Introduction

Radiomonitoring receivers – design and applications

Basic functionalities of T&M and radiomonitoring equipment are converging to an increasing extent. As a result, cross-sectional applications beyond the equipment's original field of application become possible. Selecting the right equipment for specific monitoring and T&M tasks has thus become more difficult. The basic design features and signal processing methods of the different types of receivers can be used as fundamental decision criteria for choosing the equipment suitable for a specific task.

In the following, the differences between radiomonitoring receivers and other types of receivers are highlighted and their main design features and operating principles are presented.

Types of receivers and typical applications

Test receivers

Test receivers are available for various applications. They are divided into the following groups:

- EMI test receivers:
  EMI test receivers measure conducted or radiated interference in accordance with relevant international standards (CISPR, MIL, VG, etc.). These receivers are needed to demonstrate equipment compliance with EMC standard specifications, which is the prerequisite for putting a product on the market
- Test receivers measuring useful signals:
  These test receivers measure the level and the modulation of known useful signals and the bandwidth they occupy. For example, they are used to verify whether radio services comply with the limit values specified for these parameters
- Calibration test receivers:
  Calibration test receivers measure the level of RF signals at extremely high accuracy and over a wide dynamic range. They are mainly used to calibrate signal sources

Spectrum analyzers

Spectrum analyzers are typically connected to the device under test (DUT) via a cable during the measurement. Featuring a broadband RF frontend, they are usually not suitable for measurements on antennas. They are mainly used in development, production, quality assurance and certification. Typical measurements include the RF level, spectral purity, adjacent channel power and spurious emissions. Today's spectrum analyzers can be used, in particular, to measure the modulation characteristics of RF signals with analog or digital modulation.

Radiomonitoring receivers

Radiomonitoring receivers are optimized specifically for spectrum monitoring tasks and differ fundamentally from test receivers and spectrum analyzers. Radiomonitoring receivers are used for the following tasks:

- Fast detection of unknown signals
- Search for activities over wide frequency ranges
- Monitoring of individual frequencies, lists of frequencies or frequency ranges
- Measurement of spectral characteristics of very short or rarely occurring signals
- Storage of activities
- Triggering of further activities after a signal is detected
- Demodulation of communications and/or transfer of demodulated signals for processing
- Integration into civil and military dedicated systems
- Homing, i.e. localization of signal sources
- Simple coverage measurements
- Measurements in line with ITU recommendations

The above tasks place special requirements on the receivers' hardware and software, the type of control via front panel or remote control interface, the provision and processing of captured data, and the receivers' integration into complex systems. Radiomonitoring receivers must be able to process antenna signals with high cumulative loads and wide dynamic range. In particular, seamless (gapless) realtime processing is a requirement that other receiver types usually cannot meet.

To meet the above requirements, radiomonitoring receivers rely on special design principles and operating methods, which are discussed in the following.

Design principles and operating methods of radiomonitoring receivers

Frontend – handling real antenna signals

Radiomonitoring receivers are operated almost exclusively on antennas in real signal scenarios. Especially when connected to omnidirectional antennas, receivers may have to cope with very high cumulative signal loads and also with a wide dynamic range between strong and weak signals in specific frequency ranges. This difficulty can be overcome by tailoring receivers to specific frequency ranges, usually to the HF, VHF/UHF and SHF bands. This makes it possible to meet the frequency-range-specific design requirements placed on the frontend.

To enable applications as universal as possible, tuners for the individual frequency ranges can be used in a single device. In this way, it is possible to cover a frequency range from 9 kHz to 26.5 GHz, for example, using a dedicated HF, VHF/UHF and SHF module each, as in the case of the R&S®ESMD. Wide-range tuners, which in the case of the R&S®PR100 cover a frequency range from 9 kHz to 7.5 GHz in a single module, do not allow the same excellent reception characteristics to be achieved across the entire frequency range, but they permit extremely compact designs. For portable receivers and their applications, the performance achievable with a single tuner module is sufficient because, among other reasons, these receivers are not operated on highly sensitive, stationary antenna systems.

How the frontend works

The receiver frontend receives the RF signal and processes it for the subsequent A/D converter.

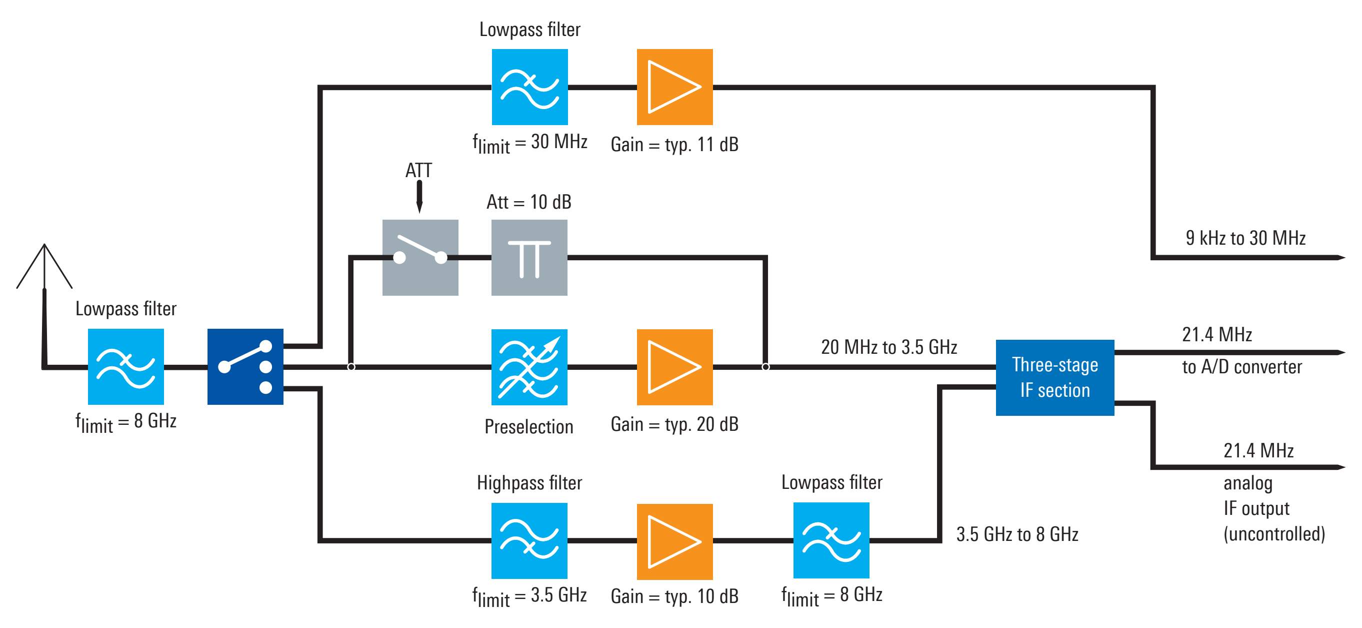
A distinction is made between two basic concepts:

