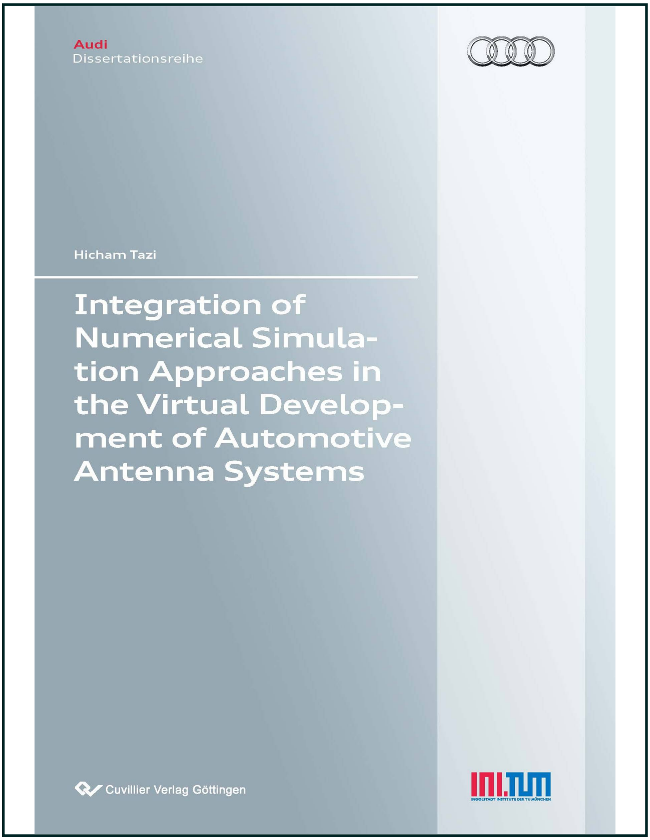
Hicham Tazi (Autor)

Integration of Numerical Simulation Approaches in the Virtual Development of Automotive Antenna Systems



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1 Introduction

Many automotive engineering fields have started to use simulations profiting from the continuously increasing performance of computers in terms of computation time and memory capacity [Konr 07; Reif 11]. Computational methods are used to develop complex systems with variation of different system parameters. Simulations can also be used in different stages of development in order to achieve the best possible system performance in very short development time. However, the benefit depends on the application time as shown in Figure 1.1

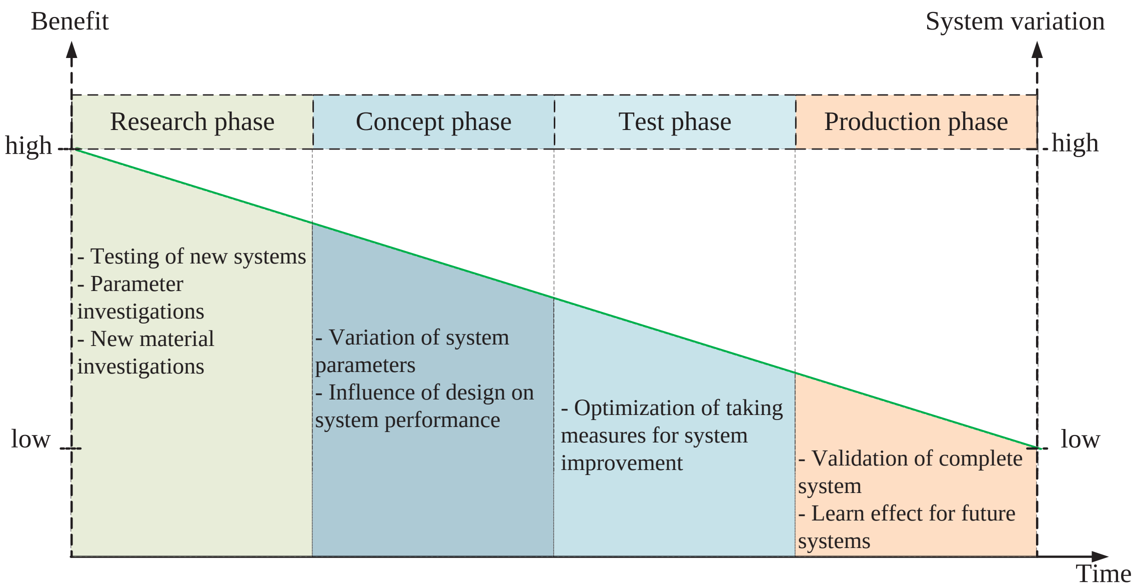

Figure 1.1: Benefit of the simulation.

[Frei 09]. When simulations are applied in the development process of automotive antenna systems, four different phases can be distinguished:

- *Research phase*: The highest benefit can be reached in this phase of development because the developer still has the possibility to change different system parameters to reach the best result. In addition, the developer has the opportunity to test completely new systems and new concepts to analyze their usability. For example, it is possible to evaluate new antenna positioning concepts in cars. The results obtained could be considered for new antenna system concepts.

- *Concept phase*: Usually, geometries of the system are already defined in this phase. The developer still has the eventuality to look for the best position of the antenna layout in the car. More than one integration location should be available in case of geometry change.

- *Test phase*: During this stage, only a few alternatives are available for the developer to improve system quality. Nevertheless, he still has a powerful tool to ensure the development of the best optimized system by changing the antenna layout.

- *Production phase*: In this stage of development only an understanding of the system performance is feasible, and troubleshooting relating to EMC problems can be performed. The results achieved could be used for development and to improve the next system generation.

1.1 Automotive Antennas

The number of the radio services offered in the automotive field has increased in recent years [Reif 11]. A need to elate customers and to differ from low cost car manufacturers leads to the integration of more and more **R**adio **F**requency (**RF**) services in cars. Initially, the only RF service offered in cars were the **A**mplitude **M**odulation (**AM**) with antennas working in **L**ow/**M**edium **F**requency (**LF**/**MF**) and **F**requency **M**odulation (**FM**) radio [Wern 06; Schn 06]. Due to a revolution in RF services worldwide [Fuji 94], further services were integrated first in luxury cars and then in regular cars. Examples for this are the introduction of telephone and navigation systems in expensive cars in the mid 90s [Talt 01]. Today, a multitude of RF systems can be found in cars, for example central locking, Bluetooth systems and **T**ire **P**ressure **S**ystems (**TPS**) [Rabi 10]. Even for multimedia services, a wide choice is available for **T**ele**V**ision (**TV**) and radio. The differences in frequency ranges in each country have to be considered. Also, differences in the technology used, such as radio based on satellite transmission or broadcast terrestrially based on LF/MF especially in the USA and Canada, or radio based on **V**ery **H**igh **F**requency (**VHF**) as it is the case in large parts of Europe. Figure 1.2 shows the development of the number of the RF services offered in cars in recent years. The number of the antennas will still increase in the years ahead and in 2015 will include some new services like Car2Car and the new mobile technology - **L**ong **T**erm **E**volution (**LTE**)- [Saut 11]. More than 20 RF services will be available in cars in the coming few years. Even taking of antenna diversity into account with two or even three antennas for some of the services offered, the number of antennas in any car could surpass 30.

