Milestones in shortwave receiver/ transceiver development at Rohde & Schwarz for worldwide communications

Education Note

Authors:

Ulrich L. Rohde, University of the Bundeswehr, Department of Informatics, Germany, N1UL/DJ2LR
Thomas Bögl, Rohde & Schwarz Germany, Technology Systems Division, DL9MDB

The authors would like to dedicate this article to their former colleague Robert Träger who played a key role in the development of shortwave radio equipment at Rohde & Schwarz over many years.

Version 1 | 08.2024

ROHDE & SCHWARZ

Make ideas real

CONTENTS

1 INTRODUCTION

In the German-speaking world, the abbreviation "HF" generally stands for "Hochfrequenz" (high frequency), but it does not imply any specific frequency ranges. The related discipline of "Hochfrequenztechnik" (RF engineering) is generally focused on finding scientific and engineering solutions in the domain of RF equipment and systems, but without any specific band limitations.

In international usage, however, "HF" explicitly implies the frequency range from 3 MHz to 30 MHz, which is referred to in German as “Kurzwelle” or “KW” (shortwave). In practice, this frequency range is usually considered to begin at 1.5 MHz, which makes sense due to the many similarities in terms of how these frequencies are used. The corresponding wavelengths are between about 10 m and 100 m (200 m). From our modern perspective, however, these "short" wavelengths seem very long when compared with today’s applications in the millimeter wave range, e.g. some 5G mobile radio bands. In any case, it is good to be aware that some of the band designations in use today were created at a time when radio technology was still in its infancy.

In the early years of the 20th century, radio pioneers like Guglielmo Marconi succeeded in transforming the still new technology of radio waves into practical solutions for global communications. Marconi was in fact awarded the Nobel Prize in Physics in 1909 for his accomplishments. The importance of radiocommunications became apparent through events like the tragic sinking of the Titanic. Thanks to the availability of this new radio technology, hundreds of passengers on the ship were saved who would have otherwise perished.

Shortwave equipment is capable of supporting global communications in a very straightforward manner. Following the introduction of the Internet, however, this fundamental capability had been forgotten for several decades. During this time, amateur radio operators remained among the few users of shortwave technology – broadcasters and the military had largely shut down their HF operations. However, the changing geopolitical situation in recent years has brought about a renaissance for shortwave. Why? Because it is the only technology that can function without infrastructure like satellites and mobile networks, which could be destroyed (or at least rendered unusable) with relative ease.

This article highlights some of the outstanding capabilities of shortwave equipment from Rohde & Schwarz. These capabilities have set new standards in the marketplace for shortwave equipment and helped to make Rohde & Schwarz a leader in this field for decades now – a position the company maintains to this day.

2 THE RESURGENCE OF SHORTWAVE

The impressive capabilities of state-of-the-art shortwave technology have led to its rediscovery, particularly among military users. For example, Canada has decided to build out and extend its own shortwave stations. Canada’s purchases include radio systems from Rohde & Schwarz that offer excellent radio specifications thanks to their advanced software defined radio (SDR) technology – along with easy integration into fully digital IP systems.

An announcement from NAV CANADA (the operator of Canada’s civil air navigation system):

NAV CANADA, after an extensive supplier evaluation, awarded Rohde & Schwarz a contract to supply 17 HF transmitter systems, each with an output power of four kilowatts (kW) for voice communications in its North Atlantic region. Deliveries will take place from 2019 to 2020 and be operational that same year.

The HF system being introduced is part of the R&S®M3SR Series 4100 software defined radio (SDR) family, specifically the R&S®XK4100 SDRs. It is also equipped with the new ED137 IP interface. These radios follow the requirements of the international standard EUROCAE ED137 for Voice-over-IP (VoIP) Air Traffic Management (ATM) applications. These transmitters will support NAV CANADA HF communications for decades.

Source: Rohde & Schwarz GmbH & Co. KG

We also recommend reading the white paper entitled *The Rebirth of HF*, which contains further details on the topic of shortwave radio technology.

3 THE EARLY DAYS OF SHORTWAVE RECEIVER ENGINEERING

Around the year 1962, the highly revolutionary EK07 HF receiver was developed based on vacuum tube technology. The EK07 was sold in large quantities for applications such as radiotelephony and radiotelegrapy to the navy.

Later, an enormous effort was expended attempting to achieve the same outstanding large-signal behavior in similar transistor receivers. Even to this day, however, comparable results have not been fully attained. But we will come back to this topic later.

