How to utilize the I/Q Software Interface of the R&S®RTO Oscilloscope with MATLAB®

Application Note

Products:

- R&S®RTO-K11
- R&S®RTO1002
- R&S®RTO1004
- R&S®RTO1012
- R&S®RTO1014
- R&S®RTO1022
- R&S®RTO1024
- R&S®RTO1044

This application note presents the I/Q Software Interface (R&S® K11 option) of the R&S®RTO in the context of remote applications. It demonstrates the basic operation, application examples, and an analysis in MATLAB®.

ROHDE&SCHWARZ

Application Note RTO-K11 SW-IQ

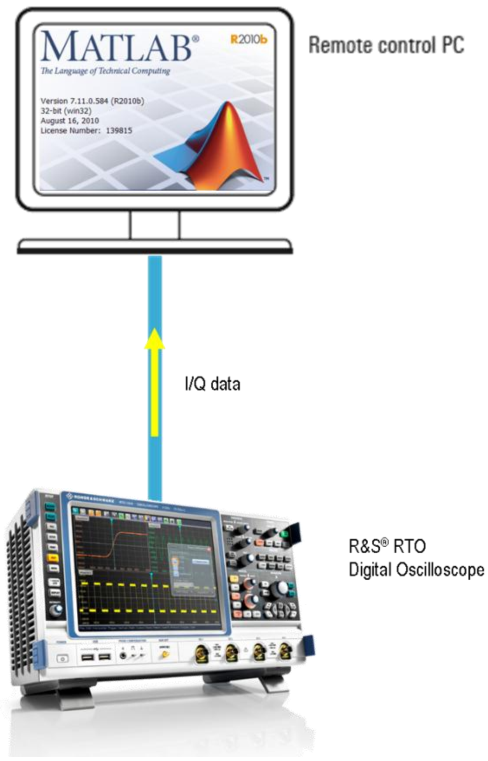
Rafael Ruiz;Dr. Mathias Hellwig

11.01.2013

Table of Contents

1 Introduction

This application note presents the R&S®RTO-K11 I/Q Software Interface option for the R&S®RTO Digital Oscilloscope in the context of MathWorks MATLAB® applications. MATLAB remotely accesses and controls the R&S®RTO-K11 I/Q Software Interface, and extracts the acquired data for analysis of I/Q modulated signals.



In the following, the term R&S®RTO Digital Oscilloscope will be abbreviated as RTO for simplified reading.

The I/Q modulation is a widely used modulation scheme for analog and digital signals [1], frequently referred to as quadrature amplitude modulation (QAM). The variety of applications, which can be addressed, ranges from e.g. NFC, WCDMA, LTE, DVB-T to proprietary digitally modulated signals.

With activated I/Q Software Interface the RTO acquires digitally modulated signals and provides the corresponding I/Q data at a user-defined sample rate. This I/Q data can then be exported to external software tools to be demodulated and analyzed. There are three options to utilize the I/Q Software Interface:

Users can configure the RTO manually and start the acquisition of the I/Q data. In this case the acquired I/Q data can be stored in various formats on a USB memory or the internal hard disk for a later analysis.

A second possibility is remote control of the RTO. A few simple SCPI commands suffice to set up the I/Q Software Interface and to transmit the acquired I/Q data to the analysis tool. Several programming languages can be used for this purpose. However for this task MATLAB® is an ideal tool, as it offers a wide range of analysis functions and convenient remote operation.

As third alternative Rohde & Schwarz offers off-the-shelf tools for application specific analysis, for example the R&S®FS-K10xPC [2] LTE analysis software, the R&S®FS-K112PC [3] NFC analysis software or the R&S®FS-K96PC [4] OFDM Vector Signal analysis software. Those tools provide a complete integration of the RTO with installed I/Q Software Interface option.

First, this application note explains the benefits and the functionality of the RTO I/Q Software Interface. Afterwards it explains the associated MATLAB® instructions via SCPI commands. These instructions allow a MATLAB® program to connect to the RTO, to configure the I/Q Software Interface, to run an acquisition, to download I/Q data from the RTO and to import it to MATLAB® for further processing.

1.1 Benefits of the I/Q Software Interface Option

The I/Q Software Interface option offers the following major benefits:

The first one is the wide bandwidth of up to 4 GHz (RTO1044) for the acquisition of I/Q modulated signals. This is advantageous for applications like wideband radar, pulsed RF signals, high data rate satellite links and frequency hopping communications, which require a wide bandwidth.

As a second benefit, the RTO provides a multichannel measurement capability. If an application requires a multi-channel measurement setup like LTE MIMO [5] signals, the RTO synchronously samples up to 4 channels and maintains the timing relationship among all channels. In the LTE MIMO application example a synchronous acquisition of all channels is mandatory.

Another benefit is the ability to acquire long sequences of I/Q data, due to an efficient use of the acquisition memory. Due to hardware based digital processing steps in the acquisition path (down-conversion, filtering, resampling - see chapter 2), the total acquisition time is increased compared to an acquisition without the aforementioned digital processing. In chapter 3.1 an example will describe this benefit in more detail.

In addition, the bandwidth reduction of the I/Q signal results in an enhancement in resolution so that the user will benefit from a more precise signal analysis. Filtering and resampling implement this bandwidth reduction and spectral components of noise outside the filter bandwidth is removed. This results in an improvement of the SNR and hence in an enhanced resolution.

The RTO shows good hardware performance. It has a highly sensitive, wideband, low-noise front-end, in combination with a high precision, single core ADC, featuring an ENOB greater than 7. This leads to very good signal analysis results, e.g. EVM. An example is the analysis of an IEEE802.11ac signal with a channel bandwidth of 80 MHz. The IEEE802.11ac signal, down-converted into the baseband or IF band, is acquired with the RTO and analyzed with the FS-K96 OFDM Vector Signal Analysis. The EVM comes out to -42 dB [6], which is very close to the EVM figure that an analysis with a mid-range spectrum analyzer would provide.

The RTO is the only oscilloscope currently on the market, which offers a processing of I/Q modulated signals. In comparison with other products, the user does not have to care about down-conversion, filtering and resampling in his external analysis tool. Implementing this functionality in software turns out to be slow and error-prone. With the RTO, which takes care of it, the user can start right away with the analysis of I/Q modulated signals.

2 I/Q Software Interface Functionality

In order to gain a good understanding of the potential of the I/Q Software Interface, a simple example is chosen, to elaborate on the features of the I/Q Software Interface.

Figure 1 shows a conventional I/Q receiver, which should serve in the following section as a model for discussion (DUT). It feeds an I/Q modulated RF signal, received from an antenna to an input amplifier. In the next step, the signal is split and multiplied with two orthogonal sinusoidal signals, derived from the same source with the carrier frequency f_c. Whether the input signal is shifted into the baseband or to an IF frequency does not matter for the I/Q Software Interface as the RTO will deal with both measurement setups. The conventional receiver digitizes the down-converted I/Q signal and makes it available for further digital signal processing steps.

In the provided example, the RTO can tap the signal at various stages up to 4 GHz, either directly at the antenna, past the first amplifier stage or as an already down-converted I/Q signal past the band filter. The letters A, B, C in Figure 1 denote the corresponding measurement points respectively. Based on the measurement point (A, B, C) the appropriate mode in the RTO-K11 needs to be selected. Each mode shows a block diagram (see Figure 3, Figure 6, and Figure 8) to ease configuration of the RTO.

