Active Antennas for Radiomonitoring
Application Note

Products:

Generally applicable to all active antennas from Rohde & Schwarz,
in particular this Application Note covers the following products:

- R&S®HE600
- R&S®HE010E
- R&S®HE010D
- R&S®HE016
- R&S®HK014E
- R&S®HL033
- R&S®IN600

The fundamental working principles of active antennas are asserted and it is described what makes them different compared to passive antennas. Furthermore the important parameters relating to active antennas are explained and typical system applications are discussed - including a comparison with passive antenna solutions and a chapter explicitly dealing with radio monitoring in the HF frequency range.

Note:

Please find the most up-to-date document on our homepage
http:\\www.rohde-schwarz.com/appnote/8GE02

Application Note
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ROHDE&SCHWARZ

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1 Introduction

The usage of active antennas for radio monitoring purposes is nowadays well established. This is due to good reason. When it comes to broadband capabilities and significant size reduction, there is no better solution than an active receiving antenna. Care must only be taken when the active antenna is used at locations where very high field strength values are present. But even then, problems tend to occur mainly due to improper installation and not by reason of the active antenna itself.

Active antennas employ optimum matching of the passive radiator(s) to the active electronic circuit. Consequently the function of the radiator(s) and the electronics can no longer be described independently - like it is possible for a passive antenna with a preamplifier. This application note starts with a fundamental description of the working principle of active antennas. Furthermore it explains their characteristic parameters which should help the reader to decide if an active antenna is appropriate for a certain application. Typical application examples will aid to the understanding here.

2 Working principles

By definition an active antenna contains at least one active component (e.g. a field effect transistor) which is installed in immediate vicinity of the radiator(s) of the antenna. The purpose of this active component is primarily to match the impedance of the electrically short radiator (or pair of radiators) to the nominal impedance (i.e. 50 Ω).

A careful selection of the active device allows reasonable matching over a very wide range of input impedances and thus allows the design of an active antenna with a very broad frequency bandwidth.

Figure 1 shows the principal build-up of an active monopole antenna.

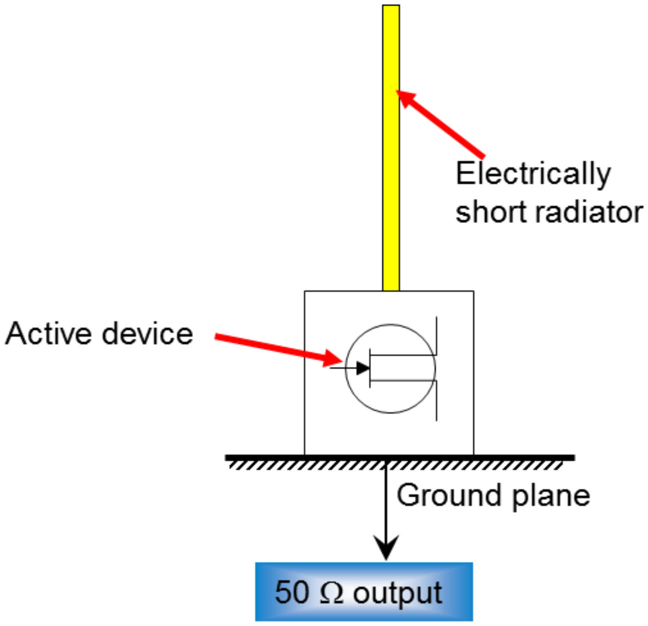

Figure 1: Concept of an active monopole antenna

To understand the fundamental working principle of an active antenna, two physical phenomena must be visualized:

- The quality of reception (of a signal of interest) is not only determined by the signal voltage measured with a connected receiver, but predominantly by the ratio of the signal level compared to the noise level present at the output of the receiver - the so-called *Signal-to-Noise Ratio* (abbreviated S/N or SNR).
- The signal voltage that can be measured at the output of a radiator (or a pair of radiators) will depend on the field strength present at the location of the antenna - or to be more precise, on the field strength vector which matches the polarization of the antenna - and on the physical dimensions of the antenna itself. An acceptable approximation here is that for a given constant field strength, the voltage is proportional to the length of the antenna.

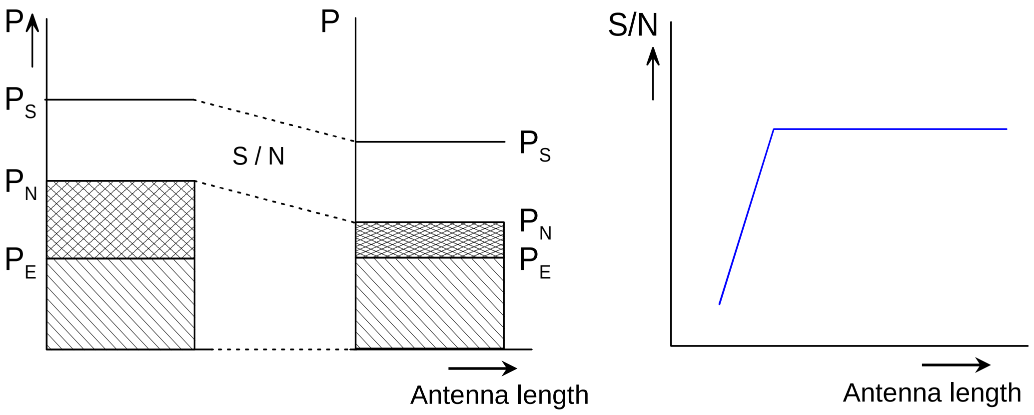

Figure 2: Fundamental working principle of S/N versus antenna length

Obviously the active antenna cannot differentiate between the wanted signal and the noise that arrives at the antenna simultaneously. Figure 2 shows on the left side that if the antenna length is reduced, the wanted signal (P_S) and the noise (P_N) picked up from the environment are reduced by the same amount. This leads to a constant Signal-to-Noise Ratio (S/N) as shown on the right side. So the quality of reception does not suffer.

However the reduction of radiator length cannot be driven to extremes. As soon as the received noise (P_N) picked up from the environment reaches the order of the internally generated noise of the receiver (P_E) the S/N will be reduced.

Hence, the optimum length of a radiator is depending on the noise figure of the receiver as well as on the environmental noise present at the antenna location.

According to [2] there are different contributions to the environmental noise as shown in Figure 3. For the majority of the HF frequency range the man-made noise is dominating, together with contributions from atmospheric and galactic sources. Man-made noise strongly varies with location and is worst for city locations.

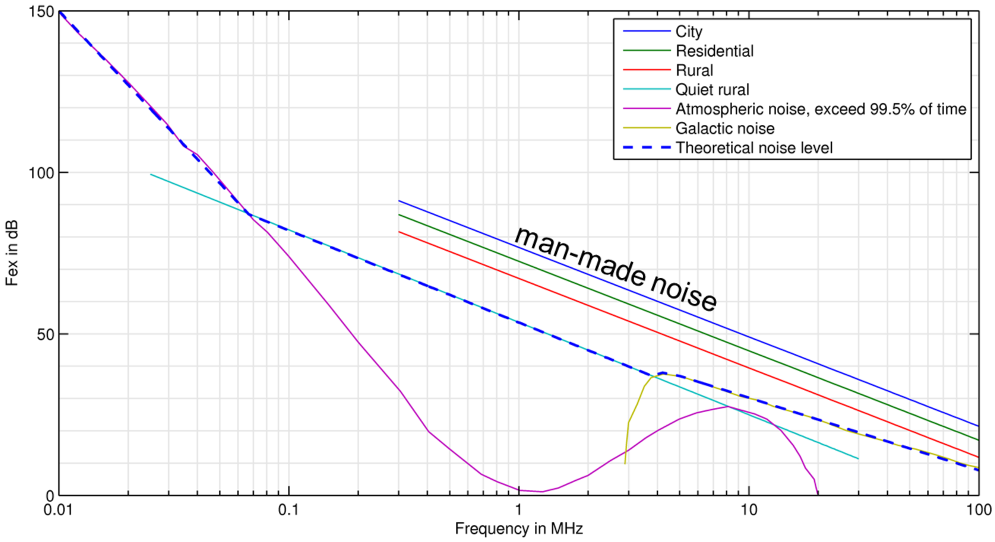

Figure 3: Different sources of environmental noise versus frequency compared to the theoretical minimum noise level

3 Characteristics of active antennas

3.1 Antenna impedance

As mentioned in [1], the antenna input impedance depends strongly on the antenna length. Figure 4 shows the equivalent circuit of an antenna where

U_{OC} is the open circuit voltage at the antenna terminals

R_L is the loss resistance of the antenna

R_r is the radiation resistance of the antenna

X_a is the antenna reactance and

Z_0 is the receiver (and cable) impedance (nominal 50 Ω)

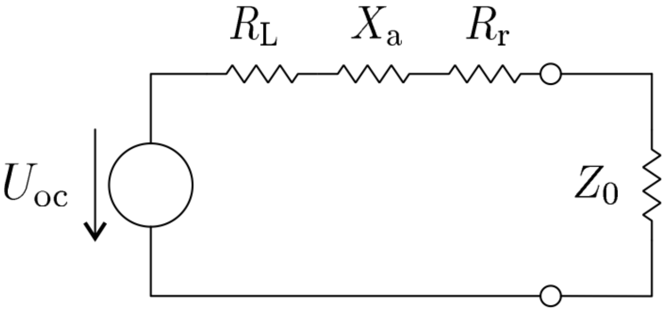

Figure 4: Equivalent circuit of an antenna

At resonance (i.e. radiator length of approx. λ/2 for a dipole) the antenna reactance X_a becomes zero and the antenna impedance is purely resistive.

But as active antennas usually feature electrically short radiators (radiator length << λ) the radiation resistance R_r and the loss resistance R_L can be neglected and the major contribution for the impedance is due to the radiator reactance X_a.