Figure 1: Three generations of shortwave receivers. EK07/D2 HF receiver (bottom) and EK056/4 and EK896 (above), connected to the same antenna for comparison

The picture above shows the first two receivers R&S built on the bottom and then the latest standalone version on top. The HF current receivers are derived from the receive parts of current HF transceivers. A somewhat simplified block diagram of the famous EK07 is shown on the following page.

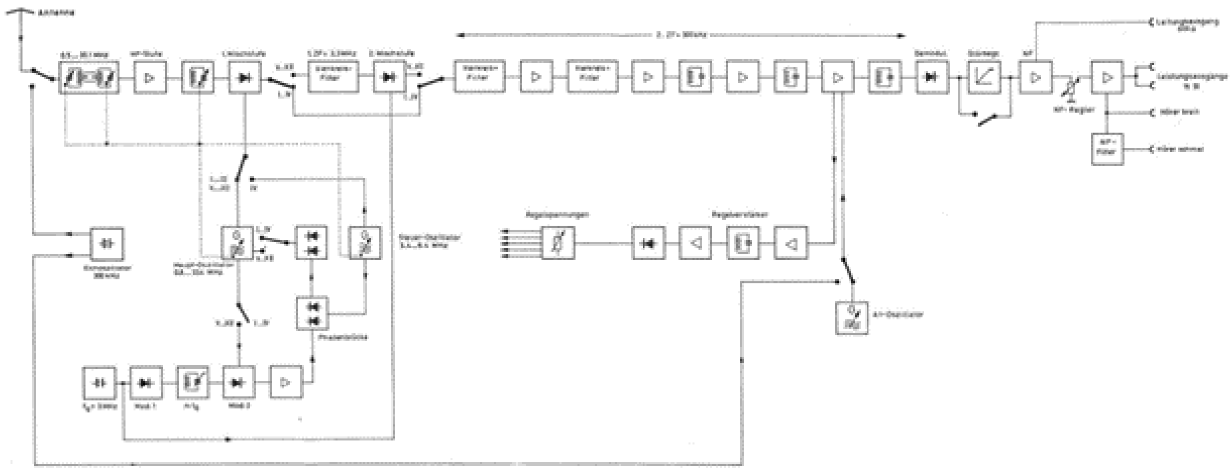


Figure 2: Block diagram of the EK07 shortwave receiver

The oscillator section was a 3 MHz crystal harmonic based synthesizer, a high performance mixer and a high gain IF amplifier and demodulator for AM and CW (on-off keying / Morse code). SSB demodulation was done in a separate box.

The subdivisions of the frequency range as well as the intermediate frequencies and filter limits for the subranges were chosen as follows (excerpt from original manual):

Frequency coverage:		0.5 – 30.1 MHz
Range A		3.1 – 30.1 MHz
Coarse dial: Range	IV	3.1 – 6.1 MHz
	V	6.1 – 9.1 MHz
	VI	9.1 – 12.1 MHz
	VII	12.1 – 15.1 MHz
	VIII	15.1 – 18.1 MHz
	IX	18.1 – 21.1 MHz
	X	21.1 – 24.1 MHz
	XI	24.1 – 27.1 MHz
	XII	27.1 – 30.1 MHz

Intermediate frequency	
In ranges I – IV:	300 KHz
V – XII:	1st IF: 3.3 MHz
	2nd IF: 300 kHz
IF selectable bandwidth:	±0.15, ±0.3, ±0.75 kHz
	±1.5, ±3.0, ±6.0 kHz

Selectivity (stationary) at IF bandwidth	20 db	40 db	60 db
±0.15 kHz	< ±0.45	< ±0.95	< ±1.35 kHz
±0.3 kHz	< ±0.55	< ±1.00	< ±1.50 kHz
±0.75 kHz	< ±0.85	< ±2.05	< ±3.25 kHz
±1.5 kHz	< ±1.00	< ±2.00	< ±2.90 kHz
±3.0 kHz	< ±1.00	< ±2.10	< ±3.50 kHz
±6.0 kHz	< ±1.70	< ±3.50	< ±6.00 kHz

Separation from the band limit

Above 3 MHz, the receiver functioned as a "double superhet (dual conversion) receiver". It used intermediate frequencies at 3.3 MHz and 300 kHz and achieved image rejection of better than 90 dB.

In a preliminary stage, the EK07 used the E180F, a special pentode between two tuned bandpass filters, which allowed the gain to be controlled via a "remote cut-off grid" without affecting the filter matching. At the same time, this special circuit allowed a high drive level of up to over 10 V (RMS), and is thus determines the basis for the high linearity of the receive path: clearly a wise choice. The two bandpass filters are mechanically synchronized and there is an active mixer after the second filter.