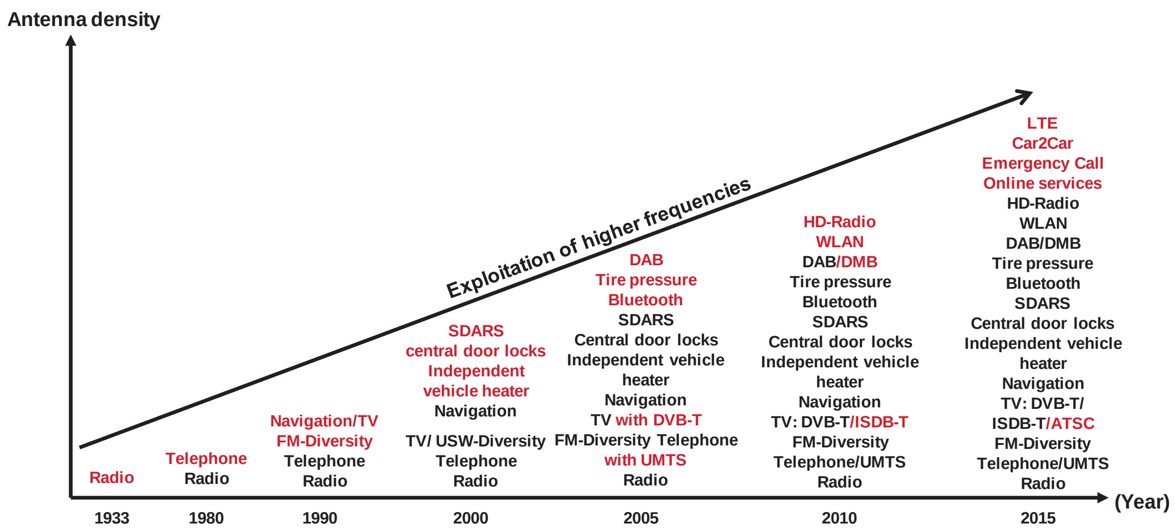

Figure 1.2: Automotive RF services evolution over the last decades.

The multiple antennas typically work in different frequency ranges. Figure 1.3 gives an overview of the diverse frequency ranges used for automotive applications. The various systems operate at frequencies starting at around 10 kHz for the keyless entry and keyless go systems and ranging up to some 10 GHz for radar systems. Several systems operate in the frequency range around 2 GHz such as the **U**niversal **M**obile **C**ommunication **S**ystem (**UMTS**), **G**lobal **S**ystem for **M**obile communication (**GSM**) [Saut 11], Bluetooth or **S**atellite **D**igital **R**adio **S**ervice (**SDARS**) [Wies 07b; Xue 04]. Radio services start with LW at 125 kHz and end at 2.4 GHz with SDARS. **D**igital **A**udio **B**roadcating (**DAB**) operating in frequency ranges starting at around 100 MHz for low band and ending at 1.9 GHz for the highest band will replace the widespread VHF system in the future [Luo 09]. The TV services operate in different bands starting at about 100 MHz for low band and ending at 1 GHz [Luo 09].
Figure 1.4 shows a typical car antenna system with the multiple positions of the antennas and the antenna amplifiers. The blue colored areas show potential positions of further antennas. Typically, several multimedia antennas, especially radio antennas operating in VHF frequency range and TV antennas, are mounted in the rear window. Side widows are often used for DAB antennas and TV.

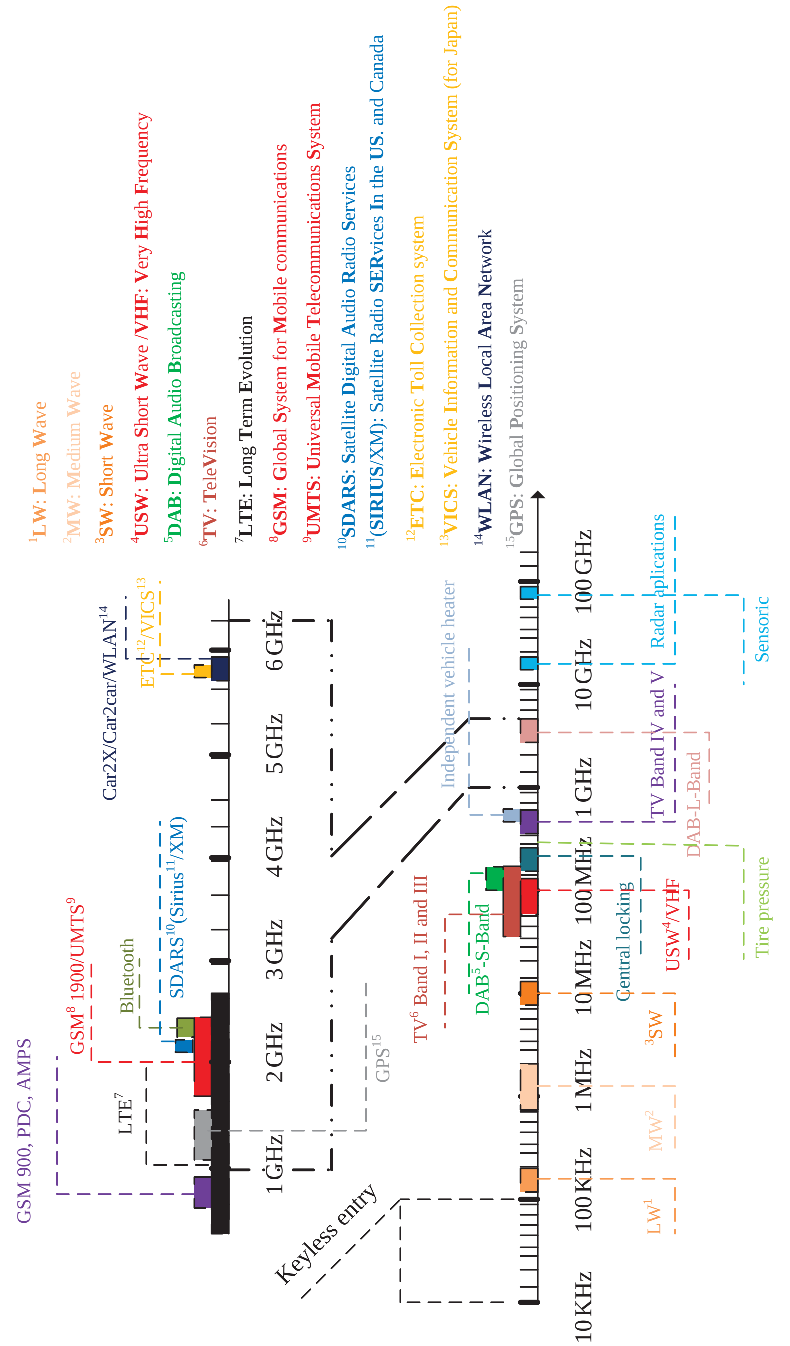

Figure 1.3: Operating frequency ranges of the multiple RF automotive services.