The result is a total mismatch between radiator impedance and the nominal impedance Z_0, assuming that the radiator is directly connected to the nominal impedance of the cable or the receiver.

If an active circuit (i.e. a field effect transistor) is directly located at the radiator(s) of the antenna it can match the high radiator impedance (in terms of magnitude) to the low nominal impedance Z_0. So the main task of the active device is impedance transformation rather than amplification of the signal. This results in an impedance of $Z \approx 50\ \Omega$ at the antenna connector.

Figure 5 shows the impedance characteristics of a 1 m long rod (monopole antenna) for the frequency range from 1 MHz to 200 MHz. The capacitance C_a is equal to approx. 14 pF. For frequencies up to approx. 30 MHz the reactance of C_a dominates the antenna impedance. The first resonance (λ/4) is visible at approx. 70 MHz where X_a equals zero and a second resonance (λ/2) can be found at approx. 125 MHz.

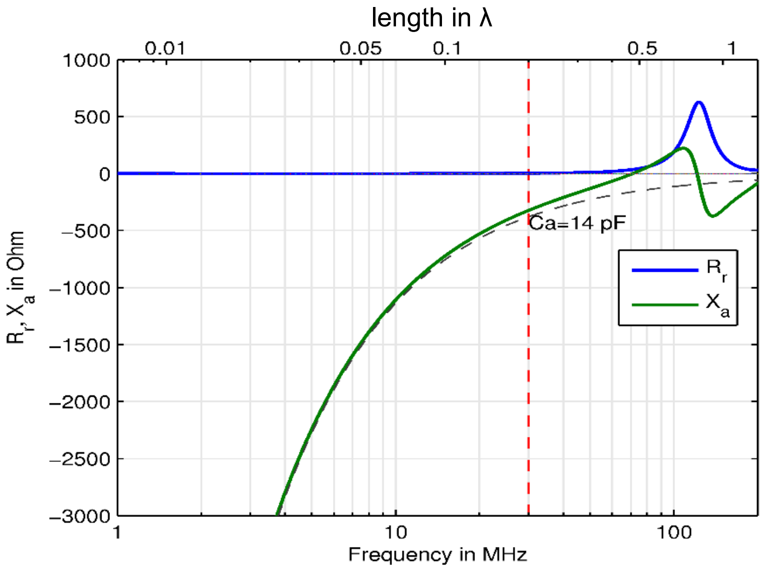

Figure 5: Impedance characteristic of a 1 m long rod (or monopole) antenna

3.2 Antenna factor

Like for passive antennas, the antenna factor (or also called transducer or conversion factor) is defined as the ratio of incident electric field strength E_i and the output voltage of the antenna at its load impedance

$$K = \frac{E_i}{U_L} \tag{1}$$

The small signal equivalent circuit of an active antenna with an electrically short radiator using a field effect transistor (FET) in common source configuration is shown in Figure 6.

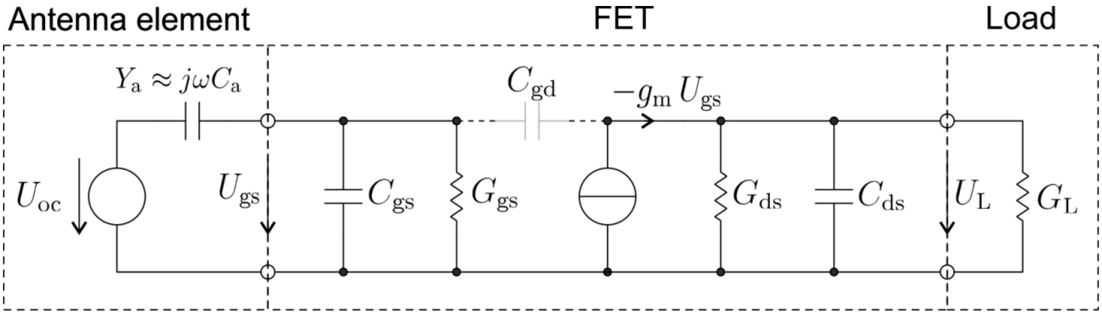

Figure 6: Small signal equivalent circuit of an active antenna

If the influence of the gate-drain capacitance C_{gd} and the conductance G_{gs} and G_{ds} are neglected the voltage at the load U_L can be calculated with the simplified formula

$$U_L \approx \frac{-gm}{G_L} \frac{C_a}{C_a + C_{gs}} U_{OC} \tag{2}$$

As already mentioned in chapter 2, the open circuit voltage U_{OC} is proportional to the antenna length h_{eff}

$$U_{OC} \approx E_i \, h_{eff} \qquad (3)$$

Consequently the antenna factor can be approximated with the formula

$$K = \frac{E_i}{U_L} = \frac{G_L(C_a + C_{gs})}{g_m \, C_a \, h_{eff}} = const \qquad (4)$$

The formula shows that the antenna factor K is almost constant over a wide frequency range. This can also be seen in Figure 7 which shows the typical antenna factor versus frequency for the R&S®HE010E active rod antenna.

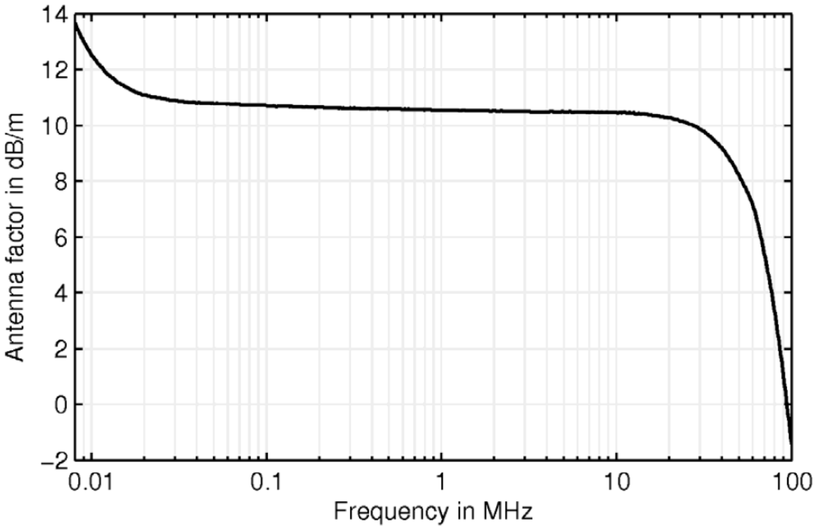

Figure 7: Typical antenna factor of R&S®HE010E active rod antenna

3.3 Antenna noise

While the active circuit directly at the antenna is able to match the impedance of the short radiator(s) to the nominal impedance Z_0, it also adds a certain amount of noise to the output of the circuit which will affect the noise figure of the antenna.

As an example Figure 8 shows the basic equivalent circuit of a junction field effect transistor (JFET) in common source configuration identifying the equivalent noise sources e_n and i_n that can be calculated with an appropriate FET model. While the noise voltage e_n is independent of the source impedance, the noise current i_n is directly depending on the source impedance Z_a.

JFET type transistors are preferred for active antenna applications due to their inherently lower noise current i_n compared to bipolar devices [4].

Note that active antennas can also utilize other types of active devices or other amplifier configurations, e.g. common drain or common gate. For simplicity reasons the noise and antenna factor calculations here are based on the JFET common source circuit.

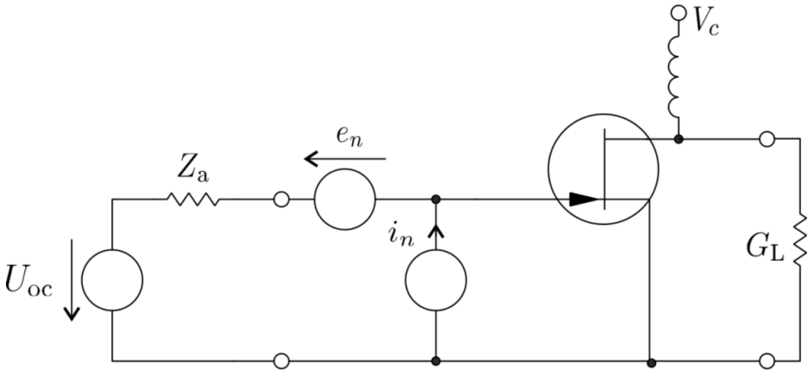

Figure 8: Noise model of a junction FET transistor

According to [3] the noise factor of a noisy two-port (i.e. an active antenna) can be calculated with the formula

$$F_a = 1 + \frac{e_n^2 + |Z_a^2| i_n^2 + 2\,Re(e_n i_n^* Z_a)}{4kT_0B\ Re(Z_a)} \tag{5}$$

where e_n and i_n are the before mentioned equivalent noise sources and Z_a is the antenna impedance.

If again a 1 m long rod antenna with an impedance curve as shown in Figure 5 connected to a JFET circuit in common source configuration is assumed, the equation above will be dominated by the magnitude of the antenna impedance and the corresponding noise figure of such an antenna is shown in Figure 9.