For the first time ever, a cascode circuit was used here as a mixer instead of the usual pentagrid arrangement. Mixing of two HF signals (HF input signal and local oscillator) is implemented by having one tube of the cascode operating as a modulated constant current source, while the other tube transfers this current to the output as a multiplier. Compared to conventional mixers that make do with a simple non-linear characteristic, this circuit allows much better dynamic range to be achieved along with lower distortion. In principle, this circuit can also be regarded as a forerunner of the active "Gilbert cell" mixers that are commonly used today.

Due to its superior large-signal characteristics, the EK07 could be operated with very large antennas. It was used, for example, by Norddeich Radio and Kiel Radio as well as in marine radio applications worldwide. In addition to its excellent technical specifications, the audio quality was also significantly better than that of other receivers. This was partly due to combined HF and IF control (automatic gain control, AGC), but also because low-noise oscillators were used that were continuously tunable while simultaneously exhibiting very high temperature stability.

Instead of the usual plethora of quartz crystals for mixing, a synthesizer concept was implemented here – probably the first of its kind. More details, such as the elaborate selection circuitry at the input, can be seen in the block diagram.

This receiver was sold at the time for about 12,000 Deutschmarks, the price of a small single-family home. Later, it was equipped with quasi-continuous IF bandwidth setting (using crystal-steepened bandpass filters), and a frequency counter with 100 Hz resolution was built into the window for the fine-resolution scale. As mentioned previously, an external add-on device was available for modern operating modes like SSB.

4 TRANSISTORS BEGIN TO REPLACE VACUUM TUBES

Once Rohde & Schwarz was optimally positioned in the HF receiver sector, the goal was to develop an equivalent fully transistorized receiver. The EK056/4 was the start.

A block diagram of the EK056/4 is shown below.

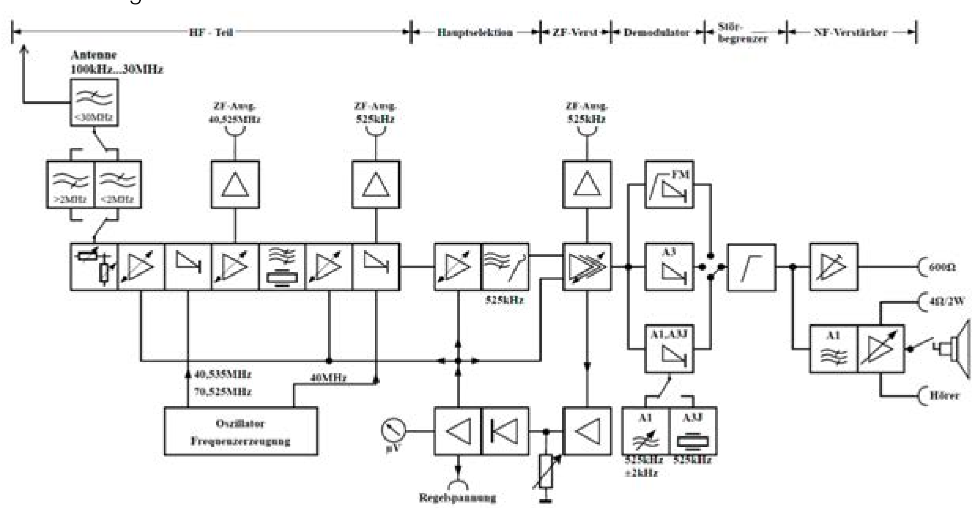


Figure 3: Block diagram of the EK056/4 shortwave receiver

The EK056/4 differs from the EK07 in that it first mixes up to a 1st IF at 40.525 MHz and then down to 525 kHz in order to reduce the problem of image rejection. A 40.525 MHz crystal filter with a bandwidth of less than 20 kHz makes the job easier for the subsequent stages.

The sensitivity at 2.4 kHz was –20 dBµV for a 6 dB S/N ratio, which corresponds to a voltage of 0.1 µV into 50 Ohm.

This value can be used to calculate the noise figure of the receive path. The first step is to calculate the noise voltage V_{Noise}, which is 6 dB below the received signal.

$$V_{Noise} = \frac{0.1\ \mu V}{10^{\left(\frac{6}{20}\right)}}$$

$$V_{Noise} = 50.1\ nV$$

The equivalent thermal noise voltage Vth at the input to a receiving system is calculated as follows:

$$V_{th} = \sqrt{k * T * F * R * \Delta f}$$

where
k = 1.381 * 10^{-23} Ws * K^{-1}
T = Absolute temperature in Kelvin
F = Noise figure of receiver (linear factor)
R = System resistance (in our case, 50 Ohm)
Δf = Bandwidth used (in our case here, 2.4 kHz)

If we now set V_{Noise} equal to V_{th} and solve for F, we obtain a value of approx. 6 dB for the noise figure of the receiver. This is a very good value if we take into account that passive filters are first connected directly at the antenna.

