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Technological Trends of Antennas in Cars

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1. Introduction

Antennas have become a commonplace in automotive applications. These are broadly classified as wire and patch antennas which are used in cars for inter-vehicle communication. Besides its use in the automotive sector, these antennas are also used as arrays in the aviation sector e.g. fuselage integrated microstrip phased antenna arrays. These wire and patch antennas can either be modeled analytically e.g. using the Green's function, derived from Eigen functions or numerically using various approaches e.g. MoM, FDTD, FEM etc. Besides the common usage of wire and patch antennas of various shapes, integrated antennas are also widely used. Antennas starting from the traditional monopole antenna followed by patch antennas on car roof tops and mesh antennas on car windscreens will be discussed in this chapter.

2. Figures of merit

This section lists and explains some salient figures of merit of antennas. The input impedance and the radiated fields (near and far) are termed as the primary figures of merit since they form the basis on which other secondary figures of merit such as VSWR, bandwidth, and directivity etc. are determined. Section 2.1 elaborates on the primary figures of merit viz. input impedance. Section 2.2 explains some secondary figures of merit which are obtained from the input impedance. The theory of how the effective radiating power is calculated from the far-field gain patterns is explained in section 2.3.

2.1 Input impedance

The input impedance Z_{in} is defined as the impedance presented by an antenna at its input terminals a – b, as shown in Fig. 1. In other words, the input impedance of an antenna is the ratio of the voltage to the current or the ratio of the electric to the magnetic field measured at the input terminals (feeding point). The input impedance of an antenna is expressed in terms of its real and imaginary parts as

$$Z_{in} = R_{in} + jX_{in},\qquad(1)$$

where Z_{in} is the antenna impedance at the input terminals a – b,

R_{in} is the antenna resistance at the input terminals a – b,

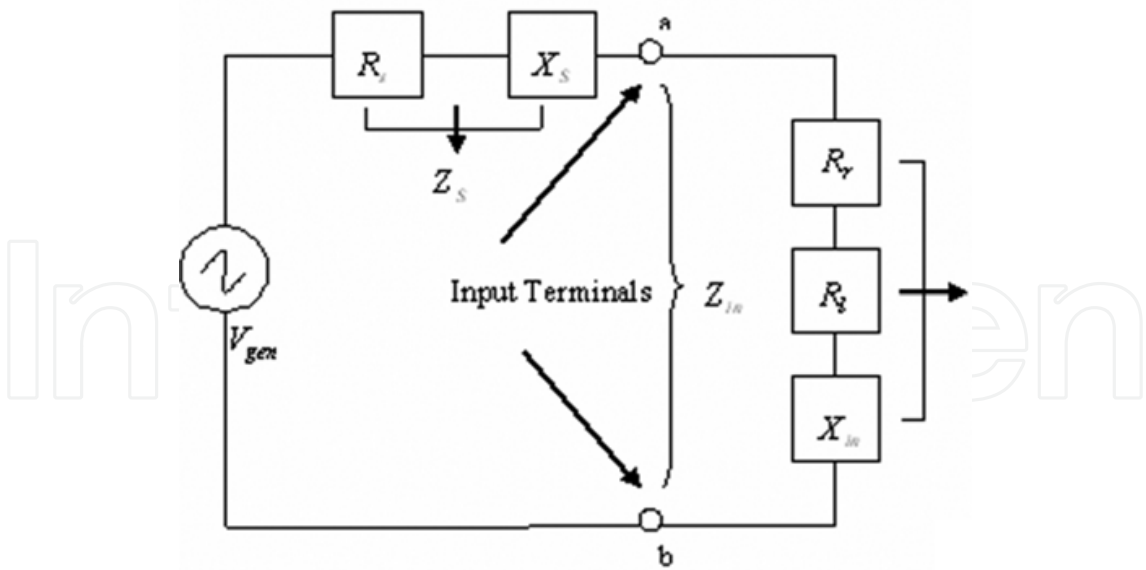and X_{in} is the antenna reactance at the input terminals a – b.

Fig. 1. Block diagram of a transmitting antenna

The imaginary part X_{in} of the input impedance represents the power stored in the near field region of the antenna. The resistive part R_{in} of the input impedance consists of two components, the radiation resistance R_r and the loss resistance R_l. The power associated with the radiation resistance R_r is the power actually radiated by the antenna and the loss resistance R_l represents the dielectric or conducting losses resulting in power dissipation.

The input impedance is of great importance in wire and patch antennas and is therefore discussed here. The input impedance is used as a foreboding of unwanted radiation for EMC related aspects especially in the automotive sector. However, in the case of antennas, the input impedance with the source impedance is used as an intermediate parameter for determining the *S11* parameter, return loss, Voltage Standing Wave Ratio (*VSWR)*, and bandwidth. This is explained in more detail in section 2.2, where the matching characteristics of a patch antenna and its bandwidth are explained.

2.2 Reflection coefficient / S11 / VSWR / return loss

Antennas are commonly used in various type of smart antenna systems. In order for any given antenna to operate efficiently, the maximum transfer of power must take place between the feeding system and the antenna. Maximum power transfer can take place only when the input impedance of the antenna (Z_{in}) is matched to that of the feeding source impedance (Z_S). According to the maximum power transfer theorem, maximum power can be transferred only if the impedance of the source is a complex conjugate of the impedance of the antenna under consideration and vice-versa. If this condition for matching is not satisfied, then some of the power may be reflected back. This is expressed as

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|},\tag{2}$$

with

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_{in} - Z_S}{Z_{in} + Z_S},\tag{3}$$

where Γ is called the reflection coefficient, V_r is the amplitude of the reflected wave, and V_i is the amplitude of the incident wave. The *VSWR* is basically a measure of the impedance mismatch between the feeding system and the antenna. The higher the *VSWR*, the greater is the mismatch. The minimum possible value of *VSWR* is unity and this corresponds to a perfect match. The return losses (*RL*), obtained from equations (2) and (3), indicate the amount of power that is transferred to the load or the amount of power reflected back. In the case of a microstrip-line-fed antenna, where the source and the transmission line characteristic impedance or the transmission line and the antenna edge impedance do not match, waves are reflected. The superposition of the incident and reflected waves leads to the formation of standing waves. Hence the *RL* is a parameter similar to the *VSWR* to indicate how well the matching is between the feeding system, the transmission lines, and the antenna. The *RL* is

$$RL = -20\log|\Gamma| \ (dB). \tag{4}$$

To obtain perfect matching between the feeding system and the antenna, $\Gamma = 0$ is required and therefore, from equation (4), RL = infinity. In such a case no power is reflected back. Similarly at $\Gamma = 1$, RL = 0 dB, implies that all incident power is reflected. For practical applications, a *VSWR* of 2 is acceptable and this corresponds to a return loss of 9.54 dB. Usually return losses ranging from 10 dB to 12 dB are acceptable.

