Verification of an RF Transmitter with Rigol's RSA5000N Real-time Spectrum Analyzer

Wireless communication is very often used to successfully transfer data from one point to another or to implement successful communication with the Internet. This is the case with an IoT system, for example, when the data is communicated via the Internet, or with the different technologies of mobile phones. An essential component is the RF transmitter, which is integrated in every contactless communication system. A cell phone can contain different transmitters, e.g. the transmitter for the WiFi connection, the transmitter/receiver component for the actual mobile connection (conversation, SMS, Internet), for the NFP connection or for the Bluetooth connection, which is used to adapt external components (Audiobox or telephone system in the car). On the one hand, it is important to achieve good, stable communication, why the component selection for the transmitter is crucial to achieve a very good modulation quality. An example for this is an amplifier for the baseband which has a large stable linear range and can handle the power budget (supply). On the other hand, it is also important to develop an RF transmitter that only works in the desired bandwidth without additional interference signals. Here, clean and good filtering must be implemented. Last but not least, EMC also plays an important role in the development of an RF transmitter in order to protect the environment from unnecessary and unwanted electrosmog or vice versa to protect the transmitter from interference. **Figure 1** shows the block diagram of an RF transmitter.

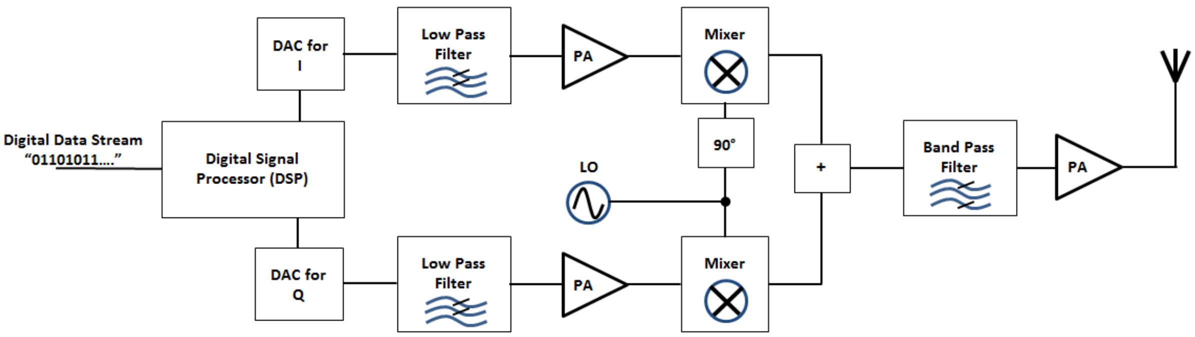

Figure 1: Simple block diagram of an RF transmitter for digitally modulated signals

The first part of the RF transmitter is the implementation of the baseband for digital modulation. For this purpose, a Digital Signal Processor [DSP] uses the digital data (e.g. speech, characters, data for images, sound, etc.) for line coding, interleaving and modulation. For the modulation, the bits are combined into symbols - depending on the type of modulation. With the modulation formats such as Quadrature Phase-Shift Keying [QPSK], M-ary Quadrature Amplitude Modulation [QAM], each symbol can be described with the digital in-phase [I] and quadrature components. 64QAM modulation is shown here as an example. With 64QAM, a symbol contains six bits. With QPSK modulation, there are two bits (dibits) per symbol. QPSK is a phase modulation in which the amplitude remains the same for all symbols (**see Figure 2**). QAM, on the other hand, is a modulation of the phase and the amplitude. The positions of the symbols thus depend on the phase and the amplitude of the IQ vectors.

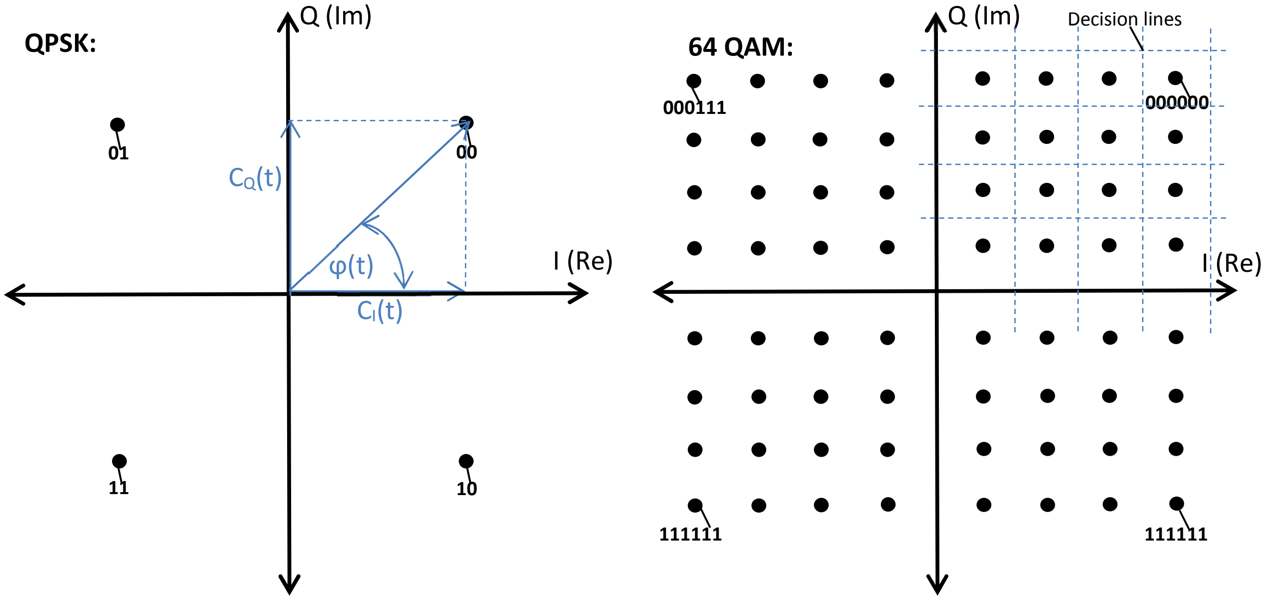

Figure 2: Modulation formats QPSK (left) and 64QAM (right)

As in complex mathematics, the IQ vectors can also be described with a sine (Q) and a cosine (I). These two signals therefore have a phase offset of 90° and are orthogonal to one another - or in other words: they are quadrature to one another. The components C_I (t) and C_Q (t) describe the baseband of the modulation.