Sometimes an additional FM antenna is placed in the side window, for example as part of a diversity system [Kim 03]. Front windows are used often for radio and for TV in convertibles due to the small rear and side windows, which are retracted when the roof is down. Side mirrors are often used for **G**lobal **P**ositioning **S**ystem antennas **GPS** or UMTS antennas [Dode 10].

The inside mirror can also be used for this purpose. Further antennas can be hidden in the bumper as well as in the spoiler.

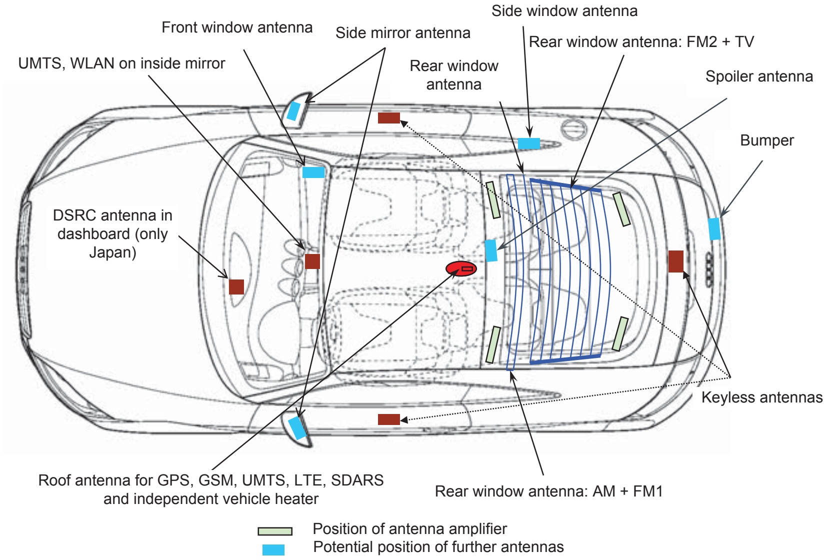

Figure 1.4: Typical car antenna system.

Keyless antennas are usually magnetic antennas, which are placed in the doors or in the luggage trunk. In limousines, several antennas operating in the high frequency range are located in the roof antenna assembly, such as GPS, GSM, UMTS and SDARS. Figure 1.5 shows a typical roof antenna system composed of two patches for GPS and SDARS and one **R**eceiving/**T**ransmitting (**Rx/Tx**) telephone antenna covering the GSM and UMTS frequency ranges.

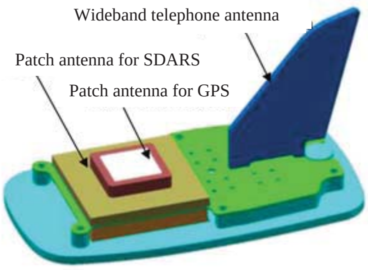

Figure 1.5: Typical roof antenna system.

Figure 1.6 shows a block diagram of a receiving system composed of a receiving antenna with a gain G_{Ant} and a **L**ow **N**oise **A**mplifier **(LNA)**, an RF cable and a receiver [Rabi 10]. The role of the LNA is to amplify the weak received signal with preferably minimal addition of noise and it is characterized by the gain G_{LNA} and a noise factor F_{LNA}. Both, the RF cable and the receiver are also characterized by the gain G_{Cable} and G_{rec} and a noise factor F_{Cable} and F_{rec}, respectively. The LNA is connected to an input matching circuit from the antenna side and to an output matching circuit from the receiver side [Matt 80]. This is very important to ensure minimal signal loss due to the mismatching between antenna or receiver and amplifier [Russ 03]. The signal is led through the RF cable to the receiver.

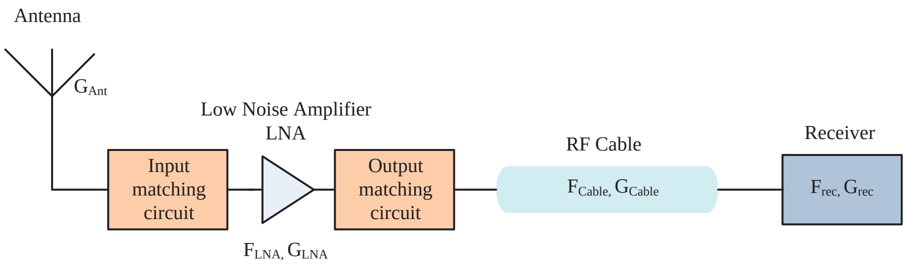

Figure 1.6: Block diagram of an automotive active antenna system.

Figure 1.7 shows a special case of Figure 1.6 [Rabi 10]. The difference between both graphs is the tuner representing a part of the car radio. The role of the tuner is to demodulate and decode the encrypted received signal.

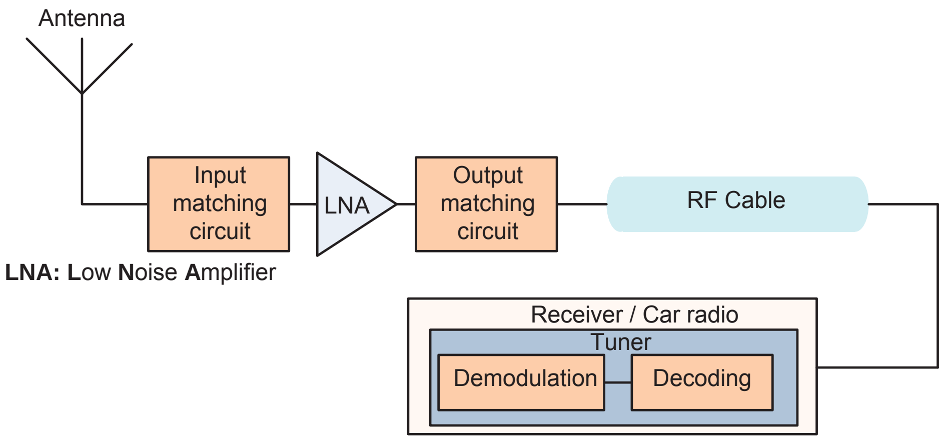

Figure 1.7: Block diagram of an automotive active multimedia antenna system.