In addition to a large number of sub octave filters, an innovative circuit was developed (a double balanced diode attenuator) to allow continuous variation of the attenuation. This circuit used push-pull and symmetry adjustment operation to reduce harmonic distortion. This type of control exhibits significantly less distortion than the usual vacuum tube AGC control.

In the block diagram of the EK056/4, we see that an amplitude controller is positioned before and after the crystal filter in order to adjust the HF levels. There is also a synthesizer circuit that synchronizes the main oscillator (VFO) with the temperature-compensated reference oscillator in a continuously tunable manner. The figure below shows the measured noise of the main oscillator, which was remarkably good for that era.

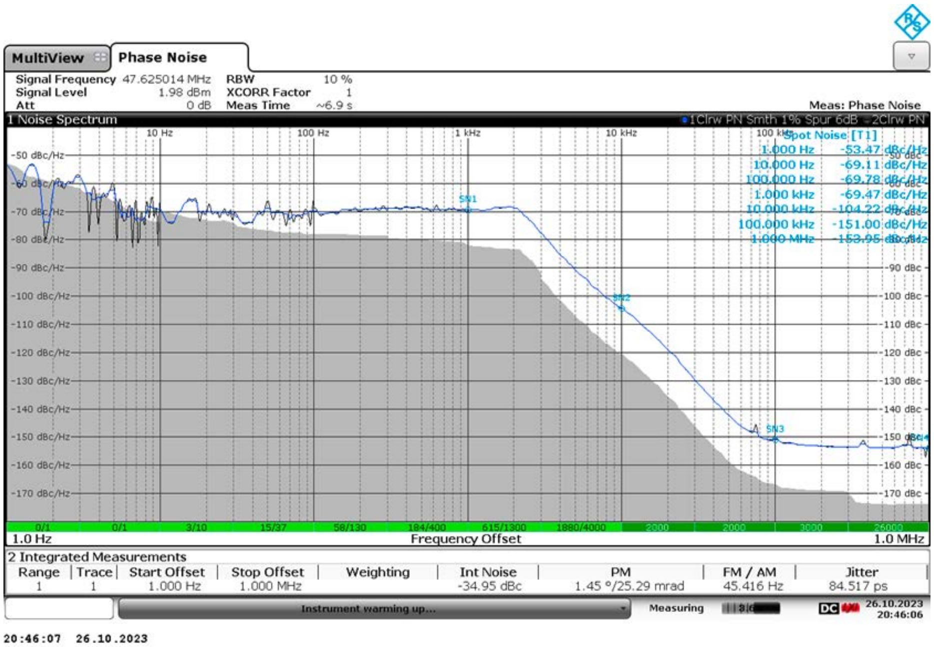


Figure 4: Phase noise of the main oscillator in the EK056/4 measured with a R&S FSWP

A "double balanced" mixer with preamplifier is positioned before the crystal filter to eliminate the harmonic distortion products. It is built using silicon diodes with a 0.6 V threshold voltage that allow greater FR voltages than e.g. hot carrier / Schottky barrier diodes. When using the latter, three diodes with a threshold voltage of approx. 0.2 V had to be connected in series to obtain the same dynamic range.

The receiver also used a quasi-continuous bandwidth controller that was based on a similar principle to the "Wadely loop". See https://televideo.ws/index.php/the-wadley-loop for more details.

The following block diagram provides details about this circuit. The IF signal is mixed twice in succession with a higher and a lower auxiliary oscillator to a significantly lower auxiliary IF and then mixed back to the original IF frequency. At the lower auxiliary IF, there is a very steep bandpass filter built using crystals. By varying the offset of the two auxiliary oscillators, the spectrum can now be variably suppressed either at the upper end or the lower end. The entire circuit thus functions like a bandpass filter with upper and lower edges that can be independently adjusted in a continuous manner.

