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Basic Antenna Principles for Mobile Communications

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Mobile Communications - Antenna Technology

1. Introduction

In the last few years a large technological jump has taken place in the field of mobile communications due to the introduction of new mobile communication networks (GSM/PCN). The number of subscribers worldwide has risen to over 150 Million. Fig. 1 shows an overview of the mobile communications services and the relevant frequency ranges within Germany alone.

The requirements on the antennas needed for the ever expanding networks are becoming continually higher:

- strictly defined radiation patterns for a most accurate network planning.
- growing concern for the level of intermodulation due to the radiation of many HF-carriers via one antenna.
- dual polarization
- electrical down-tilting of the vertical diagram.
- unobtrusive design.

The following essay will give an insight into antenna theory in general, as well as the most important types of antennas and the special methods used for GSM/PCN systems.

2. Theory

Antennas transform wire propagated waves into space propagated waves. They receive electromagnetic waves and pass them onto a receiver or they transmit electromagnetic waves which have been produced by a transmitter. As a matter of principle all the features of passive antennas can be applied for reception and transmission alike (reciprocality). From a connection point of view the antenna appears to be a dual gate, although in reality it is a quad gate. The connection which is not made to a RF-cable is connected to the environment, therefore one must always note, that the surroundings of the antenna have a strong influence on the antennas electrical features (Fig. 2).

The principle of an antenna can be shown by bending a co-axial cable open (Fig. 3):

a) A transmitter sends a high frequency wave into a co-axial cable. A pulsing electrical field is created between the wires, which cannot free itself from the cable.
b) The end of the cable is bent open. The field lines become longer and are orthogonal to the wires.
c) The cable is bent open at right angles. The field lines have now reached a length, which allows the wave to free itself from the cable.
The apparatus radiates an electromagnetic wave, whereby the length of the two bent pieces of wire corresponds to half of the wave length.

This simplified explanation describes the basic principle of almost every antenna - the $\lambda/2$-dipole. Not only is an electrical field (E) created due to the voltage potential (U) but also a magnetic field (H) which is based on the current (I) (Fig.4). The amplitude distribution of both fields corresponds to the voltage and current distribution on the dipole.
The free propagation of the wave from the dipole is achieved by the permanent transformation from electrical into magnetic energy and vice versa.
The thereby resulting electrical and magnetic fields are at right angles to the direction of propagation (Fig.5).

3. Definitions

3.1 Polarization

Polarization can be defined as the direction of oscillation of the electrical field vector.
Mobile communications: vertical polarization
Broadcast systems: horizontal polarization

3.2 Propagation Pattern

In most cases the propagation characteristic of an antenna can be described via elevations through the horizontal and vertical radiation diagrams. In mobile communications this is defined by the magnetic field components (H-plane) and the electrical field components (E-plane). Very often a 3-dimensional description is chosen to describe a complex antenna.

3.3 Half-Power-Beam-Width

This term defines the aperture of the antenna. The HPBW is defined by the points in the horizontal and vertical diagram, which show where the radiated power has reached half the amplitude of the main radiation direction. These points are also called 3 dB points.

3.4 Gain

In reality one does not achieve an increment in energy via antenna gain. An antenna without gain radiates energy in every direction. An antenna with gain concentrates the energy in a defined angle segment of 3-dimensional space. The $\lambda/2$-dipole is used as a reference for defining gain. At higher frequencies the gain is often defined with reference to the isotropic radiator. The isotropic radiator is an non-existant ideal antenna, which has also an omnidirectional radiation characteristc in the E-plane and H-plane.
Calculation:
Gain (with reference to the isotropic radiator dBi) = Gain (with reference to $\lambda/2$-Dipole dBd) + 2.15 dB

The gain of an antenna is linked to the radiation characteristic of the antenna. The gain can be roughly calculated by checking the HPBW`s in the horizontal and vertical planes (Fig.6).

3.5 Impedance

The frequency dependant impedance of a dipole or antenna is often adjusted via a symmetry or transformation circuit to meet the 50 Ohm criterion. Adjustment across a wider frequency range is achieved using compensation circuits.

3.6 VSWR /Return Loss

An impedance of exactly 50 Ohm can only be practically achieved at one frequency. The VSWR defines how far the impedance differs from 50 Ohm with a wide-band antenna. The power delivered from the transmitter can no longer be radiated without loss because of this incorrect compensation. Part of this power is reflected at the antenna and is returned to the transmitter (Fig.7). The forward and return power forms a standing wave with corresponding voltage minima and maxima (U_{min}/U_{max}). This wave ratio (**V**oltage **S**tanding **W**ave **R**atio) defines the level of compensation of the antenna and was previously measured by interval sensor measurements.

A VSWR of 1.5 is standard within mobile communications. In this case the real component of the complex impedance may vary between the following values:

Maximum Value: 50 Ohms x 1,5 = 75 Ohms
Minimum Value: 50 Ohms : 1,5 = 33 Ohms

The term return loss attenuation is being used more often in recent times. The reason for this is that the voltage ratio of the return to the forward-wave U_R/U_V can be measured via a directional coupler. This factor is defined as the co-efficient of reflection. Figure 7 shows the relationship between the coefficient of reflection, return loss attenuation, VSWR and reflected power.

3.7 Mechanical features

Antennas are always mounted at exposed sites. As a result the antenna must be designed to withstand the required mechanical loading. Vehicle antennas, for example, must withstand a high wind velocity, vibrations, saloon washing and still fulfill a limited wind noise requirement. Antennas for portable radio equipment are often exposed to ill-handling and sometimes even played with by the user. Base station antennas are exposed to high wind speed, vibrations, ice, snow, a corrosive environment and of course also extreme electrostatic loading via lightning.

4. Base Station Antennas

4.1 Omnidirectional Antennas

4.1.1 Groundplane and λ/4 Skirt Antennas in Comparison

The classical omnidirectional λ/2antennas are of a groundplane or λ/4-skirt nature (Fig. 8). The names indicate how the antenna is decoupled from the mast. In the first case a conductive plane is achieved via 3 counterweighted poles, in the other case the decoupling is achieved by using a λ/4-skirt. The second type however only works across a very limited bandwith, so that for example three versions are needed to cover the 2-m band. The groundplane antenna on the other hand can cover the complete frequency range because it is a wideband antenna.

4.1.2 Side-mounted Omnidirectional Antennas

Unfortunately it is not always possible to mount one of the above antennas on the tip of a mast because this position is not always available. As a result one cannot avoid mounting an omnidirectional antenna on the side of a mast which results in a significant change in the horizontal diagram. The distance to the mast has a decisive influence on the radiation characteristic. If the distance is λ/4 then an off-set characteristic is achieved, if on the other hand the mast-antenna distance is λ/2 a bi-directional diagram is the result (see Fig. 9).
The radiation diagram can therefore be compensated by varying the mast-antenna distance in order to supply the required area with coverage.
In order to achieve this effect one chooses a groundplane or λ/4 skirt antenna with a corresponding bracket arm or one uses a dipole which has a special mounting bracket supplied.

4.1.3 Omnidirectional Antennas with Gain

The λ/2 antennas discussed up until now have all radiated the same power from the tip of the mast in all azimuth directions (Fig.8). The vertical half power beamwidth was 78 Degrees. One can see that a large proportion of the energy is radiated both upwards and downwards, as a result a lot of power is lost in the desired horizontal plane.
By connecting single, and vertically stacked dipoles at a middle distance of one wavelength the half power beamwidth can be reduced (Fig.10). As a result the radiated power in the horizontal plane is increased. This increase is called gain, which is nothing other than binding the radiated power in a defined direction. A doubling of the number of dipoles results in a gain increase of 3 dB (double the power).
Fig.11 shows an example of a GSM-Gain antenna which has several dipoles stacked inside a common fibre-glass tube.

4.2 Directional Antennas

4.2.1 Gain Achieved via Horizontal Beaming

Gain can also be achieved via binding in the horizontal plane if the radiation is not omnidirectional. By radiating the existing energy in a semi-circle (180°) one achieves 3dB gain; 6dB gain can be achieved by radiating in a quadrant (90°). The patterns shown in Figure 12 are purely theoretical because in reality directional antennas cannot produce such sharp corner points.

4.2.2 End-fire Arrays

Directional antennas whose mechanical features are parallel to the main radiation beam are called "End-fire Arrays".
Yagi and logarithmic periodic (log-per) antennas are typical examples of this type of antenna (Fig.13).
Yagi antennas are very common due to their simple and cheap method of construction.
However, Yagi antennas are only sometimes suitable for professional applications. The gain and bandwidth of Yagi antennas are electrically coupled with one other which is an electrical disadvantage, ie. one criterion is weighed off the other. The mechanical concept is not suitable for extreme climatic conditions because ice and snow have a strong influence on the radiation diagram.
A “log-per“ is often used because it is less sensitive to ice and its radiation diagram is constant over a wide frequency range, furthermore there are fewer side-lobes. A “log-per“ antenna is often used for applications where an exact radiation diagram is needed.

4.2.3 Broadside Arrays

Directional antennas whose mechanical features are orthogonal to the main radiation beam are called "Broadside Arrays".
Panels and corner reflector antennas are typical for this type (Fig.14).
Panel antennas are made up of several dipoles mounted in front of a reflector so that gain can be achieved from both the horizontal and vertical plane. This type of antenna is very well suited for antenna combinations. An antenna with 6 dipoles is referred to as a “zwölfer-Feld“ (12 dipole panel), which is a little confusing. Theoretically the reflector plate can be replaced with a second set of dipoles which radiate with the inverted phase. The virtual dipoles are counted and find their way into the above mentioned name.
The reflector plate of a corner reflector antenna is, as the name suggests, not straight but bent forwards. The chosen angle influences the horizontal half-power-beamwidth, normally the angle is 90°. The corner reflector antenna is only used singly, for example: for the coverage of railway lines and motorways.

4.2.4 Antenna Systems

Special applications which cannot be realised by using a single antanna are very often achieved via antenna combinations. The combination is made up of several single antennas and a distribution system (power splitter and connecting cable). Very often a combination is designed in order to achieve a higher gain. Many different antennas are also used to achieve a wide range of horizontal radiation characteristics by varying the number of antennas, the azimuth direction, the spacing, the phase and the power ratio. Figure 15 shows 3 simple examples.
A quasi-omnidirectional pattern can also be produced. The required number of antennas increases with the diameter of the tower. For examples 8 Panels are required at 900MHz for a mast with a diameter of approximately 1.5m. The omnidirectional radiation is not continuous but a result of the one or two optimas per panel mounting diameter.
The calculation of such radiation patterns is achieved via vector addition of the amplitude and phase of each antenna. The amplitude of each pattern can be read from the data sheet but the phase is only known by the antenna manufacturer. However the phase is the most important factor for the calculation because a rough estimate using only the amplitude can lead to completely incorrect results.

5. Particular Techniques used in GSM and DCS 1800

5.1 Diversity

Diversity is used to increase the signal level from the mobile to the base station (uplink). The problem with this path is the fact that the mobile telephone only works with low power and a short antenna. Diversity is applied on the reception side of the base station.

A transmitted signal extremly rarely reaches the user via the most direct route. The received signal is very often a combination of direct and reflected electromagnetic waves (Fig.16). The reflected waves have differing phase and polarization characteristics.

As a result there may be an amplification or in extreme cases a cancelling of the signal at specific locations. It is not unknown, that the reception field strength may vary 20-30 dB within several meters.

Operation in a canyon-like street is often only possible by using these reflections. These reflections from buildings, masts or trees are especially common, because mobile communications predominantly uses vertical polarization.

5.1.1 Space Diversity

This system consists of two reception antennas spaced a distance apart. One antenna has a certain field strength profile with maxima and minima from its coverage area, the other antenna has a completely different field strength profile although only spaced a few meters away. Ideally the minima of one antenna will be completely compensated by the maxima of the other (Fig. 17). The improvement in the average signal level achieved with this method is called diversity-gain.

Diversity antennas are not RF-combined because this would lead to an unfavourable radiation characteristic. Both antennnas function separately on different reception paths, whereby the higher signal per channel and antenna is chosen by the base station.Separation in the horizontal plane is preferred (horizontal diversity).
The results of vertical diversity are considerably worse.

5.1.1.1 Omni Base Station

The typical GSM Omni Base Station is made up of 3 antennas (Fig. 18):
– one transmitting antenna (Tx)
– two receiving antennas (Rx)

The transmitting antenna is mounted higher and in the middle in order to guarantee a cleaner omnidirectional characteristic. Furthermore the influence of the Rx and Tx antennas on each other is reduced (higher isolation). The two receiving antennas are spaced at 12-20 λ to achieve a diversity gain of 4-6 dB.