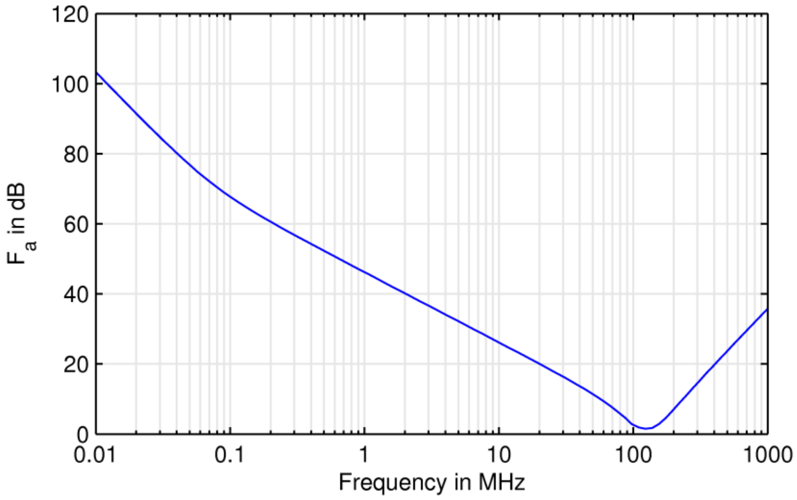

Figure 9: Noise figure of a 1 m long active rod antenna with JFET common source configuration

Note that noise figure NF and noise factor F are related via the formula:

$$NF = 10\log(F) \tag{6}$$

So essentially the matching of the short rod antenna to the nominal impedance Z_0 is causing a largely increased noise figure. Of course the antenna impedance can be chosen to give the lowest possible noise figure, but as can be seen in Figure 9 this is only possible for a very narrow frequency range.

3.4 Sensitivity

Based on the noise factor F_a it is possible to calculate the sensitivity of an active antenna E_{min}. This parameter, which is also referred to as the **field strength sensitivity**, indicates the minimum field strength value an antenna can detect in a certain bandwidth. It is calculated with the formula

$$E_{\mathrm{min}} = \frac{1}{\lambda}\sqrt{\frac{4\pi\, Z_0 k\, T_0 B\, F_a}{D}} \tag{7}$$

where

Z_0 is the impedance of free space (≈ 377 Ω)

k is Boltzmann's constant (1.38 x 10^{-23} J/K)

B is the bandwidth in Hertz and

D is the directivity of the passive radiator

In a practical application it may be more convenient to use the logarithmic formula

$$E_{min} = -96.8\, dB\mu\mathrm{V/m} + 20\log\left(\frac{f}{MHz}\right) + 10\log\left(\frac{B}{Hz}\right) + \frac{NF_a}{dB} - \frac{D}{dB} \tag{8}$$

The field strength sensitivity of an active antenna always has to be seen in the context of the environmental noise. This is especially important at LF, MF and HF frequencies where the environmental noise level is usually high. Figure 10 shows the field strength sensitivity of the R&S®HE010E active rod antenna compared to the theoretical minimum field strength sensitivity (blue curve). This theoretical curve has been determined based on the environmental noise curves from Figure 3 where a **quiet rural** location is assumed. If the antenna is installed in a **residential area** where higher levels of man-made noise are usually present (red curve), it can be seen that the inherent noise of R&S®HE010E is almost equal or even below those values.

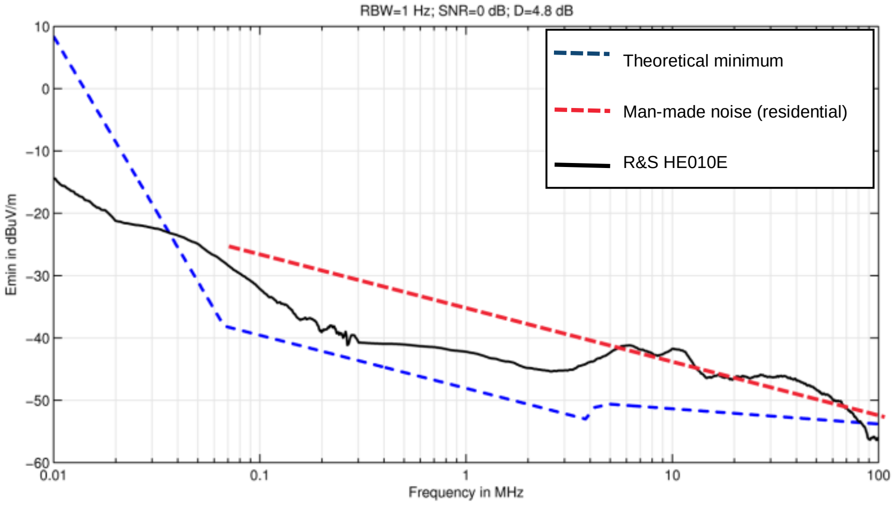

Figure 10: Field strength sensitivity of R&S®HE010E compared to the theoretical minimum and to the man-made noise in a residential area.

Consequently a further reduction of the antenna noise figure does not lead to a perceivable improvement of sensitivity in such surroundings

If the antenna noise factor F_a is equal to the external noise factor F_{ex}, the overall S/N ratio is degraded by 3 dB.

The sensitivity of an active antenna is normally specified for the antenna alone. However as already mentioned the antenna must be seen not only in the context of the external noise but also in the overall system. In combination with a receiver, the system noise factor F_S can be calculated in order to determine the overall system sensitivity.

$$F_S = F_{ex} + F_a + \frac{F_1 - 1}{G_T} + \frac{F_2 - 1}{G_1 G_T} + \cdots \qquad (9)$$

where G_T is the electronic gain of the antenna and F_x and G_x are the noise factors and gain values of all stages following the antenna (including the receiver).

Usually active antennas are designed in a way that the electronic gain G_T is chosen so that the noise contribution from the following stages can be neglected in comparison to the external noise F_{ex} - resulting in a system noise factor:

$$F_S \approx F_{ex} + F_a \qquad (10)$$

3.5 Gain

For active antennas the gain definition is different compared to passive antennas. The following two different gain definitions according to [1] are normally used in the context of active antennas:

$$Electronic\ gain\ G_T = \frac{Received\ power\ into\ the\ nominal\ resistance}{\begin{array}{c}Maximum\ received\ power\ that\ can\ be\ extracted\ with\\ an\ antenna\ with\ the\ same\ directional\ characteristics\end{array}} \qquad (11)$$

$$Practical\ gain\ G_P = \frac{Received\ power\ into\ the\ nominal\ resistance}{\begin{array}{c}Received\ power\ of\ a\ lossfree\ isotropic\ reference\\ antenna\end{array}} \qquad (12)$$

Electronic gain and practical gain are linked via the directivity D:

$$G_P = D\ G_T \qquad (13)$$

The directivity depends on the type of the passive section of the active antenna. For example a short monopole ($l \ll \lambda$) has a directivity D = 3 while a short dipole in free-space has a directivity D = 1.5.

So from the gain value of an active antenna alone (either practical or electronic gain) it is impossible to draw any conclusion on the directional characteristics or the field strength sensitivity of the antenna. As explained in 3.4, it is essential to know the antenna noise figure and the directivity in order to determine the sensitivity.

3.6 Non-linear distortion

Due to the fact that active antennas feature a non-linear transfer characteristic, the output signal will contain not only the field strength proportional wanted signal but also the harmonics and intermodulation products of all signals present at the antenna location.

From an application point of view, the key question is what level of field strength (at a certain frequency) can be tolerated in order not to affect the reception of a signal with a certain modulation type. This level will depend on various parameters of the receiver and/or the active antenna. In the majority of cases it is only necessary to evaluate the 2nd and 3rd order harmonics for single tone interferers and additionally the intermodulation products of 2nd ($f_{m2} = f_1 \pm f_2$) and 3rd order ($f_{m3} = 2\ f_1 - f_2$, $f_{m3} = 2\ f_2 - f_1$) for two-tone interferers.

The key parameters here are the intercept points of 2nd order (IP2) and 3rd order (IP3) that are usually specified in reference to the output of an active antenna.

In theory the intercept point defines the output power level where the level of the interfering signals and their corresponding intermodulation products are equal. In practice this power level is never reached because either the active device is driven into saturation or even destroyed by the high input power which may cause a failure of the FET device due to excessive gate-source voltage.

While the intercept point for an antenna is specified for the antenna alone, it also has to be seen in the system context like the noise figure in 3.4.

For a system consisting of an active antenna with output intercept points $\mathrm{OIP3_A}$ and $\mathrm{OIP2_A}$ connected to a receiver with output intercept points $\mathrm{OIP3_R}$ and $\mathrm{OIP2_R}$, the system output intercept points can be calculated with the formulas:

$$\mathrm{OIP3_{Sys}} = \frac{1}{\frac{1}{\mathrm{OIP3_R}} + \frac{1}{\mathrm{OIP3_A} \cdot G_{cable}}} \tag{14}$$

and

$$\mathrm{OIP2_{Sys}} = \frac{1}{\left(\sqrt{\frac{1}{\mathrm{OIP2_R}}} + \sqrt{\frac{1}{\mathrm{OIP2_A} \cdot \mathrm{G_{cable}}}}\right)^2} \tag{15}$$

where G_{cable} is the gain - or here the insertion loss - of the cable that interconnects antenna and receiver.

3.7 Dynamic range

As already explained in [1] an active antenna needs to achieve two slightly contradictory aims:

- It should achieve maximum sensitivity with respect to the expected external noise. Consequently it should have a low noise figure
- It should generate minimum intermodulation products when exposed to strong interfering signals. Consequently it should have high intercept point values (IP2 and IP3)

The margin between these two aims is called the dynamic range. A differentiation can be made between:

- **Linear dynamic range (DR1)** where the lowest usable signal level is determined by the smallest signal level that can be differentiated from the noise and the highest usable signal level by the 1 dB compression point (CP1) of the active circuit.
- **Spurious-free dynamic range (SFDR2 or SFDR3)** where the lowest signal is again determined by the smallest signal that can be differentiated from the noise and the highest usable signal is defined as the level where its intermodulation product(s) can also just be differentiated from the noise.