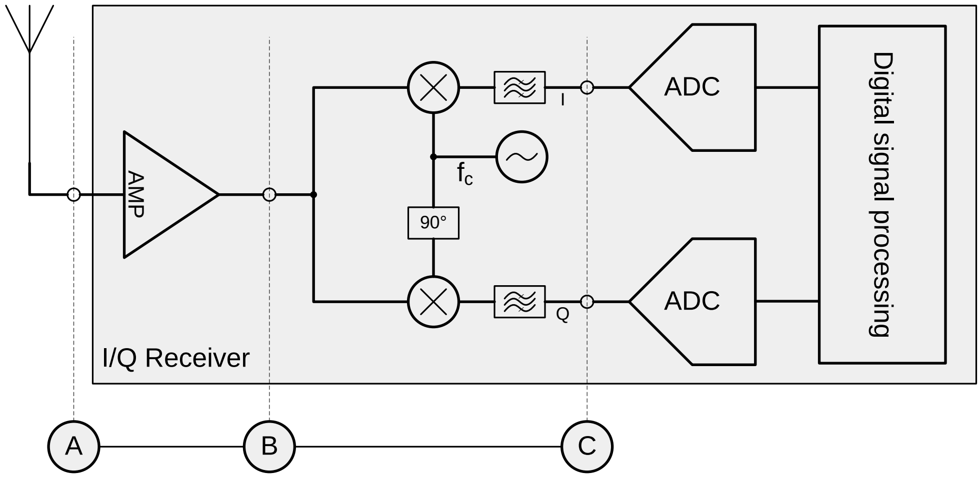


Figure 1 Conventional I/Q receiver with measurement points A, B, C

The RTO supports the acquisition of I/Q modulated signals for test purpose. Depending on the selected mode in the I/Q Software Interface a down-conversion in real-time is done in the acquisition path of the RTO. This is accomplished by digitally multiplying the digitized signal with a complex number ($e^{j2\pi f_c t}$) generated by a NCO. The down-conversion stage is followed by a low-pass filter, which prevents an aliasing in the subsequent stage. A resampling of the signal in hardware reduces data rate and conversely increases the acquisition time under the assumption of a limited acquisition memory size.

The resampling in conjunction with the low-pass filter also increases the SNR of the acquired signal or in other terms enhances the resolution due to bandwidth reduction and the associated noise filtering. As an example Figure 2 demonstrates this effect. A band-limited signal $S(f+f_c)$ is located in the baseband after a down-conversion from a frequency f_c. The allocated spectral bandwidth of the signal is less than $2*f_B$. Additionally there is a noise signal $N(f)$ in the range from $-f_s/2$ to $f_s/2$ present, with f_s as the sample rate of the ADC. This noise signal has an uniformly distributed power density. Both, signal and noise power, determine the SNR. The low-pass filter attenuates the spectral content outside the cut-off frequency f_B, which affects only the noise signal $N(f)$. This results in an improvement in SNR and subsequently in an enhanced resolution.

The hardware provides sufficient precision so that after the resampling step the data is stored with higher precision in the acquisition memory than the originally sampled 8-bit. The user's benefit in his signal analysis is the enhanced resolution and higher accuracy.

The different blocks of the I/Q Software Interface are activated based on the selected configuration. The effect of these functional blocks to the I/Q signal is discussed in the associated figures (see Figure 4, Figure 7) in the specific sub-sections.

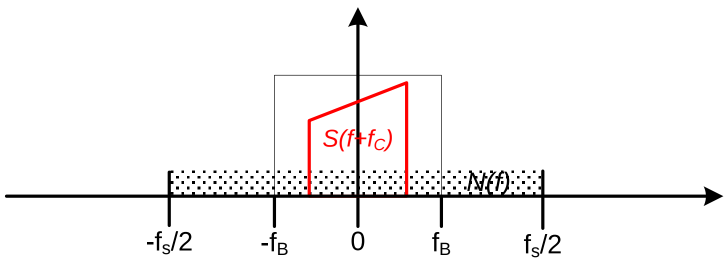


Figure 2 SNR enhancement based on bandwidth reduction

After the I/Q data is processed and stored in the acquisition memory, it is available for remote download. To keep the computational and transmission overhead small, the recommended data format for the transmitted I/Q data is a binary floating point number.

2.1 I/Q Modulated RF Signals

The most intuitive way to connect an I/Q modulated RF signal to a RTO is depicted in Figure 3. It occupies just a single channel. Using the example of Figure 1 the RTO in this case is connected to the measurement points A or B. The RTO acquires the RF signal, performs the A/D conversion followed by a hardware based down-conversion. The resulting complex data is low-pass filtered, and resampled to the selected sample rate.

At max four channels can be acquired in parallel depending on the number of channels, which the oscilloscope provides. Figure 3 shows a block diagram and the configurable parameters associated with the block diagram. Table 1 at the end of this section clarifies parameters, which are specific for this mode (carrier frequency, sideband option, input type). Table 4, in chapter 2.4, discusses common settings (relative bandwidth, sample rate, record length).

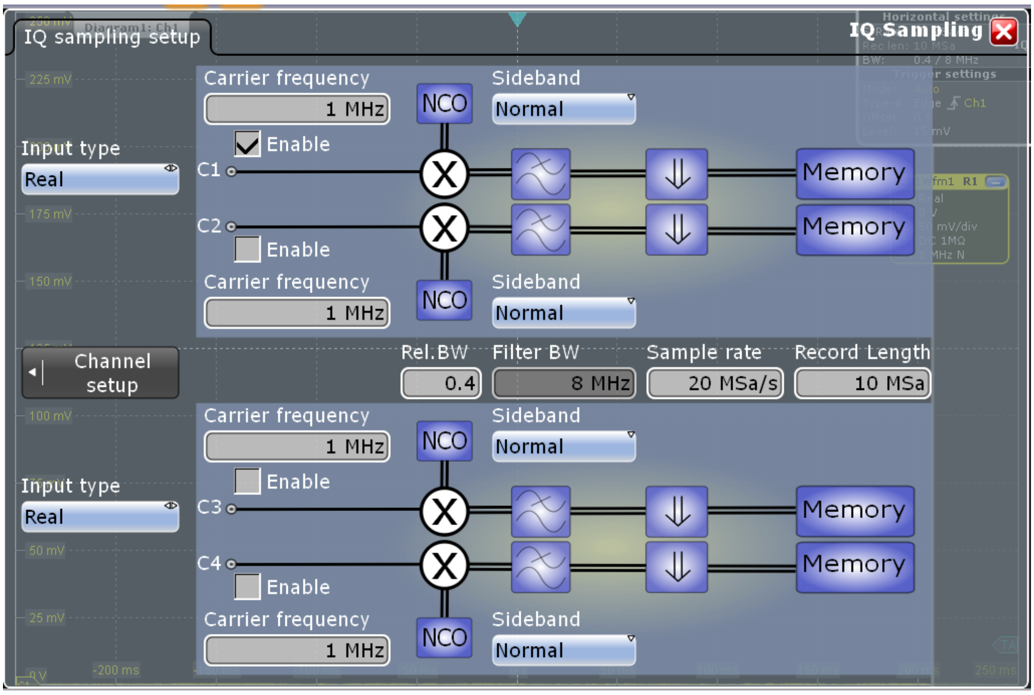


Figure 3 RF signals

The associated effect on the signal in the frequency domain is shown in Figure 4 for either sideband option. The I/Q modulated RF signal exhibits a band-limited spectrum around the origin shown in black, solid lines. Due to the down-conversion, which is a multiplication with $e^{\pm j2\pi f_c t}$, the spectrum is shifted. The direction of the shift depends on the algebraic sign in the exponent, and is controlled by the sideband option. The resulting spectrum is shown in solid, red lines. The low-pass filter is denoted with a dashed black line, and will remove the shifted undesired part of the spectrum at $\pm 2f_c$.

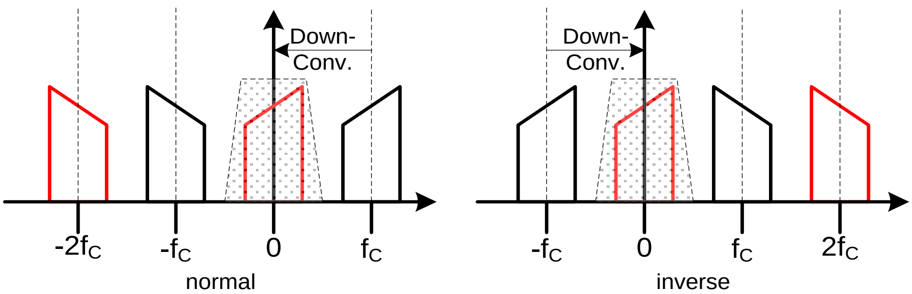


Figure 4 RF signals – sideband options

Parameter	Min	Max	Incr	SCPI command
Carrier frequency [Hz]	0.1k	5.0G	0.1k	IQ:CFRequency <*IQCarrierFreq*>
Sideband	Normal / Inverse			IQ:SBRF <*IQSidebandRF*>
Input type	Real			IQ:INPType <*IQInputType*>
SCPI commands are prefixed by the channel				CHANnel<*m*>:

Table 1 specific configuration options for RF signals

The maximum, configurable carrier frequency of 5 GHz in Table 1 denotes the mathematical limit of the down-conversion.