A direct-conversion receiver routes the received signal with the original frequency through preparatory stages (preselection filter, amplifier, gain control) directly to the A/D converter. With a satisfactory resolution of the A/D converter (e.g. 16 bit), this works up to input frequencies of approx. 32 MHz.

Direct-conversion receivers offer the advantages of very low phase noise and complete elimination of image frequencies, IF feedthrough, etc.

For higher frequencies (starting from approx. 20 MHz up into the SHF range), three-stage intermediate frequency (IF) conversion is used. The RF receive signal is converted in stages to the third IF of, for example, 21.4 MHz while it undergoes processing (preselection filter, amplifier, gain control) at the same time. Next, the signal is taken to the A/D converter. The use of three-stage IF conversion makes it possible to receive even very high frequency signals at 16 bit resolution of the A/D converter while offering good image frequency rejection at the same time.

Simplified block diagram of the R&S®PR100 frontend

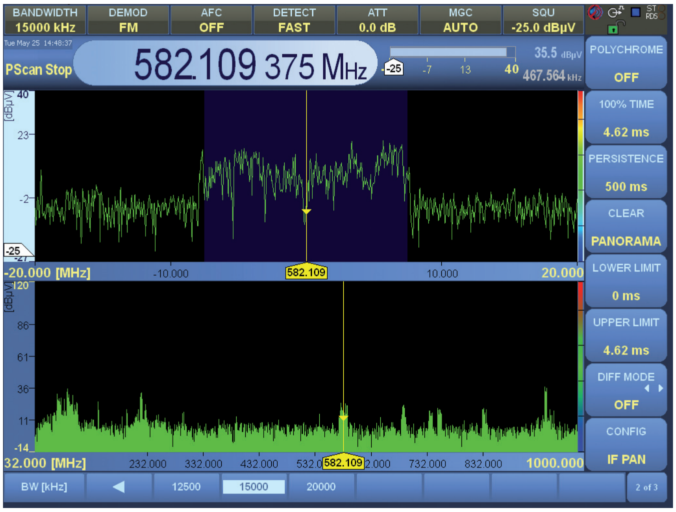


If the first IF of such a superhet receiver is above the highest receive frequency, it can be kept constant. If the IF is in the lower region of the reception range, conversion concepts that are complex but not perceivable by the user are implemented to prevent inherent spurious responses.

Another special feature found in the frontends of radiomonitoring receivers is the built-in preselection. This stage comprises multiple switchable and tunable bandpass filters that protect the first mixer stage of multiple-conversion receivers, or the A/D converter of direct-conversion receivers, against high cumulative signal loads. The preselection stage is indispensable especially when the receiver is operated on a broadband omnidirectional antenna, where the cumulative signal load from numerous radio services operating over very wide frequency ranges is present at the receiver input. Without preselection, this operating mode would lead to strong intermodulation products or even drive the receiver to saturation. In contrast to fixed, switch-selected preselection filters, the use of a tracking preselection ensures optimal filtering for the selected realtime bandwidth for any input frequency.

Digital signal processing

Unknown signals are normally detected by performing high-speed scans over wide frequency ranges, and then analyzed in detail in fixed-frequency mode. A radiomonitoring receiver's scan speed and probability of intercept (POI) are determined by its realtime bandwidth, sensitivity, and the type and speed of signal processing employed.



BANDWIDTH 15000 kHz
DEMOD FM
AFC OFF
DETECT FAST
ATT 0.0 dB
MGC AUTO
SQU -25.0 dBµV

Tue May 25 14:48:37
PScan Stop
582.109 375 MHz
35.5 dBµV
467.564 kHz

POLYCHROME OFF
100% TIME 4.62 ms
PERSISTENCE 500 ms
CLEAR PANORAMA
LOWER LIMIT 0 ms
UPPER LIMIT 4.62 ms
DIFF MODE OFF
CONFIG IF PAN

BW [kHz] 12500 15000 20000

IF spectrum, with selected demodulation bandwidth highlighted in blue. Lower part: panorama scan.

To provide high realtime bandwidth without compromising sensitivity and dynamic range, some radiomonitoring receivers from Rohde & Schwarz feature multiple different and switchable broadband receive paths. Multifunctional IF panorama displays with a wide range of setting functions are available in addition to allow powerful, in-depth analysis of detected signals.

Separate spectrum and measurement paths

Another special feature of radiomonitoring receivers is their capability to provide an overview of all signal activities in a wide frequency range while at the same time allowing the detailed analysis and demodulation of individual signals.

To achieve this, the signal path is split up after A/D conversion: In the first path, the IF spectrum is calculated by means of a digital downconverter (DDC), a digital bandpass filter and an FFT stage. The user can select the bandwidth of the bandpass filter from typically 1 kHz to 10 MHz, or 20 MHz, or even 80 MHz. Results are postprocessed by means of the Average, MinHold or MaxHold function, as selected by the user, before the IF spectrum is output on the display or via the LAN interface. In the second path, the signal is processed for level measurement and demodulation. Here, too, the signal passes through a DDC and a bandpass filter. High-end receivers include multiple DDCs for the parallel demodulation of multiple signals.

To process the different signals with optimum signal-to-noise ratio, receivers from Rohde & Schwarz contain digital IF filters with demodulation bandwidths from 150 Hz to 20 MHz in the measurement path. The filters can be selected independently of the IF bandwidth. Prior to the level measurement, the absolute value of the level is determined and weighted by means of a user-selected detector (Average, Max Peak, RMS or Sample). The measured level is output on the display or via the LAN interface.