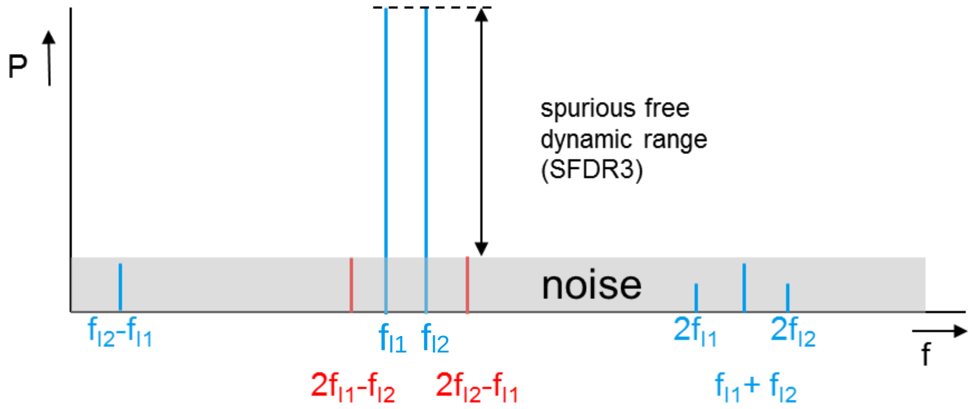

Figure 11: Spurious-free dynamic range example for SFDR3

The more important parameter in the context of interference is the spurious-free dynamic range Figure 11 explains this parameter as an example for the third order intermodulation products of two interfering signals f_{I1} and f_{I2} (long blue lines). The corresponding 3rd order intermodulation products are at 2 f_{I1}-f_{I2} and 2 f_{I2}-f_{I1} (red lines). In order to determine the SFDR3 the power level of the two interfering signals is increased until the two intermodulation products just rise above the noise floor of the system (grey bar at the bottom). The difference between the power level of the interfering signals and the noise floor is then the SFDR3.

The spurious/free dynamic ranges can also be calculated from the noise power P_N and the intercept points IP2 or IP3 with the following formulas:

$$SFDR2 = \frac{1}{2}(IP2 - P_N) \tag{16}$$

and

$$SFDR3 = \frac{2}{3}(IP3 - P_N) \tag{17}$$

Note that the spurious-free dynamic range is bandwidth dependent, as the noise power P_N depends on the measurement (or resolution) bandwidth B

$$P_N = k\, T_0 B\, F \tag{18}$$

while noise figure and intercept point are **not** depending on the bandwidth.

4 Application examples

4.1 Calculation of field strength in the far field

An isotropic radiator that is fed with a power P and transmits equally and loss-free into all spatial directions generates a power density S at the distance r:

$$S = \frac{P}{4\pi r^2} \tag{19}$$

Poynting's theorem defines the relationship between power density and the E- and H-field vectors as follows:

$$\vec{S} = \vec{E} \times \vec{H} \tag{20}$$

In the far field the E- and H-vectors are perpendicular and related to each other via the impedance of free space Z_0.

$$Z_0 = \frac{E}{H} = 120\pi\ \Omega \tag{21}$$

So the two equations can be solved for the electric field strength:

$$E = \frac{\sqrt{30\frac{V}{A} \cdot P}}{r} \tag{22}$$

As the isotropic radiator is considered to have a gain $G_i = 1$ (or 0 dB), the field strength at a distance r for an antenna with arbitrary gain G_T that is fed with power P_T can be calculated - assuming that the location is in the main beam of the antenna:

$$E = \frac{\sqrt{30\frac{V}{A} \cdot P_T G_T}}{r} \tag{23}$$

This method of calculation is only valid for free-space and far field conditions. In reality the field strength at a distance r will be influenced by further parameters, e.g. the antenna height, and various physical phenomena like reflection, absorption or refraction on the path due to the terrain properties. Accurate field strength predictions can be made based on radio wave propagation models. These are empirical mathematical formulations for the characterization of wave propagation as functions of frequency, antenna height, terrain irregularities etc.

A conversion between linear and logarithmic values for the field strength can be easily performed. Usually the logarithmic unit dBµV/m is used for the electric field strength which can be derived from the linear value given in V/m by:

$$E\ [dB\mu V/m] = 20\log\left(E\left[\frac{V}{m}\right]\right) + 120\ dB \tag{24}$$

4.2 VHF example scenario

This chapter explains how to determine if a certain antenna is suitable for a dedicated VHF monitoring task. Detailed calculations are performed and explained for different scenarios and for passive and active type of antennas. System performance in terms of sensitivity and susceptibility to intermodulation is calculated and compared. Based on these example calculations the reader learns how to perform similar calculations for his individual system in order to judge if his antenna selection is suitable.

4.2.1 Scenario 1 - Reception of a weak signal

A scenario as shown in Figure 12 is assumed. The signal of a mobile station should be received over a distance of 30 km. The mobile station has the following parameters:

Frequency	f_m= 200 MHz
Transmitter power	P_m = 1 Watt
Transmit antenna gain	g_m = 0 dBi
Bandwidth of signal	B_m = 10 kHz

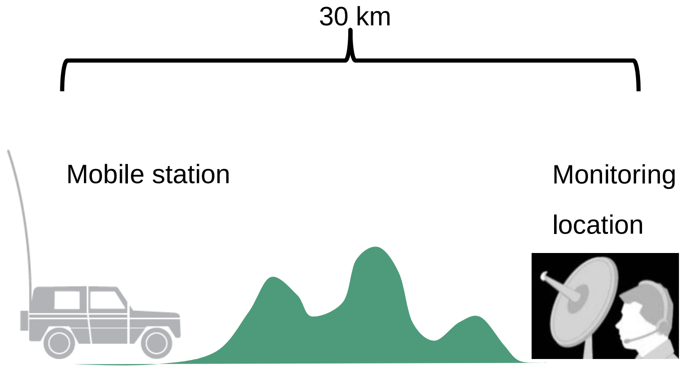

Figure 12 Example scenario for monitoring of a weak mobile station signal

4.2.1.1 Expected field strength values

Based on the free-space formula (23), the field strength of the mobile station at the monitoring location can be calculated as

$$E_{mobile,free-space} = \frac{\sqrt{30 \cdot 1 \cdot 1}}{30000}\,\frac{V}{m} = 1.83 \cdot 10^{-4}\,\frac{V}{m} \cong 45\ dB\mu V/m \qquad (25)$$

Obviously the path of 30 km is not in free-space, so the wave propagation will be affected by reflection, refraction and absorption along the path. Simulation tools like R&S®PCT-X propagation calculation tool, which allows the selection of different radio propagation models, could be used to determine the exact value of field strength to be expected. In this particular example it was determined that the terrain between the two locations will cause an **additional loss of approx. 30 dB** to the signal. So the field strength expected from the mobile station results in

$$E_{mobile} = E_{mobile,freespace} - 30\ dB = 15\ dB\mu V/m \qquad (26)$$

4.2.1.2 System sensitivity with a passive antenna (R&S®HK014E)

In this example the system setup shown in Figure 13 is assumed. It features the R&S®HK014E VHF/UHF coaxial dipole antenna and the R&S®ESMD wideband monitoring receiver.

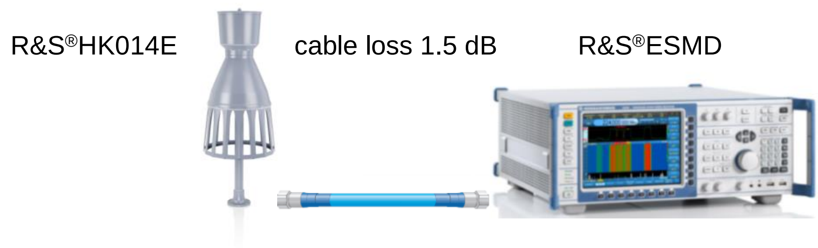

Figure 13: Monitoring system setup with a passive antenna R&S®HK014E

For simplicity reasons a frequency independent cable **loss of 1.5 dB** is assumed for the interconnecting cable. In reality this loss may be higher - and will also vary with frequency. Exact values can be taken from the datasheet of the particular type of coaxial cable used.

From the datasheets [11] of the components the following technical specification parameters are summarized. They are needed to perform the system calculation:

R&S®HK014E	R&S®ESMD
Antenna gain g = 2 dBi	Noise figure NF_R*= 21 dB
	$IP3_R$ = +20 dBm
	$IP2_R$ = +55 dBm

*) R&S®ESMD in low-distortion mode

In order to determine the system sensitivity, the system noise figure must be calculated. Due to its passive nature, the antenna does not contribute to the total system noise figure. The only contribution is from the cable which increases the noise figure by its attenuation. So the noise figure at the input of this subsystem becomes:

$$NF_S = NF_R + 1.5\,dB = 22.5\,dB \qquad (27)$$

Based on the noise figure NF the noise power P_N in a given bandwidth B can be calculated according to (18) or in logarithmic format according to:

$$P_N\,[dBm] = -174\,dBm + 10\log(B) + NF \qquad (28)$$

With the given system noise figure NF_S, a noise power P_N referred to a signal bandwidth B = 10 kHz is determined:

$$P_{N(10\,kHz)} = -174\,dBm + 10\log(B) + NF_S = -111.5\,dBm \qquad (29)$$

This represents the sensitivity threshold in terms of input power. To convert this power level to a voltage level Ohm's law and the definition of electrical power can be used

$$I = \frac{U}{R}\,, \qquad P = U\,I \;\rightarrow\; U = \sqrt{PR} \qquad (30)$$

In a system where R = 50Ω and where the below mentioned logarithmic units are given, the simplified formula

$$U\,[dB\mu V] = P_{50\Omega}\,[dBm] + 107\,dB \tag{31}$$

can be used yielding in a minimum detectable voltage level of

$$U_{\min(10\,kHz)} = -4.5\,dB\mu V \tag{32}$$

As explained in [1] the transformation from voltage to field strength is done via the antenna factor k. If k is not specified for an antenna (which is the case for R&S®HK014E) it can be derived from the gain value g with the formula:

$$k[dB/m] = -29.8 + 20\log\left(\frac{f}{MHz}\right) - g\,[db] \tag{33}$$

At the relevant monitoring frequency f_m= 200 MHz a gain of g = 2 dBi is specified in the antenna datasheet, resulting in an antenna factor of

$$k_{(200MHz)} = 14.2\,dB/m \tag{34}$$

As stated in (1) the antenna factor relates field strength to the measured voltage. If logarithmic values are used, the minimum detectable field strength can now be calculated by adding the antenna factor k to the minimum detectable voltage U_{min}

$$E_{\min(10\,kHz)} = U_{\min(10\,kHz)} + k \approx 10\,dB\mu V/m \tag{35}$$

The mobile station as calculated in (26) generates a field strength of 15 dBµV/m. Consequently the signal to noise ratio of the signal from the mobile station is only

$$SNR_{mobile} = 15\,dB\mu V/m - 10\,dB\mu V/m = \mathbf{5\,dB} \tag{36}$$

which is a very low value that can be regarded "at the edge" of intelligibility of an FM modulated signal in a 10 kHz bandwidth.