2.2 Complex I/Q Modulated Signals in low-IF Range

Referring back to the example of a conventional I/Q receiver in Figure 1, the RTO also supports the measurement of complex I/Q modulated signals in the low-IF range. The RTO can tap such a signal at the measurement point C in Figure 1, if it needs to be analyzed to test the correctness of the design. The RTO acquires the signals (I & Q) at this measurement point and down-converts them. The entire measurement setup is shown in Figure 5, where on the left-hand side the example I/Q receiver implements the analog front end up to the point C, marked with a red dashed line. The RTO connects from this point on the right-hand side, implementing the digital back end for test purpose.

A concept using a low intermediate frequency f_{IF} is commonly the choice, if the design of a I/Q receiver is sensitive to DC offset and *1/f* noise of elements in the signal path. E.g. A/D converters tend to have a DC offset, causing signal problems and SNR degradations. Therefore the I/Q receiver in the example does not down-convert the signal into the baseband, rather it converts the I/Q modulated RF signal down to a non-zero low intermediate frequency f_{IF} in a first step. In a second step, the digital back-end of the low-IF-receiver will digitize the signal, shift it from the IF frequency to baseband. In a last step it simply filters out the undesired spectral components. In the application example (see Figure 5), the RTO, which taps the I/Q signal at measurement point C, does the same as the digital back-end of the example receiver.

The effect on the signal in the frequency domain is shown in Figure 5 with the measurement points B, C, D, E. The original I/Q modulated RF signal (B), is down-converted by the analog front end of the I/Q receiver (C), marked with “1st”. The resulting intermediate frequency f_{IF} is typically only a few MHz. Once this signal is sampled, the unintentionally inserted DC offset and *1/f* noise are added to the spectrum (D). For simplicity only the DC offset is shown. Offset and noise can be then easily removed by a digital low pass filter (LPF) after the final digital down-conversion, marked with “2nd”, as these spectral components are shifted out of the baseband (E) due to the second down-conversion.

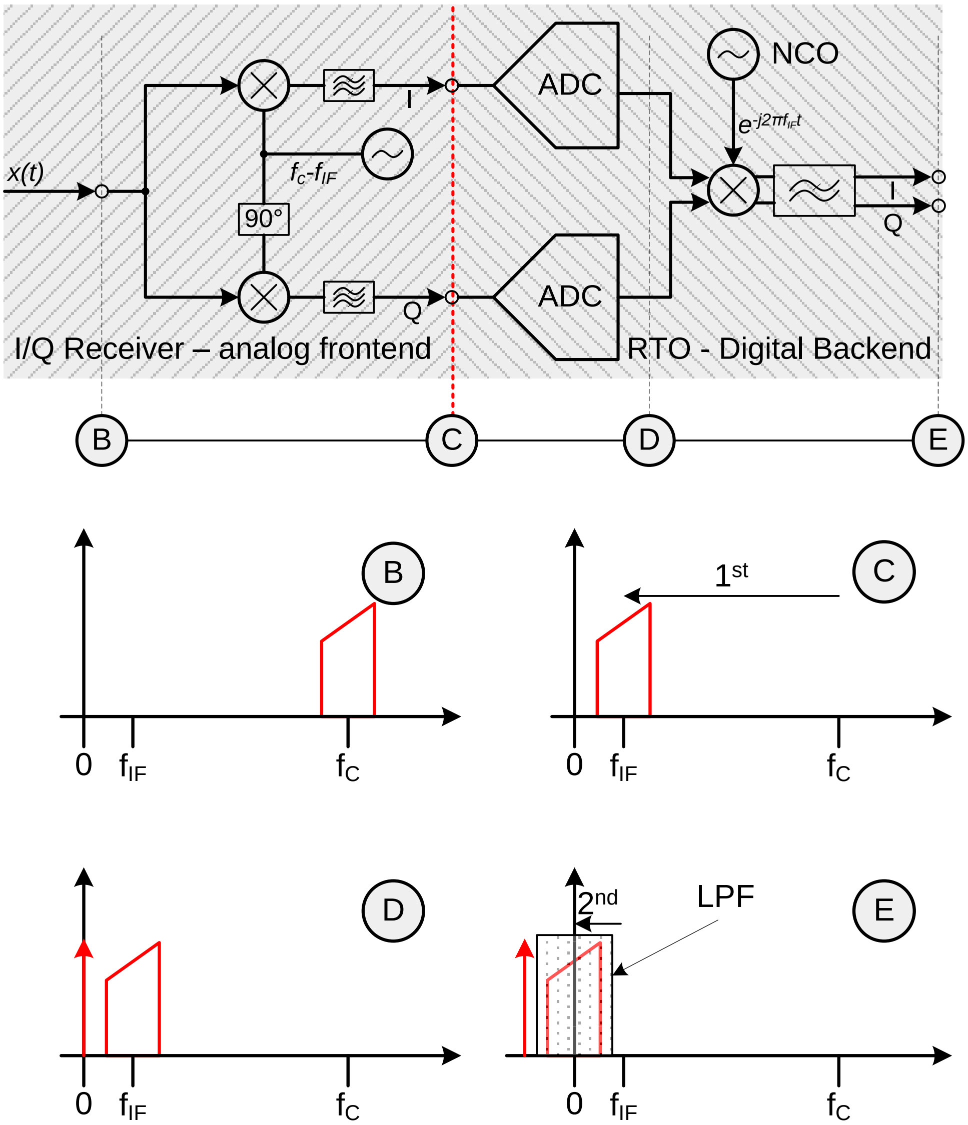


Figure 5 Complex modulated signals in low-IF range

Such low-IF-receivers are nowadays widely used in the tiny FM receivers incorporated into MP3 players and mobile phones; and it is becoming common place in both analog and digital TV receiver designs.

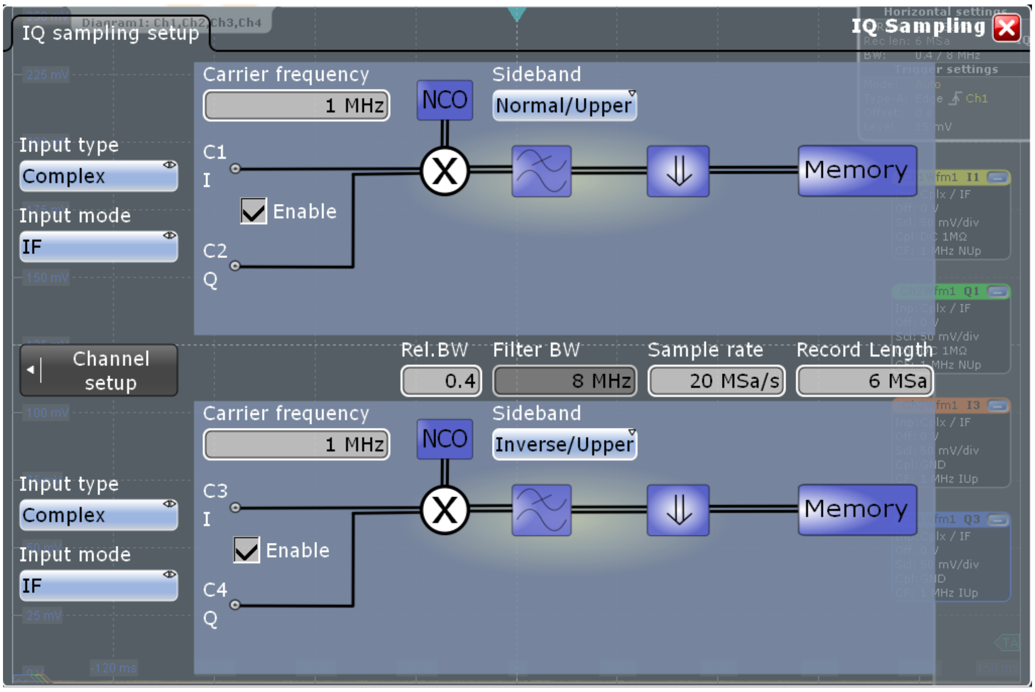


Figure 6 complex modulated signals in low-IF range

The digital backend of a low-IF-receiver can be emulated by the RTO by connecting the separate I and Q signals to channels 1 & 2 or 3 & 4 as shown in Figure 6. The RTO acquires the IF signal, performs the A/D conversion followed by a hardware based down-conversion from the IF band into the baseband. The resulting complex data is low-pass filtered, and resampled to the selected sample rate.