The bandwidth could be defined in terms of its Voltage Standing Wave Ratio (*VSWR*) or input impedance variation with frequency. The *VSWR* or impedance bandwidth of an antenna is defined as the frequency range over which it is matched with that of the feed line within specified limits. The *BW* of an antenna is inversely proportional to its quality factor Q and is expressed as

$$BW = \frac{VSWR - 1}{Q\sqrt{VSWR}} \ . \tag{5}$$

The bandwidth is usually specified as the frequency range over which the *VSWR* is less than 2 (which corresponds to a return loss of 9.5 dB or 11 % reflected power). Sometimes for stringent applications, the *VSWR* requirement is specified to be less than 1.5 (which corresponds to a return loss of 14 dB or 4 % reflected power). In the case of a patch antenna, the input impedance with the source impedance is used as an intermediate parameter for determining the *S11* parameter (a measure of the reflection coefficient Γ), return loss, Voltage Standing Wave Ratio (*VSWR*), and bandwidth. The return loss is expressed in dB in terms of *S11* as the negation of the return loss. The bandwidth can also be defined in terms of the antenna's radiation parameters such as gain, half power beam width, and side-lobe levels within specified limits.

2.3 Effective radiating power

For every other antenna, the directivity is defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity U_0 averaged over all directions. If the direction is not specified, the direction of maximum radiation intensity is implied. Hence mathematically the directivity is

$$D_0 = \frac{U_{\max}}{U_o} = \frac{4\pi U_{\max}}{P_{rad}} \ , \tag{6}$$

where $U_{\max}$, P_{rad} are the maximum radiation intensity and total radiated power, expressed in Watts / solid angle and Watts respectively.

The antenna gain is directly associated with the directivity of an antenna and is therefore associated with only the main lobe. The term K is the radiation efficiency expressed in terms of the conduction efficiency K_c and dielectric efficiency K_d as

$$K = K_c K_d , \tag{7}$$

Gain and directivity extraction are based on the source power. Let us assume that P_t is the source power and P_v are some losses in the structure (e.g. dielectric losses), then a power P_t $P_r = P_t - P_v$ will be radiated. The directivity (as compared to an isotropic point source) is then defined as

$$D = 4\pi R2 * (S_s/P_r), \tag{8}$$

where $S_s = (1/2)(|E_\vartheta|2 + |E_\phi|2 / Z_{F0})$

Z_{F0} denotes the wave impedance of the surrounding medium.

From the equation the gain is extracted from the directivity as

$$G = K \cdot D , \tag{9}$$

where G is the gain and D is the directivity. (For an antenna with 100% efficiency, $K = 1$.)

The far field gain is determined from the electric far-field components E_θ and E_ϕ and the source power. The electric field components E_θ and E_ϕ are calculated from the surface electric current densities. The effective radiating power is extracted from the gain by removing the effect of the losses in the form of metallic or /and dielectric losses.

$$Effective\ Radiating\ Power = Gain - Power\ loss \tag{10}$$

3. Numerical approaches for determining figures of merit

The numerical analysis e.g. MoM can be carried out either in the spectral or in the time domain. A patch antenna comprising metallic and dielectric parts with a feeding pin or microstrip line is solved using the traditional MoM by decomposing the antenna as

- discretized surface parts
- wire parts
- attachment node of the wire to the surface element.

Metallic surfaces contain different basis functions as shown in Fig. 2. The MoM uses surface currents to model a patch antenna. In the case of ideal conductors, the boundary condition of $E_{tan} = 0$ is applied.

The most commonly used basis functions for line currents through wires are stair case functions, triangular basis functions, or sine functions. The MoM code uses triangular basis functions. In contrast to wires, two-dimensional basis functions are employed for surfaces. The current density vectors have two-directional components along the surface. Figure 2 shows the overlapping of so-called hat functions on triangular patches. An integral equation is formulated for the unknown currents on the microstrip patches, the feeding wire / feeding transmission line, and their images with respect to the ground plane. The integral equations are transformed into algebraic equations that can be easily solved using a

computer. This method takes into account the fringing fields outside the physical boundary of the two-dimensional patch, thus providing a more exact solution. The coupling impedances Z_{ik} are computed in accordance with the electric field integral equation.
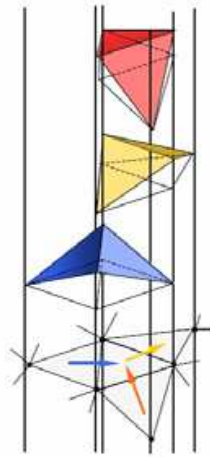

Fig. 2. Hat basis functions on discretised triangular elements on patches

The MoM uses either surface-current layers or volume polarization to model the dielectric slab. In the case of dielectric materials we have to consider 2 boundary conditions

$$\vec{n} \times \vec{E}_1 = \vec{n} \times \vec{E}_2 \ , \tag{11}$$

$$\vec{n} \times \vec{H}_1 = \vec{n} \times \vec{H}_2 \ . \tag{12}$$

The traditional full-model applied in the MoM code uses a surface-current approach which is categorised as

- double electric current layer approach or
- single magnetic and electric current layer approach.

4. Various type of antennas

Various type of antennas are described here. Antennas e.g. the conventional monopole, which is of historical importance is still widely used due to its simplicity in construction. The following sections deal with technological trends with respect to the monopole family of antennas as well as patch antennas.