4.2.1.3 System sensitivity with an active antenna (R&S®HE600)

It is assumed that the system setup as shown in Figure 14 is used at the monitoring location.

Figure 14: Monitoring system setup with an active antenna and bias unit

This setup comprises of the R&S®HE600 active omnidirectional receiving antenna, the R&S®IN600 bias unit and the R&S®ESMD wideband monitoring receiver.

From the datasheets of the components [9, 10] the following specification values required for the system calculation can be derived:

R&S®HE600	R&S®IN600	R&S®ESMD
Practical gain g_p= 12 dB (@ 200 MHz)	Insertion loss l = 1.5 dB	Noise figure NF = 21 dB
Sensitivity E_{min}= -41 dBµV/m (@ 200 MHz, measured in a 1Hz bandwidth)		$IP3_R$ = +20 dBm
$IP3_A$ = +28 dBm		$IP2_R$ = +55 dBm
$IP2_A$ = +50 dBm		

For simplicity the loss of the cables interconnecting the three devices is neglected in this example.

In the first step the overall system sensitivity is determined. Due to the fact that various components add noise to the system, the specification of the antenna alone is not sufficient and the overall system sensitivity must be calculated.

For the active antenna, the field strength sensitivity is already provided in its datasheet. In order to perform a system calculation that sensitivity must be converted into a noise figure.

Using formula (8) in 3.4 and solving it for the antenna noise figure results in:

$$NF_a = E_{min} + 96.8\ dB\mu V/m - 20\log\left(\frac{f}{MHz}\right) - 10\log\left(\frac{B}{Hz}\right) + \frac{D}{dB} \qquad (37)$$

For the directivity, D = 2.15 dB is assumed because the antenna can be approximated as a half-wave dipole at 200 MHz. B is the bandwidth for which the sensitivity is specified, so B = 1 Hz, consequently the noise figure results in:

$$NF_a = 11.9\ dB \qquad (38)$$

For further calculations it is also required to know the electronic gain G_T which can be determined from the practical gain by solving formula (13) for G_T

$$G_T = \frac{G_P}{D} \qquad (39)$$

or - when the values are given in logarithmic units - by simply subtracting the directivity from the practical gain resulting in:

$$g_T = 12\ dB - 2.15\ dB = 9.85\ dB \qquad (40)$$

With these values it is now possible to calculate the total system noise figure F_S based on (9). Prior to this, the insertion loss l of the bias unit is added to the noise figure of the receiver resulting in a combined noise figure

$$NF_R = 21\ dB + 1.5\ dB = 22.5\ dB \qquad (41)$$

This simplification can be done due to the passive nature of the bias unit (in terms of the RF path). The overall system noise figure F_S can then be calculated:

$$F_S = F_a + \frac{F_R - 1}{G_T} \approx 33.8 \quad \rightarrow \quad NF_S \approx 15\ dB \tag{42}$$

Based on the system noise figure NF_S the minimum detectable field strength in a bandwidth B =10 kHz can now be calculated using formula (8) in 3.4:

$$E_{min(10\ kHz)} = -96.8\ dB\mu V/m + 46\ dB + 40\ dB + 15\ dB - 2.15\ dB \approx \mathbf{2\ dB\mu V/m} \tag{43}$$

As already calculated in 4.2.1.1, the mobile station will generate a field strength of E_{mobile}= 15 dBµV/m. Thus the achievable signal-to-noise ratio of a setup comprising of the R&S®HE600 active omnidirectional receiving antenna can be calculated:

$$SNR_{mobile} = 15\ dB\mu V/m - 2\ dB\mu V/m = \mathbf{13\ dB} \tag{44}$$

This results in a significant improvement of signal intelligibility compared to the solution with a passive antenna described in 4.2.1.2.

Not to forget the reduced space requirements of the active antenna solution, and the fact that the monitoring system is capable of covering a much larger bandwidth compared to the passive antenna approach.

4.2.2 Scenario 2 - Reception of a weak signal in the presence of strong interference

Now additionally to scenario 1 described in 4.2.1 an FM broadcast station is located at a distance of 3 km from the monitoring location - so in close vicinity (see Figure 15)

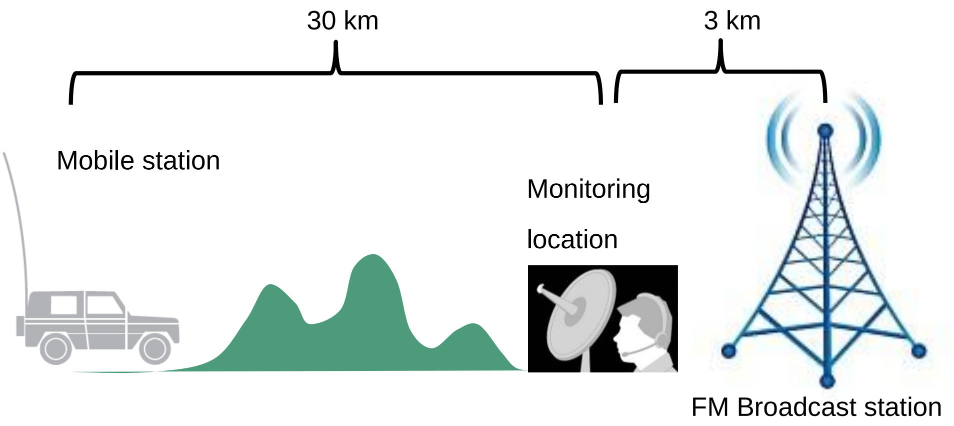

Figure 15: Example scenario for monitoring of a weak signal in the presence of strong interference

The FM Broadcast station transmits two radio programs on different frequencies with the following parameters

TX Frequencies	f_1= 101 MHz f_2 = 99 MHz
Transmitter power	$P_{1,2}$ = 500 Watts
Transmit antenna gain	$g_{1,2}$ = 2 dBi
Bandwidth of signals	$B_{1,2}$ = 200 kHz

The question is now, if the weak signal from the mobile station can be properly received with an active antenna - of which the technical parameters are known - or if a passive antenna is more suitable due to the interference from the transmitter in close vicinity of the monitoring location.

4.2.2.1 Expected field strength values of the interfering signals

While the signal of the mobile station E_{mobile} was already calculated - see (26), the signals from the FM broadcast station are calculated in the following. For this calculation free-space conditions will be assumed - obviously also for simplicity reasons - and due to the close proximity. Consequently the electrical field strength can be calculated with (23) resulting in

$$E_{1,2} = \frac{\sqrt{30\,V/A \cdot\ 500W \cdot 10^{0.2}}}{3000\ m} = 0.051\frac{V}{m} \cong 94\ dB\mu V/m \tag{45}$$

The 2nd order intermodulation product f_1+f_2 of the two FM broadcast signals falls right onto the monitoring frequency f_m. Consequently it must be ensured that the spurious-free dynamic range SFDR2 fulfills the following requirement for this scenario:

$$SFDR2\ \geq \left(E_{1,2} -\ E_{mobile}\right) \geq 79\ \text{dB} \tag{46}$$

This requirement regarding the SFDR2 must be fulfilled in a bandwidth corresponding to the one of the mobile station (B_m =10 kHz).

4.2.2.2 System IP2 and SFDR2 with a passive antenna (R&S®HK014E)

The system setup shown in Figure 13 is assumed for the calculation. A passive antenna does not influence the system IP2, thus the system IP2 can easily be determined by adding the cable loss to the IP2R of the receiver

$$IP2_{Sys} =\ IP2_R + 1.5\ dB = 56.5\ dBm \tag{47}$$

And consequently the spurious-free dynamic range SFDR2 can be determined according to the formula (16) in 3.7 as

$$SFDR2_{(10\ kHz)} = \frac{1}{2}\left(IP2_{Sys} - P_{N(10\ kHz)}\right) = 84\ dB \tag{48}$$

where $P_{N(10kHz)}$ = -111.5 dBm is the noise power threshold of the system determined in (29). Based on the minimum detectable field strength E_{min} calculated in equation (35) the maximum field strength for intermodulation-free reception results in

$$E_{\max(10\,kHz)} = E_{\min(10\,kHz)} + SFDR2_{(10\,kHz)} = 10\,dB\mu V/m + 84\text{ dB} = 94\,dB\mu V/m \quad (49)$$

This corresponds exactly to the field strength caused by the FM broadcast station as determined in equation (45).

