Optimum PLL settings for Phase Noise Measurements with the R&S®FSUP

Application Note

Product:

| R&S®FSUP

In this application note we focus on the theoretical background of the PLL measurement method and illuminate its application in the R&S®FSUP. Based on measurement examples on different sources, the loop settings for optimum measurement performance are discussed.

ROHDE&SCHWARZ

Application Note

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1 Introduction

Nowadays the phase locked loop (PLL) method is the most comfortable and flexible method for analyzing phase noise. By using the cross correlation method, the PLL method is able to overcome the performance limitation of the reference oscillator by 20 dB or more. Thus the delay line method, which takes a huge mechanical effort, has been largely displaced from the measurement laboratories. In production sites the simple setup of the PLL method allows automated phase noise measurement.

In this application note we focus on the theoretical background of the PLL measurement method and illuminate its application in the R&S®FSUP. Based on measurement examples on different sources, the loop settings for optimum measurement performance are discussed.

2 Technical background

Let us consider the input signal

$$v_1(t) = V_1 \cos(\omega_0 t + \varphi_{PN1}(t)). \qquad (1)$$

The phase noise perturbation is described by the time varying phase $\varphi_{PN1}(t)$. Technical relevant oscillators are generally operating in a steady state oscillation and the signal noise can be treated as a small signal compared to the oscillator signal. The phase noise deviations act tangential to the limit cycle of the oscillation. Thus the perturbed oscillation meets the limit cycle always exactly, showing only a phase shift. Amplitude noise in contrast is perpendicular to the limit cycle and leads to deviations from it. In a stable oscillator, however, restoring forces towards the steady state take effect and keep the oscillation on the limit cycle. As amplitude and phase noise are perpendicular a definite separation is possible.

The common method to separate phase noise from amplitude noise is to use a mixer as phase detector. The signal under test is multiplied by a second signal $v_2(t)$ showing the same frequency and a phase difference of + π/2 or – π/2. To keep the derivation simple we consider the case of + π/2:

$$v_2(t) = V_2 \cos(\omega_0 t + \varphi_{PN2}(t) + \pi/2). \qquad (2)$$

A low pass filter removes the higher frequency components in the mixer output signal. Thus the phase detector output signal is given by

$$\begin{aligned} v_{PD}(t) &= k_{PD} \cos(\omega_0 t + \varphi_{PN1}(t) - \omega_0 t - \varphi_{PN2}(t) - \pi/2) \\ &= k_{PD} \cos(\varphi_{PN1}(t) - \varphi_{PN2}(t) - \pi/2) \\ &= k_{PD} \sin(\varphi_{PN1}(t) - \varphi_{PN2}(t)), \end{aligned} \qquad (3)$$

while k_{PD} is the phase detector constant in V/rad. With the approximation for small angles $\sin(x) = x$ equation (3) can be simplified as

$$v_{PD}(t) \approx k_{PD} (\varphi_{PN1}(t) - \varphi_{PN2}(t)). \qquad (4)$$

The phase detector voltage depends only on the phase deviations whereas amplitude deviations and thus amplitude noise are suppressed by the phase detector. This way phase noise is distinguished from amplitude noise. The subtraction of $\varphi_{PN1}(t)$ and $\varphi_{PN2}(t)$ needs to be carried out under consideration of the correlation of the two noise signals. In the case of an ideal reference oscillator we assume $\varphi_{PN1}(t) \gg \varphi_{PN2}(t)$. Thus, in this case, the total phase noise is given by $\varphi_{PN}(t) = \varphi_{PN1}(t)$.