When the baseband is available, the digital I and Q components are converted to an analog signal, which is then filtered. This filter is important in order to assign the necessary pulse shape for the best band-limited transmission to the signal. The sine or cosine signal is then mixed into the signal components using a local oscillator. In the block diagram in **Figure 1**, this is already the RF carrier. Both signal components are now added together, amplified, filtered again and fed to the antenna. The second filtering is necessary in order to achieve the band limitation and, if necessary, to suppress unwanted interference components by the previous components.

Each individual component in a transmitter has an impact on the functionality and quality of the communication. In order to achieve the expected quality of the transmission and thus a good functionality of the communication system of the wireless transmission, a detailed analysis of the individual components and the overall system is necessary.

Modulation analysis

With the Vector Signal Analyzer [VSA] option of the RSA5000N series it is possible to measure the modulation quality of the RF transmitter in detail. Different modulation types can be selected for this in VSA mode.

For this analysis, the VSA must create an optimal reference signal that is used as a comparison to the measured signal. This requires some information from the transmitter, such as the sampling rate of the modulation, the filter used in the transmitter (and optimally also in the receiver), the filter edge and the modulation format (e.g. 64QAM). The reference signal is generated with the measured signal. The measured signal is now compared with the reference signal, and measured values such as the Error Vector Magnitude [EVM] or other important parameters (e.g. phase errors) can be calculated and displayed. As already described, the measuring and reference filters can be set and changed in the VSA. The reference filter contains the information of the filters from the sender and the receiver. The measuring filter, on the other hand, contains the information of the recipient:

- Transmitter [TX]: Root cosine filter [RRC]
- Receiver [RX]: Root cosine filter (= measurement filter in the VSA)
- RX and TX: RRC * RRC = cosine filter [RC] (= reference filter in the VSA)

The table (**Figure 3**) describes the different types of analysis of the RSA5000N VSA mode

Time	Spectrum	Demodulation Error Traces		Demodulation	Error View	BER
Log or linear magnitude over symbols	Log or linear magnitude over symbols	Error vector time	Log or linear magnitude over symbols	Demodulated bits of symbols (Hex or Bin)	EVM [%rms and %peak]	Bit error rate analysis
Inphase or quadrature over symbols	Inphase or quadrature over symbols	Error vector spectrum	Inphase or quadrature over symbols		Magnitude error [%rms and %peak]	
Wrap or unwrap phase over symbols	Wrap or unwrap phase over symbols		Wrap or unwrap phase over symbols		Phase error [%rms and %peak]	
IQ trace or constellation diagram		IQ magnitude error	Log magnitude over symbols		Gain imbalance [dB]	
Inphase or quadrature eye diagram		IQ phase error	linear magnitude over symbols		Frequency offset [Hz]	
					Quadrature error [deg]	
					IQ offset [dB]	
					SNR(MER) [dB]	

Figure 1: Overview of measurement capabilities in RSA5000N VSA Mode

The VSA can display up to four measurements simultaneously on one screen. An important measurement is, for example, the constellation diagram in combination with the error measurement in a second window. The EVM value is one of the most meaningful parameters about the quality of the modulation. EVM describes the error vector between the optimal reference and the measured vector (**see Figure 4**)

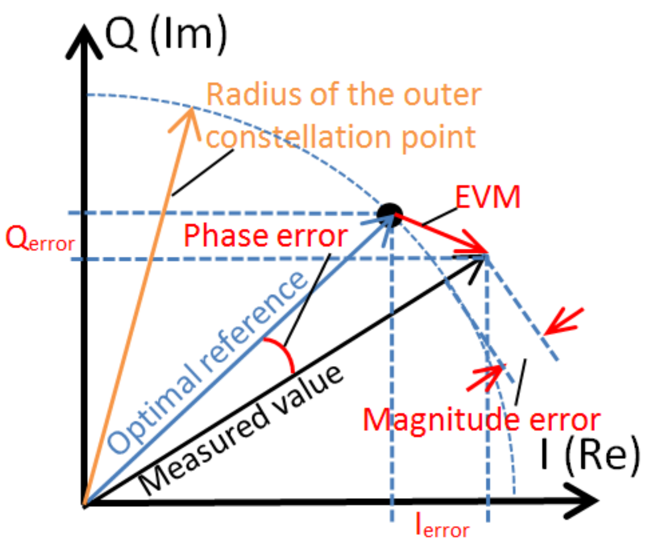

Figure 2: EVM, Phase error, Magnitude error and I/Q error in the constellation diagram

The reference value of the percentage calculation at EVM is the radius of the outermost constellation point. The EVM value can be measured as an effective value (considering all symbols) or as a peak value (the largest deviation). A noisy signal would result in a higher EVM value, which could be problematic for the receiver to be able to correctly recognize the symbol again. Depending on what the transmitter specification looks like, the measured EVM value must be lower directly at the transmitter.

Figure 4 also shows the amount and phase error. Both measured values can also be seen in the error measurement.

Another measured value is the Modulation Error Ratio [MER]. This value is very similar to the Signal-to-Noise Ratio [SNR]. The MER must be at least so good that the symbol value at the receiver stays within the decision lines (**see Figure 2, 64QAM**). A very good MER value for 64QAM modulation is between 32 and 64 dB. An MER of approx. 20 dB would lead to increased bit errors and reduce the quality of the entire communication. The higher the number of symbols of the modulation, the smaller the decision areas and the better the MER value must be.