5.1.1.2 Sectored Base Station

Omni base stations are mainly installed in regions with a relatively low number of subscribers. For capacity reasons the communications cell is divided into 3 sectors of 120° in urban areas. Directional antennas, for example panels, are used to cover these sectors. All 3 antennas per sector can be mounted at the same height because directional antennas have higher isolation in comparison to omnidirectional antennas.

5.1.2 Polarization Diversity

The reflections which take place within urban areas are not all of the same polarization, ie. horizontal components also exist. Furthermore a mobile telephone is never held exactly upright which means that all polarizations between vertical and horizontal are possible. It is therefore logical that these signals be also used. Space diversity uses 2 vertically polarized antennas as reception antennas and compares the signal level. Polarization diversity uses 2 orthogonally polarized antennas and compares the resulting signals.

5.1.2.1 Horizontal and Vertical Polarization

The dipoles of both antenna systems are horizontally and vertically polarized respectively.
A spacial separation is not necessary which means that the differently polarized dipoles can be mounted in a common housing. Sufficient isolation can be achieved even if the dipoles are interlocked into one unit so that the dimensions of a dual-polarized antenna are not greater than that of a normal polarized antenna.

As a result there are the following advantages:

– 2 antennas only are now needed per sector: 1 x hor./vert. for polarization diversity
1 x vert. for Tx
(Figure 20)
– A minimum horizontal spacing is only required between the antennas, the antennas can also be mounted one above the other on the same mast. This makes the complete sector very compact, thereby easing permission procedures.

– If in addition the vertical path of the dual polarized antenna is fed via a duplexer for Rx and Tx, then only one antenna is needed per sector. As a result all 3 sectors can be supplied from one mast (Fig. 21).

The diversity gain in urban areas is the same as that achieved via space diversity (4-6 dB).

5.1.2.2 Polarization +45°/-45°

It is also possible to use dipoles at +45°/-45° instead of horizontally and vertically (0°/90°) placed. One now has two identical systems which are able to handle both horizontally and vertically polarized components. This combination brings certain advantages in flat regions because the horizontal components are fewer due to the fewer reflections. A further advantage is that both antenna systems can be used to transmit. Experiments have shown that pure horizontal polarization achieves considerably lower results than vertical polarization when transmitting.

Two transmitting channels using hor/ver antennas are combined via a 3-dB-coupler onto the vertical path. As a result half the power of both transmitting channels was lost.

Both polarizations are fully suitable for Tx if you use cross-polarized antennas resulting in a system as in Figure 22.

5.2 Indoor Antennas

It is often difficult to supply the inside of buildings with radio coverage at higher frequencies. Mirrored windows and steel-webbed concrete walls block the electro-magnetic waves.
As a result airports, underground railway stations, shopping or office centres are very often supplied with their own small lower power network via a repeater which is connected to the next base station. Special indoor antennas are mounted in the various rooms and corridors in an unobtrusive design which blend in with the surroundings.
For example there are wide-band omnidirectional antennas available which can be mounted on the ceiling and can be used for GSM aswell as DCS 1800 (DECT) systems. If used in conjunction with wide-band splitters then an indoor network can be achieved which covers several mobile communications services.
Extremely flat directional antennas can be mounted on walls (Fig. 24). The small depth of the antenna is achieved using so-called "Patch Technology". A rectangular metal plate is thereby mounted over a conductive plane (Fig. 25). The patch is electrically fed via the middle of one of its sides, thereby creating an electrical field between the patch and the conductive plane. The field strength vectors of the slit of the feed-point and the opposite point of the conductive plane have the same phase and therefore define the direction of polarization. The field strength vectors of both of the other patch sides are counter-phased and cancel each other.

6. Car Antennas

Are car antennas needed at all these days?
Operating a hand-held portable within a vehicle without a mounted antenna is very often possible, especially with public mobile networks. However, the use of an externally mounted antenna is recommend in every case!

Mobile telephones are at the centre of the controversial discussions over the effects of electromagnetic waves on the human body. As a result the output power of the base station is controlled to a minimum required for operation. The power of the mobile telephone, on the other hand, has to be turned to maximum inside the car so that the connection with the base station, and thereby the conversation, be upheld because the car attenuates the signal significantly. As a result the mobile subscriber submits himself unnecessarilly to a higher level of electromagnetic radiation. If an externally mounted car antenna is used then the occupant is protected via the shielding of the car body.

6.1 $\lambda/4$ Antenna on the Car Roof

The $\lambda/4$ -antenna is the basic car antenna just as the $\lambda/2$ -dipole is the basic antenna for base station systems (Fig. 26). However, the $\lambda/4$ antenna cannot function on its own. The $\lambda/4$ -antenna needs a conductive plane which virtually substitutes an image of the antenna under test. This virtual length increases the electrical length of the antenna to $\lambda/2$.

Electrically speaking the best place to mount a car antenna is the car roof. The electrical characteristic of this antenna is shown in Fig. 27. The lifting of the radiation pattern is caused by the relatively small counter weight of the car roof surface area and the thereby resulting incorrectly closed field lines. This lifting of the pattern is inversely proportional to the surface area, theoretically if an infinite conductive area was available then the pattern would be untilted.

If the antenna is mounted at the side of the roof then the horizontal pattern is no longer circular because the surface area in all directions is no longer the same. As a result the vertical pattern shows variations with the corresponding different antenna gain in the horizontal plane.
The above description is only valid if the car roof is made of metal. Sometimes car roofs are made of plastic. If this is the case then a conductive surface has to be brought into contact with the antenna base. This surface should have a diameter of at least one wavelength and be made of brass, copper or aluminium foil, brass-plated material, mesh, etc.

6.2 Gain Antennas

The reference antenna for gain measurements for car antennas is the λ/4 -antenna. In order to achieve a higher gain the vertical dimensions of the antenna must be increased. Figure 27 shows the vertical pattern of a 5/8 λ antenna. The additional gain of 2 dB is achieved mainly by the tilting of the vertical pattern.

If the length of the radiating element is further increased then the current components of opposite phase become to high and a phase inversion becomes necessary. The correct phaseing of a λ/4 and λ/2 radiating elements results in an antenna gain of 4dB (Figure 28).

6.3 Rear Mount Antennas

Many customers do not favour roof-mounted antennas. Firstly, the installation is difficult and secondly drilling a hole in the roof reduces the re-sale value of the car. The required feeder cable is relatively long and the resulting attenuation is significant. Rear-mounted antennas offer an alternative as they can be mounted in already existant drilled car radio holes.
λ/4 or 4 dB-gain antennas create unsymmetrical horizontal radiation patterns which show shadows in the direction of the car when mounted on the rear of the car (Figure 30). A rear-mounted antenna must be significantly longer so that a proportion of the antenna is higher than the car roof. Figure 30 shows an example of an NMT rear-mounted antenna with an approximately 900 mm long radiating element (2 x λ/2 elements vertically stacked with a phasing section in between).
The car inner cell causes more significant distortion at 900 MHz because of the shorter antenna lengths. As a result so called elevated antennas are used.The feed point of the antenna is not the base but the middle of the antenna, whereby the radiating upper part of the antenna is extruding above the car roof. An almost ideal omnidirectional characteristic is the result (Figure 31).

6.4 Screen Surface Direct Mounting Antennas

Screenfix antennas offer mounting without drilling any holes. These antennas are made up of two functioning parts (Figure 32):

– Exterior part: radiating element
– Interior part: coupling unit with electrical counter weight and connecting cable

Both parts are stuck on either the inner or outer side of the rear, front or side window.
Both parts are capacitively coupled through the glass and are therefore electically connected to one another. One works predominantly with decoupled radiating elements because the electrical counter weigth of this type of antenna is very small. A colinear antenna is used, which in the case of a good Screenfix antenna is made up of 2 $\lambda/2$ elements and a phasing system. The electrical counter weight which defines the dimensions of the coupling unit prevents radiation into the inside of the vehicle and therefore should not be too small.

6.5 Clip-on Antennas

If the vehicle antenna is only needed perodically and should be removed easily then a series of clip-on antennas as well as magnetically mounted antennas are available (Figure 33).
The antenna is mounted on the upper edge of a wound-down window and then clipped into place. The window can then be wound back up. The antenna is electrically made up of an elevated $\lambda/2$ Antenna, ie. the part below the thickening is only a coaxial section. As a result the radiation takes place above the car roof top and a good omnidirectional pattern is achieved.

6.6 Electrically Shortened Antennas

Even $\lambda/4$ antennas are too long for some applications. For example buses or building site vehicles very often demand extremely short antennas. Figure 34 shows a "Miniflex Antenna" for the 2-m-Band with a length of L = 170mm which is composed of a metal spiral in a plastic coating. The antenna is very narrow banded due to the extremely short dimensions. Tuning to the operating frequency is achieved via the compensation circuit underneath the mounting surface.
A further possibility of shortening the antenna length can be found by using a top loading capacitance which artificially lengthens the radiating element. With this method it is possible to construct very flat antennas. Figure 34 shows a 70-cm-Band antenna with a vertical length of 70mm. The resulting gain of these shortened antennas depends on the degree of shortening whereby the thickness of the radiating element plays an important role.

6.7 Train Antennas

Car antennas are generally not DC grounded. Train antennas on the other hand must be designed to withstand possible electrical contact with the overhead lines, ie. a high level of safety is required. The train driver must not be exposed to any danger via the feeder cable of the antenna.
According to the test requirements of the German Railway Authority (Deutsche Bahn AG) the antenna must be able to withstand a voltage of 16.6 kV and a current of 40 kA, whereby a voltage of not more than 60 V is measured at the RF-connector.
Figure 35 shows a train antenna for the 450 MHz frequency range. The bandwidth is increased by using a sword-like radiating element. A short circuiting rod connects the upper end of the radiating element with ground. This short circuiting rod has an electrical length of $\lambda/4$ (approximately). Due to this length, the radiator is grounded for DC or low frequencies but open for the working frequency.
In order to have sufficient distance between the antenna and the overhead lines the length of the antenna at lower frequencies has to be less than $\lambda/4$.
Figure 36 shows a $\lambda/4$ antenna in the 2-m band. The antenna has a narrow bandwidth and has to be trimmed via 2 capacitors as a result of the mechanical shortening. The parallel capacitor Cp electrically lengthens the antenna, the capacitor in series Cs, on the other hand, trims the VSWR.
The antenna is grounded via a central vertical conductive rod.

7. Antennas for Portables

The antenna is increasingly becoming an integral part of the handheld unit especially in communication services at higher frequencies such as GSM and DCS 1800. This has the advantage that the impedance at the interface is no longer critical (50 W impedance at the connector).
Handheld equipment is available on the market with extendable antennas. These fulfill the criterion of λ/4 antennas if not extended (the handheld mobile must always be available). These antennas reach an electrical length of λ/2 if extended resulting in the required gain for mobile transmitting operation.

7.1 λ/4 Antennas

An electrical counterweight is required similar to the situation described for vehicle antennas for portable antennas, this counterweight is performed by the housing of the radio. The user of the mobile distorts the antenna - counterweight system because he carries it within its own radiation field. The performance of the antenna may vary strongly depending on the user and his habits.
Electrical interference of the mobile itself is possible, because the mobile is part of the antenna. The very simple construction of this antenna is its main advantage. A sufficient electrical compensation for 50 W is achieved without special measures. The antenna itself is a lengthened inner conductor of a coaxial cable.
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7.2 λ/2 Antennes (Gainflex)

If the antenna has a length of λ/2 than no electrical counterweight is needed. The antenna functions independantly of the mobile and one therefore speaks of a decoupled antenna. The resulting advantages are as follows:
- practically insensitive of handling/operating position.
- a defined radiation charactistic and the thereby practical gain of approximately 4 dB with reference to a λ/4 antenna.
- interference of the mobiles electronics is avoided via the decoupling of the antenna from the mobile.

The impedance at the base of this antenna is very high. Therefore a relatively complicated matching circuit at the base of the antenna is needed to compensate the impedance to 50 W.

7.3 Shortened Antennas

Shortened $\lambda/4$ antennas are generally used at lower frequencies. They are composed of spiral radiating elements which have a physical length of approximately $\lambda/4$ if extended to full length. Therefore a good matching is achieved.

7.4 Field Strength Measurements

Mobiles are always operated near the human body which may act either as a reflector or absorber thereby influencing the radiation characteristic. Figure 37 shows a comparison of the above described antennas with this in mind. The noted gain values are made with reference to a $\lambda/2$ dipole without any influence from the human body, ie. reference 0 dB.