To demodulate analog signals, the complex baseband data passes through a bandpass filter, then undergoes automatic gain control (AGC) or manual gain control (MGC), and is finally demodulated in the AM, FM, USB, LSB, ISB, PULSE or CW demodulation stage. The complex baseband data (I/Q data) of digital signals is directly output for processing after the AGC/MGC stage. Here, it is possible to output the I/Q data stream via a Gigabit LAN connection in order to buffer the stream on an external medium. Online analysis of the I/Q data stream is also possible by using appropriate software (see block diagram).

High receiver sensitivity, high signal resolution

In the following, the special aspects regarding sensitivity and signal resolution in radiomonitoring receivers are explained, assuming an IF bandwidth of 10 kHz as an example.

The IF spectrum is digitally calculated by means of a fast Fourier transform (FFT). The use of FFT computation at the IF offers a major advantage: The receiver sensitivity and signal resolution are clearly superior to those of conventional analog receivers at the same spectral display width.

IF spectrum

FFT calculation of the IF spectrum is performed in a number of steps. These steps are described below in simplified form for an IF bandwidth of 10 kHz ($BW_{\text{IF spectrum}}$ = 10 kHz), which yields maximum sensitivity.

Due to the finite edge steepness of the IF filter, the sampling rate f_s must be larger than the selected IF bandwidth $BW_{\text{IF spectrum}}$. The quotient of the sampling rate and the IF bandwidth is > 1 and is a measure of the edge steepness of the IF filter. This relationship is expressed by the following two formulas:

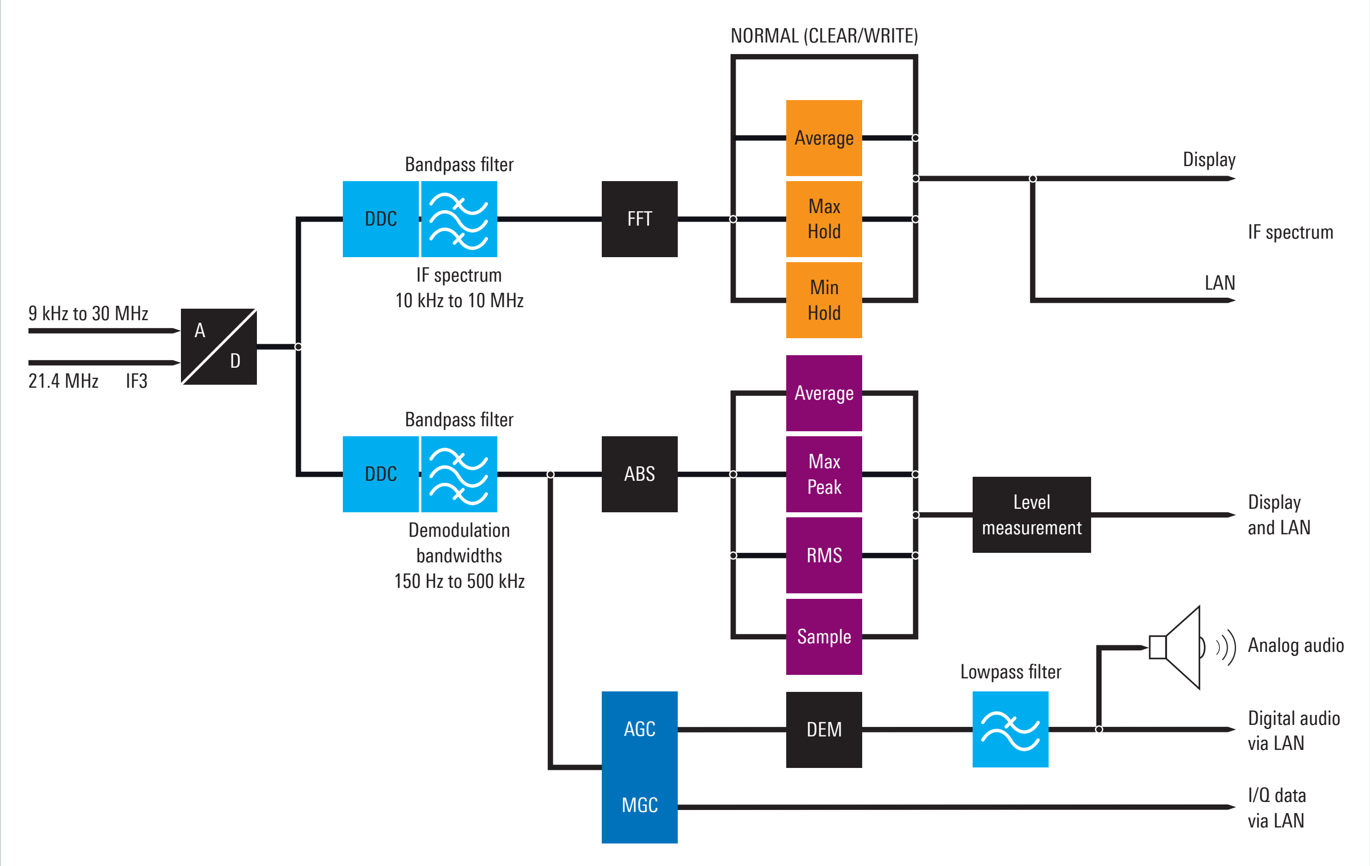
$$\frac{f_s}{BW_{\text{IF spectrum}}} = \text{const}$$

or

$$f_s = BW_{\text{IF spectrum}} \times \text{const}$$

The value of the constant is dependent on the selected IF bandwidth, i.e. it may vary as a function of the IF bandwidth.

Block diagram of the R&S®PR100 digital signal processing



For an IF bandwidth of $BW_{\text{IF spectrum}}$ = 10 kHz, the constant is 1.28. To display a 10 kHz IF spectrum, therefore, a sampling rate of f_s = 12.8 kHz is required (see upper figure).

The automatically selected FFT is assumed to have a standard length N of 2048 points in this example. To calculate these points, the 12.8 kHz sampling band is divided into 2048 equidistant frequency slices, which are also referred to as bins.