In order to get stable, high quality modulation, the baseband signal must be very accurate. Modulation errors can occur in the RF transmitter in different ways. Each individual component has its influence on the modulation quality. Depending on what the constellation diagram looks like, conclusions can be drawn about the individual components. Here are a few examples:

- If, for example, the local oscillator is not completely suppressed by the mixer, an IQ offset can be seen in the constellation diagram. This means that all measuring points experience a shift from the center of the constellation.
- Another effect could come from the baseband amplifiers. If these have a different gain at I and Q, then this amplifier distortion (IQ imbalance) can also be seen in the constellation. The symbols are then pressed more towards the axis and instead of a square arrangement, the symbols have a more rectangular positioning (**see Figure 5**).

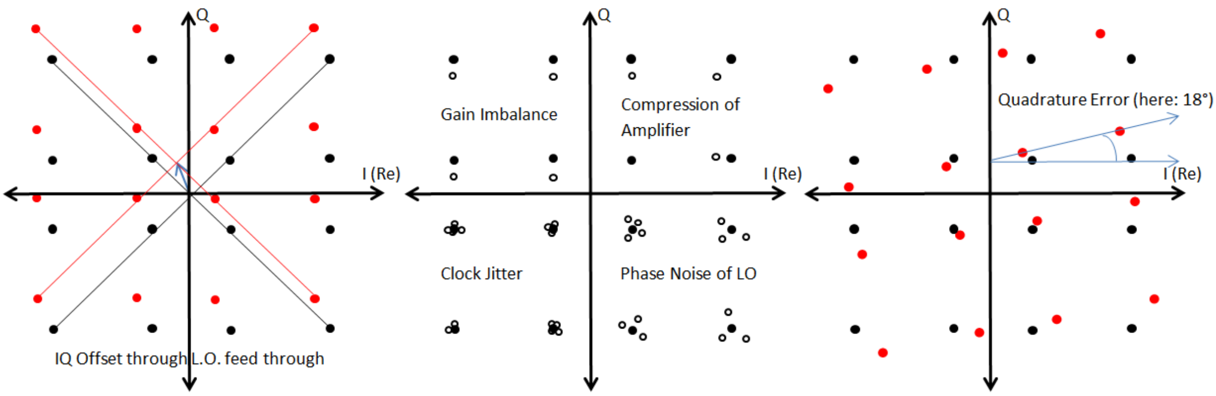

Figure 5: Different impact to constellation measurement due to transmitter components

- Especially with higher modulation schemes such as 64QAM, digitally modulated signals have a large distance between the maximum amplitude and the effective value due to the different amplitude distances on the respective constellation points. This is why amplifiers with a large linear range are required in the transmitter. The highest expected amplitude value should therefore be set directly below the 1 dB compression point in order to optimally exploit the full linearity. If the operating point of the amplifier is not correctly adjusted at both constellation points, then the maximum amplitudes could be in the compression range. This compression is also visible in the constellation measurement. The maximum amplitudes are pressed more to the middle of the diagram.

- Due to increased jitter on the clock signal or if the low-pass filter of the baseband signal is not optimally dimensioned, inter-symbol interferences can occur, which then also leads to errors because the measured symbol values deviate from the reference values.
- If the phase noise is too high with the LO, then the measured symbol points circle around the reference value.
- Another effect can be seen if the amplitude is correct but the phase difference between I and Q is not exactly 90°. Then the complete constellation diagram can incline with the error phase (quadrature error).

Figure 6 shows four different measurements. With the RSA5000N VSA it is possible to enter a synchronization pattern to stabilize the modulation. This pattern is then highlighted in the symbol display. Another possibility of modulation stabilization would be the burst search, which can also be used in the VSA.

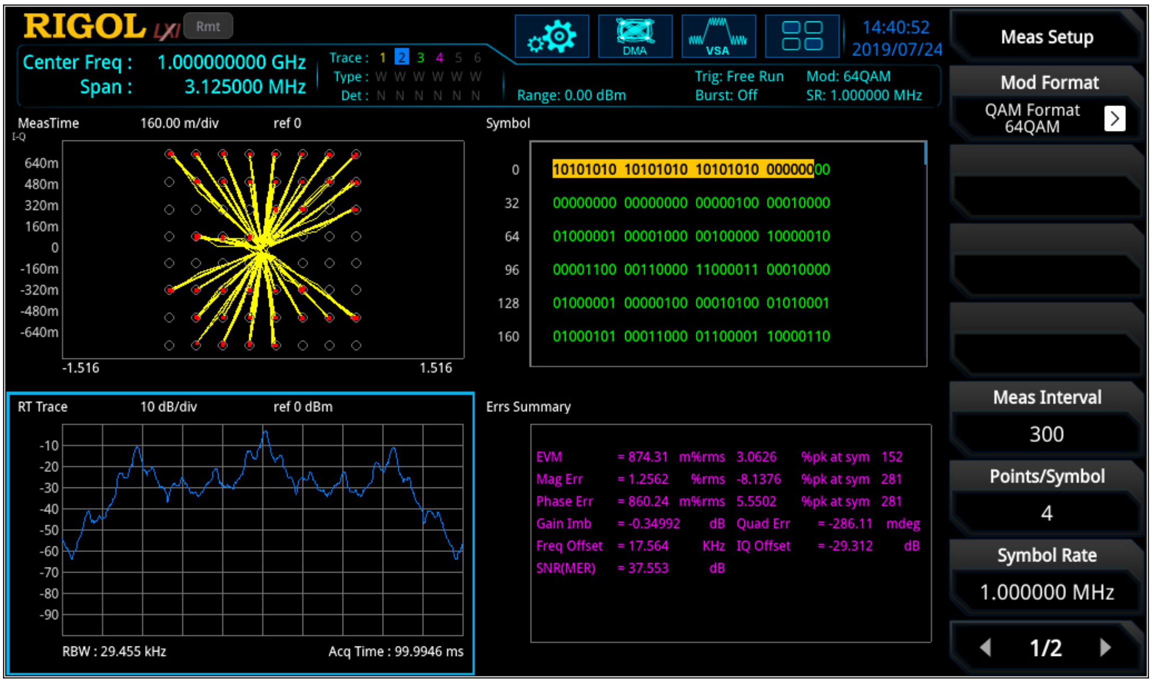

Figure 6: Measurement of an RF transmitter with the RSA5000N VSA mode: constellation view, error measurement, frequency display (real time) and the display of the decoded symbols