4.1 Wire antennas (monopole antenna)

Monopole antennas are commonly used in automotive applications where range is important. A brief description of how a monopole antenna is characterised will be illustrated e.g. a monopole antenna is suitably placed on a car and then meshed effectively for numerical simulation. These antennas are also very easy to design and tune simply by slightly varying the length. It is assumed the antenna is a quarter wavelength long, which is typical of monopole antennas in the UHF band. The radiation characteristics are linearly polarized, either horizontally or vertically, depending on antenna orientation. Radiation resistance of a quarter wave monopole is approximately 37Ω, and does not vary much with presence or absence of ground plane. The radiation resistance of monopole antennas is

length dependent. Resonance of a quarter-wavelength monopole occurs when its length is slightly less than a quarter-wavelength. The appropriate length for a quarter-wave monopole at 433.92MHz would be 2808 ÷ 433.92 = 6.47 inches. Sophisticated antenna measurements are generally not necessary unless a highly optimized design is desired. This makes the monopole very popular and easy to apply. The bandwidth of the antenna can either be broadened by providing an LC circuit or by providing a parasitic element near the wire part connected to the source. Fig. 3 shows a simple sketch of the traditional monopole antenna.
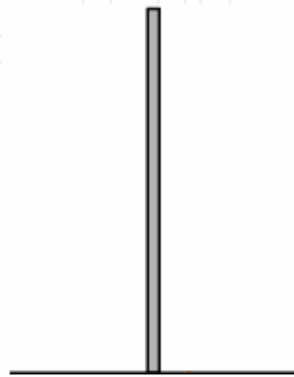
Fig. 3. The traditional monopole antenna

Some salient features are
- To increase the resonant frequency, decrease the monopole height.
- To increase the bandwidth, increase the wire thickness. Variation in wire thickness will have a small effect on the resonant frequency of the antenna. The resonant frequency of the antenna should be corrected for by adjusting the length.
- To decrease the impedance variation versus frequency, increase the element size.

4.2 Monopole antenna with sleeve
Monopole antennas have problems of low bandwidths. The aim of this section is to show a scheme to broaden the bandwidth by providing a sleeve as shown in Fig. 4. The cylindrical sleeve acts as a parasitic element. The advantage of the monopole antenna with the provision of a sleeve is clear from Fig. 5. If the diameter of the wire is not large a wire can still be used instead of cylinder.
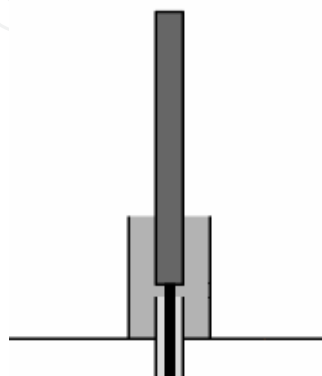

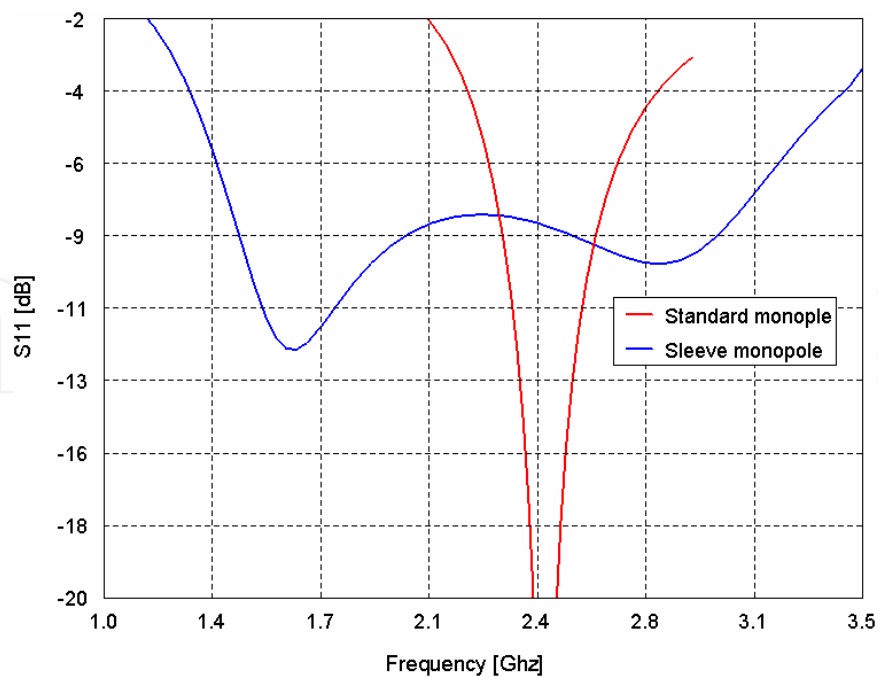Fig. 4. Monopole antenna with sleeve

Fig. 5. Comparison of sleeve monopole antenna and the traditional monopole antenna

The design approach is to adjust the exterior dimensions of the antenna to achieve pattern stability and then to use the region within the sleeve for impedance matching [Poggio et al.].

- To increase the operating frequency, decrease the monopole height.
- To increase the bandwidth, increase the wire thickness. (Note that changes in wire thickness will have a small effect on the operating frequency of the antenna. This should be corrected for by adjusting the length according to the previous guideline).
- To decrease the impedance variation versus frequency, increase the element diameter.
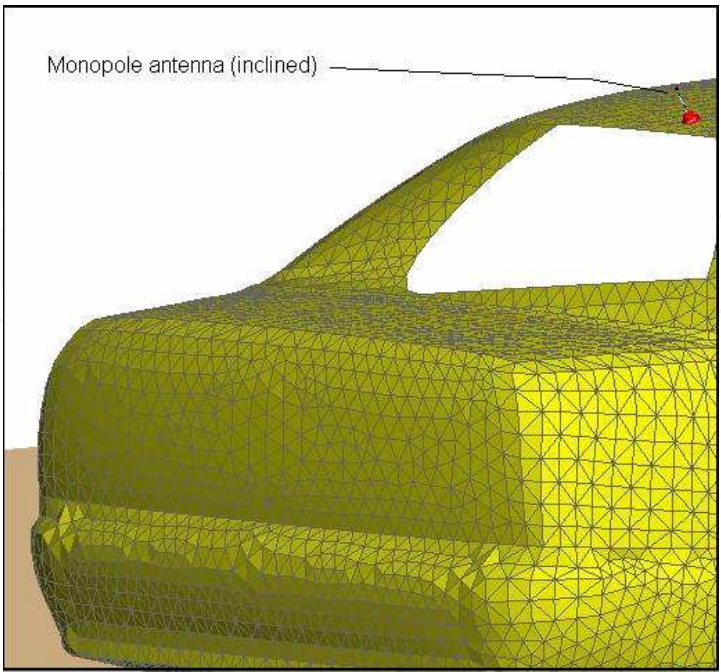
Fig. 6. Monopole antenna (inclined) mounted on a car