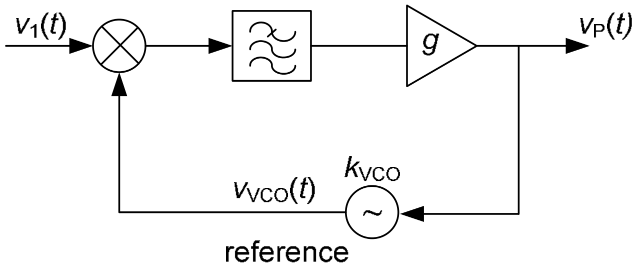

Fig. 1: PLL of the first order

In the PLL method, the phase difference of ± π/2 between the two input signals is achieved by a PLL as outlined in Fig. 1. To keep the derivation simple we focus here on a PLL with the first order. The low pass filter suppresses the higher frequency components and does not affect the loop bandwidth of the PLL. The reference oscillator is frequency tuned by the output voltage of the PLL $v_P(t)$. The phase of the reference oscillator is determined by the integration over the tuning voltage. With the VCO slope k_{VCO} in Hz/V the output voltage of the VCO is

$$v_{VCO}(t) = V_{VCO} \cos (\omega_0 t + \int v_P(t)\, k_{VCO}\, dt) \qquad (5)$$

With the constant gain g in the loop, the output voltage of the closed PLL is given by:

$$v_P(t) \quad = g\, k_{PD} \,[\, \varphi_{PN}(t) - \int v_P(t)\, k_{VCO}\, dt \,]. \qquad (6)$$

To derive for v_P we transfer into Laplace domain, where $v_P(t)$ and $\varphi_{PN}(t)$ are denoted by $V_P(s)$ and $\Phi_N(s)$, respectively. The parameter s is the complex frequency. For technical frequencies s is equal to j2πf. In Laplace domain we obtain

$$V_P(s) \; = g\, k_{PD} \,[\, \Phi_{PN}(s) - \frac{1}{s}\, V_P(s)\, k_{VCO} \,] \qquad (7)$$

and derive for $V_P(s)$:

$$V_P(s) \; = \frac{\Phi_{PN}(s)\; g\; k_{PD}}{1+\frac{g\, k_{PD}\, k_{VCO}}{s}}\,. \qquad (8)$$

The frequency characteristic of (8) is a high pass with the first order. The corner frequency

$$f_{LBW} \quad = \frac{1}{2\pi}\, g\, k_{PD}\, k_{VCO} \qquad (9)$$

is known as the loop bandwidth of the PLL. For offset frequencies >> f_{LBW} the output voltage is directly related on the phase noise $\Phi_N(s)$. Below f_{LBW} the feedback control of the PLL suppresses phase perturbations. Therefore, in a phase noise measuring system using the PLL method the noise suppression of the loop needs to be compensated.

By using the PLL method in a straightforward way, frequency deviations between the two oscillator frequencies in the range of the loop bandwidth can be leveled out. A larger frequency drift of the signal under test, however, may drive the VCO tuning voltage to its limit. Measurements with a large number of correlations may take a long time. To keep locked during the complete measurement an additional mechanism to follow the frequency drift is required.

Therefore, in the R&S®FSUP a frequency tracking algorithm is implemented. The algorithm checks continuously the sign of the voltage $v_P(t)$ and adapts the center frequency of the VCO by small steps. By this method the R&S®FSUP is able to keep locked on frequency drifting devices. In its default mode the frequency tracking speed is related to the loop bandwidth.

Frequency tracking does not distinguish between frequency drift and phase noise perturbations. It suppresses phase noise similar to a standard PLL. However, in contrast to the standard PLL it is a nonlinear process with a step function as transfer function and the noise suppression cannot be compensated completely. Therefore it is recommended to keep the frequency tracking as low as possible for the signal under test. As a rule of thumb, with the standard coupling of loop bandwidth and frequency tracking the measurement error due to frequency tracking is < 1 dB for offset frequencies larger than one tenth of the loop bandwidth. With lower tracking speeds the measurement performance for lower offset frequencies improves.

3 PLL configuration in the R&S®FSUP

In the default mode, which is considered in this application note, the R&S®FSUP uses its internal synthesizer as the tunable VCO. This is the most widespread mode of operation. By realizing two separated signal paths with two independent internal synthesizers the internal noise can be suppressed by cross correlation.