The bandwidth BW_{bin} of the frequency slices is as follows:

$$BW_{\text{bin}} = \frac{f_S}{2048} = \frac{12.8\text{ kHz}}{2048} = 6.25\text{ Hz}$$

This means that in this example only the calculated bandwidth of 6.25 Hz for each bin has to be taken into account as the noise bandwidth in the calculation of the displayed noise level (DNL) in accordance with the formula below (the effect of the window function (Blackman window) of the FFT is not considered here for simplicity's sake):

$$\text{DNL} = -174\text{ dBm} + \text{NF} + 10 \times \log(BW_{\text{bin}}/\text{Hz})$$

The quantity NF represents the overall noise figure of the receiver.

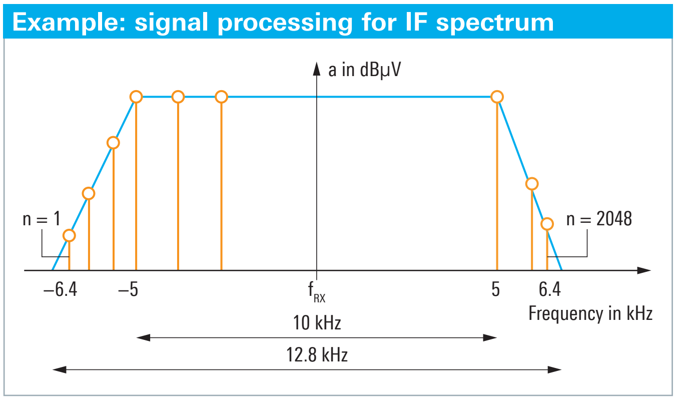
The above example shows that, due to the use of the FFT, the actual resolution bandwidth (RBW) to be taken into account in the DNL calculation is clearly smaller (i.e. BW_{bin}) than would be expected for the wide display range of 10 kHz.

Another advantage of the high spectral resolution used in the FFT calculation is that signals located close together (e.g. f_1, f_2, f_3) can be captured and represented in the IF spectrum as discrete signals.

If, on an analog receiver, a resolution bandwidth equal to the set IF bandwidth was selected (RBW = $BW_{\text{IF spectrum}}$), a sum signal f_{sum} would be displayed instead of the three discrete signals f_1, f_2 and f_3.

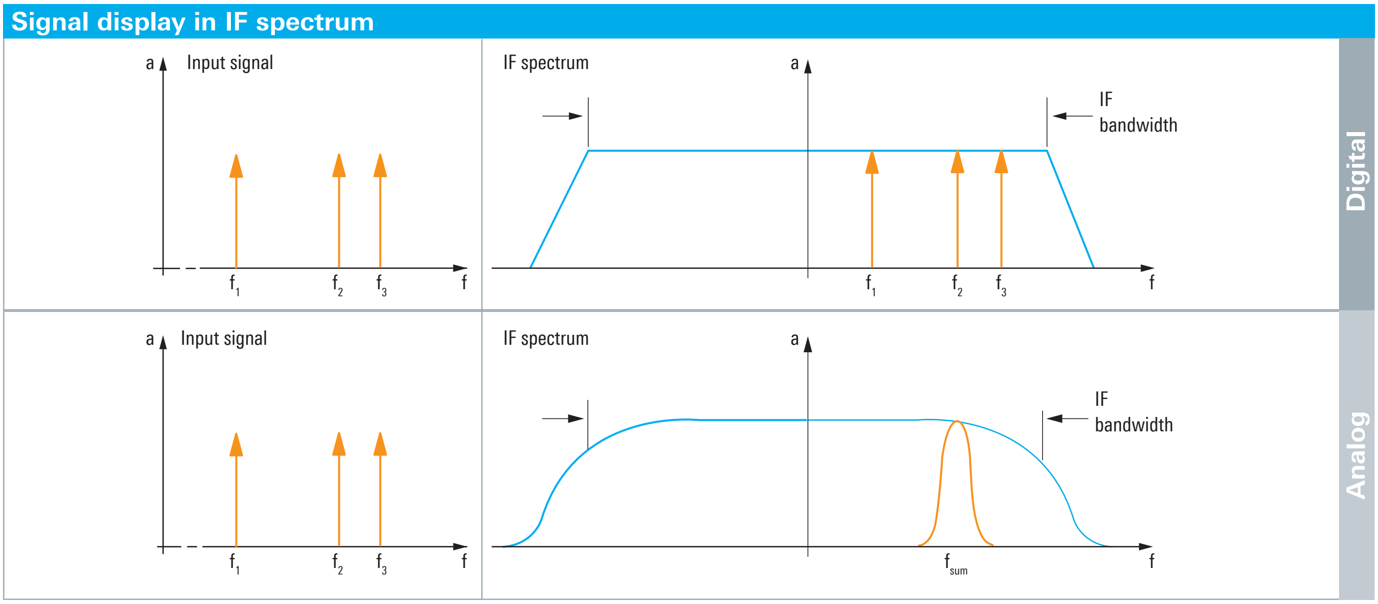
The FFT resolution can also be selected manually. This offers the advantage that the FFT resolution can be chosen to precisely match the channel spacing of the radio service to be analyzed. This ensures that the receiver will always be tuned to the center frequency of the channel in question. The channel spacings of all known radio services can be installed as FFT resolutions, with the FFT length varying between 16 and 4096 points.

Example: signal processing for IF spectrum



Actual sampling bandwidth compared with selected IF bandwidth.

Signal display in IF spectrum

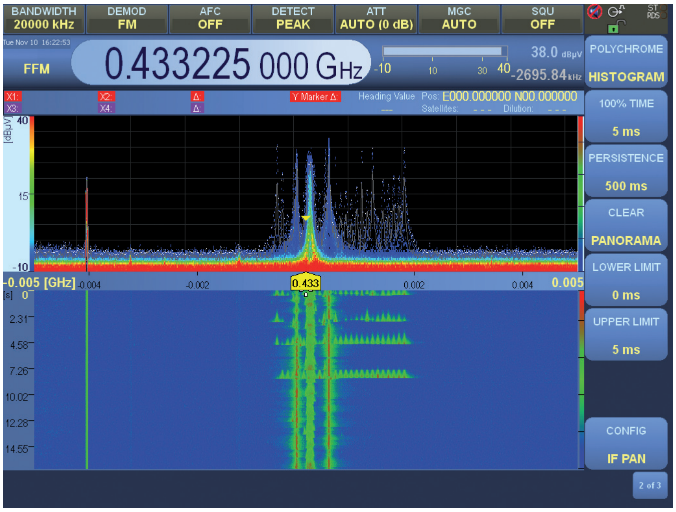


Signal resolution in IF spectrum with digital and analog receiver concept.