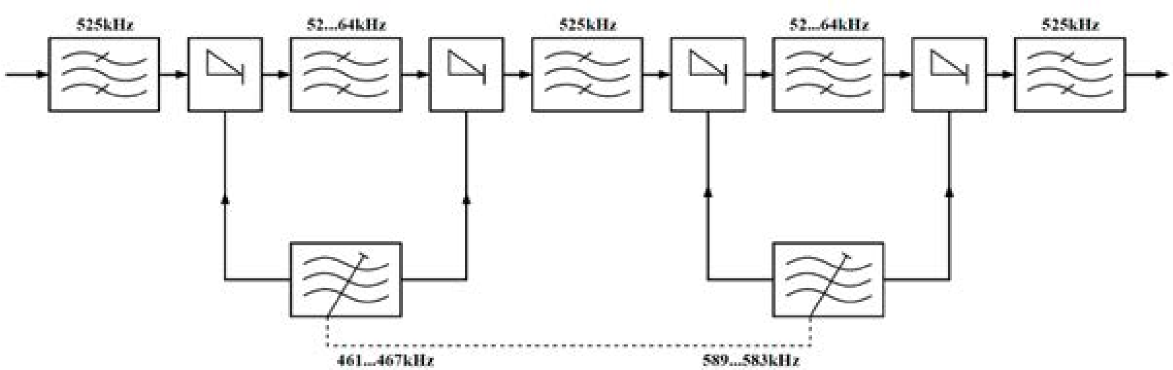


Figure 5: Block diagram for quasi-continuous bandwidth setting in the EK056/4

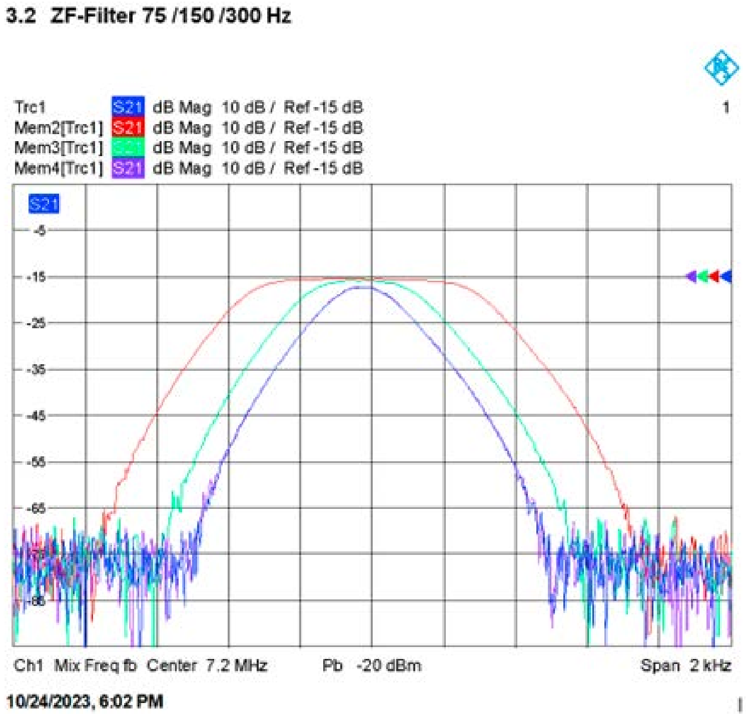


Figure 6: Tuning range for quasi-continuous bandwidth setting in the EK056/4

In the measured selectivity curve, the edges on the right and left are identical and not overly steep. This prevents ringing effects and leads to a satisfactory transient response, i.e. a reduced Gibbs phenomenon.

In later, more sophisticated receivers, analog filters with much steeper edges were also used. However, the associated problem of ringing was not really solved until digital filters were introduced in DSPs and successfully integrated into receivers like the EK890 or the R&S®XK4100 series.

Figure 7: Test setup for receiver intermodulation measurements

To characterize the robustness or the large-signal behavior of a receiver, one approach involves injecting one or more interfering signals outside the configured radio channel. A test is then performed to determine the maximum signal level for the interfering signals at which receiver operation is not yet impaired.

For example, we assume in the following discussion that a receiver generates a third-order mixing product of –108 dBm when two signals with a level of –10 dBm each are applied. Relevant details on the underlying effects are provided further below.

The R&S®SMU200A vector signal generator consists of two separate signal generators that each provide a stimulus signal which represents an interfering signal outside the receive channel. The outputs were combined via a 3 dB coupler. The 3 dB coupler that is used provides isolation of greater than 35 dB between all of its ports. The CMTA radio communication analyzer at the bottom of the previous picture was used to measure the throughput losses of the 3 dB couplers and to determine the level of the intermodulation products produced by the receiver.