Appendix

Figure 1: Mobile communication services in Germany

Frequency	Communication Service / Operator
13 – 47 MHz	CB-Radio Paging systems
47 – 68 MHz	TV Band I
68 – 88 MHz	“BOS“-Services (Security Services) e.g. Police, Fire Brigade, Rescue Services, Energy Supply Services
88 – 108 MHz	UKW-Broadcasting
108 – 144 MHz	VHF ground-to-air communication VOR
146 – 174 MHz	BOS services Train Communications Public Services Taxifunk ERMES (European Radio Messaging System)
174 – 225 MHz	TV Band III
225 – 380 MHz	UHF ground-to-air communication ILS (Instrument Landing System)
380 – 400 MHz	TETRA (Trans European Trunked Radio)
400 – 430 MHz	Trunking System (Checker / Modacom / Mobitex)
450 – 470 MHz	450 MHz Mobile Network (C-Net), Train Communications Paging Systems
470 – 860 MHz	TV Band IV / V
870 – 960 MHz	GSM Mobile Network (D-Net) DIBMOF (digital train radio system)
960 –1215 MHz	DME (Distance Measuring Equipment)
1452 – 1492 MHz	DAB Digital Audio Broadcasting
1710 –1880 MHz	PCN Mobile Network (E-Net)
1880 –1900 MHz	DECT (Digital European Cordless Telefone)

Figure 2: The antenna as quad-gate

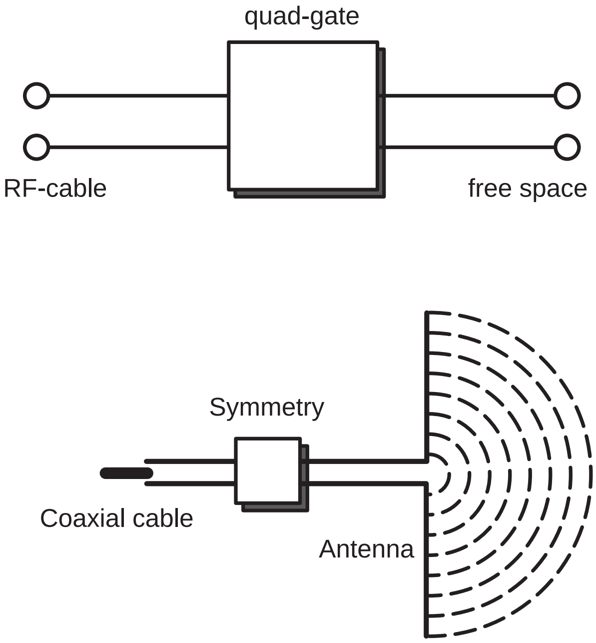


Figure 3: Evolving an antenna from a coaxial cable

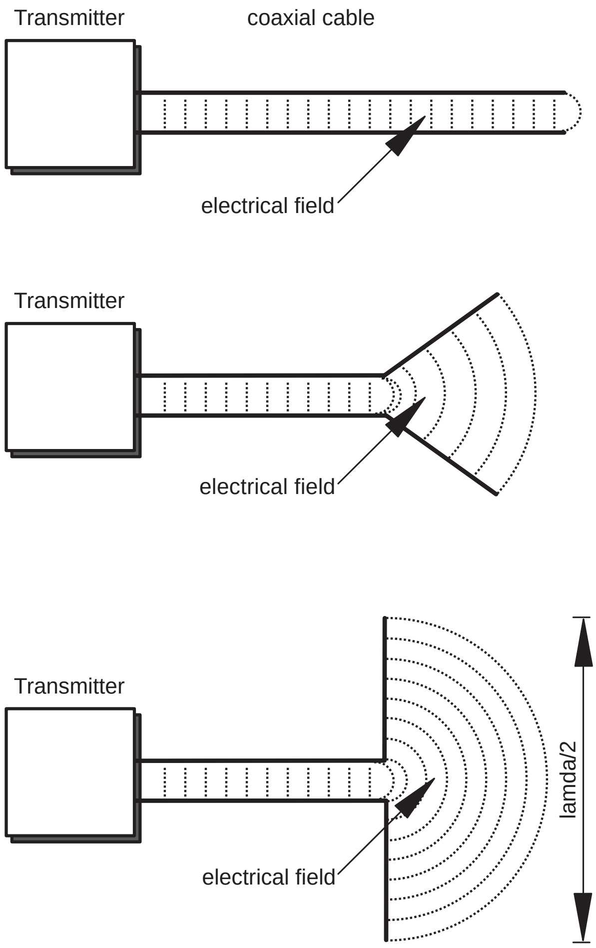


Figure 4: Field distribution on a λ/2 Dipole

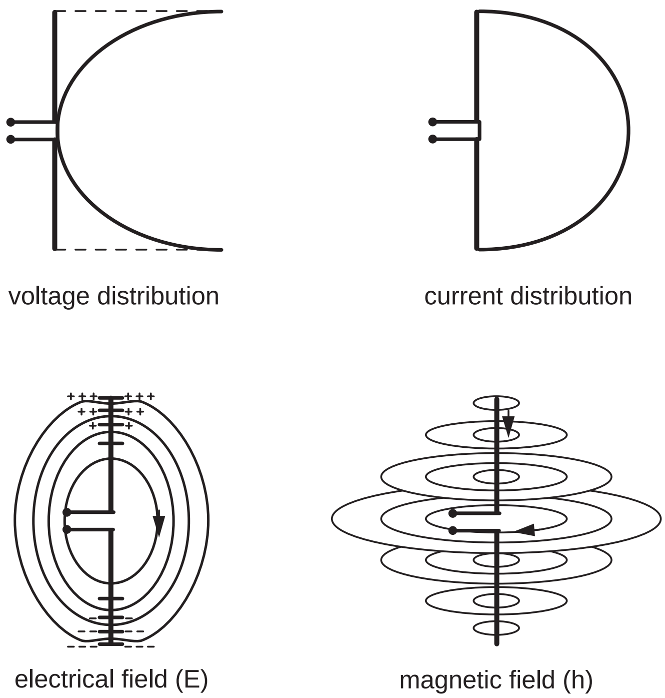


Figure 5: Wave propagation

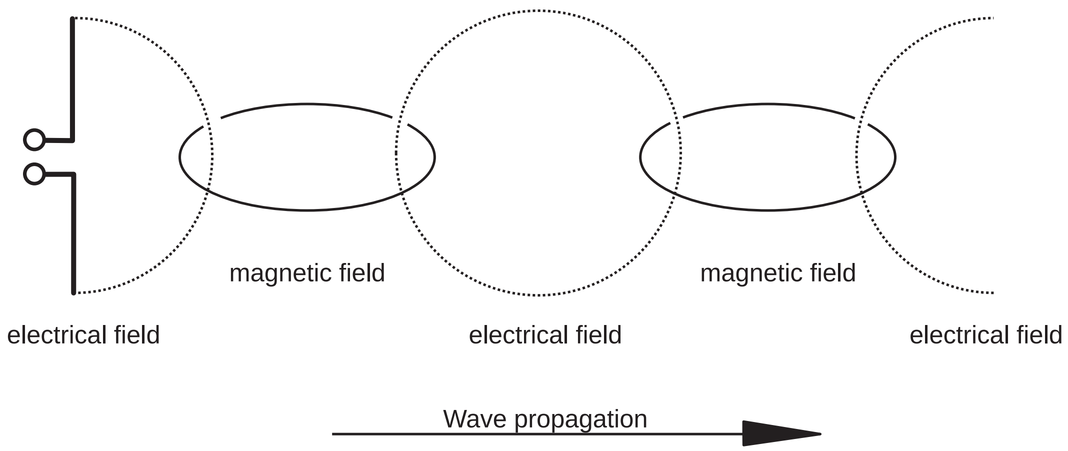


Figure 6: Antenna gain vs half-power beam width

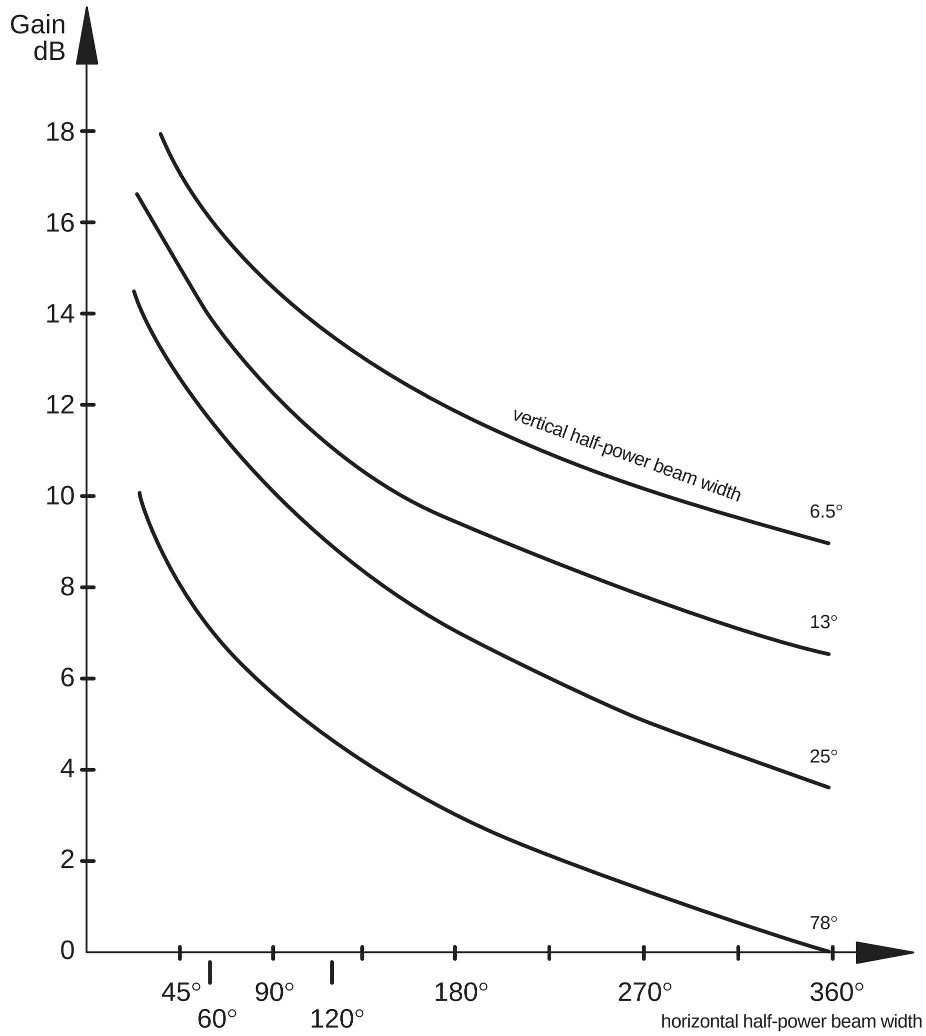
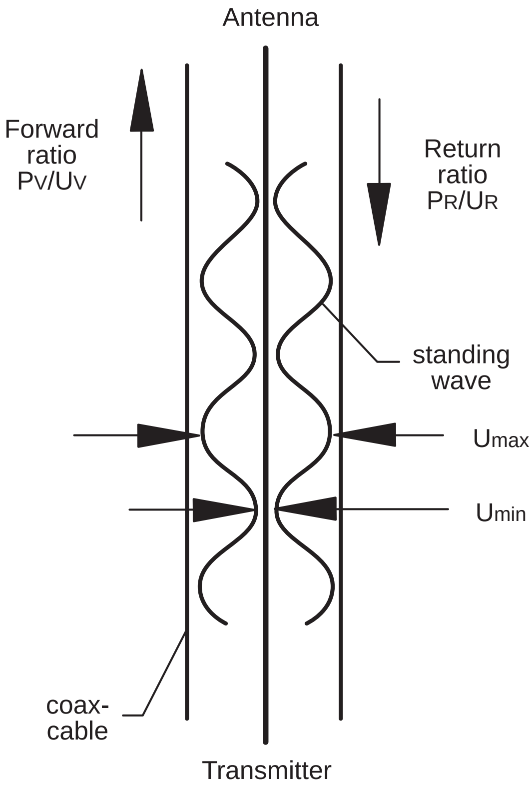