Fig 5 shows the characteristics of a traditional monopole antenna on an infinite ground plane. The far-field gain, antenna efficiency, and matching characteristics change with change in location of a monopole antenna in positions A, B, and C shown in Fig. 7. Fig 8 shows variation in the far- field gain patterns for change in the antenna location. There is also a variation in the far-field gain, shown in Fig. 9 when the monopole antenna is upright and inclined. In today's world the antenna is mounted inclined on a car as shown Fig. 6 and Fig. 7 (scheme D). The determination of antenna efficiency and matching characteristics (*VSWR*) is left as an exercise to the reader.
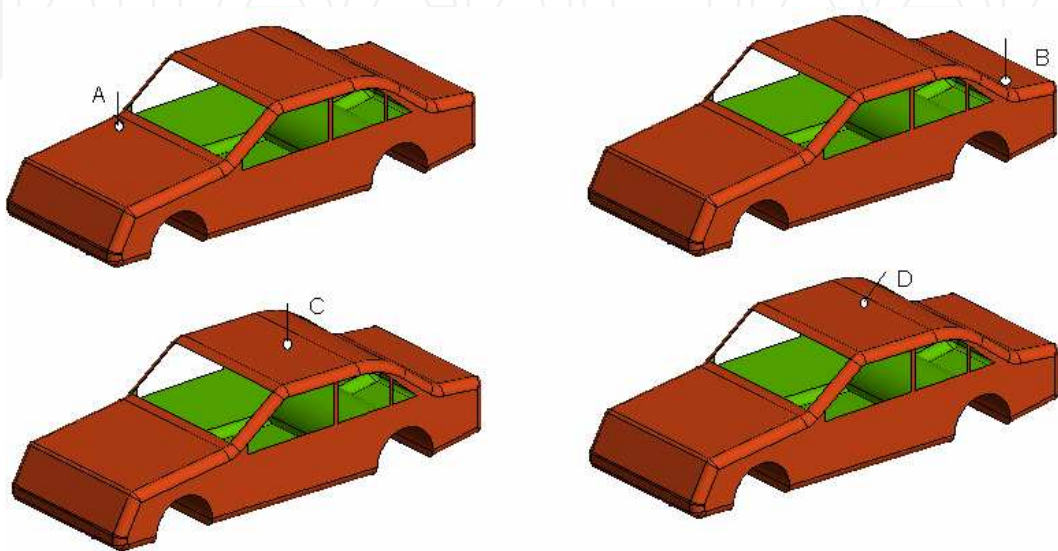
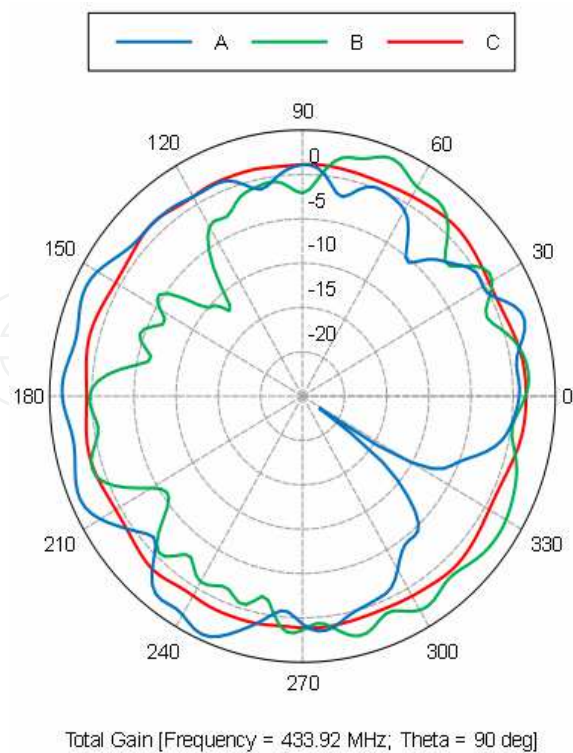Fig. 7. Monopole antennas mounted at various locations

Total Gain [Frequency = 433.92 MHz; Theta = 90 deg]

Fig. 8. Far-field gain patterns of antennas at various locations

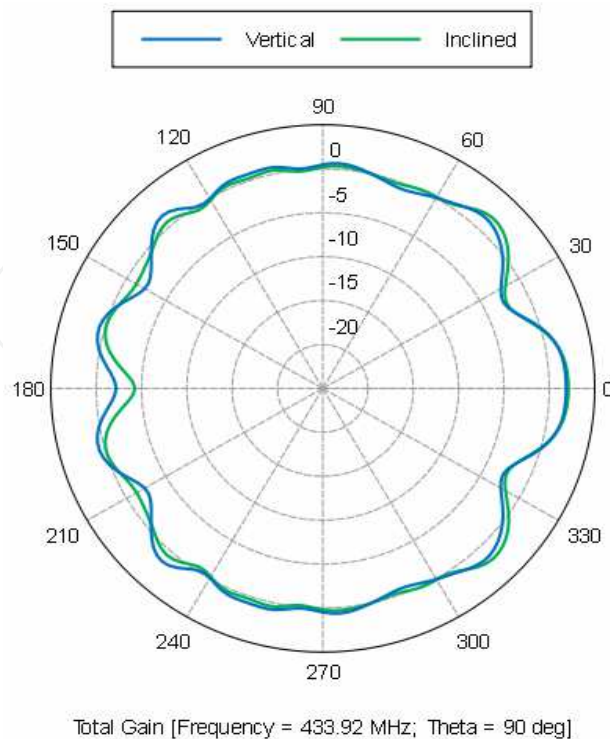Total Gain [Frequency = 433.92 MHz; Theta = 90 deg]

Fig. 9. Far-field gain patterns of antennas at orientations (vertical/tilted)

4.3 Patch antennas
The most common patch antennas in today's world are primitives such as squares, triangles, etc, metallised on a substrate backed by a ground plane. The next section gives a brief overview of a rectangular, a circular, and an elliptical patch antenna.