Table 2 at the end of this section describes parameters, which are specific for this mode (carrier frequency, sideband option, input type, input mode). Table 4, in chapter 2.4, discusses common settings (relative bandwidth, sample rate, record length).

The associated effect on the signal in the frequency domain is shown in Figure 7 for all sideband options. The IF signal exhibits a band-limited spectrum around the carrier frequency f_c shown in black, solid lines. From the RTO point of view this is the carrier frequency f_c, though from the system point of view, it is the IF frequency f_{IF}. In the following discussion only the term carrier frequency f_c will be used, instead of the term IF frequency f_{IF}. Four sideband options are possible. First, the down-conversion shifts the spectrum by a numerical multiplication with $e^{\pm j2\pi f_c t}$. The direction of the shift depends on the algebraic sign in the exponent, and is controlled by the upper/lower sideband option. Furthermore, the spectrum in the baseband is required to be in normal position. Depending on the position, the spectrum must be mirrored after the down-conversion. The mirroring is achieved by the conjugate complex operation, which is controlled by the normal/inverse sideband option. The resulting spectrum is shown in solid, red lines. A dashed black line denotes the low-pass filter, which will remove any undesired part of the original spectrum.

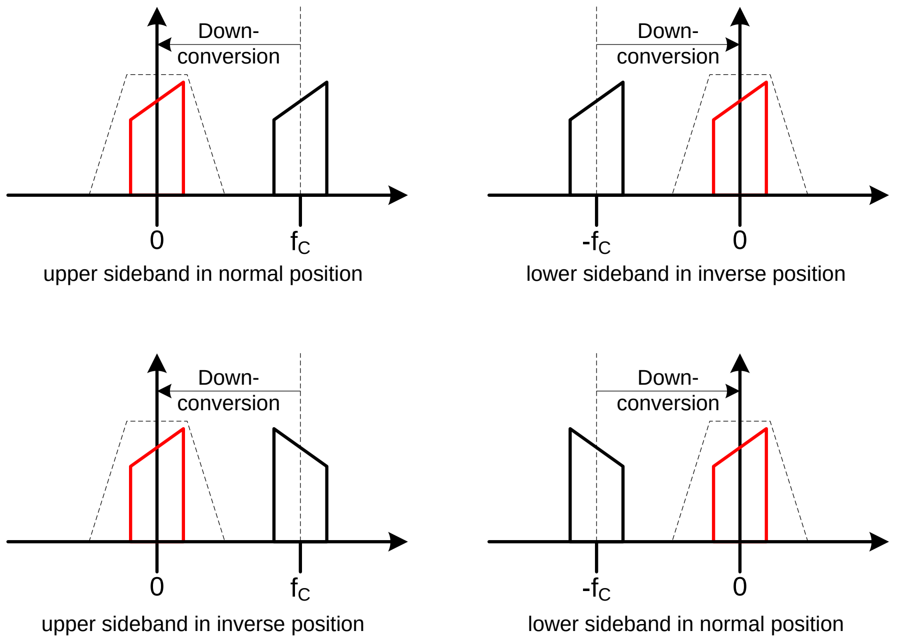


Figure 7 complex modulated signals in low-IF range – sideband options

In this setup, either one I/Q signal can be acquired with a 2 channel RTO, or two I/Q signals with a 4 channel RTO.

Parameter	Min	Max	Incr	SCPI command
Carrier frequency [Hz]	0.1k	5.0G	0.1k	IQ:CFRequency <*IQCarrierFreq*>
Sideband	Upper sideband in normal position Lower sideband in normal position Upper sideband in inverse position Lower sideband in inverse position			IQ:SBIF <*IQSidebandIF*>
Input type	Complex			IQ:INPType <*IQInputType*>
Input mode	IF			IQ:INPMode <*IQInputMode*>
SCPI commands are prefixed by the channel				CHANnel<*m*>:

Table 2 specific configuration options for complex modulated signals in low-IF range

2.3 Complex I/Q Baseband Signals

The complex I/Q baseband signal setup is the last out of three use cases as lined out in Figure 8. Using the receiver example in Figure 1 the RTO acquires signals at measurement point C that are already available as I/Q baseband signals. In this case, the carrier frequency f_c of the I/Q modulated RF signal matches the frequency of the local oscillator. As a consequence a down-conversion is not necessary. Just a low-pass filtering and a resampling to the selected sample rate is applied.

Table 3 explains parameters, which are specific for this mode (input type, input mode). Table 4, in chapter 2.4, discusses common settings (relative bandwidth, sample rate, record length).

Parameter	Value	SCPI command
Input mode	Baseband	IQ:INPMode <*IQInputMode*>
Input type	Complex	IQ:INPType <*IQInputType*>
SCPI commands are prefixed by the channel		CHANnel<*m*>:

Table 3 specific configuration options for complex I/Q modulated baseband signals

In this setup, similar as in chapter 0, either one I/Q signal can be acquired with a 2 channel RTO, or two I/Q signals with a 4 channel RTO. This mode has no effect on the signal in the frequency domain.

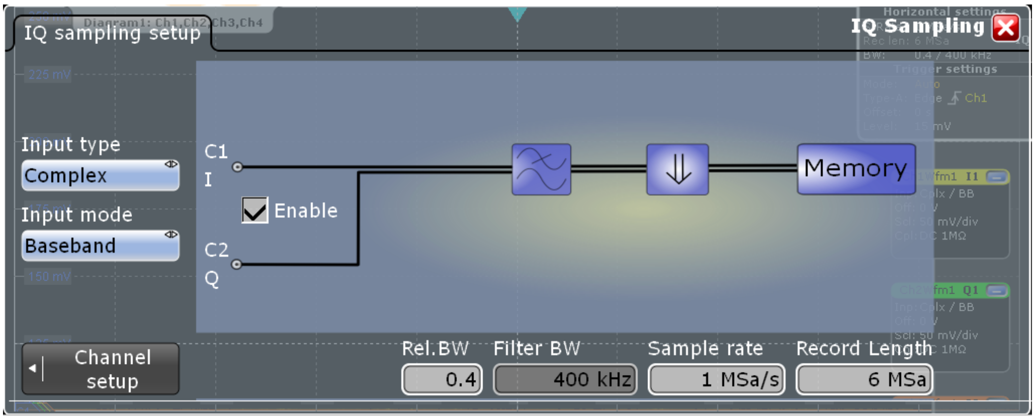


Figure 8 complex I/Q baseband signals

2.4 Common Parameters

A few parameters are common in the acquisition path of I/Q data for all use cases (I/Q Modulated RF Signals, The maximum, configurable carrier frequency of 5 GHz in Table 1 denotes the mathematical limit of the down-conversion.

Complex I/Q Modulated Signals in low-IF Range, Complex I/Q Baseband Signals); these are explained in this section. All the common parameters are summarized in Table 4. These parameters are the record length, the sample rate and the filter bandwidth, which is specified relative to the sample rate. In this section, the sample rate is the rate at which the data samples are stored in the acquisition memory. Figure 9 gives a detailed view of the menu, where to configure these parameters.