Figure 7: VSWR, Return Loss Attenuation and Factor of Reflection



VSWR s

$$s = \frac{U_{max}}{U_{min}} = \frac{1 + r}{1 - r}$$

Return loss attenuation a_r

$$\text{Factor of reflection } r = \frac{U_R}{U_V} = \frac{s - 1}{s + 1}$$

$$a_r \; [\text{dB}] = -20 \log r$$

Reflected power

$$\frac{P_R}{P_V} = 100\, r^2 \quad [\%]$$

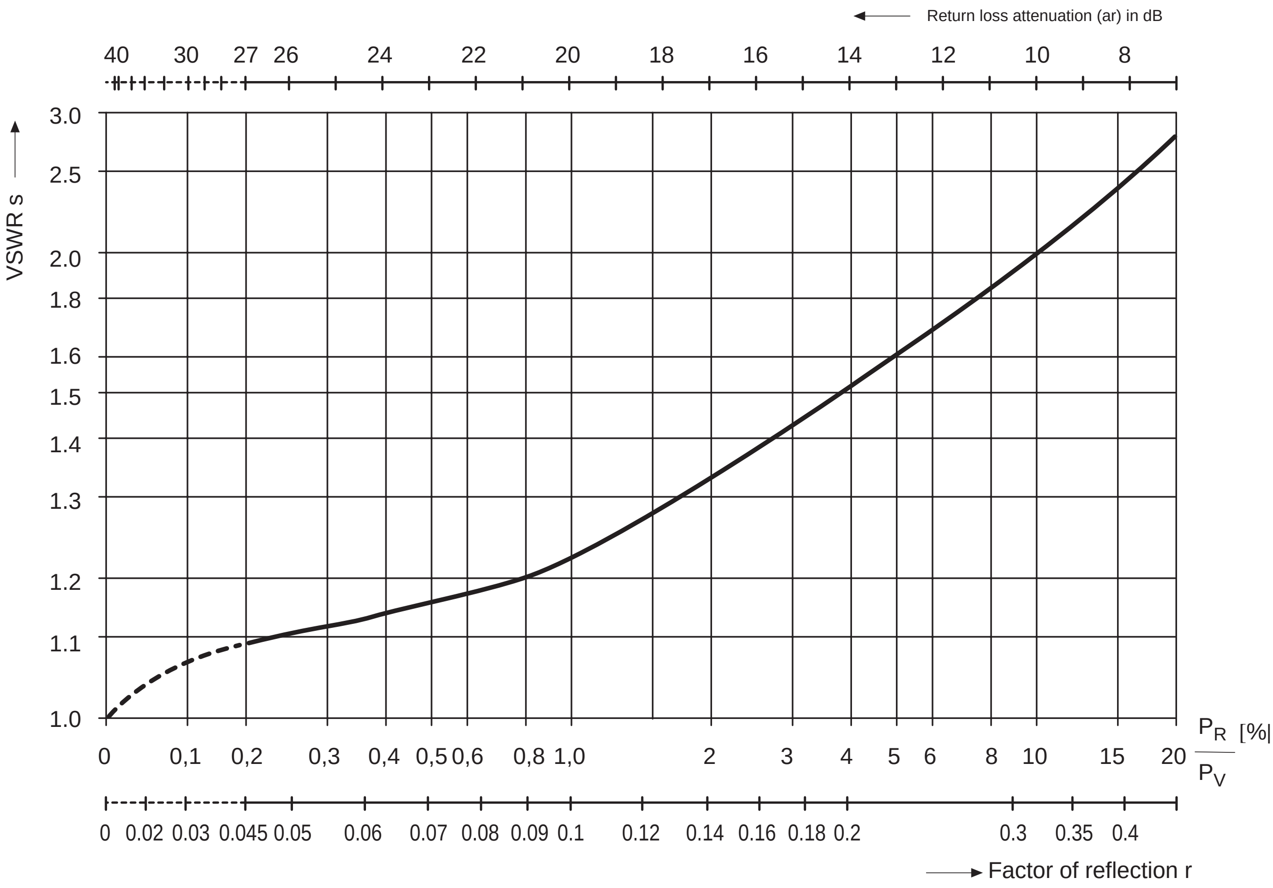
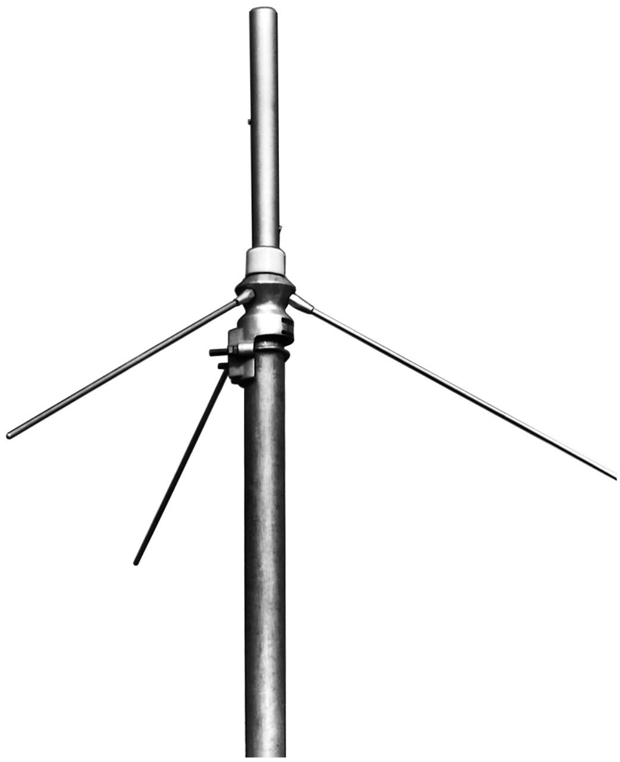
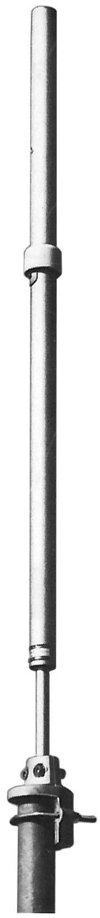


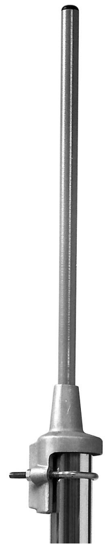
Figure 8: Groundplane and λ/4-Skirt Antenna

Groundplane



λ/4-Skirt Antenna



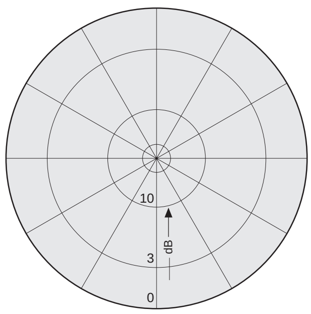


K 51 26 2
146 – 174 MHz

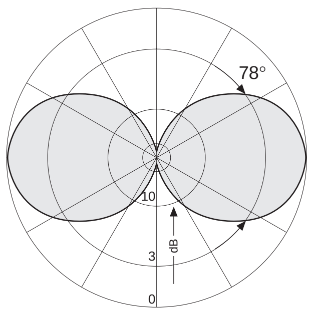
K 55 26 28
164 – 174 MHz

K 75 11 61
806 – 960 MHz

Radiation diagrams with relative field strengths

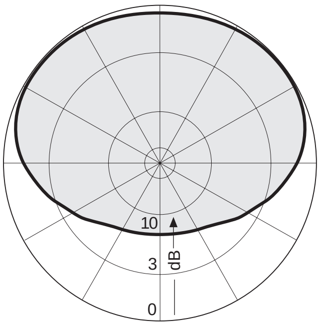


Horizontal

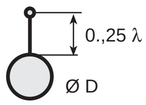


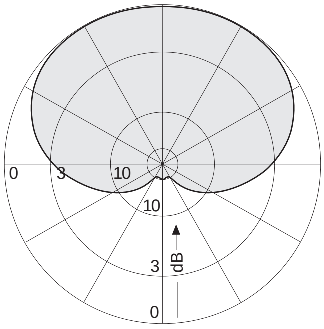
Vertical

Figure 9: Offset omnidirectional antenna



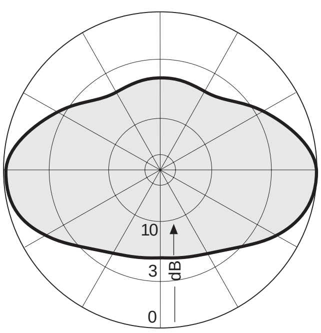
D = 0.04 λ



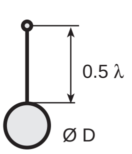


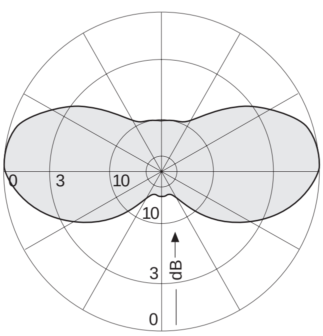
D = 0.4 λ

K 55 29 2..
146 – 174 MHz



D = 0.04 λ





D = 0.4 λ

Figure 10: Gain via vertical beaming

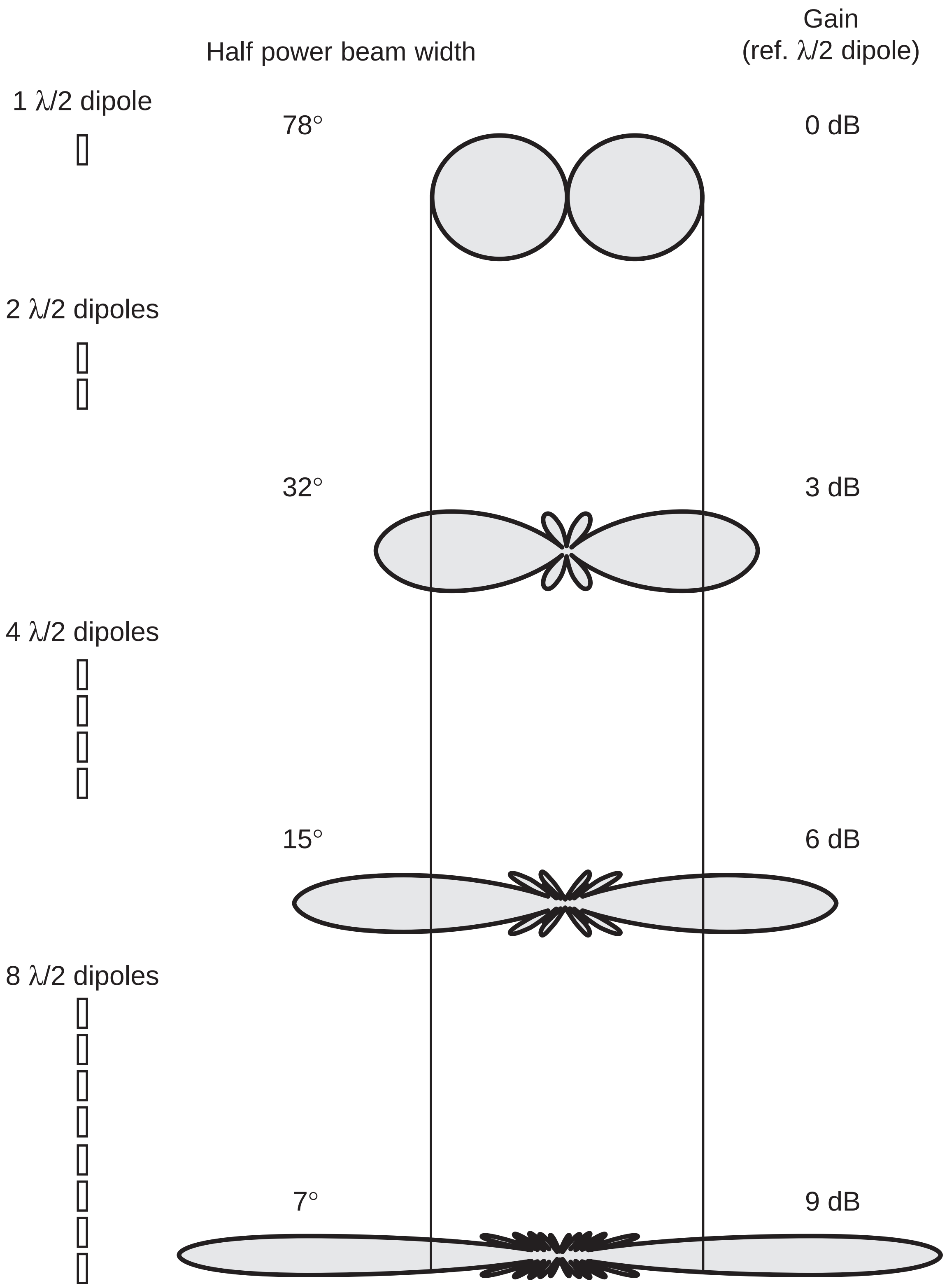
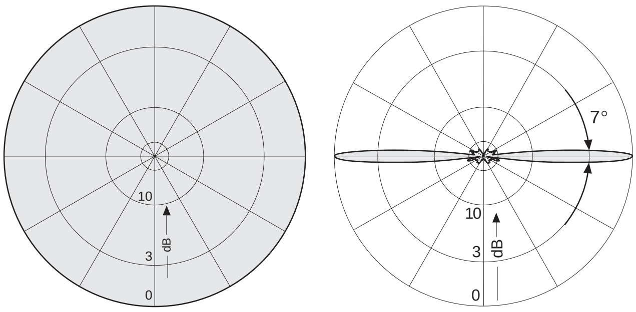
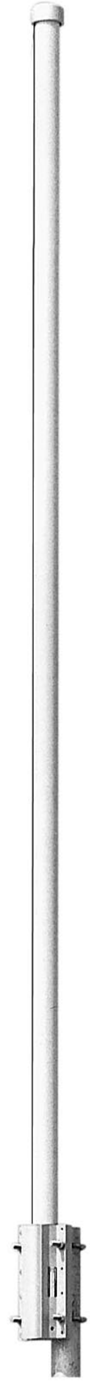