If deviations have been detected by the previous measurements, the respective I and Q components can also be analyzed separately. One way to do this is to display the eye diagram, where the waveforms for all symbols are superimposed. As soon as the eye closes, there is a problem. If the eye is well opened, it can be concluded that the baseband components are not the reason of the problem. Markers can also be used for this measurement and it can be compared with the optimal reference eye diagram. Errors in filters, clock jitter or increased noise lead to deterioration of the eye opening (**see Figure 7**).

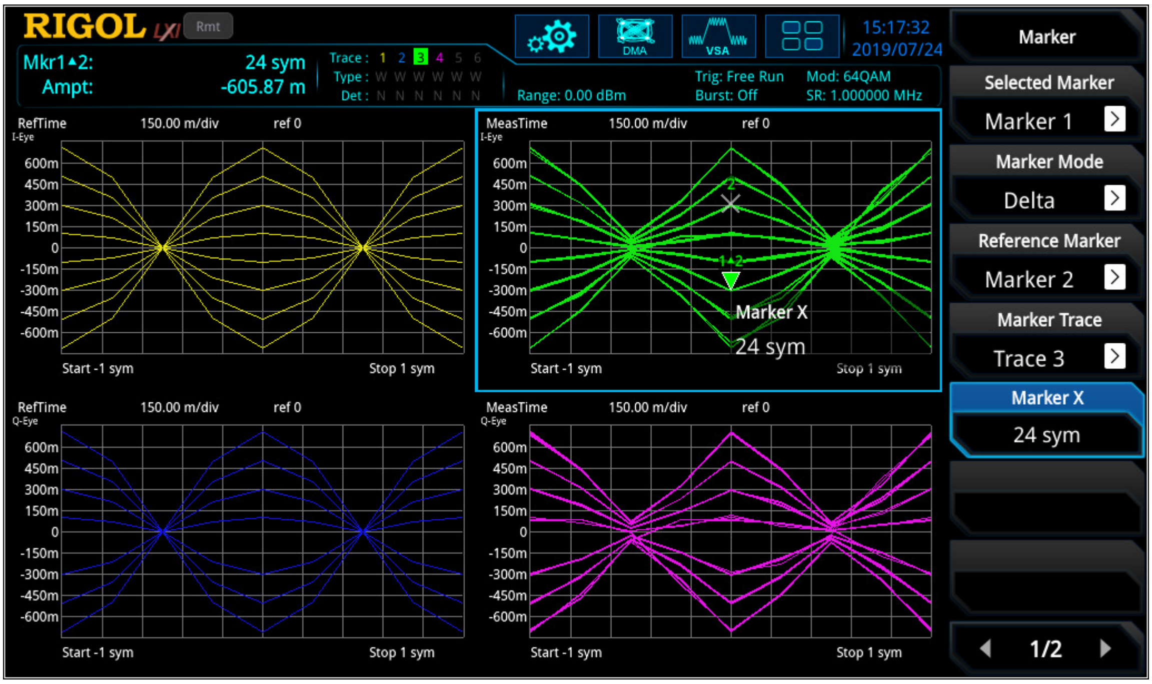

Figure 7: Eye diagram analysis of a 64QAM signal and comparison to the optimal reference

Another important indicator for an RF transmitter is the measurement of the Bit Error Rate [BER]. **Figure 8** shows the BER measurement in VSA mode. For this test, you can load a self-edited *.xml file with the data comparison content into the device. Depending on what is specified for a BER and what data rate the modulation has, the duration of the BER test should be selected.

Figure 8: Measurement of the bit error rate of a 64QAM signal

RF characteristics of components

To ensure the high quality of single components it is necessary to measure vector reflection and transmission parameters. For example, a filter can be analyzed (**see Figure 9**) if the design is according to calculation / simulation to fulfill required 3 dB bandwidth, center frequency and its slew rate of filter. Other components like antenna impedance characteristic tests or amplifier matching can be realized with VNA. Helpful tools are smith- and polar chard to evaluate e.g. the quality and the reflection factor of RF components. With the vector network analyzer [VNA] mode in RSA5000NN series RF components can be designed and matched according to the needs. A good functionality of single components of a transmitter can be ensured. On the other side, in case of failure analysis, each single component can be checked with VNA to see a possible root of failure.