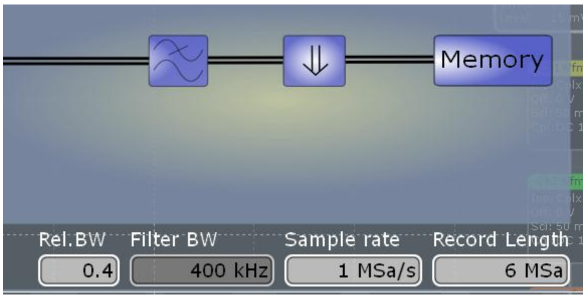


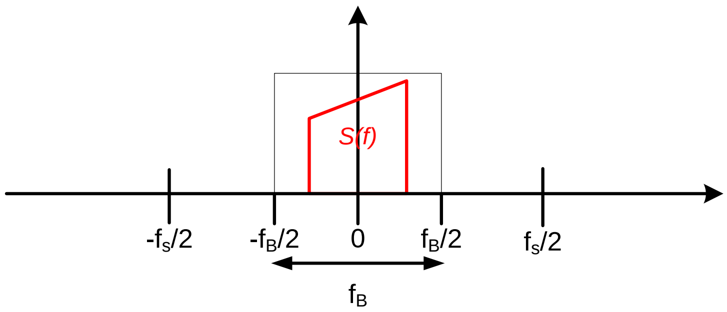
Figure 9 Common Parameters for I/Q signals

As discussed in previous chapters, the low-pass filter ensures the suppression of any undesired spectral components to comply with the Nyquist theorem [7] and it improves the SNR of the I/Q signal. The relationship between sample rate (f_S) and filter bandwidth (f_B) is visualized in Figure 10. Within the filter bandwidth the filter has a flat frequency response (no 3 dB bandwidth).

Parameter	Min	Max	Incr	SCPI command
I/Q mode activation		ON		IQ:STATe <*IQMode*>
Sample rate [Sa/s]	1.0k	10.0G	1	IQ:SRATe <*SampleRate*>
relative bandwidth	0.04	0.80	0.01	IQ:RBWidth <*RelBandwidth*>
Record length [Sa]	1.0k	10M/6M	1	IQ:RLENgth <*RecLength*>
acquisition time	= 'record length' / 'sample rate'			--

Table 4 specific configuration options for RF signals

After resampling, the data is written into the acquisition memory. The record length defines the number of contiguous samples. The maximum record length is 10 MSamples in case of one or two active channels and 6 MSamples in case of three or four active channels. The record length divided by sample rate implicitly gives the acquisition time.



‘filter bandwidth f_B’ = ‘rel. bandwidth’ * ‘sample rate’

Figure 10 relation of filter bandwidth and sample rate

For more detailed information about the I/Q Software Interface functionality, please refer to the user manual [8].

3 Analysis of RTO I/Q Data with MATLAB®

The MATLAB® access to the RTO is explained in five parts; the first one explains the measurement setup. The second one explicates the configuration of the RTO for remote access; the third part is the specific configuration of the I/Q Software Interface, which has been described in detail in the previous chapter “I/Q Software Interface Functionality”. The fourth one is the retrieval of sampled I/Q data from the RTO down to the host PC. Finally the last part demonstrates a simple analysis of the retrieved I/Q data.

Rohde & Schwarz supplies a wide set of information to support the automated measurement with MATLAB®. A detailed reference to individual SCPI commands can be found in the RTO user manual [8] chapter 17.2.16. A specific instruction, how to access the RTO remotely can be found in an application note [9], and a complete MATLAB® sample script to configure and retrieve I/Q data as discussed in this application note can be found as a separate file on the web.

3.1 Measurement Setup

The simplest way to analyze I/Q data is either plotting the baseband I and Q signals in an XY-diagram (see Figure 13, top trace) or the I/Q modulated RF signal over time (see Figure 13, yellow trace in the middle). Nevertheless, the result has limited meaning. In order to demonstrate a meaningful measurement, the recovery of the constellation diagram from an I/Q modulated RF signal, for example, would be a relevant statement about the capabilities of the RTO I/Q Software Interface.

A R&S®SMBV100A signal generator [10] generated the I/Q modulated RF signal for the analysis under discussion. The signal generator was connected to the RTO, providing a signal with a carrier frequency of 400 MHz and a magnitude of -10 dBm. The data subjected to I/Q modulation was a PRBS-9 signal with a symbol rate of 500 ksym/s 16-QAM [1] modulated, with a configured cosine window of 500 kHz (Figure 12) and a roll-off factor of 0.75.

The RF clock of the signal was referenced to the internal oscilloscope clock (REF_CLK, Figure 11), in order to simplify the MATLAB post processing. This requires the RTO to have the RTO-B4 option installed. The reference to the RTO clock avoids a non-trivial code sequence in MATLAB, which would be required to estimate the RF frequency and the symbol rate of the I/Q data. Though this kind of setup does not match a real world application like DVB-T or WCDMA, it explains in great detail the ability of the I/Q Software Interface in MATLAB.

Processing real world I/Q signals is far beyond the scope of this application note. The MATLAB communication toolbox offers complete communication models e.g. DVB-T [11]. Those can be adapted to the I/Q Software Interface.

The measurement arrangement is shown in Figure 11. The RTO was connected to the SMBV on channel 1 with the RF output and on channel 3 & 4 with the baseband I/Q signal. In the rear, the reference clock output of the RTO was connected to the reference input of the SMBV100A.

Before the signal was processed with MATLAB, a brief check with the RTO was done (Figure 13). The I/Q baseband signal was displayed as XY-diagram (pink) and the 16-QAM constellation diagram is recognizable at the top of the display. The middle trace in yellow shows the time domain representation of the RF signal.

The bottom diagram shows the Fast-Fourier-Transform of the time domain RF signal. Clearly the center frequency of 400 MHz and the approximate bandwidth of about 500 kHz can be observed. The signal bandwidth is widened by the roll-off factor.

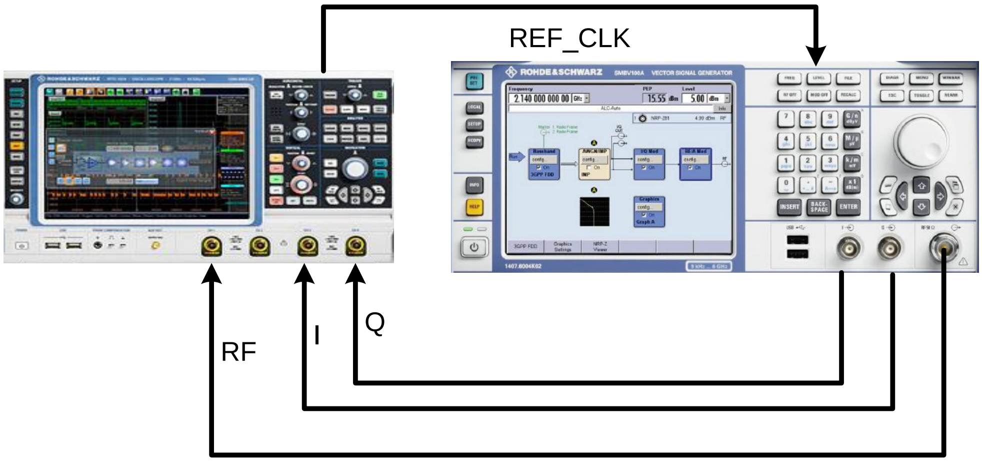


Figure 11 Measurement setup with RTO (l) and SMBV100A (r)

A brief example calculation based on the described I/Q modulated RF signal shall highlight the ability of the RTO-K11 option to acquire long sequences. In the following section, the maximal possible acquisition time for the signal is compared with the acquisition of the same signal using the I/Q Software Interface option.

For the signal analysis without the RTO-K11, the RTO is setup with a sample rate of 2.5 GSa/s, as the signal shows significant 2^{nd} and 3^{rd} harmonics in the spectrum. Using the maximal sample memory of 20 MSamples, the maximum acquisition time is 8 ms without any I/Q signal processing.