Figure 11: 9 dB Omnidirectional Gain Antenna

Radiation diagrams with relative field strength



Horizontal Vertical



736 347
870 – 960 MHz

Figure 12: Gain via horizontal beaming

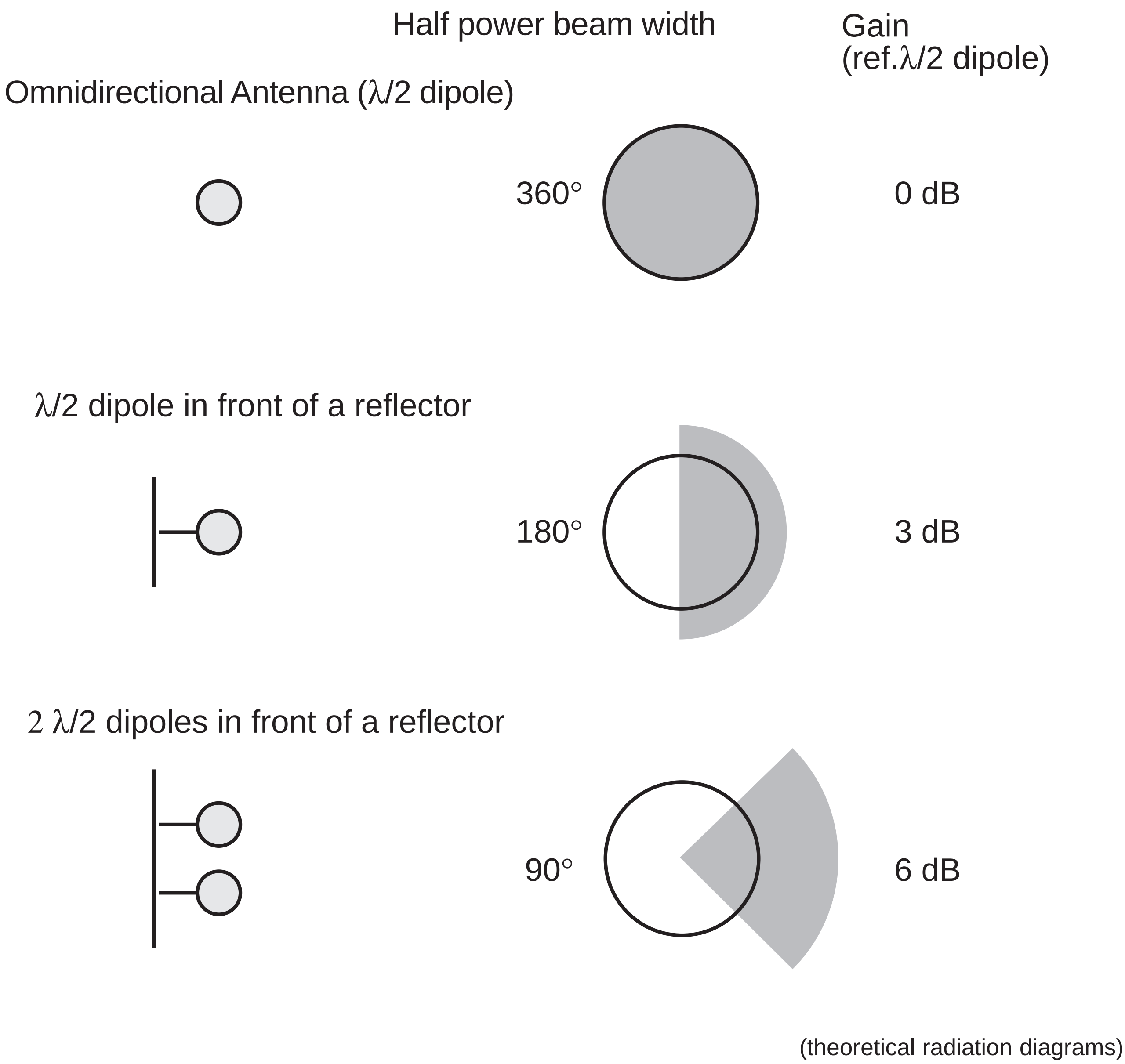
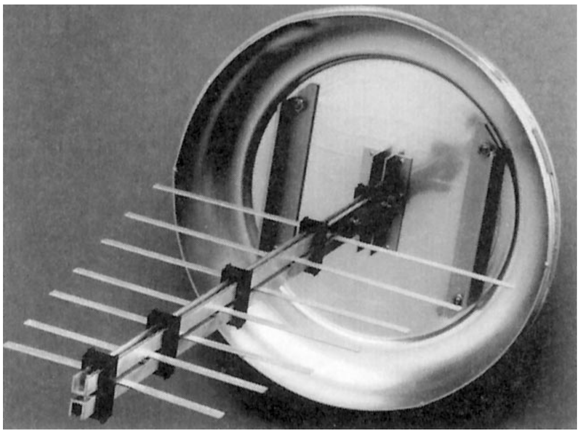
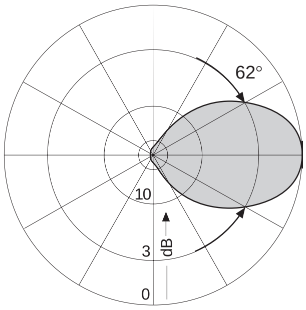


Figure 13: Yagi – and log.-per. Antennas

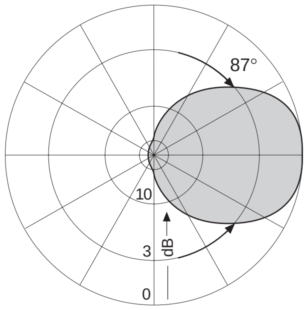


log.-per. Antenna K 73 23 2
406 – 512 MHz

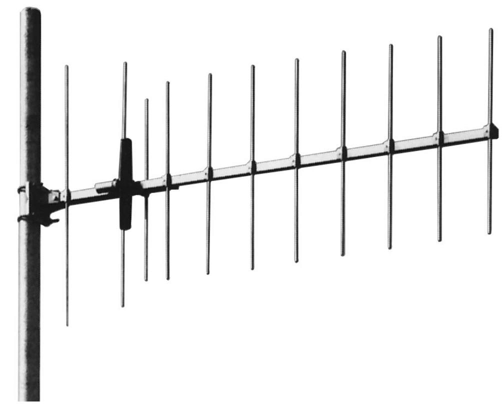
Radiation diagrams with relative field strength



in the plane of polarization

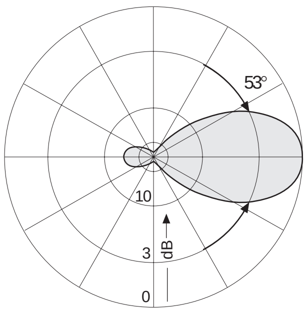


perpendicular to the plane of polarization

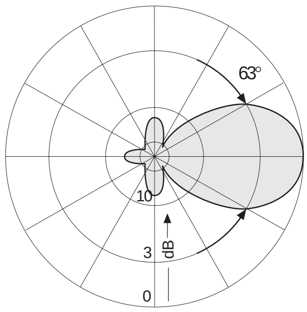


Yagi-Antenna K 52 07 21
146 – 174 MHz

Radiation diagrams with relative field strength

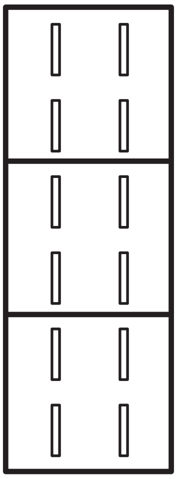


in the plane of polarization

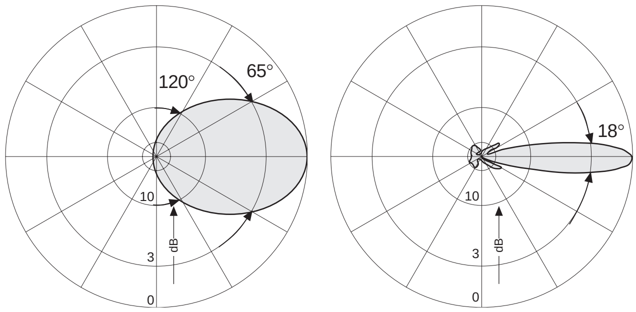


perpendicular to the plane of polarization

Figure 14: Panel Antennas and Corner Reflector Antennas



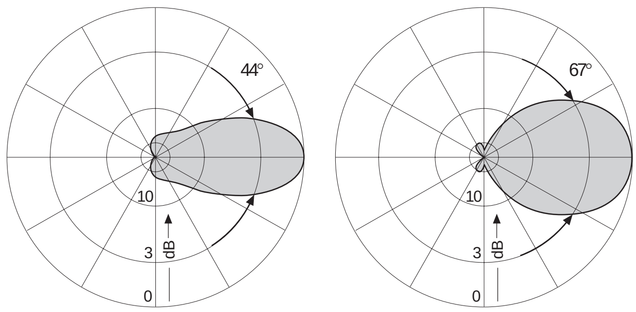
Radiation diagrams with relative field strength



Horizontal Vertical

Panel 730 684
890 – 960 MHz

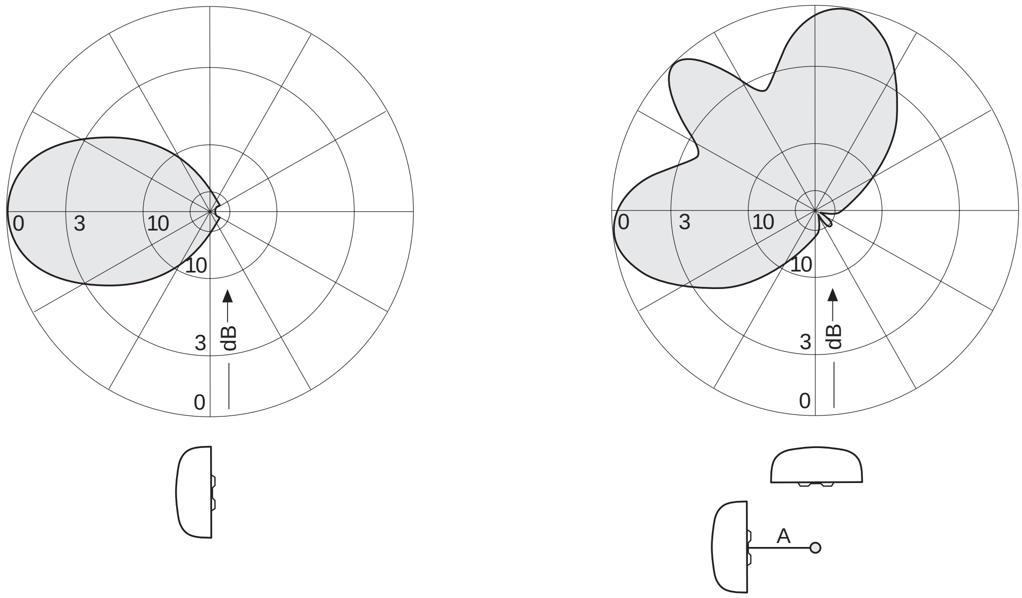
Radiation diagrams with relative field strength