4.2.2.3 Conclusion for the passive antenna approach

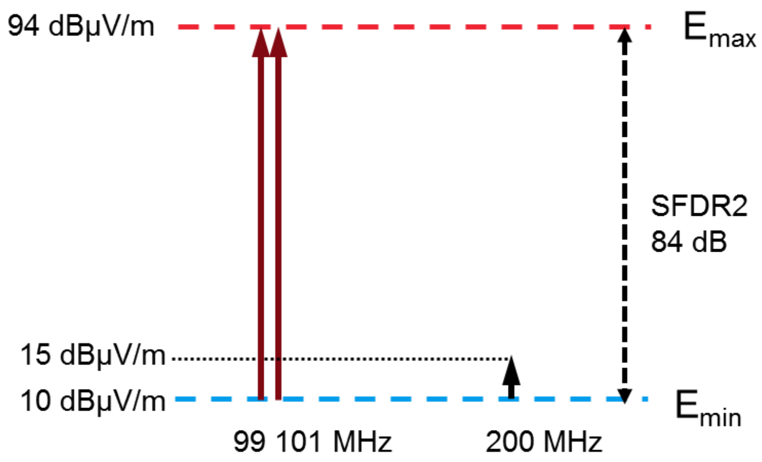

Figure 16: Levels of field strength for a system with a passive antenna

With the passive antenna system setup, the signal to noise ratio of the mobile station is marginal at only 5 dB. The SFDR2 is 5 dB higher than the requirement determined in 4.2.2.1. Figure 16 shows the different signal levels. So in order to be able to detect a signal with a certain margin, the actual SFDR2 always has to be exactly this margin higher than the SFDR2 requirement. Essentially a higher dynamic range is bought with less sensitivity. In the particular example the receiving system is ideally matched to the field strength levels caused by the interfering signal.

It was already mentioned that the achieved S/N of 5 dB is relatively low - and it may not be sufficient for the reception of certain signals. Note that the required S/N levels will depend on the type of modulation as well as on the bandwidth of the signal.

An improvement of the system sensitivity can either be achieved by using an active antenna as described in 4.2.1.3, or by using a directional antenna, for example the R&S®HL033 log-periodic broadband antenna [14]. Such an antenna will significantly improve the situation, when the interfering signal is arriving from a different direction than the wanted signal. On the one hand it will increase the signal of the mobile station due to its higher passive gain of approx. g = 6.5 dBi compared to g_{omni} = 2 dBi of an omnidirectional antenna like R&S®HK014E. On the other hand it will also reduce the signal levels of the interfering signals - simply due to its radiation pattern (see Figure 17) and the corresponding attenuation for signals arriving from directions outside the antenna's main lobe.

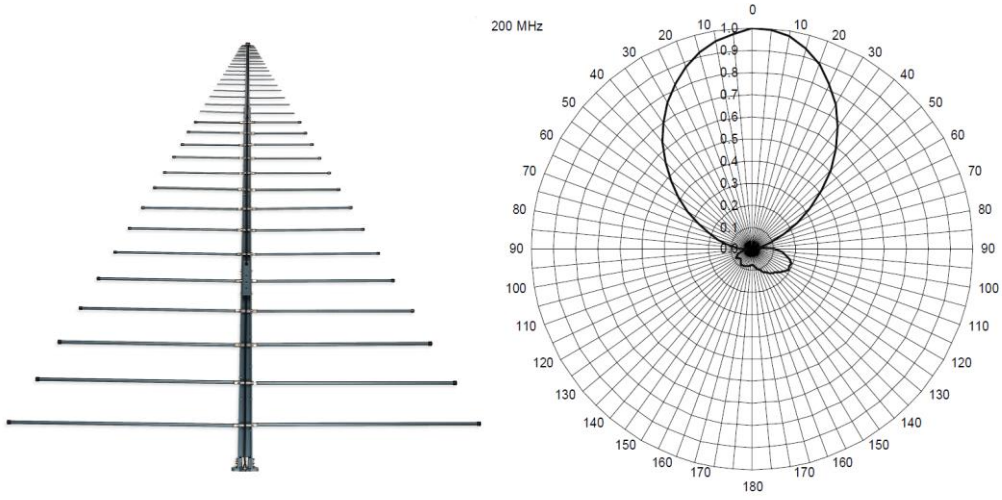

Figure 17: R&S HL033 log-periodic broadband antenna and its E-field pattern at 200 MHz

Consequently, the minimum detectable field strength can be improved to a value of E_{min} = 5.5 dBµV/m (in a 10 kHz bandwidth) - resulting in an S/N ratio of 9.5 dB - while the SFDR2 can reach values >100 dB, when the interferer is located in the opposite direction (assuming an antenna front-to back ratio of typ. 25 dB).

However it must not be neglected that a directional antenna always needs to be aligned to the target. This can be achieved by means of an antenna rotator - but limits the usability as simultaneous reception of signals arriving from substantially different directions is not possible any more.

4.2.2.4 System IP2 and SFDR2 with an active antenna (R&S®HE600)

When the setup with the R&S®HE600 active omnidirectional receiving antenna as shown in Figure 14 is used, the system IP2 can be calculated with formula (15). It is worth mentioning that the data for the antenna intercept points listed in the datasheet are already referring to the output of the antenna. Consequently the gain of the antenna must not be part of the initial calculation of the system 2nd order intercept point. The only additional parameter for the calculation of the cascaded intercept point is the loss of the cable (or here the insertion loss of the bias unit).

After using the linear values in formula (15) the system 2nd order intercept point becomes:

$$\mathrm{OIP2}_{\mathrm{Sys}} = \frac{1}{\left(\sqrt{\frac{1}{10^{5.5}}} + \sqrt{\frac{1}{10^{5} \cdot 10^{-0.15}}}\right)^{2}} \approx 32621\ \mathrm{mW} \quad \cong 45.1\ \mathrm{dBm} \tag{50}$$

As indicated by the letter "O" this value is referring to the output of the system, hence to the receiver output.

But for the calculation of the spurious-free dynamic range (SFDR2) the input intercept point of the system is required. It can be determined by subtracting the so called system gain G_{Sys} from the output intercept point.

$$IIP2_{Sys} = OIP2_{Sys} - G_{sys}\ [dB] \tag{51}$$

The system gain is defined as the overall gain in the chain between the passive radiator and the output of the receiver. In this case it can be calculated as

$$G_{Sys} = G_T + G_{cable} = 9.85\ dB - 1.5\ dB = 8.35\ dB \tag{52}$$

Consequently the following input intercept point can be determined

$$IIP2_{Sys} = 45.1\ dBm - 8.35\ dBm \approx\ 36.8\ dBm \tag{53}$$

Before the SFDR2 can be calculated by means of formula (16), the noise power P_N in the corresponding bandwidth B = 10 kHz must be known which is based on the system noise figure NF_S determined in (42).

According to formula (28) this results in the following value

$$P_{N(10kHz)} =\ -174\ dBm + NF_s + 10\log(B) = -174 + 15 + 40 = -119\ dBm \tag{54}$$

Finally the SFDR2 can be asserted:

$$SFDR2_{(10\ kHz)} = \frac{1}{2}(-36.8\ dBm\ - (-119\ dBm)) \approx 78\ dB \tag{55}$$

Based on the minimum detectable field strength previously determined (see (43)), the maximum field strength for intermodulation-free operation is calculated:

$$E_{\max(10\ kHz)} = E_{\min(10\ kHz)} + SFDR2_{(10\ kHz)} = 2\ dB\mu V/m + 78dB\ = 80dB\mu V/m \tag{56}$$

4.2.2.5 Conclusion for the active antenna approach

As already shown in chapter 4.2.1.3, the signal from the mobile station can be detected with 13 dB above the minimum detectable field strength of the system. Hence without the interference from the FM broadcast station a significant improvement compared to the passive antenna approach can be achieved

Although the SFDR2 requirement of 79 dB determined in 4.2.2.1 is nearly met, the absolute field strength of the two FM signals is **14 dB higher** than the maximum allowed field strength for intermodulation-free reception (E_{max}).

As a consequence a strong 2nd order intermodulation product is generated at $f_m = f_1 + f_2$ = 200 MHz as shown in orange color in Figure 18.

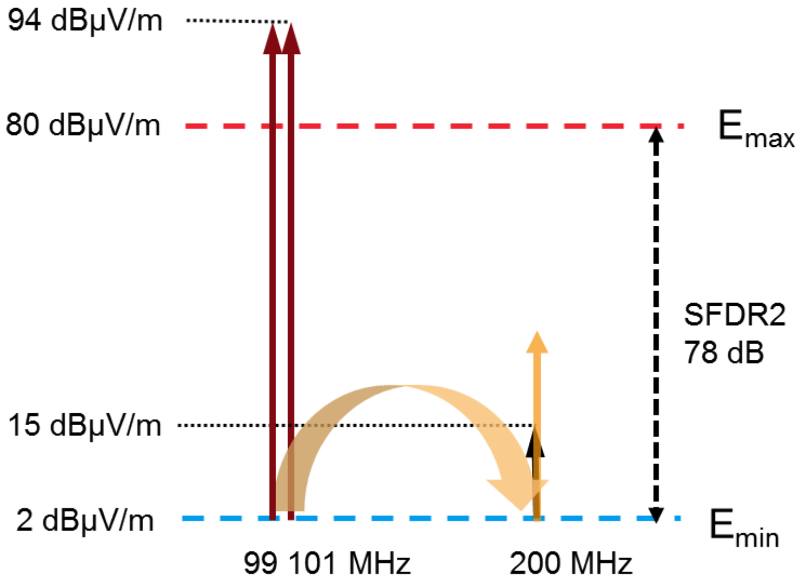

Figure 18: Levels of signals and intermodulation products for an active antenna approach

Because 2nd order intermodulation products rise with 2 dB for every 1 dB of increased input level, the IM2 product will be 28 dB above the noise floor and thus completely mask the signal from the mobile station **making reception impossible.**

Consequently the fulfilment of the spurious-free dynamic range requirement alone does not yet ensure that intermodulation products are not generated. The far more important parameter here is the maximum field strength for intermodulation-free reception E_{max}.

So the dynamic range parameters always have to be seen in the context of the absolute values for field strength.

