Wireless communication relies on RF transmitters. A typical mobile phone contains several RF transmitters: for mobile communication (audio, SMS, broadband), Wi-Fi, NFC and Bluetooth, among others. RF transmitters must provide stable and good communication, so choosing the right components at the design stage is of crucial importance. For example, when selecting a baseband amplifier, it should have a large, stable, linear range, covering the required bandwidth without spurious signals, and account for internal interferences between the transmitter’s individual components as well as electromagnetic compatibility (EMC) with the environment around it.

Figure 1 shows the block diagram of an RF transmitter. Its first section is the baseband, for digital modulation. Here, a DSP uses a digital data stream (from previously-digitised analogue signals, such as speech, text, images, sound, etc.) for line coding, interleaving and modulation. For modulation, bits are combined into symbols according to the chosen modulation scheme. For example, in schemes such as Quadrature Phase-Shift Keying (QPSK) and M-ary Quadrature Amplitude Modulation (QAM), each symbol can be described with a digital in-phase component, or vector, I, and a quadrature component, Q. In QPSK modulation, there are two bits (dibits) per symbol, whereas in 64-QAM there are six.

QPSK is a phase modulation in which the amplitude remains the same for all symbols; see Figure 2. QAM, on the other hand, modulates both, phase and amplitude, hence the positions of its symbols depend on the phase and amplitude of the IQ vectors.

To determine the reference signal, the transmitter’s modulation scheme, sampling rate, filter and filter edge are all considered.
The IQ vectors can also be described as a sine (Q) and a cosine (I), which, as we know, are offset by 90°, i.e. orthogonal to one another, also known as being “in quadrature”.

Components \( C_I(t) \) and \( C_Q(t) \) describe the modulation’s baseband. When available, the baseband’s digital I and Q are converted into an analogue signal, which is then filtered. Filtering is important in order to assign the necessary pulse shape for the best band-limited transmission of the signal. The sine or cosine elements are then mixed (Figure 1). After adding these components, amplifying and filtering them again, they are fed into the antenna. The second filtering is necessary for band limitation and to filter out unwanted interference introduced by components in the signal’s path, since each transmitter component impacts the functionality and quality of the communication. For best output, detailed analyses of each individual component and system are necessary.

### Modulation analysis

The Rigol RSA5000 series Vector Signal Analyser (VSA) option measures in detail the modulation quality of an RF transmitter for different modulation types. It creates an optimal reference signal for comparison with the measured signal. To determine the reference signal, the transmitter’s modulation scheme, sampling rate, filter and filter edge are all considered; this analysis could also involve receiver parameters, too. The comparison between the reference and measured signals then helps determine the Error Vector Magnitude (EVM), phase errors, and more.

The measuring and reference filters can be set and changed in the VSA. The reference filter contains information of the filters from the sender and the receiver; on the other hand, the measuring filter contains the information of the recipient. These include:

<table>
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<tr>
<th>Time</th>
<th>Spectrum</th>
<th>Demodulation Error Traces</th>
<th>Demodulation</th>
<th>Error View</th>
<th>BER</th>
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<tbody>
<tr>
<td>Log or linear magnitude over symbols</td>
<td>Log or linear magnitude over symbols</td>
<td>Error vector time</td>
<td>Log or linear magnitude over symbols</td>
<td>Error View</td>
<td>BER</td>
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<tr>
<td>Inphase or quadrature over symbols</td>
<td>Inphase or quadrature over symbols</td>
<td>Error vector spectrum</td>
<td>Inphase or quadrature over symbols</td>
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<td>Wrap or unwrap phase over symbols</td>
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</tr>
<tr>
<td>IQ trace or constellation diagram</td>
<td>IQ magnitude error</td>
<td>Log magnitude error symbols</td>
<td>IQ magnitude error symbols</td>
<td>Log magnitude error symbols</td>
<td>Log magnitude error symbols</td>
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<tr>
<td>Inphase or quadrature eye diagram</td>
<td>IQ phase error</td>
<td>Linear magnitude over symbols</td>
<td>IQ phase error</td>
<td>Linear magnitude over symbols</td>
<td>Linear magnitude over symbols</td>
</tr>
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</table>

**Table 1: RSA5000’s VSA mode measurement capabilities**
• 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);

Table 1 shows the different types of analysis in RSA5000’s VSA mode. Up to four measurements can be displayed simultaneously on one screen, including important measurements such as the constellation diagram in combination with error measurement. One of the most meaningful parameters of the quality of the modulation is EVM between the optimal reference and the measured vector; see Figure 3.

The reference value of the percentage calculation of EVM is the radius to the outermost constellation point. This could be an effective value (that includes all the symbols) or a peak value (the largest deviation). A noisy signal results in a higher EVM, which will cause receiver problems. Depending on the transmitter’s specification, the measured EVM must be lower than its reference.

Another important measurement is the Modulation Error Ratio (MER), similar to the signal-to-noise ratio (SNR). MER must be sufficiently good to keep the receiver symbol values within the decision lines; see Figure 2, right. For 64-QAM, a very good MER is 32-64dB. An MER of around 20dB would lead to increased bit errors, reducing the quality of the entire communication.

The higher the number of modulation symbols, the smaller the decision areas and the better the MER must be.

Figure 4: Transmitter components making different impacts on the constellation measurements

Figure 5: RF transmitter measurement with the RSA5000 VSA mode: constellation view, error measurement, frequency display (real time) and display of the decoded symbols
Figure 6: Eye diagram analysis of a 64-QAM signal and comparison to the optimal reference.