Horizontal Vertical

Corner Reflector Antenna K 73 12 21
400 – 700 MHz

Figure 15: Directional antenna systems



Distance A = 200 mm
947 MHz
Antenna 730 360

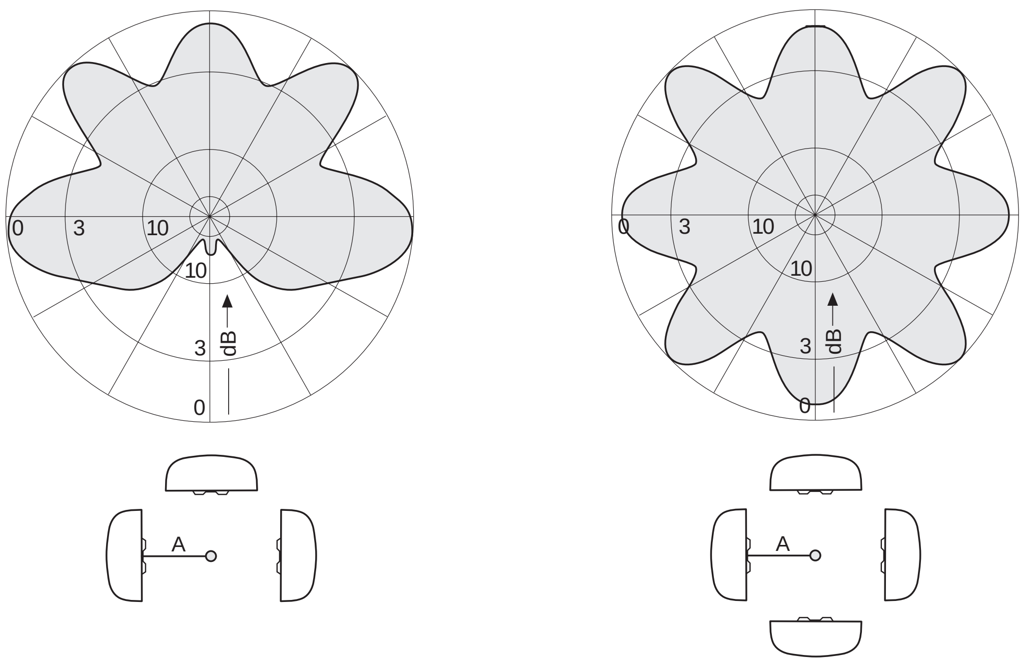


Figure 16: Multiple path propagation via reflections

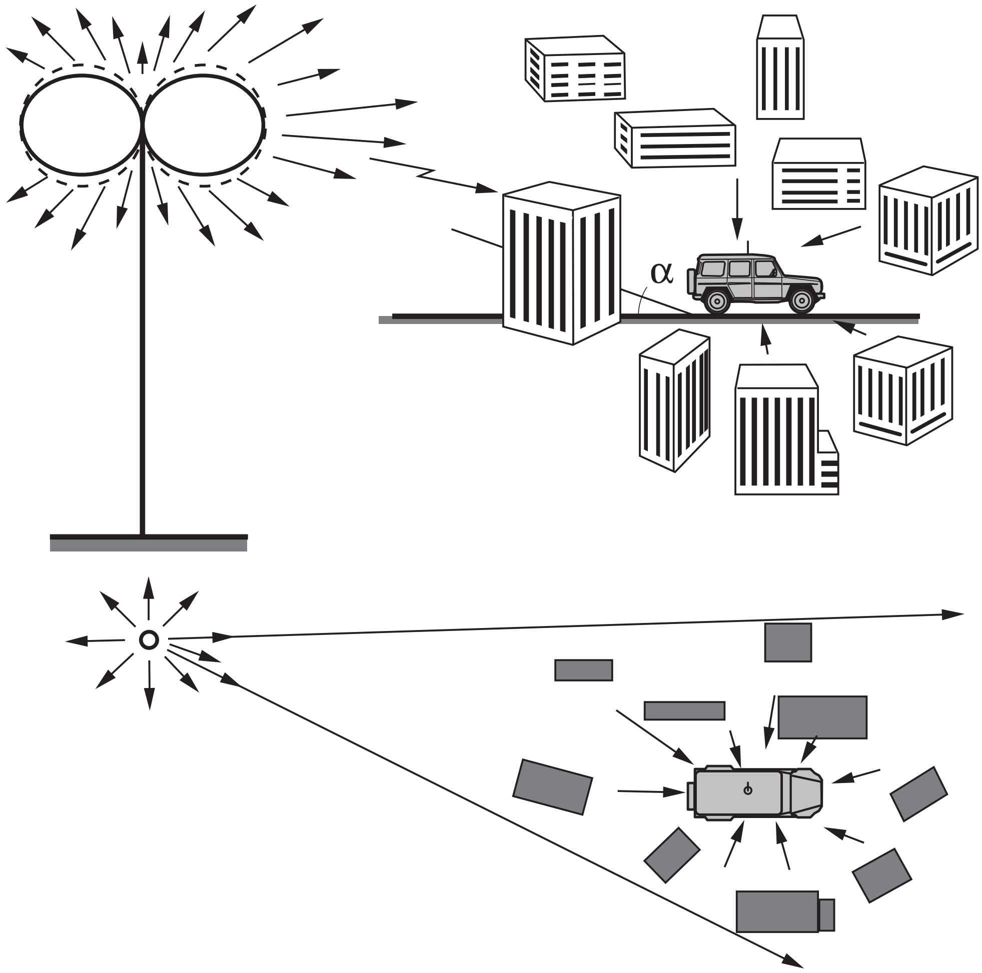
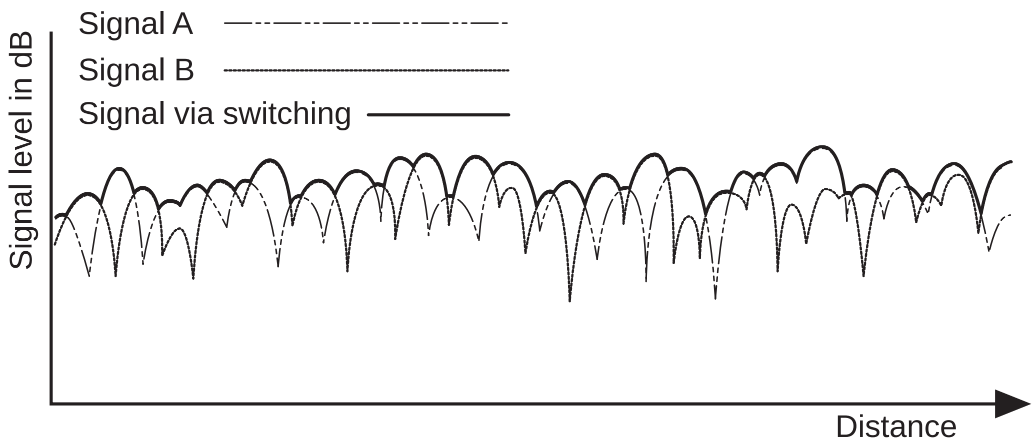