RIGOL's VNA solution in RSA5000NN and RSA3000N series can perform three different measurements, which are reflection [S_{11}], transmission [S_{21}] and Distance-To-Fault [DTF] measurements. All three of these measurements have several different views which allows engineers to easily determine a DUT's frequency response, phase, SWR, Smith Charts and Polar Plane measurements

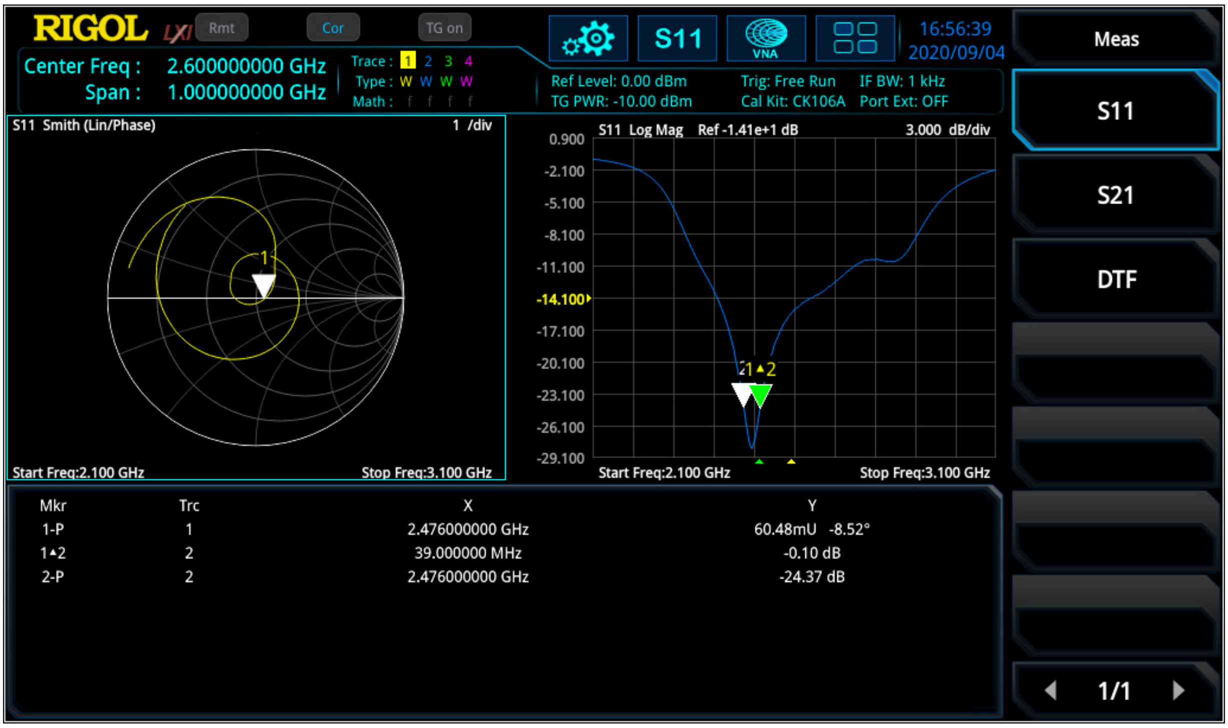

Figure 9: Filter reflection measurement [S_{11}] with RSA5000N Series

Analysis of RF performance

After analyzing the modulation, the quality of the RF signal is now analyzed. Since in theory there are only optimal filters for band limitation, it is not 100% possible to avoid the influence of the utilized channel on the adjacent channels. Part of the broadcast signal will therefore be seen in the adjacent channels. However, since this frequency range is mostly used for other communication, the influence must be kept as low as possible in order to avoid a malfunction due to the transmission of the transmitter. Therefore the absolute power value [in dBm] of the transmitter and the relative influence on the adjacent channels with respect to the transmitter [in dBc] must be known. For this measurement, it is necessary to activate the modulation. In addition, on/off situations should be measured and qualified. The measurement of the adjacent channel power is called Adjacent Channel Power [ACP] (**see Figure 10**). The ACP can be carried out with the sweep-based mode GPSA (AMK option).

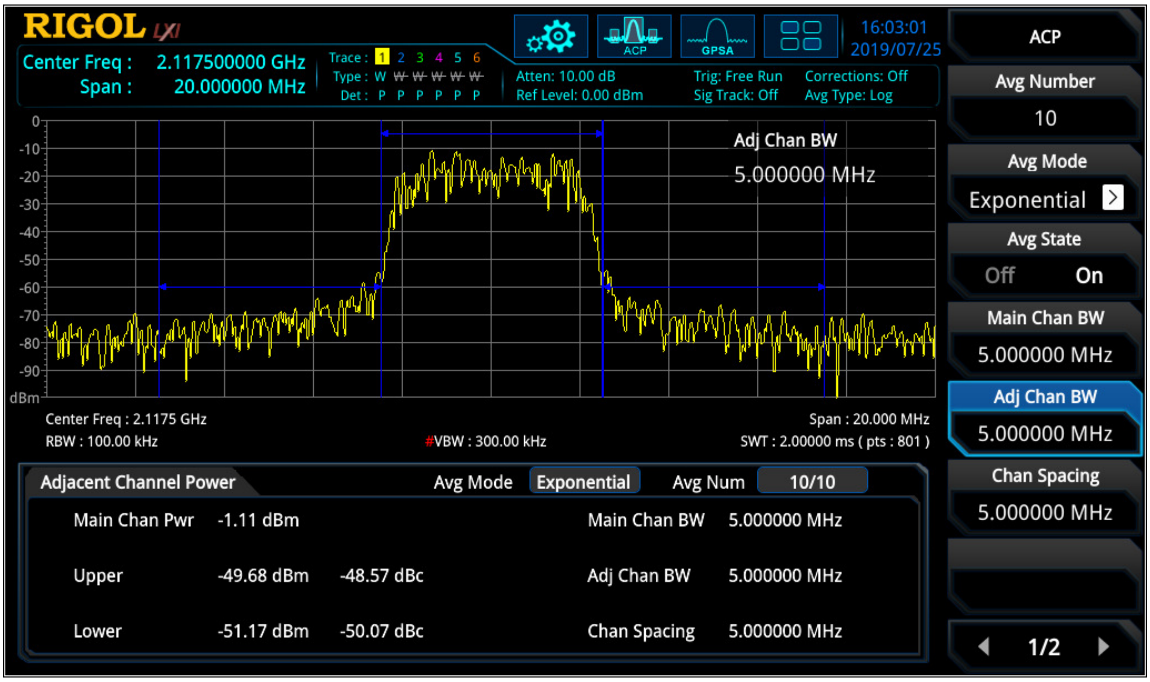

Figure 10: Adjacent channel measurement of a W-CDMA (UMTS) signal

The RSA5000N-GPSA mode can also measure the spectral power density [dBm/Hz] of the main channel and the secondary channels. The entire RF signal is considered for the actually used bandwidth. The bandwidth is broken down into its individual frequency components and their amplitude, which results in the signal power distribution over the frequency (**see Figure 11**). This measurement gives the information about the filter adaptation (for noise suppression) or for the signal-to-noise ratio.