Figure 7: Measurement of the bit error rate of a 64-QAM signal.
Individual component analysis

To achieve stable, high-quality modulation, the baseband signal must be very accurate. Modulation errors can occur in the RF transmitter in many ways, most caused by individual components. The constellation diagram sheds a light on each component; here are some examples:

- If, say, the local oscillator (LO) phase noise is not completely suppressed by the mixer, it will show as an IQ offset in the constellation diagram. This means all measurement points will look shifted away from the centre of the constellation.
- The baseband amplifiers can also be a source of problems. If they have different gains for I and Q, then amplifier distortion (IQ
feature: T&M

Figure 10: Occupied bandwidth measurement with a UMTS signal

imbalance) will show in the constellation. The symbols will appear closer to the axis and, instead of a square arrangement, the symbols will be displayed in a rectangular manner; see Figure 4.

- Especially with higher-order modulation schemes such as 64-QAM, digitally-modulated signals have large constellation distances between their maximum and effective amplitudes, hence the need for transmitters with large linear ranges. For full use of the linearity range, the highest expected amplitude value should be set directly below the 1dB compression point. If the operating point of the amplifier is not correctly adjusted at both constellation points, then the maximum amplitudes will be in the compression range, also visible in the constellation measurements – the maximum amplitudes move closer 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 adjusted, inter-symbol interferences can occur, leading to errors because the measured symbol values deviate from those of the reference.

- If the phase noise is too high, then the measured symbol forms a circle around the reference value.

- Another error 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 offsets with an error phase (quadrature error). Figure 5 shows four different measurements. With the RSA5000 VSA it is possible to enter a synchronisation pattern to stabilise the modulation, which could also be achieved with burst search.

- If previous measurements have detected deviations, the respective I and Q components can also be analysed separately. One way to do this is with the eye diagram, where the waveforms for all symbols are superimposed. If the eye is closing, there is a problem. If the eye is wide open, it can be concluded that the baseband components are not causing the problem.

Markers can also be used for this measurement, for easy comparison with the optimal reference eye diagram. Errors in filters, clock jitter or increased noise lead to deterioration of the eye opening; see Figure 6.

Another important indicator of an RF transmitter’s performance is bit error rate (BER); see Figure 7. For this test, a self-edited *.xml file can be downloaded into the device, together with data comparison content.

RF performance analysis

After analysing the modulation, the quality of the RF signal is next. Optimal filters for band limitation exist only in theory, which means it’s not 100% possible to avoid adjacent-channel influences. Part of the broadcast signal will therefore be seen in the adjacent channels. However, since this frequency range is mostly used for other communication, any interference must be kept to a minimum. This means that the transmitter’s absolute power (in dBm) and its influence on the adjacent channels (in dBc) must be known. For this, it is necessary to activate the modulation, as well as measure the switch-on/switch-off scenarios and their effects.

The Adjacent Channel Power (ACP) measurement is shown in Figure 8. It can be carried out with the sweep-based mode GPSA, or the AMK option in the VSA.

The RSA5000-GPSA mode can also measure the spectral power density (dBm/Hz) of the main and secondary channels. The entire RF signal is considered for the actual bandwidth used. The bandwidth is broken down into individual frequency components and their amplitudes, which results in signal power distribution over frequency; see Figure 9. This measures the filter’s adaptation (for noise suppression), or SNR.

Another important measurement is that of occupied bandwidth. In a UMTS example (Figure 10), the blocked bandwidth is 5MHz. The chip rate for a W-CDMA signal (QPSK modulation) is 3.84Mcps. Due to the influence of the filter and its edge (roll-off: 0.22), the true bandwidth is around 4.6MHz. This measurement determines the bandwidth that contains 99% of the signal’s spectral power, which, with reasonably good transmitters, is around 4.2MHz.
To measure the individual high-frequency components, an RF signal generator from Rigol’s DSG3000-IQ or DSG800A series can be used. These instruments generate the baseband signal and output it at their analogue IQ ports; see Figure 11. These can be connected to the respective mixer inputs for the I and Q components. An optimal baseband signal could thus be guaranteed in order to measure malfunctions caused by the mixer, RF amplifier and bandpass, step by step. If this structure shows no errors, further troubleshooting can be limited to the baseband module.

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

The RSA5000 series is available with or without a tracking generator (TG), which can be used in GPSA mode to reduce component (e.g. filter) losses 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. To detect this unexpected interference from a transmitter, the real-time mode of the RSA5000 can be used. Figure 12 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 density display in combination with the spectrum, additional information can be generated, such as the repetition rate and duration of the interference signal.

To obtain more precise knowledge of signal bursts in modulated signals in real-time mode, it is possible to display a time representation with information up to 40MHz. At the same time, the spectrum and its spectrogram can be displayed here. All areas can be measured with the marker; see Figure 13. For example, the period and burst width can be measured. Unexpected events are visible in the spectrogram. Time measurement can also be used to measure switch-on/switch-off situations.
EMC pre-conformity evaluation

Taking EMC into account during the development of the transmitter is an important step. The earlier EMC is measured, the fewer the problems from it in the future. This requires a very good test system at the beginning of the development. RSA5000’s EMI mode offers a comprehensive test system for analysis and troubleshooting through the entire system development; see Figure 14. This mode includes 6dB filters (200Hz, 9kHz, 120kHz and 1MHz) and weighted detectors (QP, CISPR-AV). A frequency resolution of RBW/2 or RBW/4 can be achieved with pre-defined frequency ranges. There’s also the possibility of a quick scan with an average or peak detector. When the peak values are determined, the measurements can be carried out with the evaluated detectors, and completed in a short time.  

Figure 13: Time domain measurement (top) and frequency measurement (bottom) as well as the spectrogram (left) of a modulated RF signal of a transmitter

Figure 14: View of EMI measurements