The third-order intercept point (IP3) can now be calculated from the previously measured values as follows:

$$IP_3 = \frac{-10\ dBm - (-108\ dBm)}{2} + (-10\ dBm)$$

$$IP_3 = +39\ dBm$$

The background for this calculation is explained in greater detail in the rest of this article. This is an impressive value for a transistorized receiver. It was identical in measurements performed with a 200 Hz and a 20 kHz difference between the two test carriers.

How could this have been achieved with an early transistorized receiver? One main approach involved the use of a multi-loop controller, which can be used, for example, to precisely regulate the level at the mixer. The designers also exploited the fact that the HF signal-to-noise ratio is limited by the external broadband noise and has a value of approx. 0 dBµV between 6 MHz and 9 MHz on a large dipole.

5 SYSTEM SPECIFICATIONS AND THEIR RELATIONSHIP TO THE CIRCUIT DESIGN

Dynamic Range

Thermal noise determines the lower limit of the power range in which a radio system can operate. Distortion – i.e. impairment of a signal's ability to transmit information – determines the upper limit of the power range. Since the power level at which distortion becomes intolerable varies depending on the signal type and application, a general definition has emerged: The upper limit of the power range of a network is the level at which the power of an IM product of a certain order is equal to the power of the receiver's noise floor. The ratio between the power of the noise floor and the signal power at the upper limit is referred to as the dynamic range (DR) of the network. This is often described more precisely as the two-tone IMD dynamic range. When evaluated with stimulus signals of equal power, it represents a commonly used performance parameter for receivers.

For the sensitivity limit, the term MDS is commonly used. MDS stands for "minimum discernible signal", or sometimes also "minimum detectable signal", which are the same thing in principle. The difference between these terms is actually related to practical considerations. Depending on the signal waveform that is used, the term "minimum detectable signal" is relevant when a certain signal-to-noise ratio (SNR) is given as the minimum threshold for a specific transmission technique. In contrast, the term "minimum discernible signal" comes more from the field of telegraphy – where experienced operators are capable of decoding Morse characters "out of the noise". Here, we will focus on the context of Morse telegraphy and specify that the "minimum discernible signal" is one whose signal strength leads to an SNR of only 0dB. This situation occurs when the level of the wanted signal is identical to the level of the receiver noise in the selected bandwidth.

This makes it easy to calculate the level (i.e. the power of the minimum wanted signal S in mathematical terms) because this level is equal to the equivalent noise power N within the used bandwidth B. In this context, we prefer to work with power levels instead of voltages. This is because we will make reference later to the maximum permitted drive power at the antenna input in order to determine the dynamic range.

The power of the MDS relative to the input is calculated as follows:

$$MDS_{in} = kTB + F$$

where
k = 1.381 * 10^{-23} Ws * K^{-1}
T = Absolute temperature in Kelvin
B = Bandwidth
F = Noise figure of receiver (linear factor)

An important parameter for a receiver is the so-called intercept point (IP), which plays a key role in characterizing the robustness of a receiver.

If the intercept point (IP) of a receiver is known, it is possible in principle to calculate the inherent interference products (i.e. intermodulation products) that will occur in this receiver for almost any interference spectrum. Intermodulation products are new signals that can arise internally within the receive path due to non-linear effects. These can potentially prevent reception of signals on certain frequencies due to the interference they produce. Since intermodulation effects are caused by non-linearities, not only the fundamental waves of any interfering signals that might be present are relevant, but also their harmonics and the harmonics of any interfering signal that arises – as well as the sums and differences of all the involved signals. Thus, depending on which signal components are dominant in a given situation, the so-called order of the intermodulation effects can vary. For this reason, the intercept point also has different values depending on the order of the generated products.

Concerning the intercept point, it is also important to be aware of the fact that it is a theoretical reference point – and not a maximum power level that we can actually apply to a receiver. If we increase the level of the interfering signals at the input to a receiver, the intermodulation products will grow faster than the increase in the interfering signals. In the case of IP3 (the third-order intercept point), the rule of thumb is that if the two interfering signals used for this measurement are increased by e.g. 1 dB, the interference products will increase by 3 dB. For every 1 dB increase in the interference spectrum, the separation between the interfering signals and the intermodulation products is reduced by 2 dB. We can now extrapolate the (theoretical) input levels for the two interfering signals at which the intermodulation products would have the same level as the interfering signals (and then basically cross with each further increase).