The R&S®FSUP allows set up of loop bandwidths from 1 Hz up to 30 kHz. Per default frequency tracking is enabled. Depending on the selected loop bandwidth, the internal synthesizer switches between three operating modes. For loop bandwidths ≤ 1 kHz it shows the lowest phase noise. For larger values up to 10 kHz the synthesizer phase noise increases marginally. For setting up loop bandwidths larger than 10 kHz, the synthesizer switches in its high deviation mode, where its phase noise level increases significantly. Hence, loop bandwidths above 10 kHz are recommended only for sources with high phase noise levels that cannot be locked with lower loop bandwidths.

When a new measurement is started, the premeasurement sequence is executed automatically, that is the basis for the PLL set up. The R&S®FSUP first analyzes level, frequency and frequency drift of the input signal. With these results it sets up the internal synthesizer for a frequency close to the input frequency. The resulting beatnote signal at the phase detector output is used to determine the phase detector constant k_{PD} for the actual input signal. The premeasurement result display contains these results and can be accessed by SETTINGS | VCO LOOP SETTINGS.

After the premeasurement the R&S®FSUP starts to lock on the input signal. In auto mode the loop bandwidth is set automatically by analyzing the phase detector output voltage while stepping down the loop bandwidth. With each step, the PLL reduces the suppression of the phase detector output voltage. With the loop bandwidth found, the two signals are kept phase locked with a phase difference of 90° and thus the approximation for small angles in (4) is justified.

DUT Type Selection	Optimum for DUT characteristics	Resulting internal R&S®FSUP settings
Auto	All type of sources	Loop-BW auto, tracking auto
Free Running Low Phase Noise Oscillator	Oscillator with frequency drift > 3e-9*f_{OSC}/s	Loop-BW ≤ 10 kHz, tracking related to Loop-BW
Synthesizer with Low Drifting Reference	Oscillator with frequency drift < 3e-9*f_{OSC}/s	Loop-BW ≤ 10 kHz, tracking ~1e-8*f_{OSC}/s
Synthesizer with OCXO Reference	Oscillator with frequency drift < sqrt (f_{OSC}*2e-3 Hz) during measurement time	Loop BW > sqrt(f_{OSC}*2e-3 Hz), maximum ≤ 10 kHz, tracking off
Crystal Oscillator	Very low phase noise oscillator with frequency drift < sqrt(f_{OSC}*1e-4 Hz) and < 1 kHz during measurement time	Loop-BW > sqrt(f_{OSC}*2e-3 Hz), maximum ≤ 10 kHz, tracking off

Fig. 2: DUT Properties selection dialog with detailed settings description

During the set up of the loop bandwidth, the frequency tracking speed decreases along with the loop bandwidth. The frequency drift, measured in spectrum mode during the premeasurement is used as second stop criteria for stepping down the two parameters. Sources that show a high phase noise level at low offset frequencies show in general a large frequency drift. In this case, large loop bandwidths and a large frequency tracking speeds are required. Vice versa, sources with very low phase noise levels at low offset frequencies can be measured with small loop bandwidths and frequency tracking can be reduced or disabled. With the example 'synthesizer', however, we demonstrate a signal where it makes sense to break this coupling.

After the setup of the loop bandwidth, the low noise amplifier (LNA) gain *g* is selected to decrease the internal noise figure and to optimize the input level at the ADC. For advanced users, the R&S®FSUP allows manual configuration of loop bandwidth, tracking speed and LNA gain. By means of the measurement wizard under SETTINGS | DUT PROPERTIES (see Fig. 2) these parameters can be chosen easily for predefined types of DUTs. The following chapter illustrates the application of these parameters for different measurement examples.

4 Measurement Applications

4.1 Free running VCO

A free running voltage controlled oscillator (VCO) is a tunable oscillator that does not use a frequency reference. In general VCOs show a large frequency drift and the close to carrier phase noise is relatively high. In the phase noise measurement of a free running VCO the measurement PLL needs to regulate the phase deviations and to follow frequency drifts.

Large phase deviations require a large loop bandwidth to hold the phase condition at the phase detector constant. To account for long term frequency drifts, large frequency tracking speeds are required.