To achieve comparable results in the signal analysis using the RTO-K11, the acquisition settings of the RTO are kept the same. For the I/Q Software Interface option, the maximum sample memory is 10 MSamples. Using the symbol rate of 500 ksym/s and a typical oversampling factor of 4, the I/Q sample rate is set to 2 MSamples/s in the RTO. This results in a maximum acquisition time of 5 s, which is 625 times longer than the acquisition time of the raw signal.

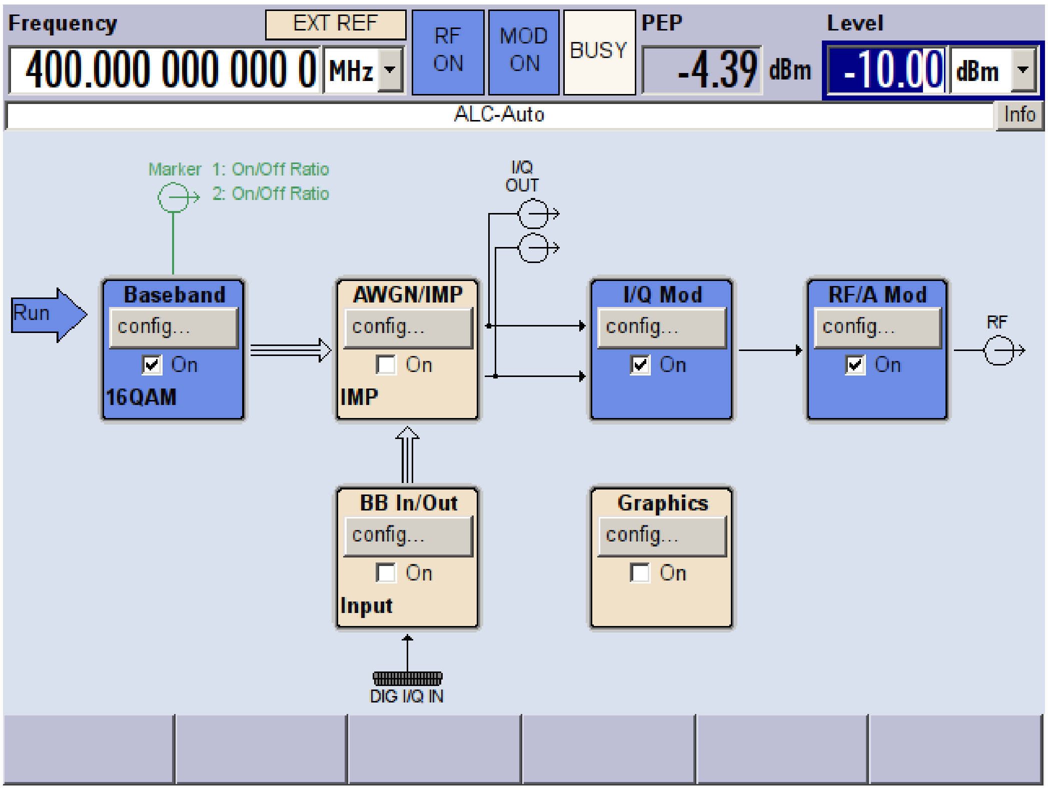


Figure 12 Configuration of the SMBV100A Signal generator

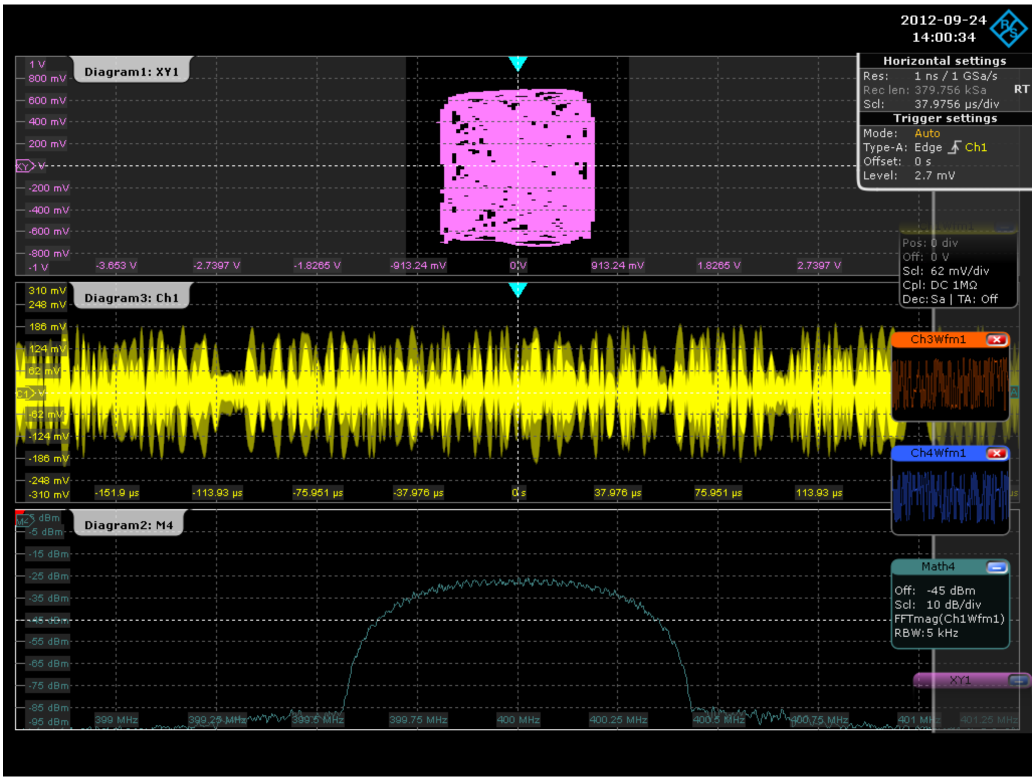


Figure 13 RTO measured I/Q signals

3.2 RTO Basic Configuration

The MATLAB® code snippet in this section demonstrates the remote configuration for the acquisition of I/Q data. In order to communicate with the instrument, the VISA object must be connected to the instrument using an IP address, based on the name resolution (line 011 & 013). A number of MATLAB® commands perform the basic setup, which consists of: turn on the display (line 019), preset the RTO (line 022), set the channel to 50Ω and DC coupling (line 025), and set the autolevelling (line 028). To be able to retrieve the I/Q data using the constructed MATLAB® object (line 013), it is necessary to increase the allocated memory. The default buffer size in MATLAB® is 512B, which is too small in this application for a single step download of data. The required buffer size in bytes can be calculated by multiplying '# of samples' * 2 (for I & Q) * 4 (IEEE 754 4 byte float value). With the maximum record length of 10 MSamples per channel of the RTO with the software I/Q option, 50MB covers the data transfer under most circumstances for the visa input buffer in MATLAB to access the R&S® RTO (line 015).

```
001     % carrier frequency 400MHz
002     nCarrierFrequency = 400e6;
003     % oversampling with a factor of 80 given a symbol rate of 500ksym/s
004     nSampleRate = 40000000;
005     % number of samples
006     nNofSamples = 800000;
007     % channel connected to the IQ signal source
008     nChannelNo = 1;
009     % name of the RTO to access remotely via network
010     sRTO_hostname = 'RTO-200300';
011     sIPAddress = resolvehost(sRTO_hostname, 'address');
012     % Create a VISA connection to the specified IP address
013     RTO = visa('ni', ['TCPIP::' sIPAddress ]);
014     % increase the buffer size to, e.g., transport IQ data
015     RTO.InputBufferSize = 80e6;
016     % Open the instrument connection
017     fopen(RTO);
018     %Activate View-Mode in Remote Mode
019     fprintf(RTO,'SYST:DISP:UPD ON');
020     %% ----- Configure the RTO -----
021     % Preset the RTO and wait till action is finished
022     fprintf(RTO,'*RST; *OPC?');
023     [~] = fscanf(RTO);
024     % Set Coupling to 50 Ohm
025     fprintf(RTO, ['CHAN' int2str(nChannelNo) ':COUP DC']);
026     % Perform Autoleveling,
027     %this might take some time so synchonization by fscanf() is appropriate
028     fprintf(RTO, ' AUToscale; *OPC?');
029     [~] = fscanf(RTO);
```