4.2.3 Other measures to reduce or avoid intermodulation

In an application scenario where the interfering signals are higher than the maximum field strength for intermodulation-free reception, it is possible to add an attenuator between the passive antenna and the receiver. Obviously such an attenuator will also decrease the sensitivity and hence the min. detectable field strength is reduced.

A better approach is the usage of band-stop filters tuned to the interfering signal's frequency. Obviously this is only possible when there is a significant offset between the receiving frequency and the interfering signal frequency. While this usually works for 2nd order Intermodulation, for 3rd order intermodulation products the approach is hardly feasible as the intermodulation products are very close to the interferer's frequencies.

Note that for the system with the active antenna as described in Figure 14 none of the before mentioned measures can easily be implemented. This is due to the fact that the interface between the passive radiators and the active circuitry is not accessible for any filtering or attenuation measures. Consequently in a system with an active antenna the intermodulation performance of the antenna is dominating the overall system performance.

Active antenna circuit design has to be projected carefully in order to avoid poor robustness to intermodulation. A common practice is to use push-pull amplifiers made of complementary transistors. Other design options are the usage of a current feedback loop or including a switching circuit to bypass the active element (which obviously increases mismatch and consequently decreases the overall system sensitivity). However it must be mentioned that improvement of the active antenna's IP2 or IP3 values beyond the receiver values will not cause noticeable improvements of the overall system intermodulation performance.

4.3 HF example scenario

In the previous examples describing the reception of VHF signals it was assumed that the polarizations of both antennas match - meaning that the signal is transmitted and received by (in this case) a vertically polarized antenna. For the simplified assumption of free space conditions this is valid. In reality however the signal may undergo certain changes regarding its polarization caused by reflections from obstacles on the propagation path.

4.3.1 Effects on polarization caused by the ionosphere

At HF frequencies the situation is different - especially if ground-wave propagation is neglected and the focus is on signals being reflected at the ionosphere - so called **sky-wave signals.** Due to the largely anisotropic permittivity of the layers in the ionosphere, the signal which is transmitted through or reflected by its different layers will always be subject to polarization changes. This means for certain frequencies at certain elevation angles the polarization may be turned from horizontal to vertical, while at other frequencies the wave may become circularly or even elliptically polarized.

It is therefore of large benefit to have an antenna where the polarization can be switched, or alternatively to have several antennas with different fixed polarizations, so that the best one for a certain signal can be selected.

4.3.2 Field strength measurement at HF using different types of antennas

Compared to VHF or UHF the determination of precise field strength values at HF frequencies is rather difficult to achieve. This is due to the particular propagation of waves in this frequency range and due to the fact that the parameters of an HF antenna are not only determined by the antenna itself but also by the properties of its surroundings. This applies to passive antennas as well as to active antennas, although active antennas are generally less sensitive to coupling effects with their surroundings.

4.3.2.1 Vertically polarized monopoles

However for monopole antennas like the R&S®HE010E active rod antenna this effect can immediately be seen by looking at the antenna's vertical radiation pattern taken from the datasheet [13] as shown in Figure 19.

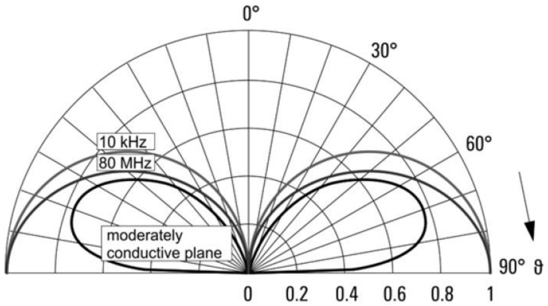

Figure 19: R&S®HE010E Vertical radiation pattern

While the two curves labeled with *10 kHz* and *80 MHz* are valid for an installation above a perfectly conducting and infinitely large plane, the curve labeled with *moderately conducting plane* shows a significant reduction of field strength for signals arriving at angles close to the horizon (here ϑ = 90°). Further reductions would occur above a poorly conducting plane and even further loss when the dimensions of the ground plane would be reduced to values below the order of approx. half a wavelength.

Antenna gain (and consequently also the antenna factor) is defined at the maximum of radiation, which in the case of a moderately conducting plane occurs at ϑ ≈ 70°, but may strongly vary depending on the properties of the ground plane.

For sky-wave signals reflected by the ionosphere the situation is even more uncertain, because the exact angle of arrival is unknown. Simulation tools can determine this value based on a series of input parameters like distance to the transmitter, frequency, time of day, time of year and the smoothed number of sunspots (SSN). However they cannot omit that for closer distances the so called **near vertical incident sky-waves (NVIS)** reflected by the F_2 layer in the ionosphere fall right into a null of the monopole's vertical radiation pattern as described in [15].

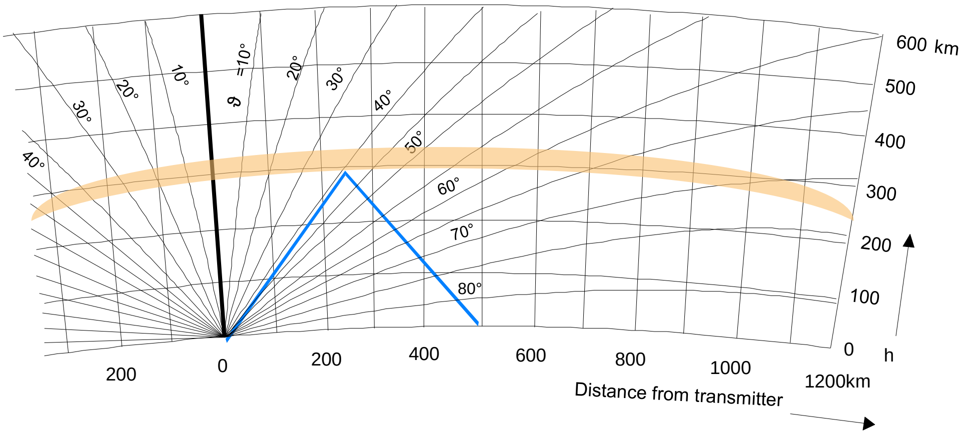

Figure 20: Angle of incidence depending on distance from the transmitter

Consequently signals from short distances (< 500 km) will arrive at angles of less than $\vartheta \approx 40°$ as can be derived from Figure 20 assuming a reflection at the F_2 layer at a height of approx. 300 km above ground (see blue curve).

Applying the antenna factor to such signals - if they can be detected at all - will cause incorrect field strength values. Generally a monopole antenna is not suitable for the reception of NVIS signals due to its particular elevation pattern. It exhibits a so-called **skip zone**. This skip zone is the area in-between the maximum distance where ground wave propagation still works and the minimum distance of reception for sky-wave signals arriving at angles of ϑ that are large enough in order not to fall into the null of the antenna.

The reception in this skip zone is largely reduced and consequently an accurate field strength calculation is not possible.

The expansion of the skip zone is not constant and will depend on all parameters that affect HF wave propagation in general. The outer limit of 500 km as shown in Figure 21 is just an average value applicable for lower frequencies. For example, during daytime in the summer season - when the height of the F_2 layer is generally higher - the skip zone can extend far beyond 1000 km for frequencies close to the MUF (maximum usable frequency).

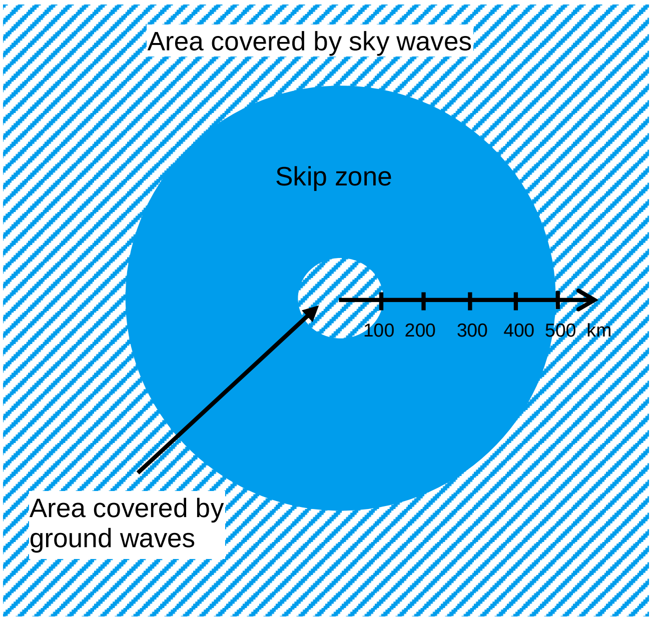

Figure 21: Skip zone of a vertically polarized monopole

In summary vertically polarized monopole antennas are ideally suited for the reception of ground waves as well as sky-waves of low angle of incidence above the horizon (ϑ close to 90°). The latter type of signals usually originate at larger distances.

4.3.2.2 NVIS antennas

For the reception of sky-wave signals from closer distances that arrive at higher angles of incidence compared to the horizon (ϑ ≤ 40° as shown in Figure 20) a different type of antenna is commonly used.

Such antennas are usually referred to as **NVIS antennas**. Looking at the vertical radiation pattern of a horizontally polarized dipole , e.g. the R&S®HE010D active HF dipole shown in Figure 22 reveals that the main lobe is pointing straight up to the sky (ϑ=0°) for the lower and middle part of the HF frequency range.