Figure 17: Signal level improvement using diversity



Source: William C.Y. Lee, Mobile Communications Design Fundamentals

Figure 18: Omni Base Station

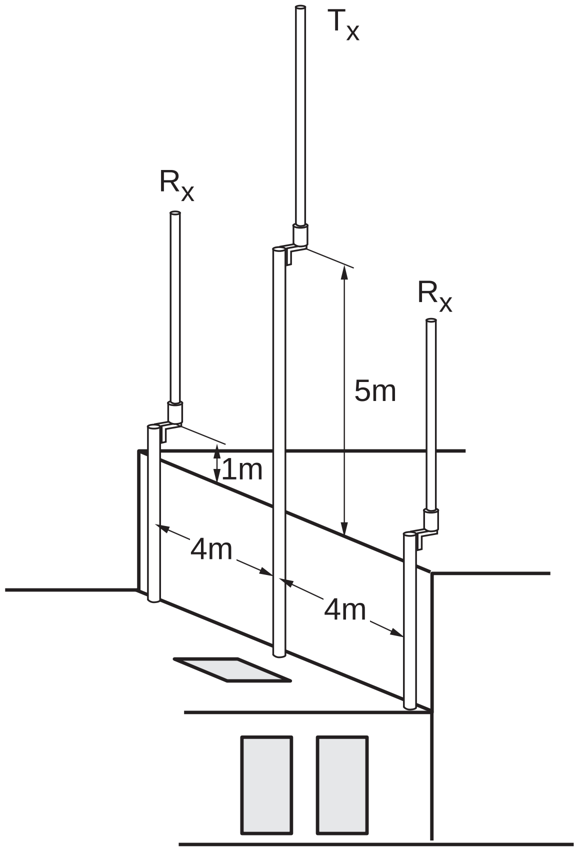


Figure 19: Sector Base Station

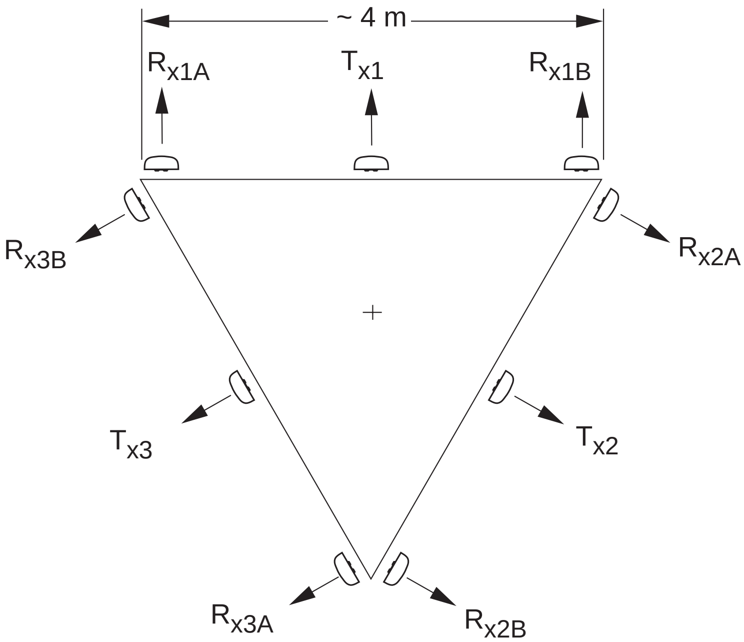


Figure 20: 2-Antenna Sector System

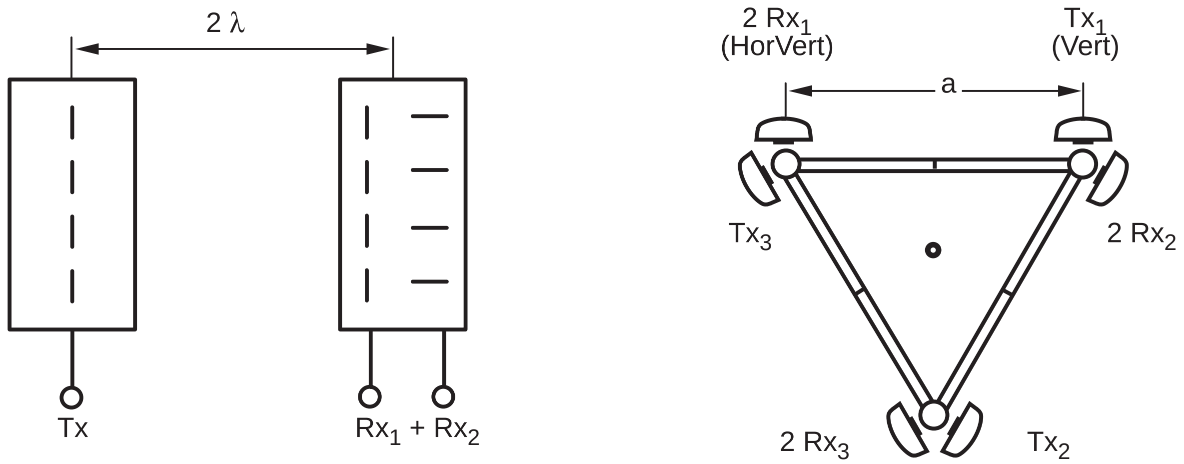


Figure 21: 1-Antenna Sector System

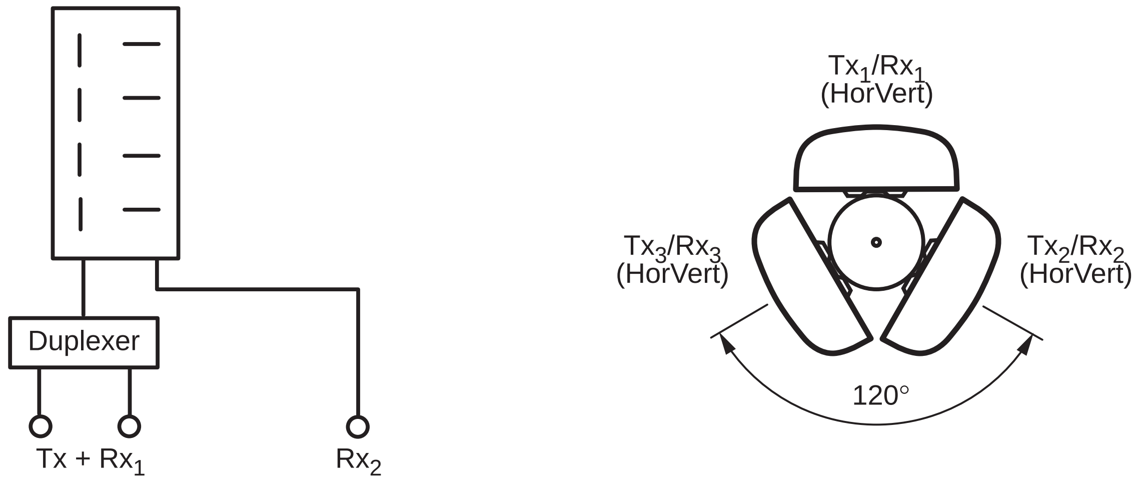


Figure 22: X-Pol Antenna System

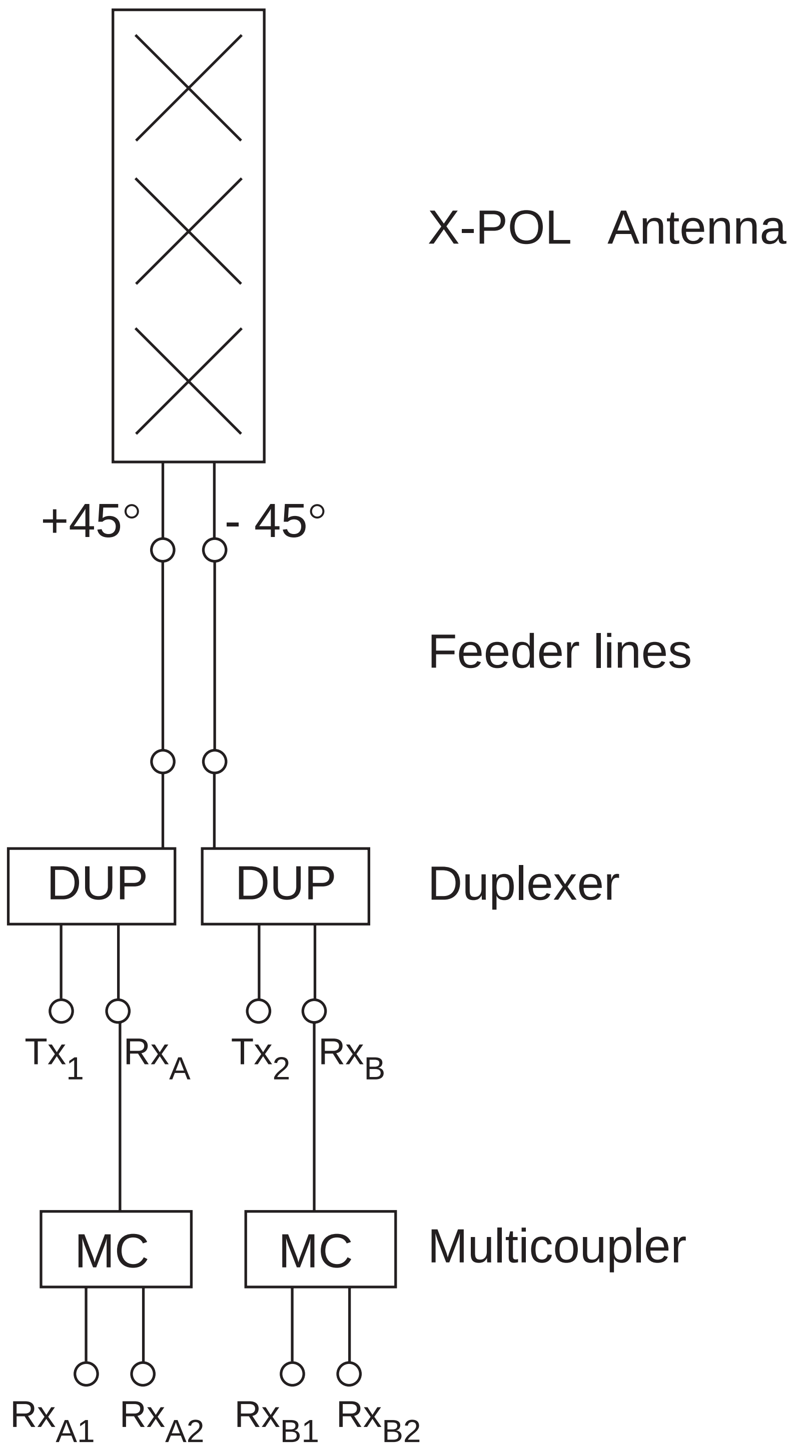


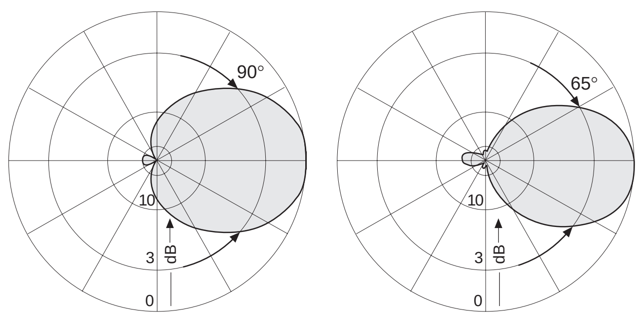
Figure 23: Indoor Omnidirectional Antenna

870 – 960 MHz / 1710 – 1900 MHz
(GSM / DCS 1800 / DECT)

Figure 24: Indoor Patch Antenna (Depth 20 mm)

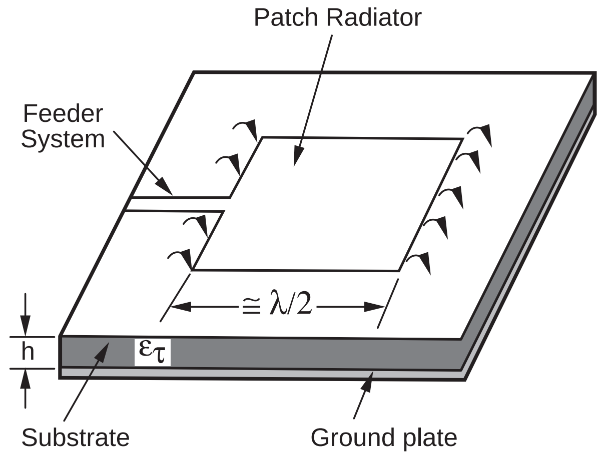
1710 – 1900 MHz
(DCS 1800 / DECT)

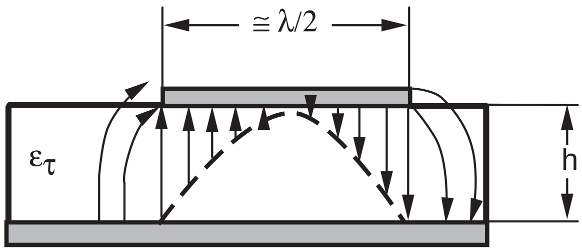
Radiation diagrams with relative field strength



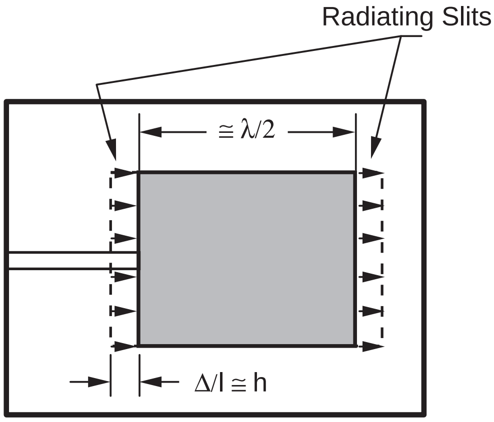
Horizontal Vertical

Figure 25: Schematic of a Patch Antenna





Side Elevation



Plan

Source: Bahl / Bhartia “Microstrip Antennas“

Figure 26: Electrical field distribution of a $\lambda/4$ antenna across a conductive plane

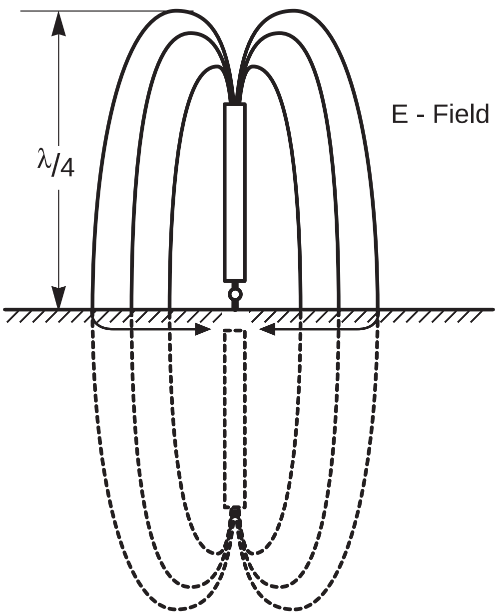


Figure 27: Vertical Radiation Diagram, center of vehicle roof

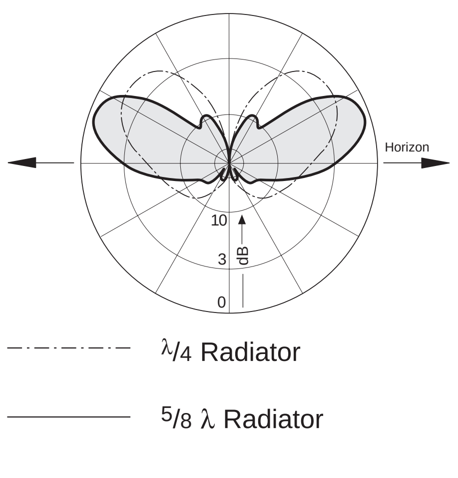


Figure 28: 4 dB Gain antenna 450 MHz

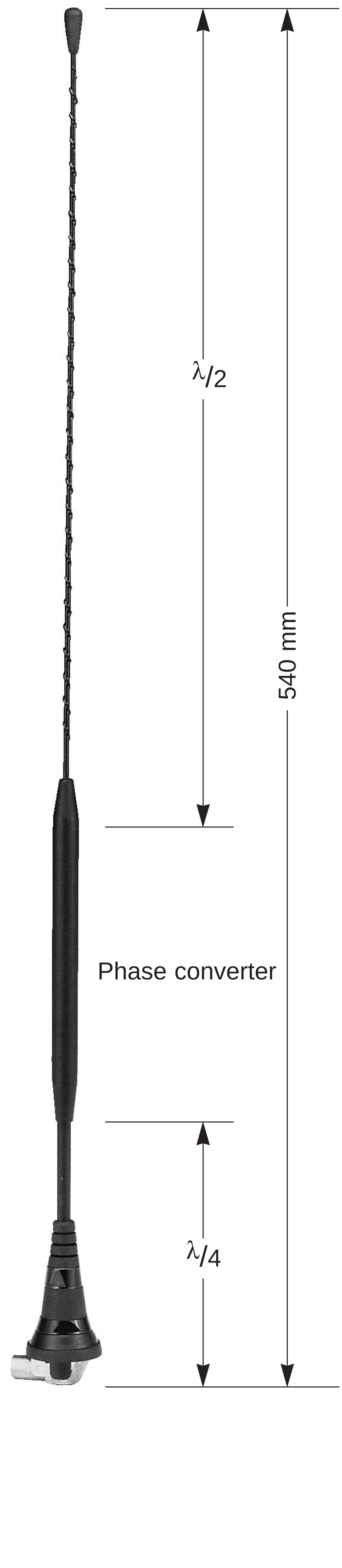
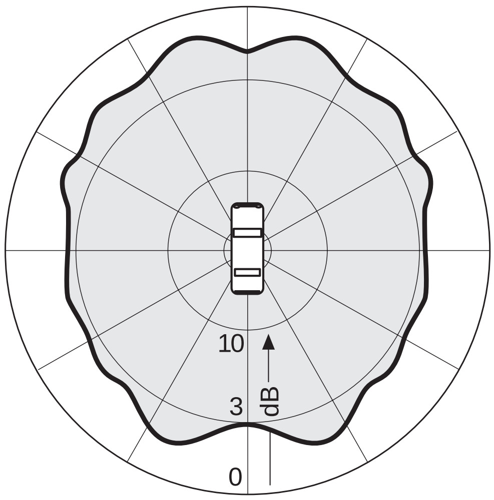
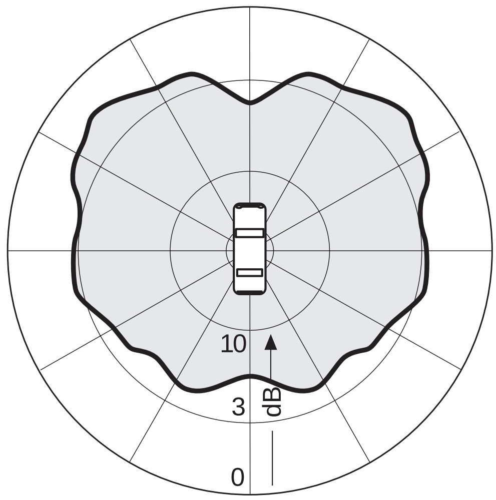