It is generally easy to calculate the nth-order intercept point that occurs when interfering signals are applied and the resulting intermodulation products are measured. The formula is as follows:

$$IP_n = \frac{nP_S - P_{IM_n}}{n-1}$$

where
n = Order of intermodulation
IP_n = nth-order intercept point
P_s = Power level of applied interfering signals
P_{IMn} = Measured power level of intermodulation products

This formula serves as the basis of all other formulas for intermodulation calculations.

However if trying to measure the IP5, the mixing products are frequently hiding under the oscillator phase noise, so this type a measurement can produce unreliable results.

If IPn and MDS are known, the intermodulation-free dynamic range (IMD DR) can be determined using the following equation:

$$DR_n = \frac{(n-1)[IP_n - MDS_{\square}]}{n}$$

where
DR_n = Intermodulation-free dynamic range in dB
n = Order of intermodulation
IP_n = nth-order intercept point
MDS = Minimum discernible signal (as previously calculated)

If the intercept point is known for a receiver, we can go back and calculate the maximum interference level that may be applied so that the intermodulation products do not exceed a certain level. In practice, the most important orders (n) for the intercept point IP_n of a receiver are the second order, i.e. IP_2 and the third order, i.e. IP_3.

In the case of the 3rd order, i.e. IP_3, the so-called spurious-free dynamic range (SFDR or DRSF) is calculated as follows:

$$DR_{SF} = \frac{2}{3}(IP_3 - MDS)$$

where
IP_3 = 3rd-order intercept point
MDS = Minimum discernible signal (as previously calculated)

This equation also suggests how we can go about measuring the spurious-free dynamic range. To do this, we apply two-tone signals (in the case of IP_3) and increase the level of the two signals until the signal-to-noise ratio degrades by 3 dB, or if the measurement is made relative to MDS, until the noise floor increases by 3"\ " dB. The 2⁄3 factor occurs because the levels of the IM_3 output signals grow by 3 dB then the input signal is increased by 1 dB.

This definition of dynamic range makes reference to a noise figure in conjunction with a bandwidth that is used, and is therefore indirectly dependent on the signal waveform that is used. By selecting smaller resolution bandwidths, e.g. 1 kHz instead of 10 kHz, a dynamic range measurement might look better, but this is a practical consideration.

The dynamic range is limited at the lower end by the minimum discernible signal. For IP2, for example, the following parameters come into play for the EK056.

$$IP_2 = \frac{-20\ dBm - (-101\ dBm)}{1}$$

$$IP_2 = +81\ dBm$$

This very good value for IP_2 was achieved, among other things, by using preselection filters, which also ensured very good image rejection of over 80 dB even with the low IF of only 300 kHz.

The successor to the EK56/4 was the EK070. It had a ring mixer with a 17 dBm LO level and a noise figure under 15 dB without a preamplifier. A switchable 20 dB attenuator was provided for use in environments with powerful interfering signals. Motorized tracking preselection (FK 101) was offered as an option. Since this receiver was commonly operated at sites with multiple transmitters up to 1 kW, the filter was needed to ensure interference-free operation.

Its excellent specifications and wide range of options made the EK070 the best-selling Rohde & Schwarz HF receiver ever of that era. It was followed by the EK085 with a passive MOSFET switching mixer. This type of mixer continues to be used today in all Rohde & Schwarz receivers and transceivers. It is still the state of the art in the HF range.

Corresponding to the EK085, the XK852 transceiver was also available with the receiver fully integrated.

Figure 8: XK859C1 transceiver

Next in line were the R&S®XK2100 series and finally the R&S®XK4100 devices from the R&S®M3SR family, which represent the benchmark today, developed under the guidance of Robert Traeger.

Figure 9: Series 4100 transceiver from the R&S®M3SR family

Features of these devices include selection units based on DSP instead of very narrowband crystal filters. The fully equipped systems can also be fitted with additional co-site filters as hardware options to avoid collocation problems when deployed in critical operating environments where other high power transmitters are present. These preselector filters with either 20 dB or 40 dB selectivity at a 10% offset from the center frequency provide preselection in the receive direction. For transmission, they are looped into the transmit path to significantly improve the transmitter noise floor.

The R&S®M3SR family of stationary radios provides with the Series 4400 radio also a UHF version of high end communication transceivers. This UHF radio is optimized for operation within highly collocated platforms such as naval vessels. It additionally combines the SDR technology with hardware based optional modules to allow an adaption to any critical requirement while maintaining low cost. The available hardware modules include co-site filters with fast hopping capability, interface modules, secondary guard receivers, etc.