3.3 RTO I/Q Software Interface – Configuration

Now the RTO can be configured for the specific I/Q mode, which is in this case an acquisition of a RF signal, according to chapter 2. The subsequent settings (line 030 - 052) follow the described settings in chapter 2.1 and 2.4.

```
030     %% ----- RTO-K11 I/Q Software Interface SETUP -----
031     sInputType = ‘REAL’;
032     sInputMode = ‘RFIF’;
033     sSideband = 'NORMal';
034     nRelBW = 0.6;
035     % Activate IQ Mode
036     fprintf(RTO,'IQ:STATe ON');
037     % Single Sweep Mode
038     fprintf(RTO,'STOP');
039     %Set the input signal, input mode and sideband
040     fprintf(RTO, ['CHAN' int2str(nChannelNo) ':IQ:INPType ' sInputType]);
041     fprintf(RTO, ['CHAN' int2str(nChannelNo) ':IQ:INPMode ' sInputMode]);
042     % Use Normal Sideband
043     fprintf(RTO, ['CHAN' int2str(nChannelNo) ':IQ:SBRF ’ sSideband]);
044     % Carrier Frequency or Center Frequency
045     fprintf(RTO, ['CHAN' int2str(nChannelNo) ':IQ:CFRequency ' …
046     num2str(nCarrierFrequency)]);
047     % Set the correct sampling rate
048     fprintf(RTO, ['IQ:SRATe ' num2str(nSampleRate)]);
049     % Set the relative Bandwidth
050     fprintf(RTO, ['IQ:BWIDth ' num2str(nRelBW)]);
051     % Record Length to be used
052     fprintf(RTO, ['IQ:RLEN ' num2str(nNofSamples)]);
```

3.4 Retrieval of I/Q Data

Once the remote access and the I/Q acquisition is configured, the RTO is ready for the acquisition of I/Q data. In the given snippet in this section the MATLAB® script configures the RTO to use floating point values in binary format (line 054). This is an efficient way to download the data to a host, saving bandwidth during the transmission and CPU load on the RTO. A single acquisition is started (line 061) and after a successful trigger the I/Q data is available for download.

Once the acquisition is completed (line 062), getting the data from the RTO is straight forward. A single command (see Table 5 in this section for more details) instructs the RTO to provide the data of the specified channel (line 069) and subsequent read commands (line 071 & 074 & 077 & 081) fetch the I/Q data. The transmission format is configured as ‘REAL,32’. An ACSII based representation of floating point number is also possible, but this format introduces more load for the CPU of the RTO and the CPU of the host. The MATLAB® function (`textscan`) would convert the entire download from a string to an array of numbers. This step can be omitted, when using binary floating point numbers.

The retrieved I/Q data is represented as one-dimensional array of data with interleaved real (I) and imaginary (Q) values. This was implemented to reduce the transmission overhead. The desired format is a two dimensional array of data, one column holding real and the other holding the associated imaginary values. An explicit rearranging of the data into a two dimensional array is not necessary in MATLAB® as the language provides flexible expressions to access the I/Q data in the desired manner (line 082).

Parameter	SCPI command
Retrieve I/Q mode data set	IQ:DATA[:VALues]?
Retrieve specified samples of recorded I/Q data.	IQ:DATA:MEMory? <*OffsetSamples*>, <*NoOfSamples*>
Retrieve header of I/Q data	IQ:DATA:HEADer?
SCPI commands are prefixed by the channel	CHANnel<*m*>:

Table 5 SCPI commands for download

```
053     %% format of the transmission [ASC/UINT/REAL]
054     sDataFormat = 'REAL,32';
055     sDataFormat = sprintf('FORM %s', sDataFormat);
056     sBinaryFormatString = 'float';
057     nSizeType = 4;
058     fprintf(RTO, sDataFormat);
059     %% ----- Perform Single Sweep -----
060     % Perform a Sweep, and sync via '*OPC?' with the following read
061     fprintf(RTO, 'RUNSingle; *OPC?');
062     [~] = fscanf(RTO);
063     %% ----- Query the IQ Data -----
064     % data comes in #NLLLLFFFFffff …
065     % with N length indicator
066     %      LLLL number of samples
067     %      FFFF/ffff 4 byte value according to IEEE 754
068     % Capture the IQ Data from the corresponding channel
069     fprintf(RTO, ['CHAN' int2str(nChannelNo) ':IQ:DATA:VALues?']);
070     % check the return beginning with a hash '#'
071     sStartIndicator = fread(RTO,1,'char');
072     if sStartIndicator ~= '#' fprintf('ooops!\n'); end;
073     % check the length of the length field in units
074     nLengthOfLengthfield = fread(RTO,1,'char');
075     nLengthOfLengthfield = str2double(char(nLengthOfLengthfield));
076     % check the length of the data record
077     nBlockLength = fread(RTO, nLengthOfLengthfield ,'char');
078     nBlockLength = str2double(char(nBlockLength)) / nSizeType;
079     % to make this work, the endianess endian must be considered!
080     % the RTO supports litte endian byte order
081     u = fread(RTO, nBlockLength, 'float');
082     u = u(1:2:end) + 1i*u(2:2:end);
```

3.5 Analysis of I/Q Data

The following snipplet demonstrates the analysis of data. The retrieved data is normalized to a mean power of one (line 085 - 086) and simply plotted in a XY-diagram (line 087). Due to the oversampling, the result is not exactly a constellation diagram, and transitions from state to state are visible. Additionally due to the uncompensated null phase of the generator, the anticipated constellation diagram is displayed as skewed (see Figure 14 left side).

```
083     %% ----- Plot I/Q data -----
084     % normalize to mean power of 1
085     nMeanMagnitude = sqrt(mean(real(u).^2 + imag(u).^2));
086     u = u / nMeanMagnitude;
087     plot(u);
088     % second plot
089     nOverSampling = nSampleRate / 500000; % symbol rate -- 500 ksym/s
090     nSync = 60;  % visually determined
091     meanPhase = mean(angle(u(nSync:nOverSampling:end)));
092     for phase=1:nOverSampling;
093         plot((u((1+phase):nOverSampling:end)*exp(-1i*meanPhase)), '.');
094         pause(0.5);
095     end
```

Two things need to be done to recover the PRBS-9, 16-QAM modulated, from the acquired data. First, the optimal sampling phase needs to be detected, and second the constellation diagram for a 16-QAM deskewed. To perform this automatically a digital PLL would be required, which is not anymore in the focus for this application note, so a simple manual correction is done.

To find the optimal phase for a correct sampling point of the symbols, the I/Q signal is over-sampled by a factor of 80 and plotted in all possible phases in a loop (line 092 - 095). The phase with the least sample deviation from the symbol grid is chosen as the optimal one. The optimal phase of the oversampled I/Q data was found to be #60.

This sampling phase is used to estimate the null phase of the generator based on the assumption that, for uniformly distributed data like a PRBS sequence, the mean phase is zero (line 091). To remove the skew, the data is multiplied with the negative, complex phase estimate ($e^{-j\varphi}$, line 093). For the phase #60, it displays a nice, recovered constellation diagram of 16-QAM modulated data (Figure 14 right side).

Another way of presentation is colorization of the complex I/Q data diagram (see Figure 15), not covered in the example code. Using a temperature color grading, the frequency of occurrence of the I/Q data reveals the constellation map.

