®ZNBT-K17	1318.8454.02
1 MHz Frequency Resolution	R&S®ZNBT-K19	1319.4000.02
TRM Extension Unit	R&S®ZVAX-TRM40	1322.6500.40
Combiner for R&S®ZVAX-TRM40	R&S®ZVAX40B213	1322.7007.40
Combiner for R&S®ZVAX-TRM40 10 MHz to 40 GHz, to generate two-tone signal at R&S®ZVAX-TRM port 2 (SRC 2 + 4)	R&S®ZVAX40B224	1322.7013.40
Pulse modulators for R&S®ZVAX-TRM40 port 1 and port 2	R&S®ZVAX40B712	1322.6969.40
Pulse modulator for R&S®ZVAX-TRM40 (10 MHz to 40 GHz, to generate pulsed signals at network analyzer port 3 or at R&S®ZVAX-TRM40 port 1)	R&S®ZVAX40B73	1322.6975.40
Output amplifiers for R&S®ZVAX-TRM40 (10 MHz to 40 GHz, for increased output powerat R&S®ZVAX-TRM40 port 1 and port 2)	R&S®ZVAX40B112	1322.6981.40
Output amplifiers for R&S®ZVAX-TRM40 (10 MHz to 40 GHz, for increased output power at network analyzer port 3 and port 4 or at R&S®ZVAX-TRM40 port 1 and port 2)	R&S®ZVAX40B134	1322.6998.40

Signal and Spectrum Analyzer*

Designation	Type	Order No.
Signal und spectrum analyzer 2 Hz to 43.5 GHz	R&S®FSW43	1312.8000K43
OCXO Precision Reference Frequency	R&S®FSW-B4	1313.0703.02
RF preamplifier, 100 kHz to 43 GHz	R&S®FSW-B24	1313.0832.43
Highpass Filters for Harmonic Measurements	R&S®FSW-B13	1313.0761.02
Resolution bandwidth > 10 MHz	R&S®FSW -B8	1313.2464.02
Pulse Measurements	R&S®FSW-K6	1313.1322.02
Vector Signal Analysis	R&S®FSW-K70	1313.1416.02
GSM, EDGE, EDGE Evolution and VAMOS measurements	R&S®FSW-K10	1313.1368.02
IEEE 802.11a/b/g Measurements	R&S®FSW-K91	1313.1500.02
Phase Noise Measurements	R&S®FSW-K40	1313.1397.02
Noise Figure Measurements	R&S®FSW-K30	1313.1380.02
2 GHz Analysis Bandwidth	R&S®FSW-B2000	1325.4750.02
OCXO Precision Reference Frequency	R&S®FSW-B4	1313.0703.02
Digital Baseband Interface	R&S®FSW-B17	1313.0784.02

Designation	Type	Order No.
Analog Baseband Inputs	R&S®FSW-B71	1313.1651.13
Electronic Attenuator, 1 dB steps	R&S®FSW-B25	1313.0990.02

Digital Oscilloscope*

Designation	Type	Order No.
Digital oscilloscope 4 GHz, 4 channels	R&S®RTO1044	1316.1000.44
Mixed Signal Option, 400 MHz	R&S®RTO-B1	1304.9901.03
OCXO 10 MHz	R&S®RTO-B4	1304.8305.02
Memory Option 400 Msample	R&S®RTO-B104	1304.8457.02
Bandwidth upgrade of the R&S®RTO1024 to 4 GHz bandwidth incl. calibration	R&S®RTO-B205	1316.1375.02