Fig. 3 depicts a measurement on a free running VCO. The premeasurement sequence returns a frequency drift of 0.5 kHz/s. The automatic locking sequence stops due to the measured drift at a loop bandwidth of 3 kHz and a corresponding frequency tracking of 1.7 kHz/s. With these settings the PLL keeps the DUT signal and the internal reference signal locked. The R&S®FSUP sets the LNA gain to 20 dB for an optimum input level at the ADC.

During the measurement, the time domain phase detector voltage $v_P(t)$ can be observed in the scope display in the upper right corner of the screen. When cross correlation is enabled the scope display draws the voltages for both paths. Depending on the offset frequency that is currently measured, the phase detector voltage is down sampled and the scope display shows the low pass filtered signal with an adaptive time scaling. The range of the scope display represents the input range of the ADC.

With this scope display the locking of the PLL and the ADC drive can be checked. For example, a frequency drift larger than the actual frequency tracking speed results in a drift of the DC offset of the phase detector signal. In the default mode the R&S®FSUP sets up a frequency tracking speed that is large enough to cover the drift measured during the premeasurement. However, a temporarily increased frequency drift, e.g. due to temperature variations, cannot be accounted for. In this case either the DUT environment should be stabilized or the frequency tracking speed should be increased. In some cases it might be useful to reduce the measurement time by limiting the number of averages or correlations.

Time domain voltage fluctuations in the scope show the noise of the phase detector output signal. When the amplitude of these voltage fluctuations is too large, the ADC may become overdriven or the measurement PLL may unlock because the tuning limit of the internal VCO is exceeded. In this case it is recommended first to decrease the LNA gain to optimize the input level of the ADC for the complete measurement. When the LNA gain is 0 dB, the loop bandwidth should be increased to improve the low frequency noise suppression by the PLL.

With the default settings the R&S®FSUP finds suitable settings for most free running VCOs. In general, the coupling of frequency tracking speed with loop bandwidth does not need to be changed for VCOs.

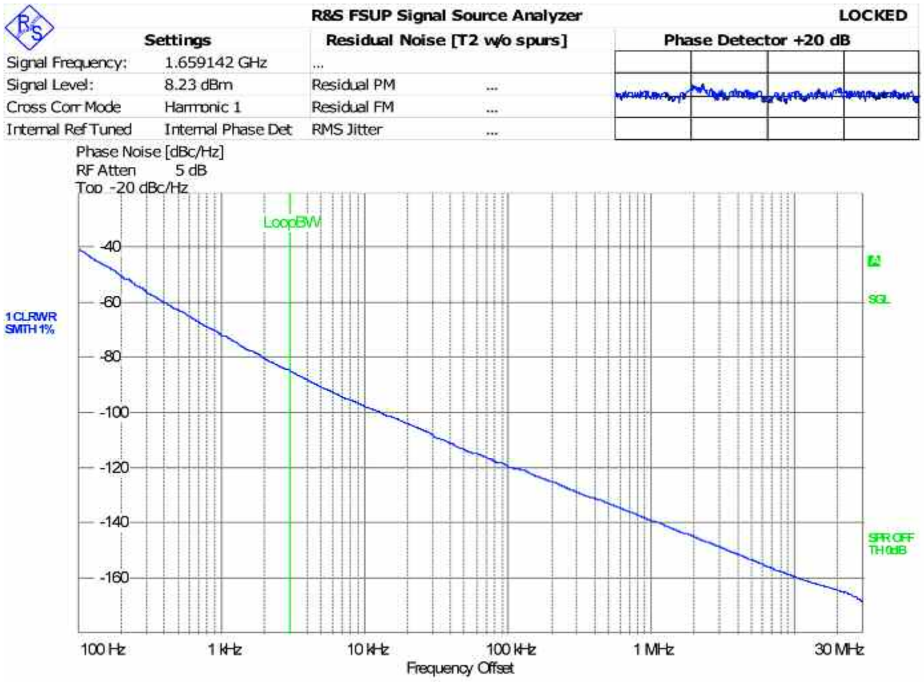

Fig. 3: Phase noise measurement of a free running VCO

In the case of unlock the scope shows a sinusoidal signal, representing the frequency difference between the DUT signal and the internal reference oscillator. Typically this beatnote signal is in the MHz-range and can be observed as a strong spurious in the phase noise measurement results. When unlock is detected a red label displays the unlocked state in the upper right corner of the screen and the measurement is aborted.