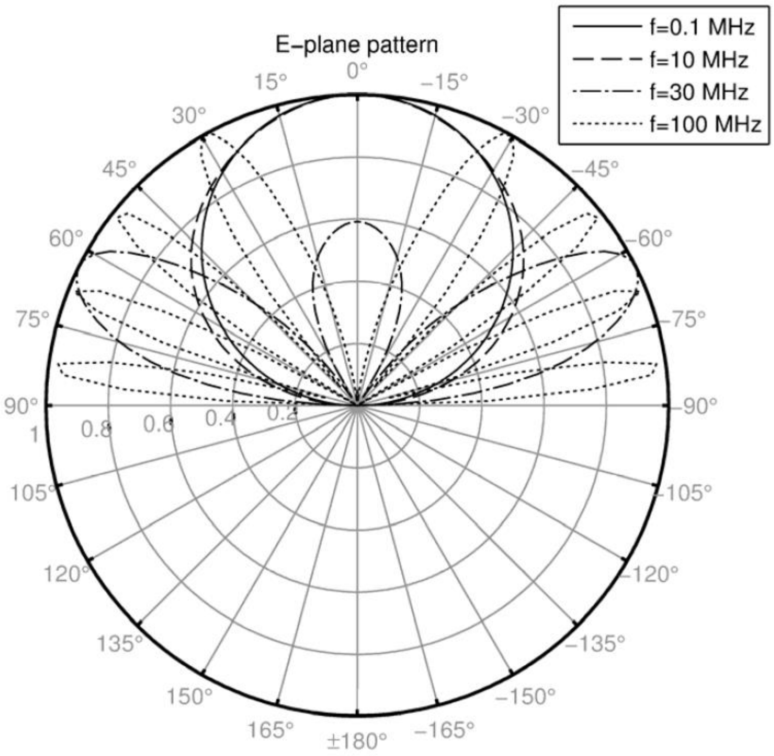

Figure 22: Vertical radiation pattern of the R&S®HE010D active HF dipole installed on a 6 m mast

Only at the upper end of the HF frequency spectrum (30 MHz) the vertical pattern starts to deteriorate and shows nulls in-between its major lobes. However as these patterns are based on an installation above a perfectly conducting plane, in a real situation (i.e. above a moderately conducting plane) the nulls will be "filled up" - and thus the antenna becomes usable for NVIS signals in the entire HF frequency range.

4.3.3 Selecting an appropriate HF antenna

As just explained, different types of HF antennas may be needed depending on the type of signal (and its corresponding angle of incidence). The R&S®HE016 active antenna system shown in Figure 23 overcomes the need for multiple antennas because it contains a vertically polarized monopole antenna and two horizontally polarized dipoles that are oriented perpendicular to each other. All antennas are of an active type with shortened radiators so that the dimensions of the system (approx. 3 x 3 x 1.5 m) can be kept relatively small.

Figure 23: R&S®HE016 active antenna system

The outputs of the two horizontally polarized dipoles are combined via a 90° coupler to form a so called **turnstile antenna**. This allows reception of horizontally polarized signals with an almost omnidirectional radiation pattern when they arrive at angles of incidence close to the horizon (ϑ approaching 90°). For high angle of incidence signals (ϑ approaching 0°) the combination of both dipoles via the coupler results in a circularly polarized antenna, which is generally suitable to receive signals of any polarization with bearable loss.

For vertically polarized signals arriving at angles of incidence close to the horizon (e.g. ground wave signals) the vertical monopole is used - its output is available at a 2nd RF connector which allows switching between the two signal paths. This makes R&S®HE016 an ideal solution for almost any kind of signals present in the HF frequency range. However there are certain effects that must be taken into account when it is installed on a mast.

4.3.3.1 Effects of installation height

For the vertical section (monopole) of R&S®HE016 the open circuit voltage U_{OC} of the passive radiator depends on the height of the mast. This will lead to a directly proportional increase of the sensitivity up to mast height of approx. 0.15 λ.

Beyond this height, mast resonances will occur at the following approximate heights:

- at resonance point $h = n \cdot \frac{\lambda}{4} (with\ n = 1,3,5, \dots)$,
  with voltage peaks causing a high risk of non-linear distortions
- at resonance point $h = n \cdot \frac{\lambda}{4} (with\ n = 2,4,6,)$,
  with voltage dips resulting in a high risk of reduced sensitivity

On the other hand a certain height of the mast has to be maintained for the horizontally polarized dipoles of the antenna system because here close proximity to the ground will result in increased loss due to coupling effects. So a reasonable compromise for vertical and horizontal polarization is obtained at mast heights between 4 m and 7 m.

Figure 24 illustrates the mast resonances by comparing the practical gain at different heights of the supporting mast. Note that the values for the horizontally polarized part are shown for installation on a 6 m mast only.

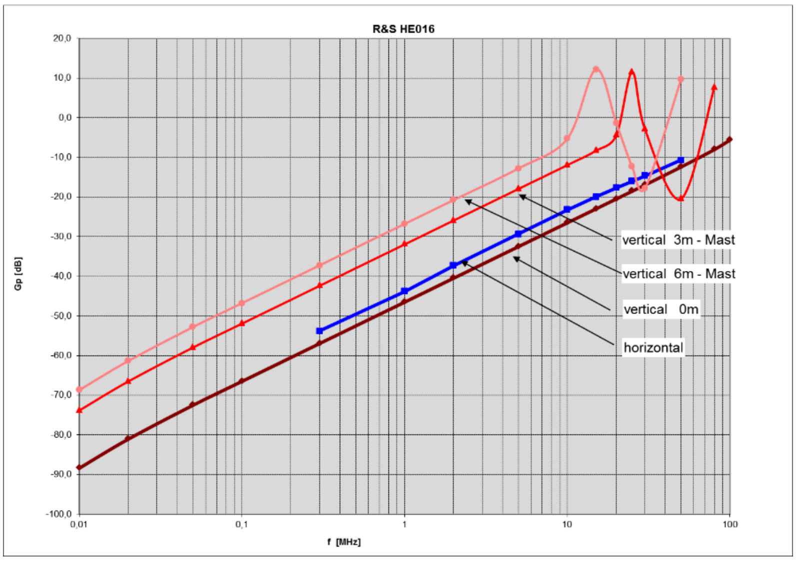

Figure 24: R&S®HE016 practical gain with mast resonances

Obviously the gain variation also influences the antenna factor. The assumption of an almost constant antenna factor for the vertical part of the antenna system - which is essentially a monopole as described in 3.2 - is no longer valid when R&S®HE016 is installed on a mast. This has to be taken into account when field strength values are to be determined at HF frequencies. Figure 25 shows this effect very clearly.

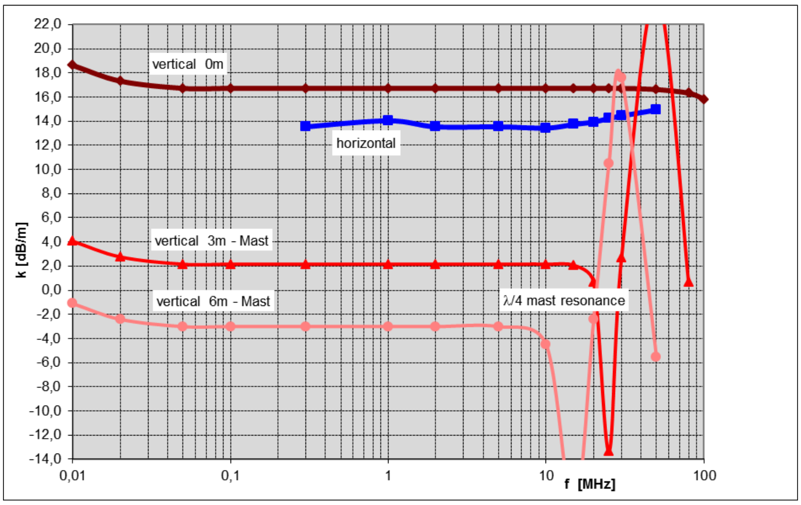

Figure 25: R&S®HE016 antenna factor depending on mast height

It must be noted that the problem of mast resonances persists if a mast made of non-conducting material is used and the coaxial cable is routed vertically without any decoupling (such as ferrite rings etc.) applied to it. The cable then acts almost like a mast. So in order to reduce the resonances, proper decoupling measures of the vertically run coaxial cable have to be taken.

4.3.4 Active HF monitoring antennas summarized

The selection of HF monitoring antennas has to be mainly based on the distance to the transmitter that they are supposed to detect. Also their installation height must be chosen carefully as it will affect many parameters that may lead to poor reception or coverage of the wanted signals. Not to forget the influence of external noise (either man-made or atmospheric) and the effects of intermodulation from close-by transmitters which have been dealt with in chapters 3 extensively, hence they are not mentioned in detail here again.

Monitoring antennas are dedicated to receive signals with the best possible S/N. It is not their aim to measure exact values of field strength. This is especially true for active HF monitoring antennas where the parameters of the antenna depend on various external factors. Consequently a **calibration of active HF monitoring antennas hardly makes sense** and is usually not offered by Rohde & Schwarz.

The **typical values** for gain, antenna factor or radiation pattern specified for defined surroundings are usually sufficient for most applications of this type of antennas.

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6 Glossary

DR1	Linear dynamic range (1dB compression)
FET	Field effect transistor
FM	Frequency modulation
HF	High frequency (3 MHz to 30 MHz)
IP2	Second order intercept point (usually referred to the input unless noted)
IP3	Third order intercept point (usually referred to the input unless noted)
JFET	Junction field effect transistor
LF	Low frequency (30 kHz to 300 kHz)
MF	Medium frequency (300 kHz to 3 MHz)
MUF	Maximum usable frequency
NF	Noise figure
NVIS	Near vertical incidence sky-wave
OIP2	Output second order intercept point
OIP3	Output third order intercept point
SFDR	Spurious-free dynamic range
SHF	Super high frequency (3 GHz to 30 GHz)
S/N or SNR	Signal to noise ratio
SSN	Smoothed sunspot number
UHF	Ultra high frequency (300 MHz to 3 GHz)
VHF	Very high frequency (30 MHz to 300 MHz)

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

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Sustainable product design

- Environmental compatibility and eco-footprint
- Energy efficiency and low emissions
- Longevity and optimized total cost of ownership

Certified Quality Management
ISO 9001

Certified Environmental Management
ISO 14001

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