1.2 Problem Definition

In the last three decades, the product portfolio of cars has increased rapidly. This is related to the fact that the number of the cars bought has increased strongly worldwide. Especially new markets like China and India have shown a huge demand for cars. Car manufacturers have to be flexible and to respond to all customers' tastes, taking into account the different cultural and socio-economical backgrounds of each market. The product range goes from small city cars through limousines up to **S**ports **U**tility **V**ehicles (**SUV**s). Besides that, customers have the possibility to configure their cars with different equipment depending on their needs and budget. Figure 1.8 shows how the number of different models has developed in recent years at AUDI AG. The trend is to offer cars to all niche markets. It can therefore be expected

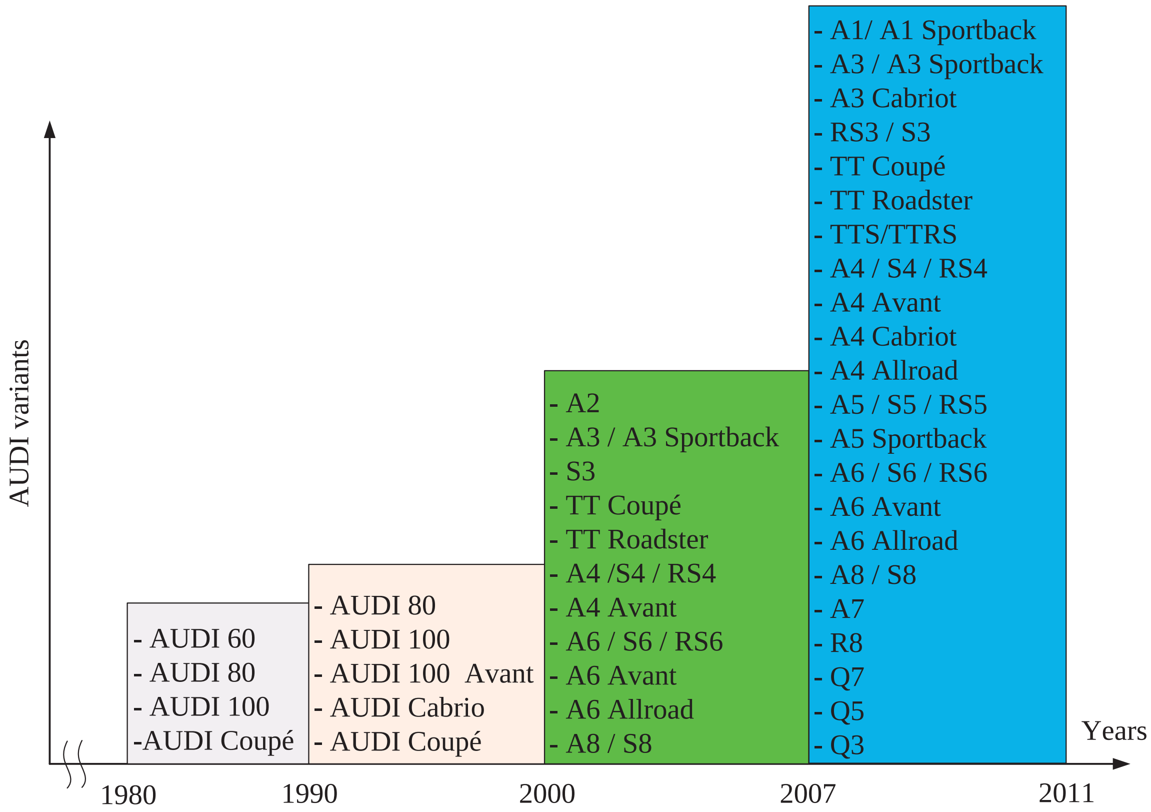

Figure 1.8: Evolution of AUDI cars in the last decades.

that the number of cars produced and of possible car configurations will increase in the years ahead. A great challenge for premium car manufacturers is to ensure the best possible quality, to be the first in the market to offer new technologies and to assure the robustness of these technologies for the car life cycle. An additional challenge is the shorter development cycle, which does often not surpass thirty-six months. Additionally, the car manufacturers try to economize resources in development such as costs related to the car prototypes, which represent an important part of the development budget of each car to stay competitive to the other car manufacturers. Thus, development time is decreasing significantly. Besides that, it is almost impossible to produce car prototypes for each potential car configuration. The application of these development challenges on the automotive antenna area makes it necessary to use new tools based on virtual system development in order to develop antennas without the need of prototypes with decreasing time consumption and without very expensive measurements. This would give the antenna engineers the possibility to get information about system quality at a very early stage of development. However, the accuracy of the results delivered from these virtual development tools must be ensured.

1.3 Objectives

The need to use simulation tools to develop new antenna systems was recognized some years ago. Different commercial 3D simulation tools can be used in the field of the antenna and electromagnetic compatibility (EMC) engineering for system development or as a part of the development process.
The objectives of the application of simulations in the field of antenna engineering are shown in Figure 1.9. The objectives of virtual automotive antenna development can be split into four categories:

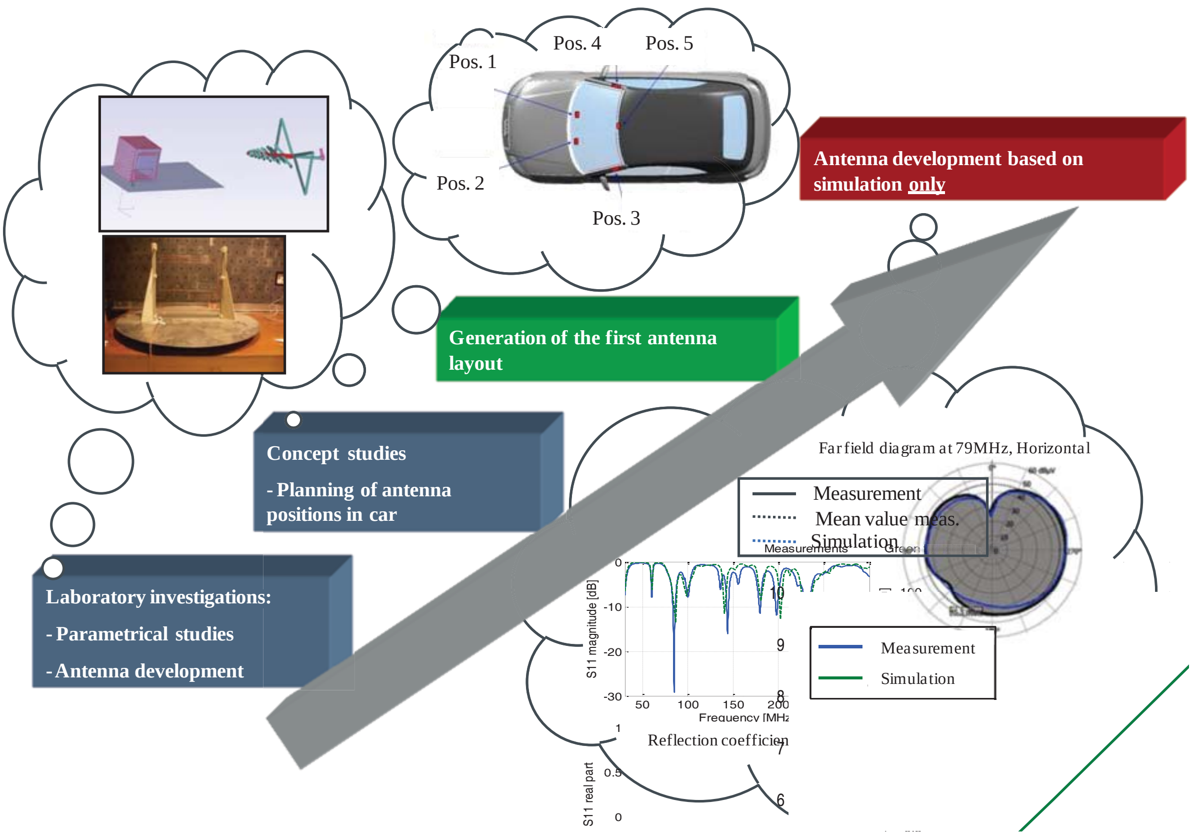

Figure 1.9: Objectives of integrating simulation into the development process.