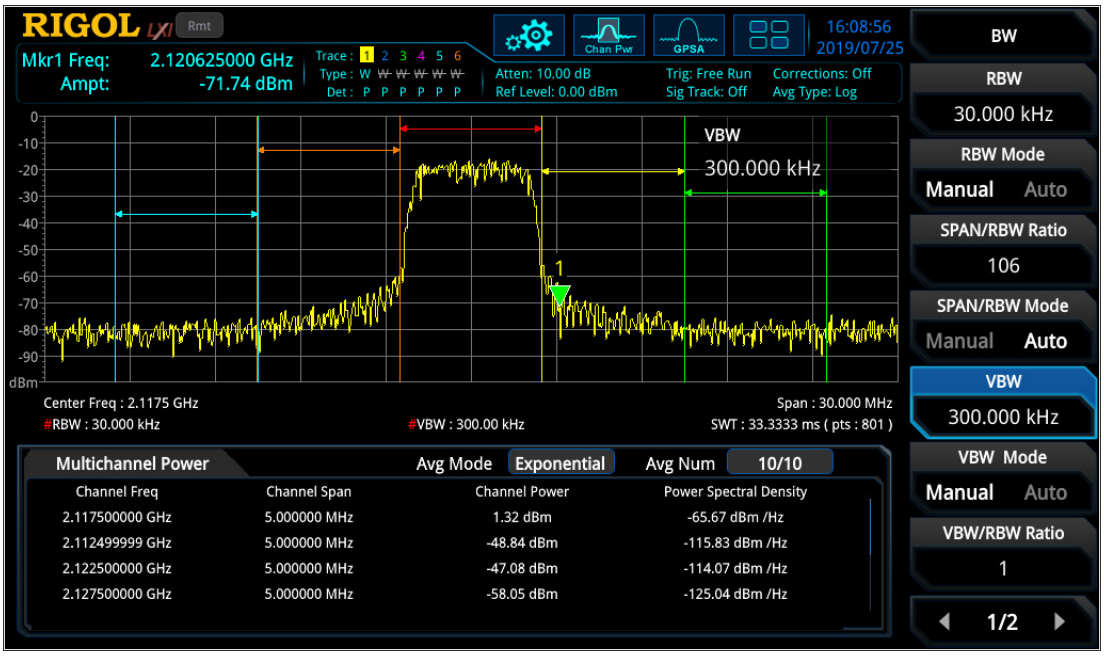

Figure 11: Multichannel power analysis with spectral density power measurement

Another important value, which is mostly specified, is the measurement of the occupied bandwidth. An UMTS signal is considered here as an example (**see Figure 12**). The blocked bandwidth here is 5 MHz. The chip rate for a W-CDMA signal (QPSK modulation) is 3.84 MC/sec. Due to the influence of the filter and its edge condition (rolloff factor: 0.22), the true bandwidth is around 4.6 MHz. This measurement determines the bandwidth that contains 99% of the spectral power of the signal. With reasonably good transmitters, this is around 4.2 MHz.

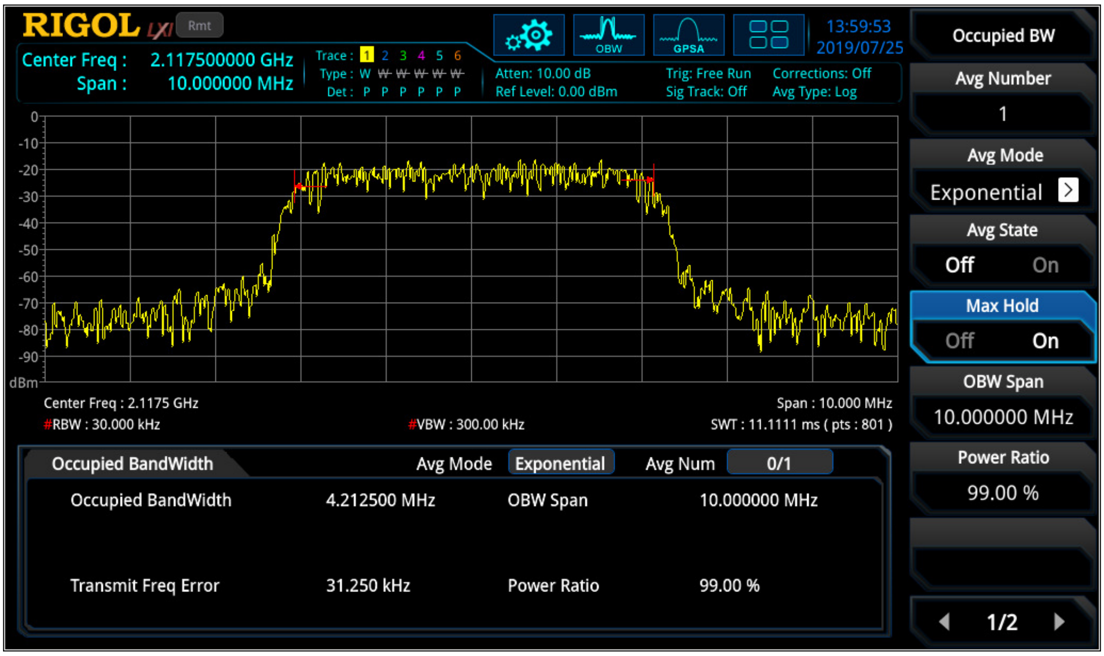

Figure 12: Occupied bandwidth measurement with an UMTS signal, values measured with [max hold]

To measure the individual high-frequency components, an RF signal generator from Rigol's DSG3000-IQ or DSG800A series can be used. These generators offer the possibility of generating the baseband signal and outputting it at the analog IQ outputs on the back (**see Figure 13**). These could be connected to the respective mixer inputs of the I and Q components. An optimal baseband signal could thus be guaranteed in order to measure malfunctions caused by the mixer, the RF amplifier and the bandpass step by step. If this structure shows no errors, further troubleshooting can be limited to the baseband module.