4.3.1 Rectangular patch antenna
From the cavity model point of analysis, the wave numbers k_x, k_y, k_z in the corresponding x', y', z' directions are

$$\left\{ \begin{matrix} k_x = \left(\dfrac{m\pi}{L} \right), m = 0,1,2,..... \\ k_y = \left(\dfrac{n\pi}{W} \right), n = 0,1,2,..... \\ k_z = \left(\dfrac{p\pi}{H} \right), p = 0,1,2,.... \end{matrix} \right\}, \tag{13}$$

where m, n, p represent the number of half-cycle field variations along the x, y, and z directions respectively. The primed cylindrical co-ordinates x', y', z' are used to represent the field within the cavity. The resonant frequency for such a patch or cavity is

$$(f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m\pi}{L} \right)^2 + \left(\frac{n\pi}{W} \right)^2 + \left(\frac{p\pi}{H} \right)^2}, \tag{14}$$

where *W, L, H* represent the width, length and height of the patch antenna. Since the substrate height *H* is very small $(H << \lambda_0)$ the electric field along the z direction is assumed constant and hence $p = 0$ and $k_z = 0$ and consequently the last term in equation (14) disappears.

Some design guidelines for a rectangular patch antenna shown in Fig. 10 are

- To increase (decrease) the resonant frequency, decrease (increase) the patch length.
- To increase bandwidth, increase the substrate height and/or decrease the substrate permittivity (this will also affect resonant frequency and the impedance).
- The bandwidth may be increased (decreased) by increasing (decreasing) the patch width.
- To increase (decrease) the input impedance decrease (increase) the pin inset.

Note: Antennas on very thin substrates have high copper-losses, while thicker and higher permittivity substrates may lead to performance degradation due to surface waves and feed-pin impedance. The maximum impedance that can be realised is governed by the impedance seen at the edge of the patch. The minimum realisable impedance is zero, at the centre of the patch. However, the practical minimum is governed by the rapid impedance variation as the centre is approached. A typical patch antenna similar in nature is mounted on a car as shown in Fig. 11 with no substrate.
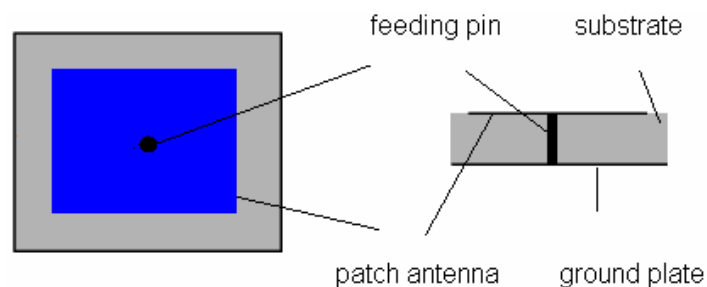

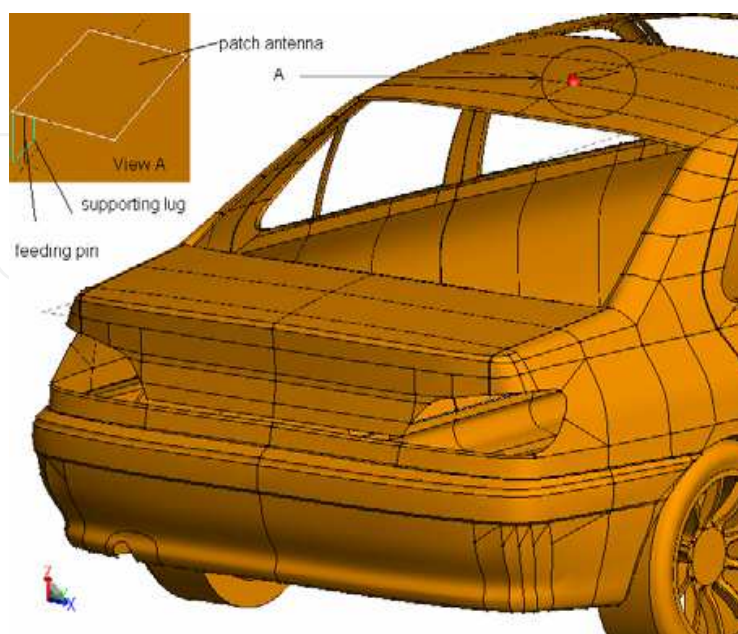Fig. 10. Square/ rectangular patch antenna

Fig. 11. Patch antenna (no substrate) mounted on a car

4.3.2 Circular patch antenna

From the cavity model point of analysis, the wave numbers k_ρ, k_ϕ, k_z in the corresponding ρ', ϕ', z' directions are

$$\left\{ \begin{array}{l} k_\rho = \left(\dfrac{\chi'_{mn}}{A'} \right), m = 0,1,2,..... \\ k_\phi = \quad 0, \quad n = 1,2,3..... \\ k_z = \left(\dfrac{p\pi}{H} \right), p = 0,1,2,.... \end{array} \right\}, \tag{15}$$

where m, n, p represent the number of half-cycle field variations along the ρ, ϕ, and z directions respectively. The primed cylindrical coordinates ρ', ϕ', z' are used to represent the field within the cavity. Taking into account the condition $k_z = 0$, as in the case of the rectangular structure, the resonant frequency for such a circular patch is

$$(f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \left(\frac{\chi'_{mn}}{A'} \right), \tag{16}$$

where A' represents the radius of the disk and χ'_{mn} represents the zeros of the derivatives of the Bessel function $J_m(x)$ whose values are given in table 1.