- *Laboratory investigations*: In this development stage important investigations relating to completely new antenna concepts can be performed. Simulations can help to predict the antenna behaviour especially when parameter studies are to be realized. One example would be changing the electric parameters of the glass the antennas are printed on. This can happen if the glass supplier is changed or if new glass requirements are needed. Besides that, measurements of some simple laboratory constructions can be used to validate numerical computations of simulation methods or new features in the simulation tools.

- *Concept studies*: The antennas installed in cars have to be hidden. This is due to the strict design criteria of the car Styling Department. Consequently, new car concepts should be improved continuously to respond to all system requirements. Simulations can help engineers to find new positions in cars, where antennas could be mounted accordingly to the design criteria and system performance requirements.

- *Generation of the first antenna layout*: The development of antennas for all RF services is very laborious and time consuming. Utilizing simulation tools, it is much easier to realize many development loops. The first antenna layout can be designed in this way. However, further investigations based on measurements are still needed to validate the antenna behaviour and for fine tuning of the antenna structure.

- *Antenna development based on simulation only:* The most important goal of simulation is to be able to realize the complete development process based on simulation only without the need to verify the simulation results with measurements. This would be possible if it could be proven that simulations have been validated for all RF services and in all frequency ranges of interest. This will be achieved in the near future.

2 Antenna Characterization

In antenna engineering literature [Bala 05; Vola 07; Orfa 04; Ante 09], one can find many parameters, which are used for the characterization of antennas. Different antenna parameters are dependent on each other. In this chapter, an overview of the most important parameters in antenna engineering is given.
For a better understanding of antenna systems, equivalent circuits are used [Voge 04]. First, it can be distinguished between an equivalent circuit of an emitting system shown on the left side of Figure 2.1 and an equivalent circuit of the receiving system represented on the right side of the figure [Wies 07a; Voge 04].

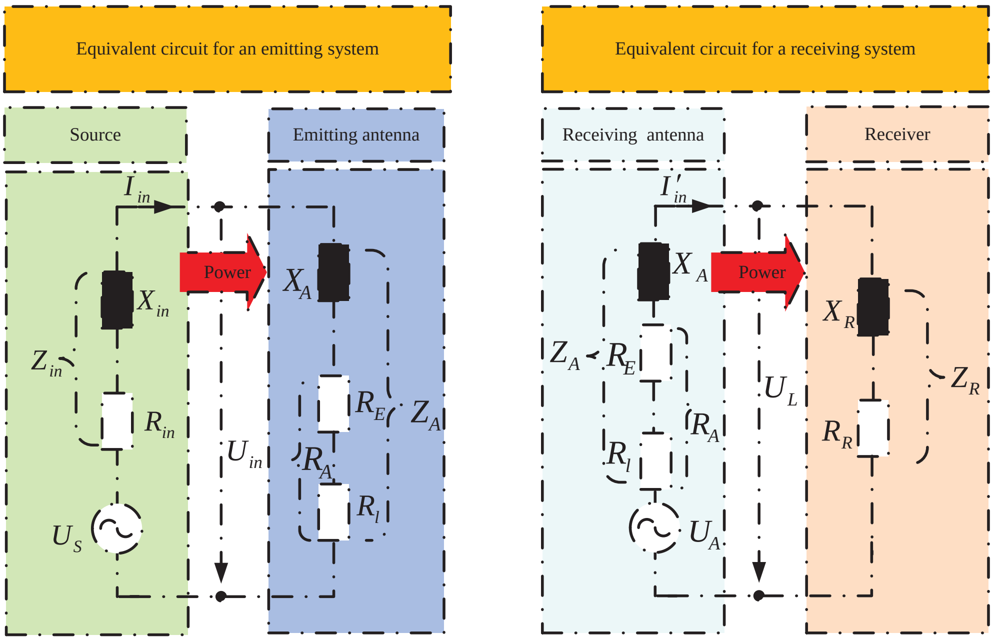

Figure 2.1: Equivalent model of an emitting and a receiving systems.

The equivalent circuit of the emitting system is composed of a source part with a source voltage U_S and a complex source impedance Z_{in}. The real part of the impedance is represented by the resistance R_{in} and the imaginary part is represented by the reactance X_{in}. Consequently, a resulting electric current I_{in} in the emitting part of the equivalent circuit can be calculated from the source voltage and the complex input impedance Z_A of the antenna. The antenna radiation power P_r can be calculated from the current I_{in} and the voltage U_{in} measured at the source ports including the impedance Z_{in}. The current I_{in} and the voltage U_{in} at the antenna terminals are given by

$$I_{in} = \frac{U_S}{Z_{in} + Z_A} \tag{2.1}$$

and

$$U_{in} = \frac{U_S\ Z_A}{Z_{in} + Z_A} \,. \tag{2.2}$$

The blue highlighted part of the emitting system's equivalent circuit consists of the complex antenna impedance Z_A that can be split in an Ohmic part R_A and a reactance part X_A. R_A represents the sum of the antenna Ohmic losses R_l and a radiation resistance R_E.
The equivalent circuit of the receiving system is, like the emitting system, composed of a receiving antenna part and a receiver. The source voltage in the receiving antenna is represented by U_A. The receiving antenna is described in addition to the source voltage U_A with the impedance Z_A composed of X_A and the Ohmic part R_A. The receiver power can be calculated from the current I'_{in} and the voltage U_L measured at the receiver source port. The receiver part is given by the complex load impedance Z_R, which can be split in an Ohmic part R_R and a reactance part X_R.

2.1 Scattering Parameters

Figure 2.2 shows an electric circuit composed of a voltage source U_S, a source impedance Z_S and a two-port network connected to infinitesimal line sections with the wave impedance Z_0. The network is terminated by the load impedance Z_L.

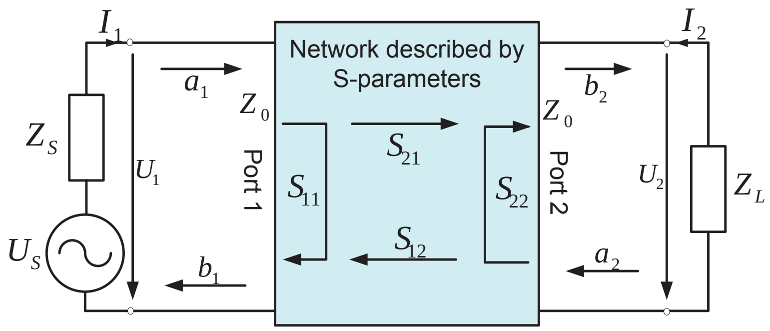

Figure 2.2: S-parameter network.