Vector Signal Generator*

Designation	Type	Order No.
Vector Signal Generator	R&S®SMW200A	1412.0000.02
100 kHz to 6 GHz	R&S®SMW-B106	1413.0104.02
100 kHz to 12.75 GHz	R&S®SMW-B112	1413.0204.03
100 kHz to 20 GHz	R&S®SMW-B120	1413.0404.02
100 kHz to 40 GHz, RF Path A	R&S®SMW-B140	1413.0604.02
100 kHz to 6 GHz	R&S®SMW-B206	1413.0904.02
100 kHz to 12.75 GHz	R&S®SMW-B212	1413.1000.03
100 kHz to 20 GHz	R&S®SMW-B220	1413.1100.02
Signal Routing and Baseband Main Module, one I/Q path to RF	R&S®SMW-B13	1413.2807.02
Signal Routing and Baseband Main Module, two I/Q path to RF	R&S®SMW-B13T	1413.3003.02
Baseband Generator with ARB (64 Msample) and Digital Modulation (realtime), 120 MHz RF bandwidth	R&S®SMW-B10	1413.1200.02
Enhanced Phase Noise Performance and FM/φM Modulator	R&S®SMW-B22	1413.2207.02
Multiple Entities	R&S®SMW-K76	1413.9624.02
Differential Analog I/Q Outputs	R&S®SMW-K16	1413.3384.02
Digital Baseband Output	R&S®SMW-K18	1413.3432.02
ARB Memory Extension to 1 Gsample	R&S®SMW-K512	1413.6919.02
Multicarrier CW Signal Generation	R&S®SMW-K61	1413.4280.02
Baseband Extension to 160 MHz RF bandwidth	R&S®SMW-K522	1413.6960.02
SGMA RF Source	R&S®SGS100A	1416.0505.02
1MHz to 6 GHz	R&S®SGS-B106V	1416.2350.02
Frequency Extension to 12.75 GHz, IQ	R&S®SGS-B112V	1416.1553.02
Electronic Step Attenuator	R&S®SGS-B26	1416.1353.02
Phase Coherent Input/Output	R&S®SGS-K90	1416.2608.02

Designation	Type	Order No.
SGMA Upconverter	R&S®SGU100A	1416.0808.02
10 MHz to 20 GHz, CW (no modulation)	R&S®SGU-B120	1418.2605.02
10 MHz to 20 GHz, I/Q (with vector modulation)	R&S®SGU-B120V	1418.2657.02
Frequency extension to 40 GHz, CW	R&S®SGU-B140	1418.2870.02
Frequency extension to 40 GHz, I/Q	R&S®SGU-B140V	1418.2928.02
Mechanical Step Attenuator	R&S®SGU-B26	1418.3401.02
SGMA Vector RF Source	R&S®SGT100A	1419.4501.02
Frequency Extension to 6 GHz	R&S®SGT-KB106	1419.5708.02
Phase Coherent Input/Output	R&S®SGT-K90	1419.6333.02
Differential Analog I/Q Outputs	R&S®SGT-K16	1419.8007.02
Digital Baseband Connectivity	R&S®SGT-K18	1419.6240.02

TRM Radar Test System *

Designation	Type	Order No.
TRM Radar Test System The all-in-one solution for efficient RF characterization	R&S®TS6710	1516.4001.02

NRPxxS/SN Power Sensor

Designation	Type	Order No.
Three-path diode power sensor	R&S®NRP8S	1419.0006.02
Three-path diode power sensor	R&S®NRP8SN	1419.0012.02
Three-path diode power sensor	R&S®NRP18S	1419.0029.02
Three-path diode power sensor	R&S®NRP18SN	1419.0035.02
Three-path diode power sensor	R&S®NRP33S	1419.0064.02
Three-path diode power sensor	R&S®NRP33SN	1419.0070.02
Three-path diode power sensor	R&S®NRP40S	1419.0041.02
Three-path diode power sensor	R&S®NRP40SN	1419.0058.02
Three-path diode power sensor	R&S®NRP50S	1419.0087.02
Three-path diode power sensor	R&S®NRP50SN	1419.0093.02
USB Interface Cable, 0.75m	R&S®NRP-ZKU	1419.0658.02

TSMW Universal Radio Network Analyzer*

Designation	Type	Order No.
TSMW Universal Radio Network Analyzer	R&S®TSMW	1503.3001.02
TSMW option: LTE	R&S®TSMW-K29	1503.4550.02
ROMES driver for TSMW	ROMES4T1W	1117.6885.02
ROMES Basis Software	ROMES4	1117.6885.04
Power supply 230V	TSMW-Z1	1503.4608.02

*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.

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