Mode (m,n)	χ'_{mn}
(1,1) or 1st mode	1.8412
(2,1) or 2nd mode	3.0542
(0,1) or 3rd mode	3.8318
(3,0) or 4th mode	4.2012

Table 1. Zeros of the derivatives of $J_m(x) = 0$ at mode (m, n) of order m at the nth zero cross-over point

The use of electrically thick substrates in designs will have degraded matching due to increased feed pin inductance.

-    Increasing the patch's diameter will decrease the resonant frequency and vice versa.
-    Increasing the substrate height will increase the bandwidth, but will decrease the resonant frequency slightly.
-    Increasing the substrate height will also result in a more inductive reactance due to the feed pin.
-    To increase/decrease the input impedance, increase/decrease the feed offset.
-    The circular patch antenna may be fine tuned for both impedance and centre frequency by the use of trimming stubs, as for the rectangular patch.

Note: Antennas on very thin substrates have high copper losses, while thicker and higher permittivity substrates may lead to performance degradation due to surface waves and feed-pin impedance. The maximum impedance that can be realised is governed by the impedance seen at the edge of the patch. The minimum realisable impedance is zero, at the centre of the patch. However, the practical minimum is governed by the rapid impedance variation as the centre is approached. The patch antenna is on the x-y plane.
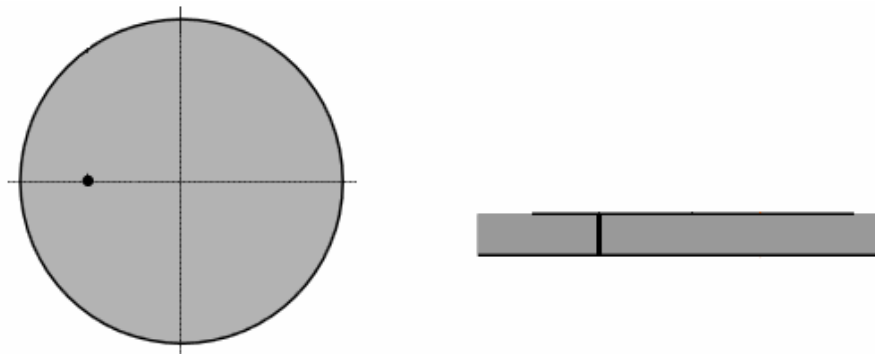
Fig. 12. Circular patch antenna

4.3.3 Elliptical patch antenna

Elliptical antennas are used for single-fed circular polarized antennas, especially in automotive applications. These antennas are characterized analytically making use of the Mathieu function in the case of elliptical antennas. A circular patch antenna could also be used however 2 feeds are necessary with the physical angle and electrical angle displaced by 90 degrees, namely

feed 1: y = 0 and V = 1 at phase angle = 0 degrees.
feed 2: x = 0 and V = 1 at phase angle = 90 degrees.

A typical substrate would have an ε_r of 2.48 and a substrate height approximately 1.5% of a free-space wavelength.

-   To increase the operating frequency, reduce the patch dimensions while keeping the ratio of the major to the minor ellipse axes constant.
-   To improve the axial ratio at the centre frequency, increase or decrease the ratio of the major to the minor ellipse axes.
-   To increase the bandwidth, try increasing the substrate height and/or decreasing ε_r.
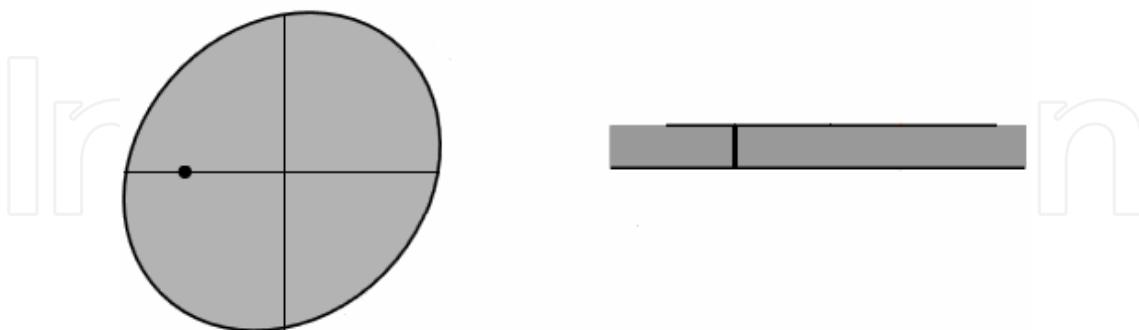-   To increase/decrease the input impedance, the feed offset should be increased/decreased.

Fig. 13. Elliptical patch antenna

Note: Antennas on very thin substrates have high copper losses, while thicker and higher permittivity substrates may lead to performance degradation due to surface waves and feed-pin inductance. The maximum impedance that can be realised is governed by the impedance seen at the edge of the patch. The minimum realisable impedance is zero, at the centre of the patch. However, the practical minimum is governed by the rapid impedance variation as the centre is approached. Furthermore the best performance is achieved when

the ratio of the minor axis to the major axis is almost unity. As in section 4.2.1 and 4.2.2 the antenna is on the x-y plane.

Properties of patch antennas of rectangular and circular geometries on planar surfaces were listed briefly. Such patch antennas also exist on cylindrical and spherical surfaces. Other patch antenna shapes (besides rectangular, circular and elliptical) widely used are triangular and annular in nature. One of the most widely used triangular shaped patch antennas is the bow-tie antenna. Annular antennas are used in applications where a broader bandwidth is required. In some cases, the inner radius of the annulus is short circuited.