4.2 Synthesizer

In contrast to a free running VCO, the output signal of a synthesizer is locked to a frequency reference. The synthesizer PLL suppresses the close to carrier phase noise and the frequency drift of the output signal. Within the loop bandwidth of the synthesizer the phase noise corresponds to the reference oscillator, whereas outside the loop bandwidth the phase noise corresponds to the internal VCO.

If the loop bandwidth of the synthesizer is large enough (e.g. > 1 kHz), a further suppression of the noise fluctuations by the measurement PLL is not necessary. Thus the synthesizer signal can be locked by the measurement PLL with loop bandwidths far below the synthesizer loop bandwidth. In contrast, when the internal loop bandwidth of the synthesizer is very small (e. g. < 100 Hz), the measurement PLL needs to regulate the phase deviations of the VCO and the same loop bandwidth as for the free running VCO measurement is required.

For both types of synthesizers, however, the frequency drift is reduced significantly by the synthesizer PLL. Thus the frequency tracking parameter in the R&S®FSUP can be reduced significantly or disabled completely.

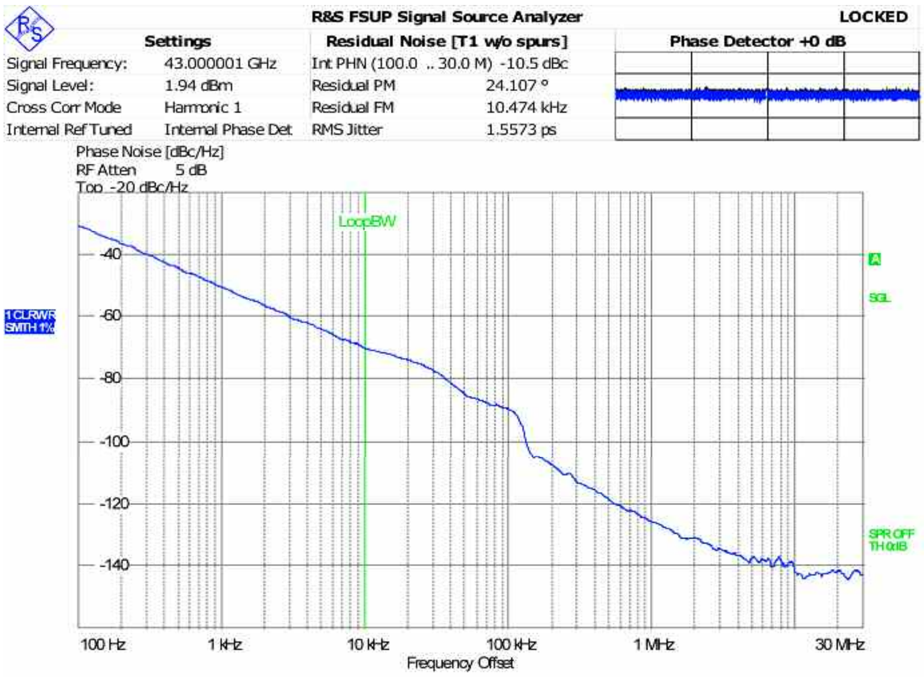

Fig. 4: Phase noise measurement on a signal corresponding to a synthesizer with a loop bandwidth < 100 Hz

In the example in Fig. 4, a signal of a synthesizer with a very small loop bandwidth is measured. A signal generator at 43 GHz is frequency modulated by white noise with a bandwidth of 30 kHz. It can be seen that the close to carrier noise is relatively high (–50 dBc/Hz at 1 kHz). This requires a large loop bandwidth to lock on the signal. The algorithm in the R&S®FSUP selects a loop bandwidth of 10 kHz for this signal automatically.