High-end radiomonitoring receivers feature DSP computing power so high that up to four times the number of FFT points actually needed is available, depending on the selected realtime bandwidth. By selecting an appropriate FFT length, even closely spaced channels can be reliably detected as discrete channels. By utilizing the higher number of FFT points available, the FFT can be expanded by up to four times. The high computing power can also be used to perform FFT calculation using overlapping windows. This makes even short pulses clearly discernible in the spectrum's waterfall display.

Polychrome IF spectrum display

In the histogram mode, a multicolor (polychrome) waterfall of the IF spectrum is displayed. The polychrome spectrum display is an excellent means of visualizing short pulses or short-duration signals. It shows, in different colors, signals of different duration and frequency of occurrence. Signals with a very short duration are shown in blue in the screenshot below, whereas continuous signals appear in red.


BANDWIDTH 20000 kHz | DEMOD FM | AFC OFF | DETECT PEAK | ATT AUTO (0 dB) | MGC AUTO | SQU OFF

FFM 0.433225 000 GHz

38.0 dBµV, -2695.84 kHz

Various short-duration signals in the ISM band.

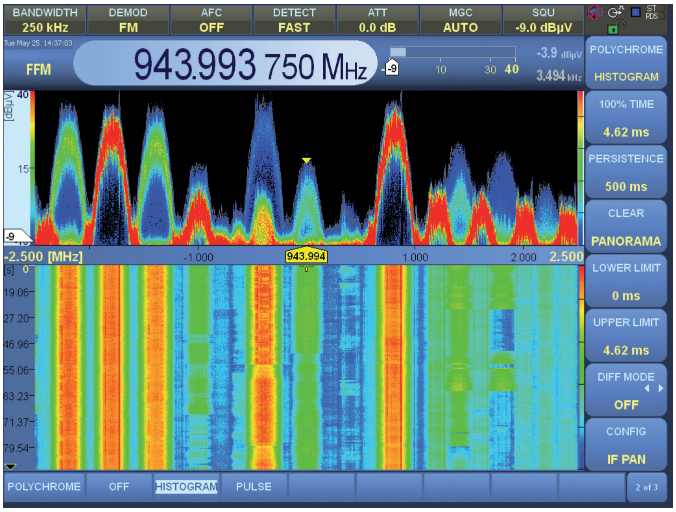
An adjustable switch-off delay ensures that even sporadic short-duration emissions are clearly distinguishable. The user can adapt the color assignment by means of diverse configuration options. If the histogram is displayed in the pulse mode, the signal duration (pulse duration) can be measured in addition. By adapting the IF bin width to the channel spacing of a specific radio service, as described under "IF spectrum," a quick assessment of TDMA channel occupancy is possible.

Video spectrum

A video panorama is available to display the spectrum of a demodulated signal. It can be used, for example, to visualize subcarriers (pilot tone, RDS carriers) in FM signals. The AM², FM² or I/Q² modes enable the user to measure signal parameters such as the baud rate or chip rate (for DSSS signals) that are used in digital transmission methods.

Realtime capability

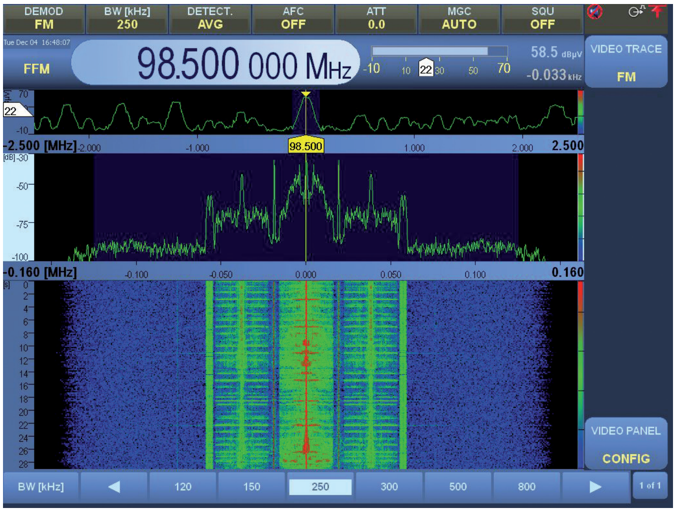
To provide a measure of the realtime capability of radiomonitoring receivers, a virtual scan speed is often specified. This figure designates the scan speed in scan ranges that are smaller than the receiver's maximum realtime bandwidth. Scans across this range can also be designated as realtime scans since the tuning time of the synthesizer can be ignored within the realtime bandwidth of the receiver. At a fixed frequency resolution and a sufficiently large realtime bandwidth, the speed of the realtime scan is determined solely by the receiver's computing power (see table on next page).


BANDWIDTH 250 kHz | DEMOD FM | AFC OFF | DETECT FAST | ATT 0.0 dB | MGC AUTO | SQU -9.0 dBµV

FFM 943.993 750 MHz

-3.9 dBµV, 3.494 kHz

GSM downlink: The histogram mode reveals co-channel occupancy and the different number of occupied timeslots per channel.