The resulting current at the input terminals of the two-port network is I_1. The voltage at port 1 is characterized by U_1. Similarly, the voltage at port 2 is characterized by U_2. Certain parts of the source energy is reflected at port 1 of the network. The rest of the energy will be transmitted to port 2 if the two port is lossless. In order to introduce the *scattering parameters*, also called S-parameters, two new entities should be introduced. The first one is the incoming wave a and the second is the reflected wave b. The indices 1 and 2 represent the ports 1 and 2, respectively [Wies 07a; Kark 04]. The parameters of the S matrix describing the two-port network are calculated based on the normalized wave parameters a and b:

$$b_1 = S_{11}\ a_1 + S_{12}\ a_2 \tag{2.3}$$

and

$$b_2 = S_{21}\ a_1 + S_{22}\ a_2\,. \tag{2.4}$$

The four S-parameters describing the relation between incoming and reflected waves are formulated by

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0},\quad S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0},\quad S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0},\quad S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}. \tag{2.5}$$

The incoming wave a_1 at port 1 can be calculated according to

$$a_1 = \frac{U_1 + I_1\ Z_0}{2\ \sqrt{Z_0}}\,. \tag{2.6}$$

Similar to equation (2.6), the incoming wave a_2 at port 2 can be described by

$$a_2 = \frac{U_2 + I_2\ Z_0}{2\ \sqrt{Z_0}}\,. \tag{2.7}$$

The reflected wave b_1 at port 1 can be calculated according to

$$b_1 = \frac{U_1 - I_1\ Z_0}{2\ \sqrt{Z_0}}\,. \tag{2.8}$$

Similar to equation (2.8), the reflected wave b_2 at port 2 can be described by

$$b_2 = \frac{U_2 - I_2\ Z_0}{2\ \sqrt{Z_0}}\,. \tag{2.9}$$

The load impedance *return loss* parameter r_L is defined as

$$r_L = \frac{\frac{Z_L}{Z_0} - 1}{\frac{Z_L}{Z_0} + 1}\,. \tag{2.10}$$

Similarly, the source return loss parameter r_S is given by

$$r_S = \frac{\frac{Z_S}{Z_0} - 1}{\frac{Z_S}{Z_0} + 1}\,. \tag{2.11}$$

The quotient of the two voltages U_1 and U_2 is given by

$$\frac{U_2}{U_1} = \frac{S_{21}(1 + r_L)}{(1 - S_{22}\ r_L)(1 + r_1)} \tag{2.12}$$

where the return loss parameter r_1 at port 1 is defined as

$$r_1 = S_{11} + \frac{S_{12}\ S_{21}\ r_L}{1 - S_{22}\ r_L} \tag{2.13}$$

and the return loss parameter r_2 at port 2 is defined as

$$r_2 = S_{22} + \frac{S_{12}\ S_{21}\ r_S}{1 - S_{11}\ r_S}\,. \tag{2.14}$$

The *transducer power gain* of the complete system can be calculated according to

$$g_T = \frac{P_L}{P_{S\max}} = \frac{|S_{21}|(1-|r_S|^2)(1-|r_L|^2)}{|(1-S_{11}\ r_S)(1-S_{22}\ r_L) - S_{12}\ S_{21}\ r_L\ r_S|^2} \tag{2.15}$$

where $P_{S\max}$ is the maximal available source power and P_L is the absorbed power from the load impedance Z_L.

In the field of antenna engineering, the antenna return loss parameter r_{ant} delivers information about the part of the energy, which can be emitted or received from the antenna. In case of one port networks, this parameter is also called the *reflection factor* or S_{11}*-parameter* [Voge 04; Mill 05].

In antenna development, engineers first evaluate this parameter during the development process to obtain the best possible emitting or receiving antenna in the frequency range of interest.

The antenna *matching* means that the *antenna impedance* is equal to the impedance of the RF cable (transmission line) Z_{TL} as well as to the impedance of the connected transmitter and receiver depending on the antenna type (Z_L). In this case, reflections do not occur. A part of the power is transformed to thermal power due to the antenna's Ohmic part R_A and the rest of the power is radiated or received, respectively. Antenna systems have often 50 Ω or 75 Ω matching impedance. It is advisable that all antenna system parts have the same impedance or to use matching circuits to avoid impedance mismatch losses. The input impedance Z_S and output impedance Z_L are typically equal to the transmission line impedance Z_{TL}:

$$Z_S = Z_L = Z_{TL}\,. \tag{2.16}$$

In this case the antenna system is perfectly matched and the resulting return loss is equal to 0.

Related to the antenna return loss parameter r_{ant}, the ***V**oltage **S**tanding **W**ave **R**atio* (**VSWR**) gives the maximum standing wave amplitude in a relationship to the minimum standing wave amplitude. An ideally matched system has a VSWR value of 1 : 1. This parameter is often used in power electronics to define the breakdown electric field of power transistors [Voge 04]. The VSWR is calculated according to

$$VSWR = \frac{1+|r_{ant}|}{1-|r_{ant}|}\,. \tag{2.17}$$

2.2 Far Field Characteristics

Far field characterizes a region, where the magnetic field component $\vec{H}$ of an electromagnetic wave is in phase with the electrical component $\vec{E}$ and where both components are perpendicular to the wave direction of propagation [Bala 05]. However, in literature [Capp 01; Gave 94], depending on the field of RF engineering, different definitions determining the distance to the source, where the far field region starts can be found. For example, in the EMC field, the commonly used definition for determining the distance d to the antenna being tested, where the antenna is assumed to be located in far field [Capp 01], is

$$d \geq \frac{5\lambda}{2\pi} \tag{2.18}$$

where λ is the wavelength. For precision antennas [Whee 75; Whee 47], the distance d is calculated depending on the largest dimension D [Capp 01] with

$$d \geq \frac{50D^2}{\lambda}\,. \tag{2.19}$$

The far field region is commonly defined in automotive antenna development at distances d from the source according to

$$d \geq 2D^2/\lambda \tag{2.20}$$

with

$$\lambda = \frac{c_0}{f} \tag{2.21}$$

where c_0 is the speed of light in medium and f is the operating frequency. The electric field $\vec{E}$ and the magnetic field $\vec{H}$ are perpendicular to the wave propagation vector in the far field. $\vec{E}$ and $\vec{H}$ are combined with the wave impedance Z_{F_0} according to

$$Z_{F_0} = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi\ \Omega \approx 377\ \Omega\,. \tag{2.22}$$