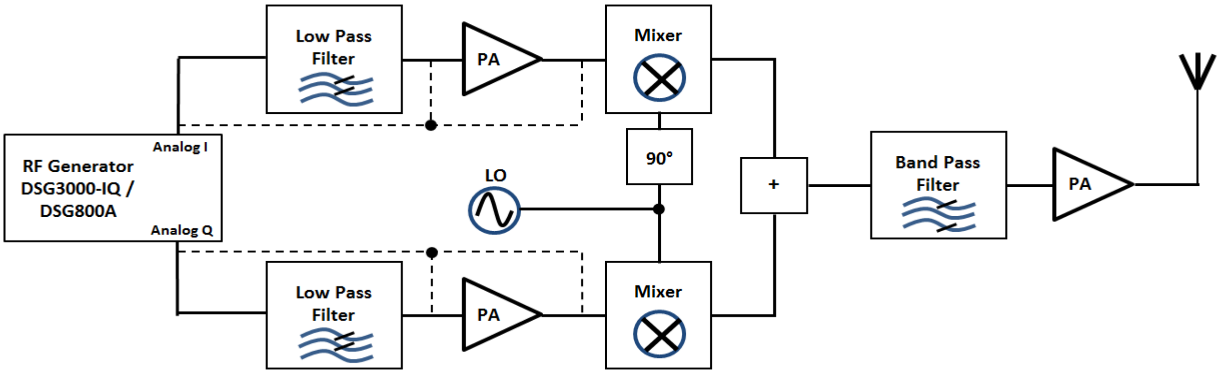

Figure 13: RF performance analysis using an RF signal generator from the DSG3000-IQ or DSG800A series for baseband generation.

The RF generator of the DSG3000 series can also generate a CW signal up to +25 dBm. A LO can also be simulated in order to analyze or rule out a source of error on the mixer or through the LO.

The RSA5000N series is available with or without a Tracking Generator [TG] which can be used in GPSA mode to reduce the passage loss of components (e.g. filters) or the VSWR value (e.g. an antenna).

With the sweep-based GPSA mode, it is sometimes difficult to measure sporadic and rapidly changing interference signals. In order to be able to detect these unexpected interference signals from a transmitter, the real-time mode of the RSA5000N can be used here. **Figure 14** shows a GSM signal that occasionally emits a fault on a side channel. This interference signal can be easily detected with the Frequency Mask Trigger [FMT] in real time mode. With the density display in combination with the spectrogram, extended information can be generated, e.g. measure the repetition rate and the duration of the interference signal.

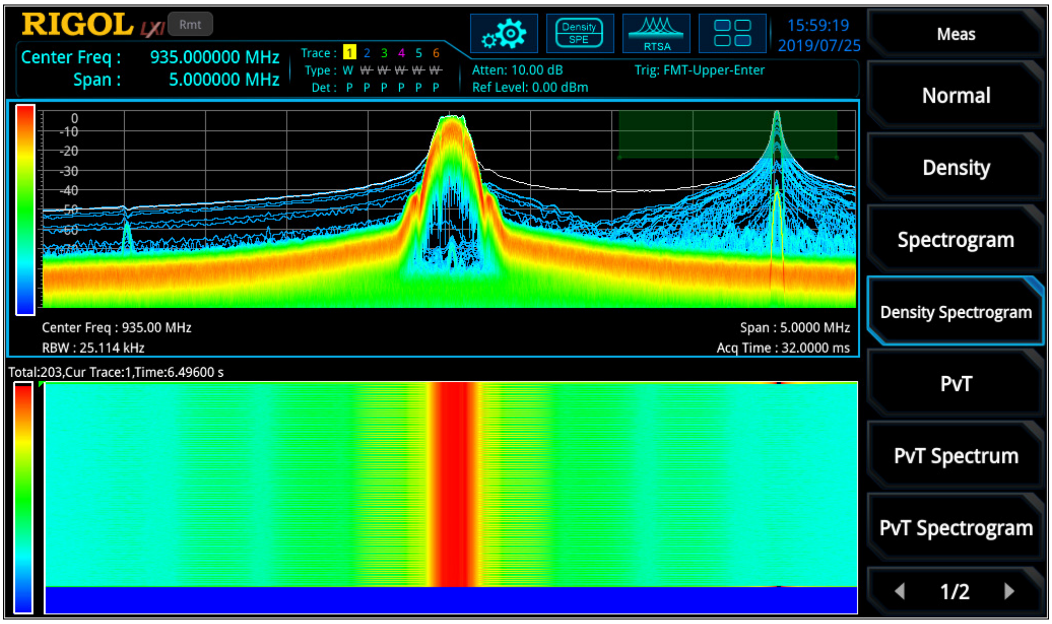

Figure 14: Measurement of an unwanted interference signal with a GSM transmitter in real-time mode

In order to obtain more precise knowledge of signal bursts in the case of modulated signals, in real-time mode it is possible to display a time representation with the maximum information content of up to 40 MHz real-time bandwidth. At the same time, the spectrum and the spectrogram can be displayed here. All areas can be measured with the marker (**see Figure 15**). For example, you can measure the period and the burst width. Unexpected events would be visible in the spectrogram. Time measurement can also be used to measure on/off situations.