DEMOD FM | BW [kHz] 250 | DETECT. AVG | AFC OFF | ATT 0.0 | MGC AUTO | SQU OFF

FFM 98.500 000 MHz

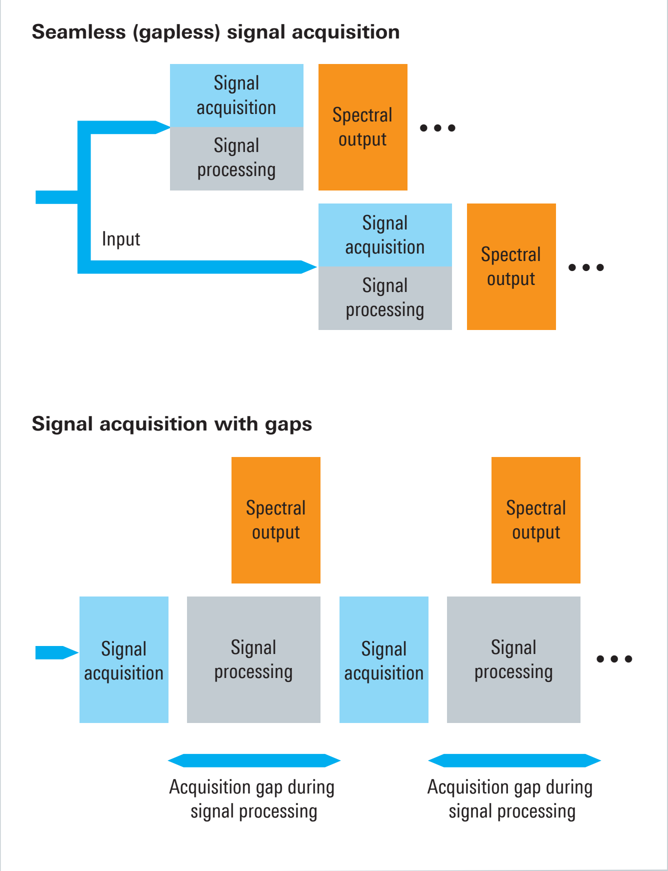
58.5 dBµV, -0.033 kHz

Spectrum of a demodulated FM signal.

When it comes to assessing a receiver's realtime capability with respect to signal processing, seamless data acquisition is the key criterion. While some "realtime receivers" are able to capture a spectrum in realtime for a specific period of time, they do not offer sufficient processing resources to continue data acquisition without interruptions, i.e. seamlessly. Instead, data has to be buffered, and signal acquisition is interrupted in order to process and display the buffered data.

By contrast, Rohde & Schwarz radiomonitoring receivers offer two parallel signal processing paths that permit the seamless capturing and processing of signals in realtime.

Signal processing



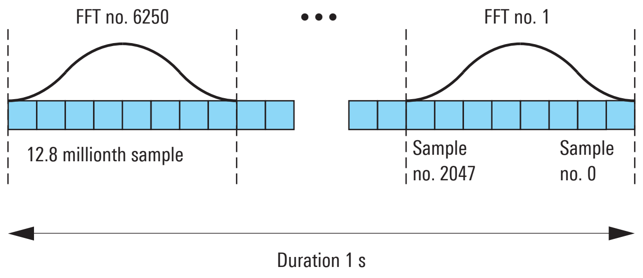
For the following description, an IF bandwidth of 10 MHz is assumed. At this bandwidth, 12.8 Msample are collected per second.

An FFT with 2048 points processes 2048 samples per frame. Consequently, 6250 FFTs are required in order to process one second of the incoming data stream. Each individual FFT therefore includes samples received during a period of 1 s/6250, which is 160 µs.

The Blackman filter indicated in the bottom right figure allows the samples within each FFT frame to be described as a function without any infinite spectral components in the time domain. The spectrum can therefore be calculated very quickly. However, a sometimes substantial attenuation has to be accepted for signals that are shorter than the duration of an FFT frame and located at the boundary between two frames.

To capture a signal with 100 % reliability and correctly measure its level, a minimum signal duration corresponding to two FFT frames, i.e. 320 µs in this example, would be required. If the focus is on detecting a signal rather than measuring its level correctly, considerably shorter pulses down to several hundred nanoseconds can be captured and processed. This type of processing is generally referred to as seamless (gapless), although pulses may go undetected if they are very short and located at

Number of samples and FFTs per second for a 10 MHz IF bandwidth



Internal computing power of the R&S®ESMD

Frequency resolution in kHz	Number of spectra per second		Time resolution in µs	
	20 MHz realtime bandwidth	80 MHz realtime bandwidth	20 MHz realtime bandwidth	80 MHz realtime bandwidth
12.5	12 500	–	80	–
25	25 000		40	
50	50 000		20	
100	100 000		10	

an unfavorable position with respect to the FFT frame (see upper processing step in the figure "Overlapping FFT"). Therefore, some Rohde & Schwarz receivers offer overlapping FFT. Two FFTs whose frames are shifted with respect to one another are calculated in parallel from the data stream. A sample located in the minimum of the Blackman filter curve of one FFT will then be found in the maximum of the other.

For a realtime bandwidth of 10 MHz as used in this example, a minimum signal duration of 240 µs is required to ensure 100 % reliable signal acquisition and correct level measurement. For shorter pulses, the level may not be displayed correctly, and only very weak signals may go undetected.

It is evident that the use of digital signal processing in a radiomonitoring receiver offers great advantages. Extremely high sensitivity (due to very fine resolution) combines with a broad spectral overview and high scan speed to significantly increase the probability of intercept over analog receivers or spectrum analyzers.

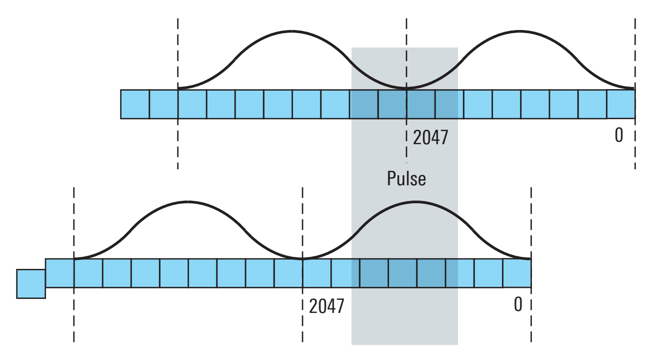
Panorama scan

In the panorama scan mode, the spectrum is displayed across a frequency range far wider than the radiomonitoring receiver's realtime bandwidth. This mode provides users with a quick overview of the spectrum occupancy.

The principle of the panorama scan is described in detail in the following using a receiver with 10 MHz realtime bandwidth (= FFT bandwidth) as an example.

To calculate the spectrum in a panorama scan, frequency windows of a width up to the receiver's maximum possible realtime bandwidth are linked in succession. The complete, predefined scan range is traversed.