In order to determine the far field region, the wave number k_0 is used and is equal to $\frac{2\pi}{\lambda_0}$. The wavelength at the frequency f_0 is λ_0 where

$$k_0 d \gg 1\,. \tag{2.23}$$

2.3 Radiation Pattern of an Automotive Antenna Mounted on the Car Roof

Antenna evaluation necessitates investigation of antenna behaviour in all spatial directions. The information delivered by the return loss parameter is very important but still not enough to evaluate antennas in the complete space. For this purpose, a further function, which delivers a statement about the three dimensional antenna behaviour is used. This function is called the *antenna radiation pattern* and is calculated according to

$$\vec{C}(\vartheta, \varphi) = \left. \frac{\vec{E}(r, \vartheta, \varphi)\, e^{j\beta_0 r}}{\left| \vec{E}(r, \vartheta, \varphi)\, e^{j\beta_0 r} \right|_{\max}} \right|_{r=const \to \infty} = C_\vartheta(\vartheta, \varphi)\, \vec{e}_\vartheta + C_\varphi(\vartheta, \varphi)\, \vec{e}_\varphi \tag{2.24}$$

where φ is the azimuth angle and ϑ is the elevation angle. It can be seen that the resulting function can be split into two components C_ϑ and C_φ in the spherical coordinate system illustrated in Figure 2.3.

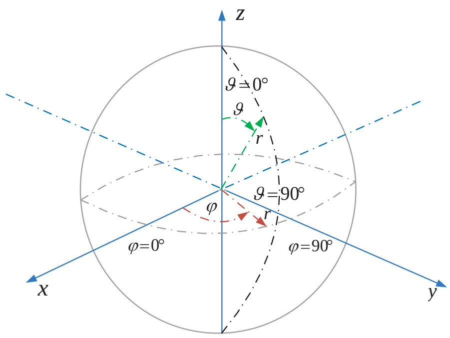

Figure 2.3: Spherical coordinate system.

The separation of these components C_ϑ and C_φ gives important information about the received or emitted signal, called *polarization* [Wies 07a; Kark 04].

There are various antenna types, which are dependent on the relationship between ϑ and φ components such as *linearly*, *circularly* and *elliptically polarized* antennas.
The investigated antenna in Figure 2.4 is mounted on the car roof. Two different axes are considered and two ordinary representations of the antenna radiation pattern types for automotive antennas are depicted in the figure. The first one, using the left green axis, delivers values in [dB] for normalized pattern in the desired elevation and azimuth angle. The same information can be read out in [dBi] by using the second representation on the right red axis. This will be annotated in the next sections.

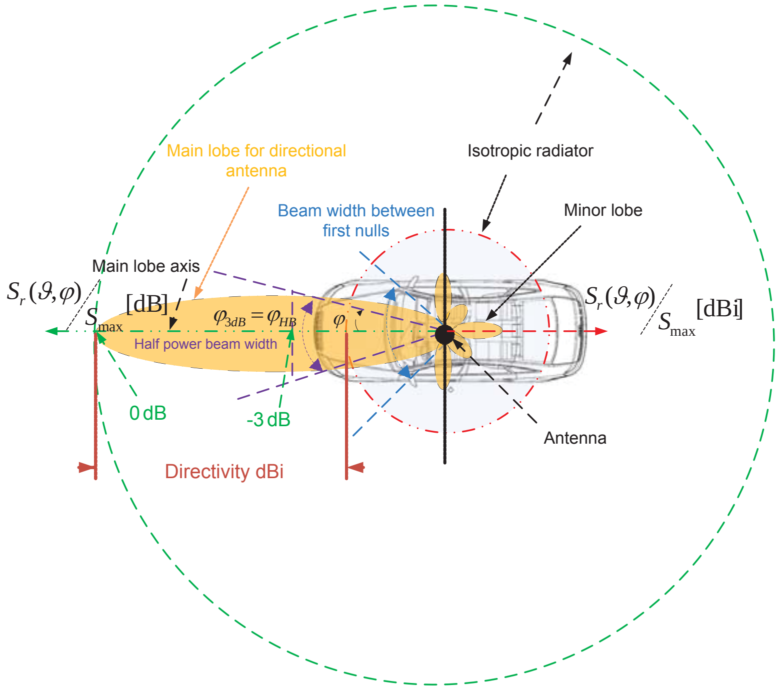

Figure 2.4: Definition of the radiation pattern for $\vartheta = 90°$.

Further information can be extracted from the presented figure like the radiation pattern *lobes,* where the antenna shows a good reception or emitting behaviour. It can be distinguished between *minor* and *main lobes.* Furthermore, we can define the *half power beam width* of the antenna pattern expressed in degrees, which gives the angle between the half power (-3 dB) points of the main lobe referenced to the effective maximum radiated power of the main lobe. The antenna gain and directivity can also be extracted from the figure. The antenna gain value corresponds to the effective maximum radiated power density of the main lobe and can be given amongst others in [dB] or in [dBi].
To ensure the best possible antenna behaviour, the antenna system should have an acceptable return loss factor in the frequency range of interest. Usually engineers use -8 dB or -10 dB thresholds to define frequency ranges, where the investigated antennas deliver an acceptable return loss. However, in the automotive field, it is quite difficult to attain these values because of the very strict antenna styling criteria presented in Section 2.6. Antenna developers try to develop directional antennas depending on the antenna service of interest to ensure optimal reception or emission behaviour of the antenna system. Figure 2.5 shows three examples of different antenna radiation patterns depending on the different services. For example, for Car2Car or Car2infrastructure communications, the antenna radiation pattern should be optimized at elevations close to 90°. That means, the main lobes have to be oriented to the direction of the potential communication participants, in this case cars or infrastructure. However, it is almost impossible to avoid some minor lobes in undesirable directions.

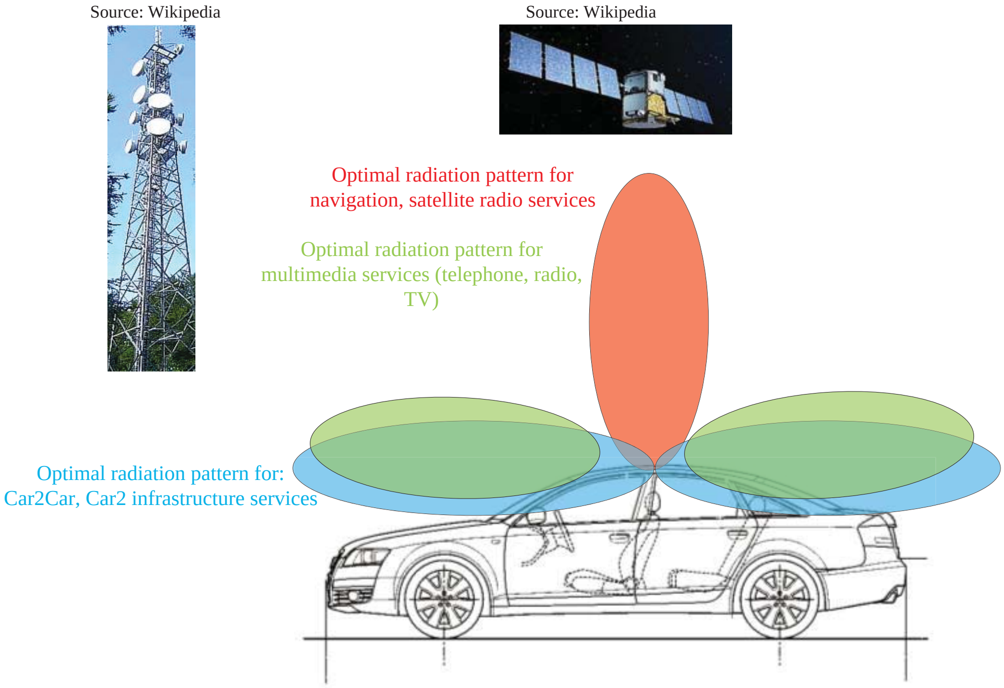

Figure 2.5: Optimal radiation patterns for different RF automotive services.