The frequency drift of the DUT is < 10^{-8} and thus the maximum frequency deviation is < 430 Hz. With the loop bandwidth of 10 kHz the R&S®FSUP can compensate for this frequency drift. Therefore frequency tracking can be disabled completely and phase noise measurements down to offset frequencies well below the loop bandwidth can be achieved.

In the standard mode the R&S®FSUP always keeps the frequency tracking enabled. By using the measurement wizard in Fig. 2 the type of DUT can be chosen easily. The dialog allows selecting between two types of synthesizers: low drifting synthesizers and synthesizers with OCXO reference. For the former frequency tracking is reduced to a minimum and for the latter it is disabled completely.

4.3 Crystal oscillator

A crystal oscillator uses a high-Q crystal resonator and therefore can obtain excellent phase noise levels. In its temperature equilibrium the frequency drift is very low. For phase noise measurements of crystal oscillators, loop bandwidths ≤ 1 kHz should be chosen and frequency tracking can be disabled completely. With the measurement wizard the recommended settings for a crystal oscillator can be applied easily.

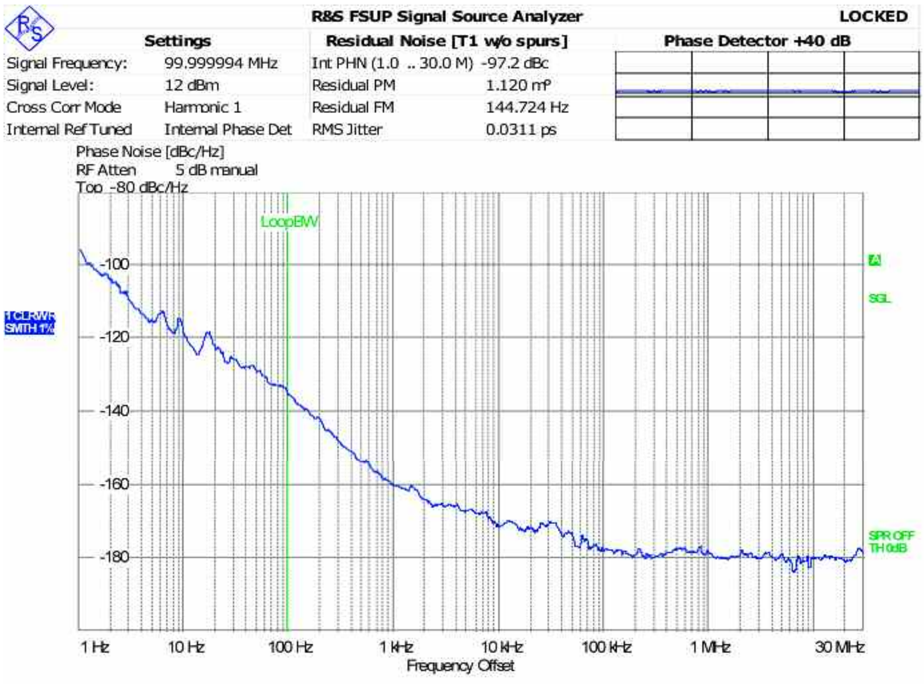

Fig. 5: Phase noise measurement on a crystal oscillator

Fig. 5 shows measurement results for a crystal oscillator at 100 MHz. The measurement wizard sets the loop bandwidth to 100 Hz and disables frequency tracking. Due to the low phase noise level, the R&S®FSUP chooses a LNA gain of 40 dB automatically.

5 Conclusion

By using the R&S®FSUP in its automatic mode, most signals can be measured easily with high measurement performance. In order to achieve the optimum measurement performance for a specific signal, the loop settings can be optimized manually or by using the measurement wizard. By means of three examples this application note gives insight into the PLL configuration in the R&S®FSUP and demonstrates how the loop settings can be adjusted for specific DUTs.