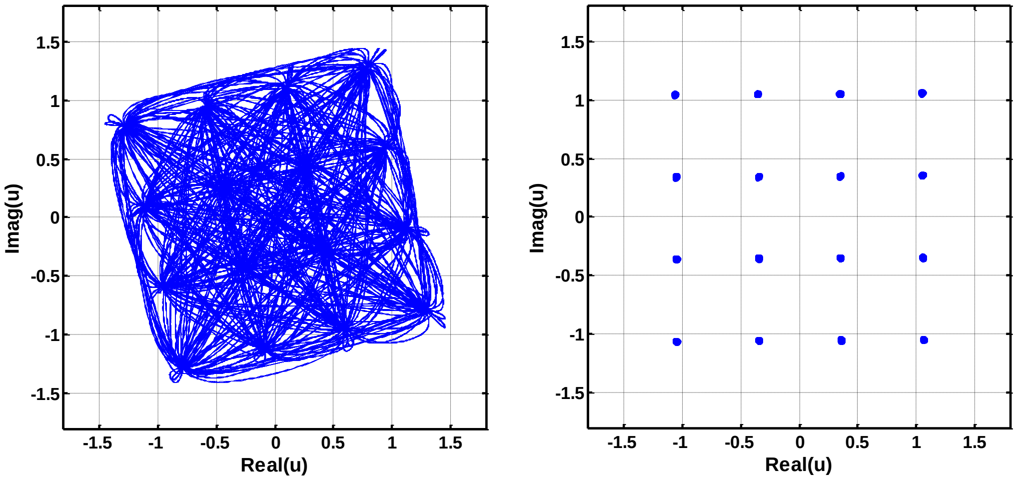


Figure 14 XY-diagram of acquired I/Q data

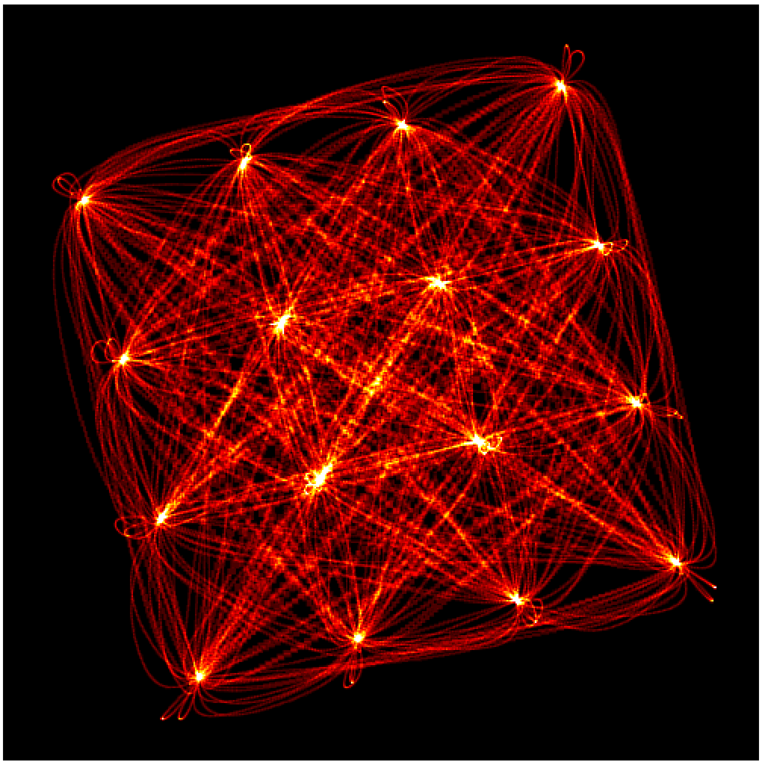


Figure 15 colorized I/Q data

4 Conclusion

The I/Q Software Interface option (RTO-K11) offers a comprehensive acquisition toolset for modern I/Q modulated communication protocols, high data rate satellite links, wideband radar, etc.. These applications implement state of the art modulation and encoding schemes, which make the I/Q Software Interface option very valuable for design and test.

Adopting the RTO for the acquisition of I/Q modulated data improves data capture and accelerates processing compared to a conventional PC based setup. The I/Q Software Interface option is easy to handle and integrates seamlessly in a common MATLAB® framework, which makes it a comfortable interface for analysis tools.

MATLAB® is a registered trademark of The MathWorks, Inc.

R&S® is a registered trademark of Rohde & Schwarz GmbH & Co. KG.

5 Literature

[1] J. G. Proakis, Digital Communications, Mcgraw-Hill Higher Education, 2008.

[2] „FS-K101PC/-K103PC/-K105PC EUTRA/LTE Uplink Specifications," Rohde & Schwarz, June 2012. [Online]. Available: http://www.rohde-schwarz.de/file_18344/FS-K101-103-105PC_FSx-K101-103-105_dat-sw_en.pdf.

[3] „FS-K112PC NFC Measurement Software Specifications," Rohde & Schwarz, July 2012. [Online]. Available: http://www.rohde-schwarz.de/file_18584/FS_K112-PC_dat-sw_en.pdf.

[4] „FS-K96 OFDM Vector Signal Analysis Software Specifications," Rohde & Schwarz, February 2012. [Online]. Available: http://www.rohde-schwarz.de/file_17782/FS-K96_dat-sw_en.pdf.

[5] Schindler, Schulz, „Introduction to MIMO -- Application Note," July 2009. [Online]. Available: http://www2.rohde-schwarz.com/file_12364/1MA142_0e.pdf.

[6] Sylvia Reitz, „R&S®RTO oscilloscope with state-of-the-art signal analysis software," *NEWS 206,* pp. 23-25, July 2012.

[7] Harry Nyquist, „Certain Topics in Telegraph Transmission Theory," in *Winter Convention of the A. i. E. E.*, New York, 1928.

[8] Test & Measurement, RTO Digital Oszilloscope - User Manual, München: Rohde & Schwarz GmbH & Co. KG, 2012.

[9] Jürgen Engelbrecht, „How to Use Rohde & Schwarz Instruments in MATLAB® -- Application Note," Rohde & Schwarz GmbH & Co. KG, 16 March 2012. [Online]. Available: http://www2.rohde-schwarz.com/file_13938/1MA171_5e.pdf.

[10] Rohde & Schwarz GmbH & Co. KG, R&S®SMBV100A Vector Signal Generator -- Operating Manual, München, 2012.

[11] MathWorks®, „Digital Video Broadcasting - Terrestrial," 2012. [Online]. Available: http://www.mathworks.com/help/comm/examples/digital-video-broadcasting-terrestrial.html.

6 Ordering Information

Naming	Type	Order number
Digital Oscilloscopes		
600 MHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1002	1316.1000.02
600 MHz, 4 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1004	1316.1000.04
1 GHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1012	1316.1000.12
1 GHz, 4 channels 10 Gsample/s, 20/80 Msample	R&S®RTO1014	1316.1000.14
2 GHz, 2 channels 10 Gsample/s, 20/40 Msample	R&S®RTO1022	1316.1000.22
2 GHz, 4 channels 10 Gsample/s, 20/80 Msample	R&S®RTO1024	1316.1000.24
4 GHz, 4 channels 20 Gsample/s, 20/80 Msample	R&S®RTO1044	1316.1000.44
Clock option - OCXO 10 MHz	R&S®RTO-B4	1304.8305.02
Software Options		
I/Q Software Interface	R&S®RTO-K11	1317.2975.02

7 Index

About Rohde & Schwarz
Rohde & Schwarz is an independent group of companies specializing in electronics. It is a leading supplier of solutions in the fields of test and measurement, broadcasting, radiomonitoring and radiolocation, as well as secure communications. Established more than 75 years ago, Rohde & Schwarz has a global presence and a dedicated service network in over 70 countries. Company headquarters are in Munich, Germany.

Environmental commitment
- Energy-efficient products
- Continuous improvement in environmental sustainability
- ISO 14001-certified environmental management system

Certified Quality System
ISO 9001

Regional contact

USA & Canada

USA: 1-888-TEST-RSA (1-888-837-8772)

from outside USA: +1 410 910 7800

CustomerSupport@rohde-schwarz.com

East Asia
+65 65 13 04 88
CustomerSupport@rohde-schwarz.com

Rest of the World
+49 89 4129 137 74
CustomerSupport@rohde-schwarz.com

Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | D - 81671 München
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com