5. Design guidelines for patch antenna arrays

For a given center frequency and substrate relative permittivity, the substrate height should not exceed 5% of the wavelength in the medium. The following guidelines are a must for designing a patch antenna and its arrays fed by microstrip lines.
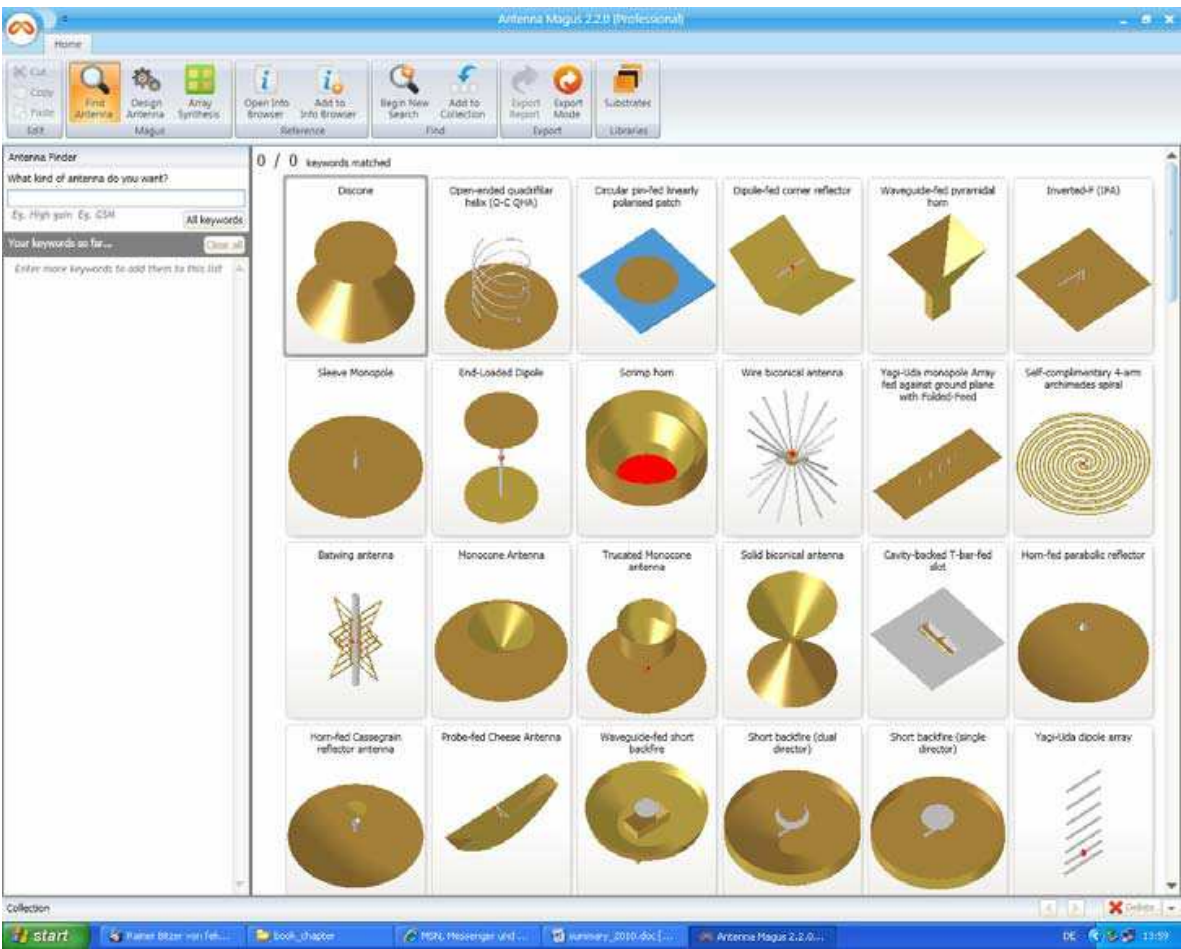

Fig. 14. Automotive patch antenna selected from Antenna Magus

- The length of the patches may be changed to shift the resonances of the centre fundamental frequency of the individual patch elements. The resonant input resistance of a single patch can be decreased by increasing the width of the patch. This is acceptable as long as the ratio of the patch width to patch length (W/L) does not exceed 2 since the aperture efficiency of a single patch begins to drop, as W/L increases beyond 2.

- To increase bandwidth, increase the substrate height and/or decrease the substrate permittivity (this will also affect resonant frequency and the impedance matching).
- To increase the input impedance, decrease the width of the feed lines attached directly to the patches as well as the width of the lines attached to the port. The characteristic impedance of the quarter-wave sections should then be chosen as the geometric mean of half the impedance of the feed lines attached to the patches and the impedance of the port lines.

Antenna Magus (see Fig. 14) is a software tool that helps choose the appropriate antenna for a given application and estimates the S11 / VSWR and the far field gain characteristics.

Caution: Antennas on very thin substrates have high copper-losses, while thicker and higher permittivity substrates may lead to performance degradation due to surface waves. Although arrays are not directly used in cars, they are used in base stations for car to car communication.

6. Modelling of a strip / mesh antenna on a windscreen

The proliferation of communication devices that are required in modern automobiles, require automobile designers to include more and more antennas into their vehicle designs. Requirements include FM/AM antennas, TV antennas, etc. Aesthetically speaking, this is a problem that can only be overcome by including such antennas into vehicle designs in unobtrusive ways. A prominent modern development is to include these antennas into the windscreens of a vehicle. These windscreens include multiple layers of glass and wiring that form the antenna. As with other antenna designs, engineers require the ability to simulate new designs to evaluate many antenna operating characteristics, including:

- Efficiency
- Impedance bandwidth
- Far-field radiation characteristics

FEKO includes a solution method based on the MoM that can be used for rigorous analysis of windscreen antennas. The method meshes only the metallic antenna elements, so the resource requirements that are devoted to modelling of the dielectric layers of the glass is almost negligible. Features of the method include:

- Boundaries of the dielectric interfaces between different layers of glass are accurately accounted for.
- Coupling between closely spaced antenna elements are taken into account.
- Finite size glass antennas can be integrated into a full car model.
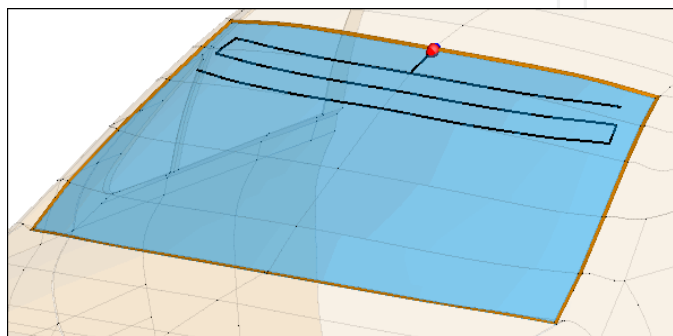- Curvature and rotation of the window is considered.
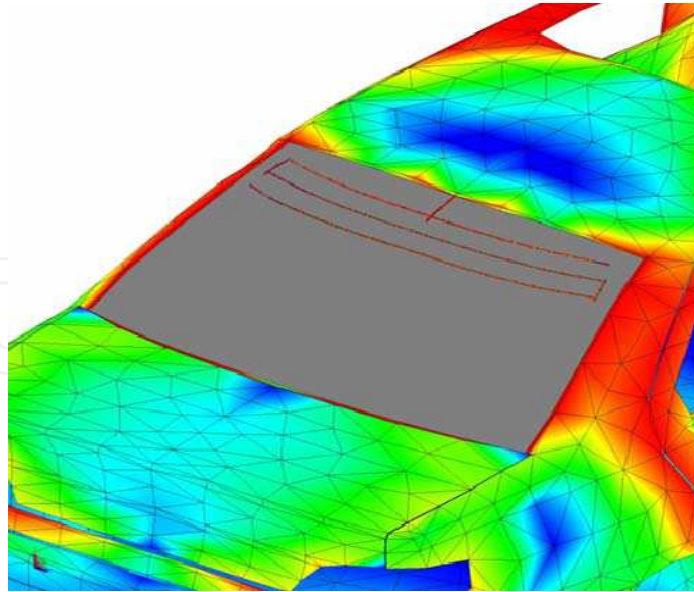

Fig. 15. Integrated windscreen antennas

Fig. 16. Current distribution due to integrated windscreen antennas

The windscreen can consist of one or more layers and the different layers do not have to be meshed and thus simulation time is greatly reduced when compared to conventional methods. Fig. 15 and Fig. 16 show a 3D representation of the car and windscreen being simulated e.g. for current distribution, the input impedance / S11, etc. Besides the use of integrated antennas on windscreens, these are also integrated to car tires, mirrors, and bumpers for collision avoidance at the 76 GHz band.
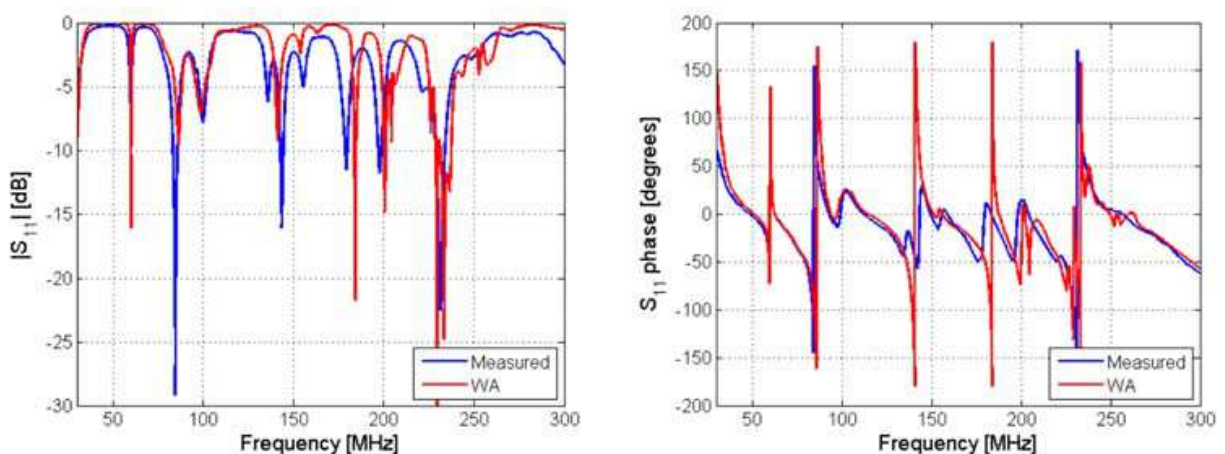
Fig. 17. Comparison of Antenna reflection co-efficient (simulation / measured results)

The currents are calculated
- Based on MoM solution with the incorporation of planar green function
- Full consideration of:
    - Boundaries between dielectric layers of glass
    - Coupling between closely spaced antenna elements
    - Curved/rotated windscreens
    - Multiple windscreens

Using the aforesaid approach only the metallic parts need to be meshed and not the dielectric parts of the windscreen elements of a car. Alternately the dielectric material i.e. the windscreen can be modelled using various methods e.g. FEM. However this approach is more time consuming as even the windscreen has to be meshed.

Results show that the planar Green's function approach (windscreen analysis - WA) is in good agreement with the measured results. Fig.17 shows a fairly good agreement between the simulation and the measured results.

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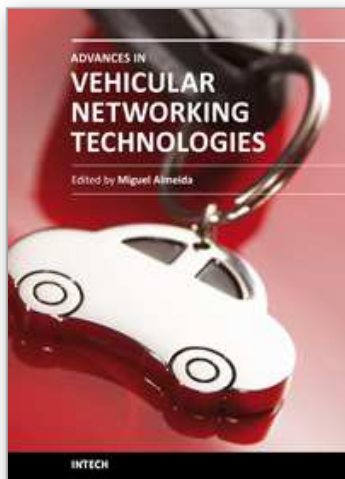
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This book provides an insight on both the challenges and the technological solutions of several approaches, which allow connecting vehicles between each other and with the network. It underlines the trends on networking capabilities and their issues, further focusing on the MAC and Physical layer challenges. Ranging from the advances on radio access technologies to intelligent mechanisms deployed to enhance cooperative communications, cognitive radio and multiple antenna systems have been given particular highlight.

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