6 Ordering Information

Designation	Type	Order No.
Signal Source Analyzer, 20 Hz to 8 GHz	R&S®FSUP8	1166.3505.09
Signal Source Analyzer, 20 Hz to 26.5 GHz	R&S®FSUP26	1166.3505.27
Signal Source Analyzer, 20 Hz to 50 GHz	R&S®FSUP50	1166.3505.51

Accessories supplied

Power cable, printed quick start guide and CD-ROM (with operating manual and service manual)
R&S®FSUP26: test port adapter with 3.5 mm female (1021.0512.00) and N female (1021.0535.00) connector
R&S®FSUP50: test port adapter with 2.4 mm female (1088.1627.02) and N female (1036.4777.00) connector

Designation	Type	Order No.	Retrofit	Remarks
Hardware Options				
Low-Aging OCXO	R&S®FSU-B4	1144.9000.02	yes	
External Generator Control	R&S®FSP-B10	1129.7246.03	yes	
Removable Hard Disk	R&S®FSUP-B18	1303.0400.05	no	
Second Hard Disk for R&S®FSP-B18	R&S®FSUP-B19	1303.0600.05	yes	requires R&S®FSUP-B18
LO/IF Ports for External Mixers	R&S®FSUP-B21	1157.1090.04	yes	for R&S®FSUP26 only
20 dB Preamplifier, 3.6 GHz to 26.5 GHz	R&S®FSU-B23	1157.0907.02	no	for R&S®FSUP26 only, requires R&S®FSU-B25
Electronic Attenuator, 0 dB to 30 dB, and 20 dB Preamplifier (3.6 GHz)	R&S®FSU-B25	1144.9298.02	yes	
Trigger Port	R&S®FSP-B28	1162.9915.02	yes	
Low Phase Noise	R&S®FSUP-B60	1169.5544.03	yes	
Correlation Extension	R&S®FSUP-B61	1305.2500.26	no	for R&S®FSUP26 only, requires R&S®FSUP-B60
Correlation Extension (with 26.5 GHz preampli-fier)	R&S®FSUP-B61	1305.2500.23	no	for R&S®FSUP26 only, requires R&S®FSUP-B60, R&S®FSU-B25, R&S®FSU-B23
Correlation Extension	R&S®FSUP-B61	1305.2500.50	no	for R&S®FSUP50 only, requires R&S®FSUP-B60
Firmware/software				
GSM/EDGE Application Firmware	R&S®FS-K5	1141.1496.02		
Bluetooth® Application Firmware	R&S®FS-K8	1157.2568.02		
Power Sensor Measurements	R&S®FS-K9	1157.3006.02		
Application Firmware for Noise Figure and Gain Measurements	R&S®FS-K30	1300.6508.02		preamplifier recommended (e.g. R&S®FSU-B25)
Vector Signal Analysis	R&S®FSQ-K70	1161.8038.02		
3GPP BTS/Node B FDD Application Firmware	R&S®FS-K72	1154.7000.02		
3GPP UE FDD Application Firmware (including HSUPA)	R&S®FS-K73	1154.7252.02		
3GPP HSDPA BTS Application Firmware	R&S®FS-K74	1300.7156.02		requires R&S®FS-K72
3GPP HSPA+ Base Station Test	R&S®FS-K74+	1309.9180.02		requires R&S®FS-K72 and R&S®FS-K74
3GPP TD-SCDMA BTS Application Firmware	R&S®FS-K76	1300.7291.02		
3GPP TD-SCDMA UE Application Firmware	R&S®FS-K77	1300.8100.02		
CDMA2000® IS-95 (cdmaOne)/1xEV-DV BTS Application Firmware	R&S®FS-K82	1157.2316.02		
CDMA2000® 1xEV-DV MS Application Firmware	R&S®FS-K83	1157.2416.02		
CDMA2000® 1xEV-DO BTS Application Firm-ware (including Rev A)	R&S®FS-K84	1157.2851.02		
CDMA2000® 1xEV-DO MS Application Firmware	R&S®FS-K85	1300.6689.02		
Generic OFDM Application Software	R&S®FSQ-K96	1308.9570.02		Windows based software, external PC required

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