Figure 29: Changes in radiation pattern and gain by tilting the antenna

0°

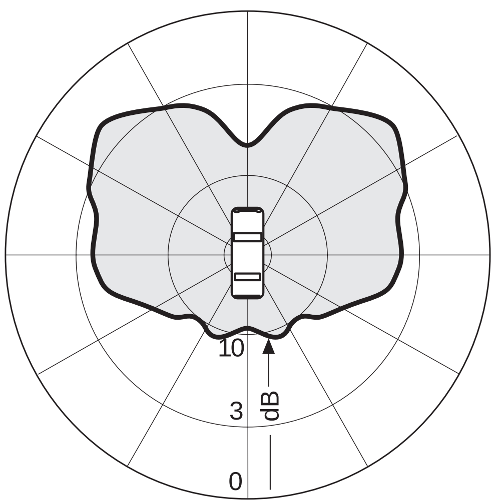


20° backward tilt



4 dB antenna placed in the centre of the vehicle roof with different angles of tilt

35° backward tilt



65° backward tilt

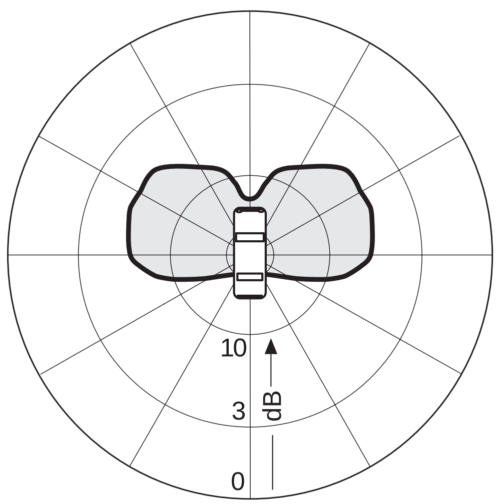
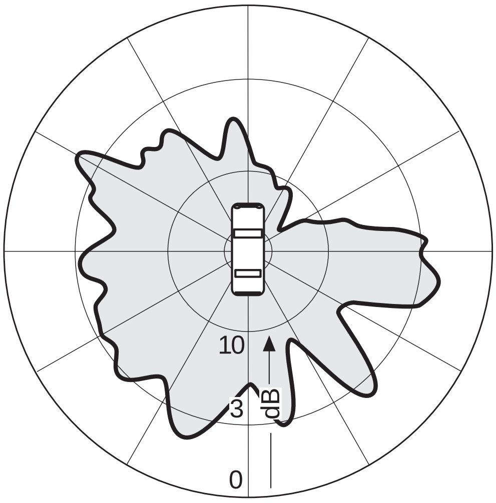
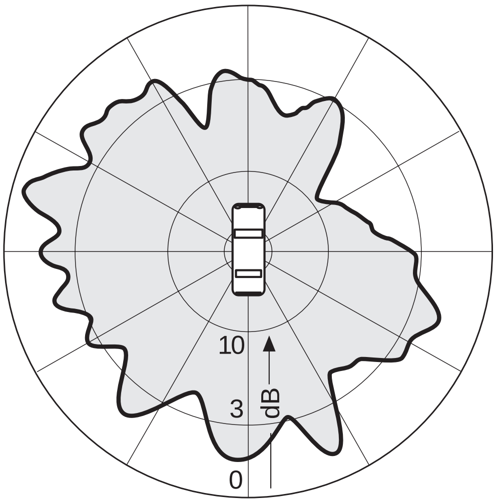


Figure 30: Horizontal diagram of rear-mounted antennas

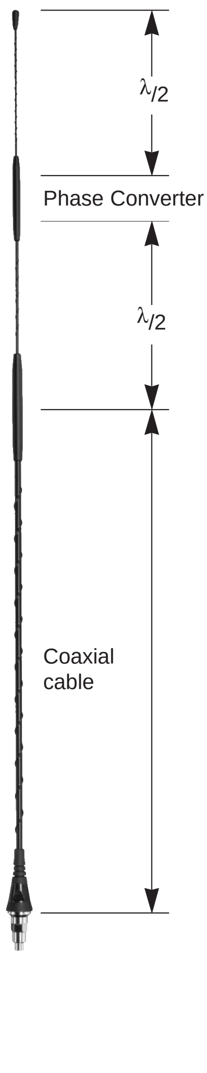


Car antenna mounted on the car roof
with 4 dB gain,
mounting point: left wing, 453 MHz

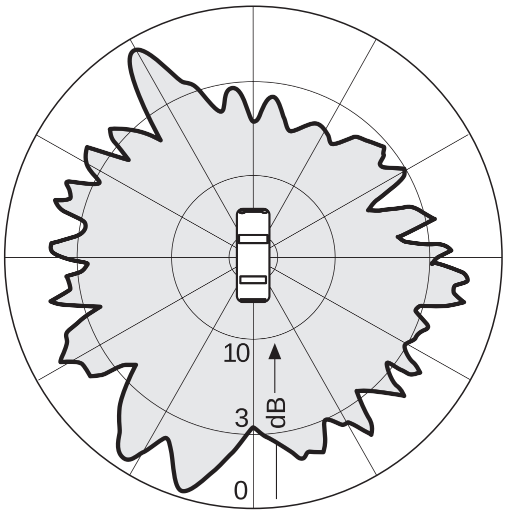


Car antenna mounted on the car roof
length 900 mm,
mounting point: left wing, 453 MHz

Figure 31: 900 MHz rear mounted antennas

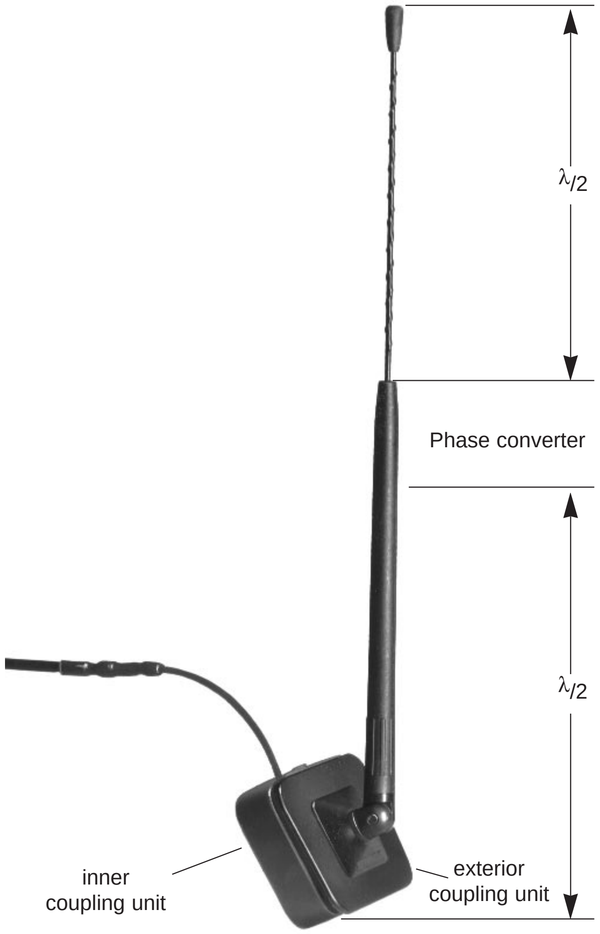


890 – 960 MHz



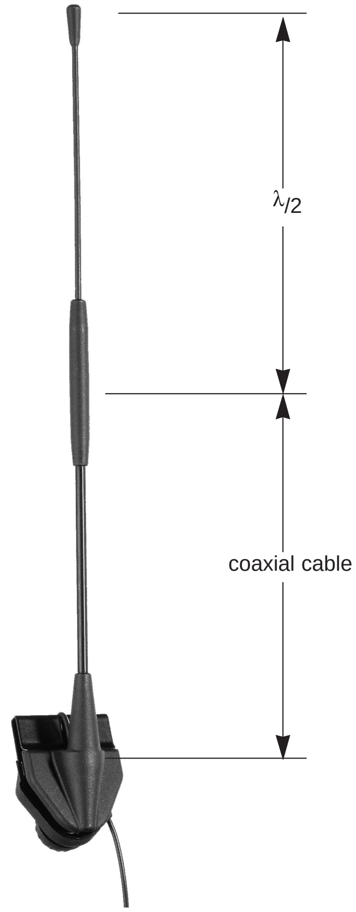
900 MHz rear-mounted antenna with elevated radiator base, mounted on the left wing

Figure 32: Screen surface direct mounting Antenna



Screenfix Antenna
870 – 960 MHz

Figure 33: Clip-on antenna



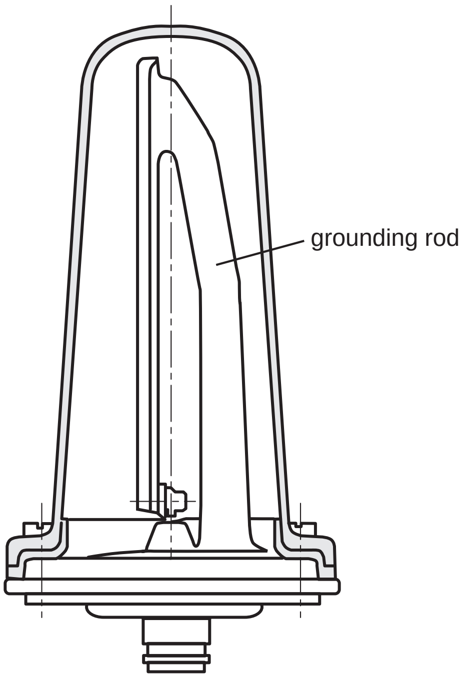
Glassic Antenna
890 – 960 MHz

Figure 34: Shortened vehicle antennas

Miniflex Antenna
K 50 39 2 ..
146 ... 174 MHz

Vehicle Antenna
K 70 23 2 ..
406 ... 470 MHz

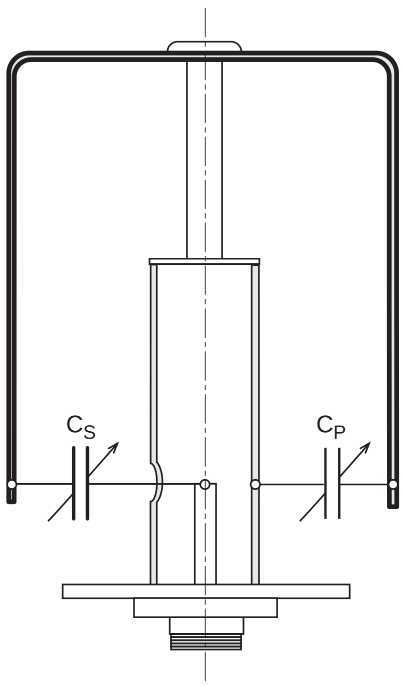
Figure 35: Train Antenna at 450 MHz



Train antenna
K 70 20 21
406 – 470 MHz

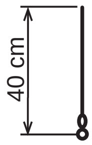
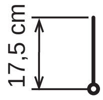
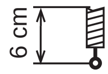
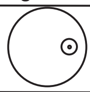
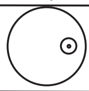
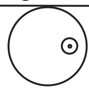
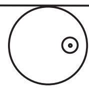
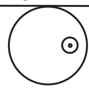
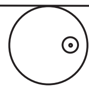
Figure 36: Shortened train antenna 2 m Band

Train Antenna
K 50 21 22
146 ... 174 MHz



Basic Principle

Figure 37: Comparable field strength measurements of antennas for portable radio sets

Frequency range: 400 - 470 MHz		antenna type					
Antenna		Gainflex antenna K 71 51 2.. 		λ/4 Stump antenna 		Miniflex Antenna K 71 39 2 	
Position		Portables at head height	Portables placed in breast pocket	Portables at head height	Portables placed in breast pocket	Portables at head height	Portables placed in breast pocket
Shape of the horizontal radiation pattern							
Field strength*	in the prefered direction	0 dB	0 dB	- 4 dB	- 6 dB	- 4 dB	- 6 dB
	in the shadowed direction	- 4 dB	-10 dB	- 12 dB	- 20 dB	- 13 dB	- 21 dB
	Average	2.5 dB	3.5 dB	- 7 dB	- 12.5 dB	- 7 dB	- 12.5 dB

* with reference to a decoupled λ/2 dipole without interference from the human body.