Overlapping FFT (example: 50%)

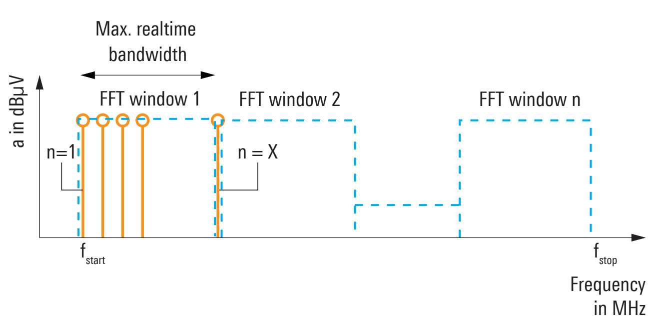


As with the IF spectrum, an FFT is used to process the broad window with finer resolution. The width of the frequency window and the FFT length (number of FFT points) are variable and are selected by the receiver.

In the panorama scan mode, the user can select among different step widths. The step width corresponds to the width of a frequency slice (bin width) as described under "IF spectrum" above. Based on the selected step width and start and stop frequency, the receiver automatically determines the required FFT length and the width of the frequency window for each scan step. The receiver selects these internal parameters so that the optimum scan speed is achieved for each step width.

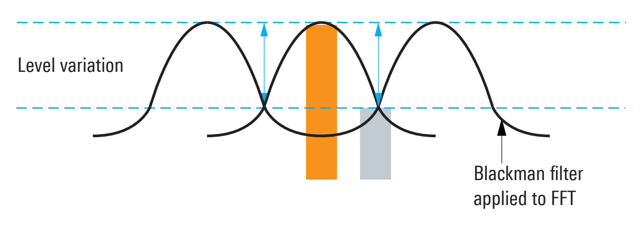
In the panorama scan mode, maximum scan speed is achieved when using the maximum step width (which means maximum window width and minimum number of FFT points). In contrast, maximum sensitivity is achieved when using the minimum step width (which means minimum window width and maximum number of FFT points, resulting in minimum scan speed). The step width (bin width) for the panorama scan therefore corresponds to the resolution bandwidth (BW_{bin}) used in the DNL calculation for the IF spectrum (see DNL formula under "IF spectrum" above) and can be used to calculate the DNL for the panorama scan. Apart from this, the user selects the step width to obtain the desired frequency resolution.

Example: signal processing in panorama scan mode



Basic sequence of steps in fast panorama scan mode.

Level variation despite 50 % overlapping FFT

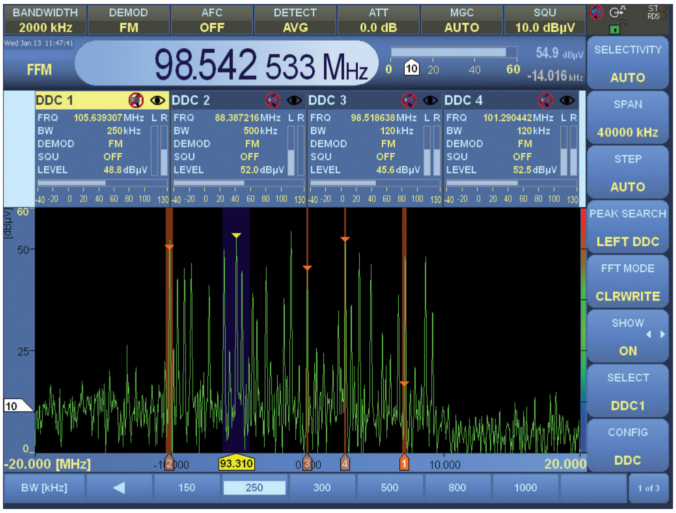


A receiver's available IF bandwidth has a direct influence on the achievable panorama scan speed. Doubling the IF bandwidth (i.e. using 20 MHz instead of 10 MHz in this example) will also double the achievable scan speed. If the IF bandwidth is increased from 20 MHz to 80 MHz, the scan speed will be boosted by a factor of four.

Operating and display modes

Fixed-frequency mode

The fixed-frequency mode, in which the center frequency of the set realtime bandwidth remains unchanged, is the normal reception mode of a receiver. It is used to continuously and simultaneously process one or more signals within the realtime bandwidth. Signals are measured and demodulated in the receiver, and the resulting analog or digital IF data is output for postprocessing. Signal measurement can be carried out automatically for specific ITU standards or manually using markers on the display.



BANDWIDTH 2000 kHz
DEMOD FM
AFC OFF
DETECT AVG
ATT 0.0 dB
MGC AUTO
SQU 10.0 dBµV

Wed Jan 13 11:47:41
FFM 98.542 533 MHz
54.9 dBµV
-14.016 kHz

	DDC 1	DDC 2	DDC 3	DDC 4
FRQ	105.639307 MHz	88.387216 MHz	98.518638 MHz	101.290442 MHz
BW	250 kHz	500 kHz	120 kHz	120 kHz
DEMOD	FM	FM	FM	FM
SQU	OFF	OFF	OFF	OFF
LEVEL	48.8 dBµV	52.0 dBµV	45.6 dBµV	52.5 dBµV

SELECTIVITY AUTO
SPAN 40000 kHz
STEP AUTO
PEAK SEARCH LEFT DDC
FFT MODE CLRWRITE
SHOW ON
SELECT DDC1
CONFIG DDC

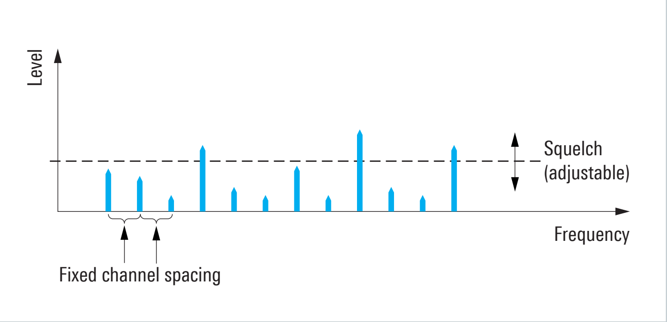
In addition to the main demodulation path (blue), another four signals (red) can be demodulated independently of each other.