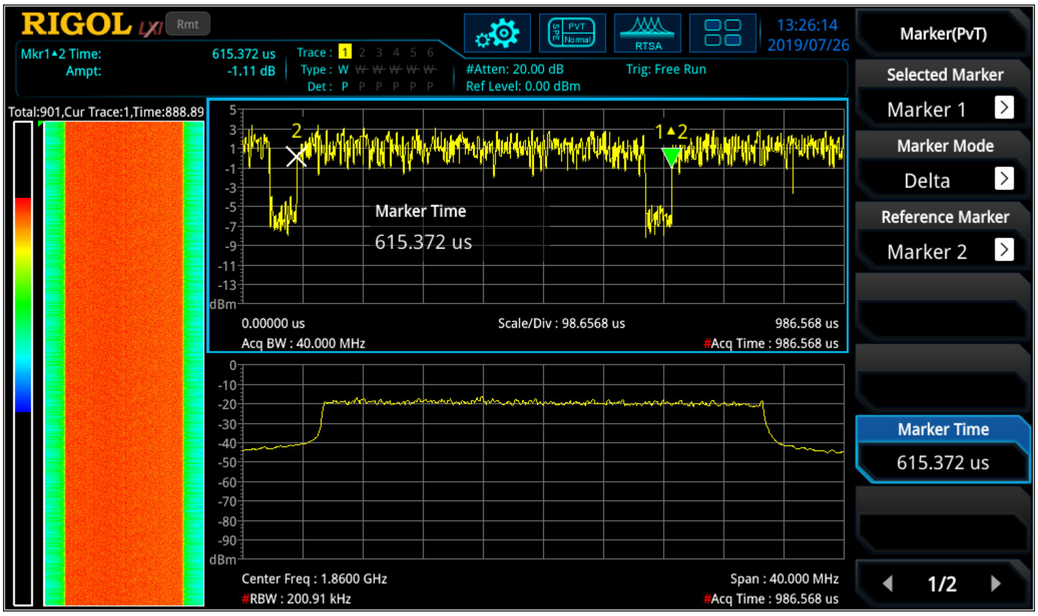

Figure 15: Time domain measurement (top) and frequency measurement (bottom) as well as the spectrogram (left) of a modulated RF signal of a transmitter

EMC Pre-conformity evaluation during transmitter development

During the development of the transmitter, taking EMC into account is an important aspect. The earlier you take EMC measures into account in the design, the less likely it is that EMC problems will ultimately arise. This requires a very good test system right from the start of development. With the EMI mode of the RSA5000N series, Rigol offers a comprehensive test system that can be used for analysis and troubleshooting through the entire development steps (**see Figure 16**). This mode includes the 6 dB filters (200 Hz, 9 kHz, 120 kHz and 1 MHz) and the weighted detectors (QP, CISPR-AV). A frequency resolution of RBW/2 or RBW/4 can be achieved with the predefined frequency ranges. It is possible to perform a quick scan with an average or peak detector. When the peak values are found, the measurements can then be carried out with the evaluated detectors. Since the measurement is only carried out at the peak values, the measurement is completed in a short time. The EMI mode also contains a measuring meter with up to 3 different detectors. The meter can be set to an interference signal and readjusted. The improvement is immediately visible. Over 300 limits of the most used standards are integrated in the device and can be selected as required. In addition, a test report with all measured values, the graph and other settings can be saved on the device in HTML or as a PDF. In addition, the signal curve can also be saved as *.csv.

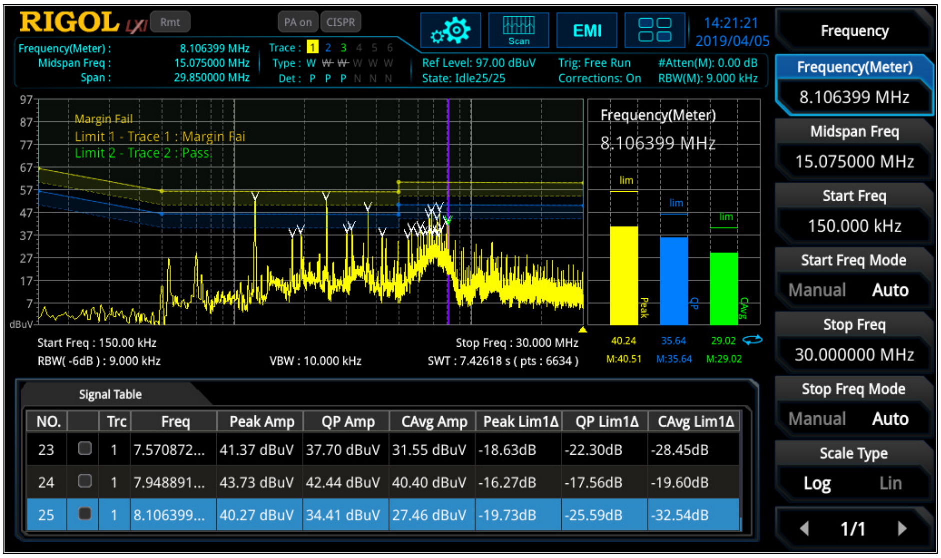

Figure 16: View of EMI measurement with the trace, meters (right side) and signal table (below) with results

Summary:

Rigol's RSA5000N series is an optimal tool with multiple test solutions that is used for the complete transmitter development. Especially with the different modes (Real-time / Sweep-based / VSA / EMI / VNA), a variety of different measurements can be carried out, which in combination with the outstanding performance means significant added value for the development engineer, regardless of whether individual components or the complete RF transmitter are measured and need to be evaluated. This device can also be used for a variety of other applications, particularly in development, research, education or in other industrial areas. This device is modularly expandable and can be expanded with the respective modes at a later date.