Figure 10: Series 4400 transceiver from the R&S®M3SR family with optional hardware modules

The stationary UHF radios provide RF parameters which match to the requirements of a variety of installations. The main features are the following:

- **Frequency Range:** 100 – 512 MHz
- **Transmit Power:** 100 W Peak and 100 W CW (for tactical data links)
- **Receive noise figure:** 8dB (low noise mode) up to 14 dB (low distortion mode)
- **Transmitter Noise floor:** down to -180 dBc/Hz with internal hopping filter
- **Embedded Communication modes:** AM DSB plus high sophisticated EPM (Electronic Protection Modes) with frequency hopping
- **Interfaces:** a high number of analog and digital interfaces to adapt to a variety of standardized system components including a 70 MHz IF interface for external modems

A combination of HF up to UHF capabilities is implemented within a family of battery operated portable radios.

The military version of this family is the MR300xH/U series from the M3TR family.

R&S®MR300xH/U multiband tactical radio

The R&S®MR300x radios form a family of high-performance digital radios covering the HF, VHF and UHF bands. Thanks to various high-speed data modes and protocols as well as multiple anti-jam modes for HF, VHF and UHF, they perfectly integrate into tactical communications networks.

The radios are software-configurable and reprogrammable. Manpacks of the R&S®M3TR family are based on one mechanical platform, with a common logistics concept, identical physical interfaces and one human-machine interface (HMI).

Key features

- Software-configurable
- Multiband capability (1.5 MHz to 512 MHz with external devices)
- Multiwaveform capability (HF House, VHF/UHF tactical and G-A-G waveforms)
- Embedded EPM (ECCM) in line with R&S®SECOM and R&S®SECOS, HAVE QUICK II
- Selective links in one net
- Integrated GPS, position report
- Removable front panel for flexible use and integration
- User-friendly HMI
- High data rate of up to 72000 bit/s
- IP over air capability (R&S®IPoA)
- SIP based remote voice operation
- MTBF > 7500 hours

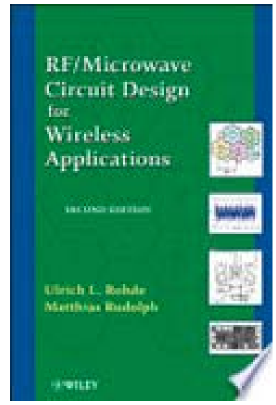
Figure 11: R&S®M3TR basic radio

Figure 12: The M3TR personalized version works worldwide even from a balcony

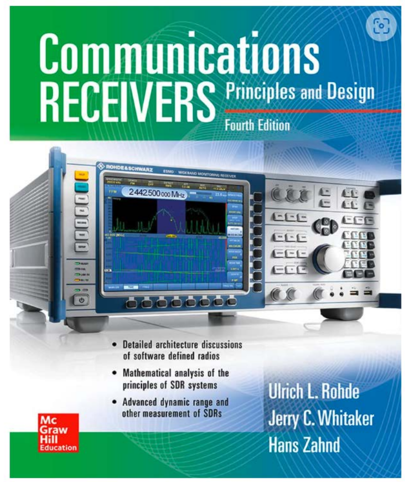
6 SUMMARY AND OUTLOOK

For more than 70 years Rohde & Schwarz offers communication receivers which outstanding performance. Innovative solutions have been the key to achieve high end quality setting standards on the market. The story of receivers at Rohde & Schwarz continues with new developments using the SDR (Software Defined Radio) technology covering new applications beyond communications like monitoring, sensor and many more. Wide frequency ranges, extremely high bandwidths and superior dynamic ranges are some of many the new requirements where Rohde & Schwarz products still will be seen as reference on the market.

7 FURTHER REFERENCES



- RF/Microwave Circuit Design for Wireless Applications
  - Ulrich L. Rohde, Matthias Rudolph
  - John Wiley & Sons, January 7, 2013 – Technology & Engineering – 920 pages



- Communications Receivers
  - Ulrich L. Rohde, Jerry C. Whitaker, Hans Zahnd
  - McGraw Hill, Fourth Edition

- 

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, monitoring and network testing. Founded more than 80 years ago, the independent company which is headquartered in Munich, Germany, has an extensive sales and service network with locations in more than 70 countries.

www.rohde-schwarz.com

Certified Quality Management
ISO 9001

Rohde & Schwarz training

www.training.rohde-schwarz.com

Rohde & Schwarz customer support

www.rohde-schwarz.com/support

Version 1 | 08.2024
Education Note | Milestones in shortwave receiver/transceiver development at Rohde & Schwarz for worldwide communications
Data without tolerance limits is not binding | Subject to change

www.rohde-schwarz.com

ROHDE & SCHWARZ
Make ideas real