Frequency scan

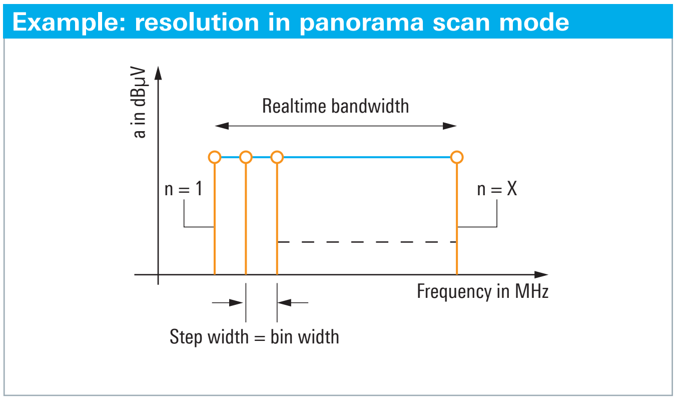
In the frequency scan mode, a user-defined frequency range is scanned using a fixed channel spacing. The radiomonitoring receiver steps through the frequency range and checks each channel for occupancy. The frequency scan mode is intended especially for monitoring radio services that use a fixed frequency (channel) spacing. The channel spacing, the dwell time per channel, the demodulation mode and bandwidth, and the squelch setting are therefore selected globally for the entire scan range.

If a level above threshold is detected, the receiver dwells at the corresponding frequency for a preselected period of time. Occupied channels of a radio service are quickly found, demodulated and output on the loudspeaker. The frequency and relevant settings of a detected channel can be stored to a memory at the press of a button during the dwell time. The memory is then available in order to call up channels quickly or to search channels in a memory scan. Conversely, occupied channels that are of no interest for further monitoring can be suppressed during the dwell time, likewise at the press of a button. These channels will no longer be displayed as the frequency scan continues. This enhances scan speed and increases the probability of intercept for signals on other channels.

Frequency scan

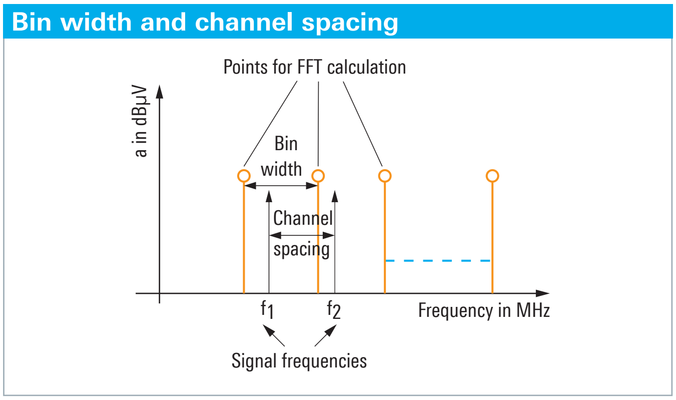


Example: resolution in panorama scan mode



Selection of resolution for panorama scan by varying the bin width.

Bin width and channel spacing



Selection of 12.5 kHz bin width to capture a radio service using 12.5 kHz channel spacing.

Memory scan

Most radiomonitoring receivers have internal memory locations (channels) to which frequencies are stored; high-end instruments, for example, offer more than 10 000. A complete, individual data record can be assigned to each memory location. In addition to the frequency, a data record may include bandwidth, detector type, demodulation mode and other settings. During a scan, the selected channels are checked for occupancy in the sequence of the memory locations. The memory scan is of interest in particular if individual frequencies are to be scanned that have no fixed channel spacing or if frequency blocks are to be scanned periodically.

Particularly important channels, for example a distress frequency, can be stored in multiple memory locations. It will then be checked multiple times during a scan. This will increase the probability of detecting activities on that channel over less important channels.

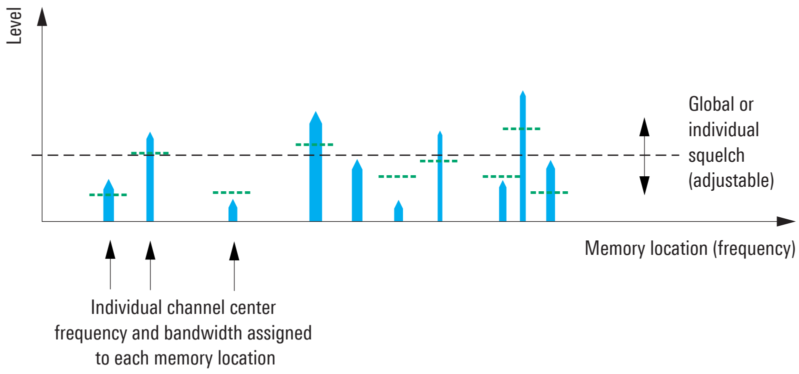
Waterfall

If frequencies are occupied at varying times, a waterfall diagram of the spectrum is ideal for displaying the history of frequency occupancy. The levels of the signals in the spectrum are color-coded. The waterfall display allows the fast and reliable detection in particular of short-duration signals that are visible only briefly in the spectrum, and of frequency-agile signals such as chirps and hoppers. Markers in the waterfall display can be used to measure signal bandwidths and, depending on the time resolution of the waterfall, to determine signal durations.

BANDWIDTH 120 kHz
DEMOD FM
AFC OFF
DETECT AVG
ATT AUTO (0 dB)
MGC AUTO
SQU OFF
FFM 900.056 250 MHz
DEMOD FREQ 900.05625 MHz
SPAN 10000 kHz
STEP AUTO
HISTORY 16:17:08.337
FFT MODE MAXIMUM
MEAS MODE CONT
MEAS TIME AUTO
CONFIG IF WF

Waterfall display with history and marker functions.

Memory scan



Additional functions

In addition to the excellent characteristics provided by the analog RF stages and digital signal processing, more and more functions are made available, partly in the instrument itself and partly on external computing platforms. A feature of particular importance in radiomonitoring receivers is an easy-to-integrate remote control and data interface. State-of-the-art receivers from Rohde & Schwarz include LAN interfaces and can be remote-controlled by means of SCPI commands. For more information on remote control software and system integration, see "Off-the-Shelf Software and Systems" on page 203.

Direction finding (DF) is another function that can be installed directly on the instrument. Adding DF capability will expand a radiomonitoring receiver to a full-featured single-channel direction finder. For details, see "Direction Finders" on page 71.

Additional signal analysis functionality on an external computer enables the user to perform automatic scans and classifications or special analyses of signals in line with ITU-R SM, 1600 recommendations. For details, see "Analyzers" on page 138.