An ideal transmitting antenna is an antenna that can radiate the complete available power at its terminal without losses. In reality, a part of the available power will be transformed into thermal energy due to Ohmic and dielectric losses. Consequently, the effective radiated power P_R should be added to the dissipative power P_D to get the input power P_{in} according to equation (2.27). The *antenna efficiency* η is a parameter that describes the relationship between the input power P_{in} and the dissipative power P_D:

$$P_D = P_{in} - P_R = (1 - \eta)\, P_{in}\,. \tag{2.25}$$

Antenna efficiency can also be formulated with the *radiation resistance* R_E and the antenna Ohmic loss R_l according to

$$\eta = \frac{R_E}{R_E + R_l} = \frac{P_R}{P_{in}}\,. \tag{2.26}$$

The radiation resistance R_E in the equivalent circuit in Figure 2.1 transforms the available effective power P_A in radiation power P_R where

$$P_A = P_{in} - P_D = P_R \tag{2.27}$$

The dimension of the receiving or transmitting antenna area is important for the amount of the energy that can be radiated or received by the antenna. The parameter that describes this area is called the *antenna effective area* A_{eff} and is usually given in [m^2] [Ante 09]. It gives an equivalent area, which is orientated normally to the path of reception. The source of the received signal is given in form of an incident electromagnetic wave with the radial radiation power density S_r according to

$$P_R = S_r\ A_{eff}\,. \tag{2.28}$$

The effective area also describes the receiving power, which an antenna can take out of the total incoming power of a certain electromagnetic power density. The effective aperture is normally smaller than the geometrical aperture and is related to the wavelength λ and the antenna gain G according to

$$A_{eff} = G\ \frac{\lambda^2}{4\pi}\,. \tag{2.29}$$

The pointing vector $\vec{S}$ is a vector that describes the radiation power flux [Kurz 08]. To determine $\vec{S}$ both the electric field $\vec{E}$ and the complex conjugate magnetic field $\vec{H}^*$ are needed according to

$$\vec{S} = \frac{1}{2}(\vec{E} \times \vec{H}^*)\,. \tag{2.30}$$

The radiation power density for an isotropic radiator can be calculated with

$$|\vec{S}| = S_i = \frac{P_R}{4\pi r^2}\,. \tag{2.31}$$

The *antenna directivity* is the quotient of the maximal radiation power density in a given direction of the antenna to the radiation power density of an isotropic radiator with the same radiating power [Wies 07a; Kark 04] according to

$$D_i = \frac{S_{r\ max}}{S_i} = 4\pi r^2 \frac{S_{r\ max}}{P_R}\,. \tag{2.32}$$

The *antenna gain* usually refers to the direction of the maximum radiation and is given as the quotient of the power required at the input of an ideal reference antenna without losses to the power supplied to the input of the real antenna in a given direction to produce the same field at the same distance [Wies 07a]. In the standards determined from the IEEE, if a direction is not fixed then the gain has to be given for the direction of the maximum radiation intensity. The antenna gain is often be expressed in [dBi], where the reference antenna is an isotropic lossless antenna. The gain can be expressed in [dBd] in cases, where a dipole antenna is used as reference antenna. Equation (2.32) makes it possible to calculate the gain including the Ohmic losses as a ratio of the maximum radiated power density in a certain direction to the average radiated power density of a spherical isotropic radiator with an input power equal to that of the antenna of interest. It is important to note that the gain does not give an amplification factor of the antenna. Gain gives a comparison of the power density of the antenna in a certain direction with the power density of an other reference radiator. The power, which is concentrated from the antenna in a certain direction is removed from other directions.

Normally, losses due to impedance and polarization mismatch are not accounted for the calculated antenna gain. The parameter that takes into account the impedance mismatch is the *realized gain* $G_{realized}$, also called *practical gain.* This parameter combines the information of the return loss parameter and the normal antenna gain according to

$$G_{realized} = \left(1 - |S_{11}|^2\right) G\,. \tag{2.33}$$

Another parameter, which is quite often used is the ***A**ntenna **F**actor* (**AF**) [Joba 04]. It represents the ratio of the incident electric field E and the voltage V. This parameter can also be described with the wavelength and the realized gain for a 50Ω system [Bred 07] according to

$$AF = \frac{E}{U} = \frac{9.73}{\lambda\sqrt{G_{realized}}}\,. \tag{2.34}$$

The ***E**quivalent **I**sotropic **R**adiated **P**ower* (**EIRP**) is the product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna (absolute or isotropic gain):

$$EIRP = G\ P_{in}\,. \tag{2.35}$$

2.4 Improvement of the Signal Reception Quality

A communication system is composed of a transmitting and a receiving antenna, which are orientated towards each other to get the maximal gain in the direction of the partner. In regular reception mode, the propagation path of the signal between the communication partners is the line of sight. Both antenna systems are defined at a certain position. The maximal attainable signal transmission efficiency is calculated using *Friis Transmission formula* [Voge 04] according to

$$\frac{P_R}{P_{trans}} = \frac{A_{effrec}A_{efftrans}}{r^2\lambda^2} = \frac{G_R G_{trans}}{\left(4\pi r/_{\lambda}\right)^2}\,. \tag{2.36}$$

The ratio of the receiving power P_R to the transmitted power P_{trans} depends on the wavelength λ, the distance between the two antennas r, the effective receiving antenna aperture A_{effrec} and the transmitting antenna aperture $A_{efftrans}$. The transmission formula can also be described using the gain of both receiving antenna G_R and transmitting antenna G_{trans}.

2.4.1 Multipath and Doppler Effect

In reality, antennas are often not fixed at a certain position. The direction of the incoming signal is usually unpredictable. Automotive antennas are especially challenging due to the fact that the car can be driven at different places like in cities, forests, highways or villages. Figure 2.6 illustrates an example of different signal propagation paths. When an **E**lectro**M**agnetic (**EM**) signal hits an object, different phenomena can occur [Povh 11; Kurz 08]: