NEW INTEGRATED SDARS ANTENNA ELEMENT
FOR AUTOMOTIVE APPLICATIONS

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Dedicated To

My beloved parents & family who show me the right path to live successfully
Abstract

In the past few years the demand for light weight compact automotive antennas in the customers desired mounting position has brought a challenge for the automotive antenna developers. Due to the high demands for the accuracy and compactness it became very difficult to develop antenna elements which fulfil all the strict requirements. Integrated SDARS (Satellite Digital Audio Radio Service) antenna element is one of such tasks which require strong gain requirements at particular elevation angles for the best reception of the satellite signals along with the car manufacturer’s desired mounting positions.

To achieve the desired objectives for SDARS element, different antenna designs were proposed and tested during the project work. Finally a newly developed two port cylindrical dielectric resonator antenna (DRA) with a parasitic element is presented due to its high performance, simplicity and compactness. The newly developed DRA antenna fulfils the strict SiriusXm gain requirements for the challenging mounting position in the car. The SDARS antenna element is simulated using CST Microwave Studio and verified by prototype measurements. The developed DRA antenna element has a broad beam with a peak gain more than 6dBi at the null position. An axial ratio of less than 3dB is achieved at the peak gain position. Real time 3D far field measurements are taken by using the MiDAS 4.1 system which verifies the simulated results of the developed integrated SDARS antenna. A good agreement is achieved between the simulated and measured results.
Acknowledgements

This thesis presents my research and development in Electronics engineering carried out at the antenna development department of WISI Automotive, Germany, to fulfil the requirement for Master degree in Electronics/Telecommunications at the University of Gävle, Sweden.

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## List of Abbreviations

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<th>Description</th>
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<tbody>
<tr>
<td>SDARS</td>
<td>Satellite Digital Audio Radio Service</td>
</tr>
<tr>
<td>DRA</td>
<td>Dielectric Resonator Antenna</td>
</tr>
<tr>
<td>LHCP</td>
<td>Left Hand Circular Polarized</td>
</tr>
<tr>
<td>RHCP</td>
<td>Right Hand Circular Polarized</td>
</tr>
<tr>
<td>LP</td>
<td>Linearly Polarized</td>
</tr>
<tr>
<td>GEO</td>
<td>Geosynchronous Earth Orbit</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System of Mobiles</td>
</tr>
<tr>
<td>DAB</td>
<td>Digital Audio Broadcast</td>
</tr>
<tr>
<td>DVB</td>
<td>Digital Video Broadcast</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulated</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulated</td>
</tr>
<tr>
<td>C2C</td>
<td>Car to Car Communication</td>
</tr>
<tr>
<td>VICS</td>
<td>Vehicle Information and Communication System</td>
</tr>
</tbody>
</table>
1 Introduction

Due to the increasing demand of infotainment and multimedia services with high performance in the daily life it also became field of interest for the automotive industry to bring the same services available for the car customers while driving on the road. To provide various high performance multimedia and infotainment services such as HD Audio/Video services, GPS, Cellular, SDARS, WLAN and Bluetooth within the car with least effects on the performance, weight, excellence and design of the car it became more challenging and important for the car manufacturers to design such innovative technologies.

Satellite Digital Audio Radio Service (SDARS) is a digital satellite radio service available in the content of USA and Canada provided by the SiriusXm. SDARS uses two GEO and three LEO satellites to provide its digital radio services with both high quality and large quantity. SDARS also provides some video channels along with large choice of audio radio channels. One of the potential customers for the SDARS is the automotive industry as the car customers desire to have high performance infotainment services available in the car.

To provide the satellite radio with in the cars is a big challenge due to the strict conditions for satellite signal availability, car performance issues and car body effects. Considering all these effects the car manufacturer demands for compact, lightweight and high gain SDARS antenna element.

1.1 Background

Automotive vehicles are increasingly being equipped with special electronic modules such as global positioning system, telematics and infotainments devices that require wireless data communications. One such system is SDARS which employs the wireless technology to provide satellite digital audio radio service. Antennas for SDARS should be able to receive an optimal satellite signal at particular elevation angles.

A lot of work is done to improve the performance and compactness of the SDARS antenna elements in past few years. Reference [1] describes an overview of SDARS automotive antennas available in the market. Different types of antenna elements such as microstrip patch, probe feed patch and ceramic patch antennas are in the market for SDARS applications. The different solutions available in literature are the quadrifilar antenna, as in [2], the standard dual polarized antennas, as in [3-7], or the low profile antenna, as in [8]).

Most of the antennas available in the field are complex and expensive which fulfils the version 1 of the SiriusXm gain requirements. However gain requirements are revised by the SiriusXm in version 2 with more strong gain requirements. In version 1 a maximum gain of 3dBi is acceptable but in version 2 it is required to have at least 4dBi gain at the particular elevation angles as shown in fig. 1.1. In this
work a newly developed antenna element is presented which fulfils the strong gain requirements at particular elevation angles according to the version 2 of SiriusXm.

### 1.2 Objective

There is a great desire for a low profile design or even hidden antenna system due to strict car design and weight limitations by the automotive industry. For the time being there are strong recommendations for a top roof mounting location of a SDARS-antenna in order to meet the required radiation pattern on a vehicle. For many vehicle models this location is considered as inconvenient and there is a strong demand to design more inconspicuous (not clearly visible) antennas.

The objective of this work is to develop a compact new integrated SDARS antenna element which fulfils the new SiriusXm gain requirements for better reception of the satellite signal. Main requirements for the developed SDARS element are

- At least 4dBi gain in the elevation angle of 50 to 70 degrees as shown in the figure 1.1.
- Left hand circularly polarized (LHCP) omni directional radiation pattern in the complete azimuth
- Compact with the maximum dimensions of 40*40*20 mm³, cost effective and easy to design
- Single feed SDARS antenna element
- Typical return loss ≤ -10dB and axial ratio ≤ 3dB

![SiriusXM Gain Specifications for SDARS](image.png)

*Fig. 1.1: SiriusXM gain requirements for SDARS antenna.*
1.3 Organization of the Report

The project report is organized as follows:

Chapter 2: Theory An introduction to the basic antenna theory related to the project work is given in this chapter. A brief description of the automotive and SDARS antenna element and its important requirements mandatory for its application in the automotive industry is given in the chapter.

Chapter 3: Design and Results a detailed description of the different proposed antenna designs is given here including their simulation and measurement results. A comparison with the finally selected SDARS antenna element with a detailed presentation and analysis of the finally developed SDARS antenna element. Finally a brief discussion summarizes the results obtained during the project work for DRA.

Chapter 4: Conclusions and Future Work to summarize the work carried out in this report a conclusion is given here along with some possible future work related to the project.
2 Theory

Selection of a suitable antenna element is the first and most important task for the development of an antenna design. In this chapter the theoretical part of the project is presented in detail which is latter implemented to complete the project.

2.1 Basic Antenna Theory

A device which can transmit and receive electromagnetic waves can be defined as an antenna. In an antenna, the direction of radiated power focuses on itself structure or shape. Like a dipole antenna has the properties of omni directional antenna in the azimuth. However, a horn antenna only has a dominated directional radiated power when it is working [9].

Antennas are widely used in radio frequency range as a key component of radio communication system. There many different types of antennas depending on their electrical characteristics, shape, size such as monopole, dipole, parabolic, micro strip, dielectric resonators, PIFA, yagi etc.

2.2 Antenna Parameters

Antenna performance varies depending on the geometry, physical size, environment and electrical characteristics of the antenna. Some important antenna parameters, which define the electrical characteristics of the antenna, such as antenna gain, s-parameters, polarization and radiation pattern are discussed below.

2.2.1 Antenna Gain

The gain of the antenna can be defined as “the ratio of the radiation intensity in a given direction to the accepted radiation intensity being radiated from the source in homogenously in all directions”. Gain can be calculated by the following equation

\[ G (\theta, \Phi) = 4\pi \frac{U(\theta, \Phi)}{P_{in}} \quad \text{(dimensionless)} \]  

Here  
\[ G (\theta, \Phi) = \text{Gain in } \theta \text{ and } \Phi \text{ directions} \]  
\[ U(\theta, \Phi) = \text{Radiation intensity in } \theta \text{ and } \Phi \text{ directions} \]  
\[ P_{in} = \text{Total input (accepted) power} \]
Antenna gain can also be defined in terms of directivity and the antenna efficiency.

\[ G(\theta, \Phi) = k \cdot D(\theta, \Phi) \text{ (dimensionless)} \]  

Here \( D(\theta, \Phi) \) is the directivity, a measure of radiation intensity in a particular direction, and \( k \) \((0 \leq k \leq 1)\) is the efficiency factor of the antenna. If the antenna efficiency is less than 100 percent, the gain is less than the directivity. The antenna efficiency depends on the ohmic losses of the antenna, which are due to the non-radiated power of the antenna causing increase in temperature of the antenna structure [10].

### 2.2.2 Scattering Parameters

For every antenna design scattering parameter is the most important parameter to analyse and compare the performance of the designed antenna. Scattering parameters provides the information for the resonating frequency, bandwidth, impedance match, power transmitted & reflected and coupling effects between the ports. In the thesis work most important S-parameter is \( S_{11} \) also called return loss.

The return loss of antenna gives the information that how much of the incident power is reflected instead of being transmitted [11]. In the presented work \( S_{11} \) is measured in dB. A lower value of \( S_{11} \) means most of the input power is transmitted through the network that is antenna and the feed network is well matched. For example if \( S_{11} = -10dB \), it means that 90 percent of the incident power will be transmitted through the network. It is defined as

\[ |S_{11}|dB = 20\log|\Gamma| \]  

Where \[ |\Gamma| = \frac{SWR - I}{SWR + I} \]  

Here \( \Gamma \) = reflection coefficient  
\( S_{11} \) = return loss  
\( SWR \) = standing wave ratio

In this project a typical value of the return loss \( (S_{11}) \) of -10dB needs to be maintained for the whole operating frequency band of 25MHz.

### 2.2.3 Polarization

Polarization of the plane wave refers to the orientation of the electric field vector, which may be in a fixed direction or may change with time [12]. The polarization of an antenna is defined as the polarization of the wave radiated when the antenna is excited, or the polarization of an incident wave
which results in maximum available power at the antenna. Polarization of a wave can be classified into linear, circular and elliptically polarized waves. 

*Linear polarization* is obtained if the field vector (electric or magnetic) possesses only one component or two orthogonal linear components that are out of phase by 180°. Linearly polarized wave has either vertical ($E_\theta$) or horizontal ($E_\phi$) component of the filed vector [12].

*Circular polarization* occurs when the two linear orthogonal components have equal magnitude and the time-phase difference between them is odd multiples of $\pi/2$. If the magnitudes are different, elliptical polarization is obtained. Clock wise rotation of the field vector is designated as the right hand circularly polarized (RHCP) wave and counter clock wise rotation of the field vector as left hand circularly polarized wave (LHCP). Left and right hand field components can be calculated from the tangential components as follows [13]

$$E_{\text{left}} = \frac{1}{\sqrt{2}} \left( E_\theta - i E_\phi \right)$$  \hspace{1cm} (5)

$$E_{\text{right}} = \frac{1}{\sqrt{2}} \left( E_\theta + i E_\phi \right)$$  \hspace{1cm} (6)

Here

- $E_{\text{left}}$ = Left hand circularly polarized field component
- $E_{\text{right}}$ = Right hand circularly polarized field component
- $E_\theta$ = Vertical field component
- $E_\phi$ = Horizontal field component

### 2.2.4 Axial Ratio

The axial ratio is the ratio of orthogonal components (horizontal and vertical) of an E-field. The axial ratio for an ellipse is larger than 1 (>0 dB). The axial ratio for pure linear polarization is infinite, because the orthogonal components of the field are zero.

An ideal circularly polarized antenna means equal magnitude of the orthogonal horizontal and vertical components and so the axial ratio is 1 (or 0 dB). In addition, the axial ratio tends to degrade away from the main beam of an antenna. As the designed antenna is circularly polarized so axial ratio is an important parameter to measure the circularity of the antenna. An axial ratio of at least 3dB is desired in the main beam direction of the designed SDARS antenna. Axial ratio can be calculated by the following formula

$$XPD = 20 \log \left( \frac{(A.R+1)}{(A.R-1)} \right) \text{ dB}$$  \hspace{1cm} (7)

Where

- $A.R$= axial ratio (linear)
- $XPD$= cross polarization discrimination
2.2.5 Radiation Pattern

The radiation pattern of an antenna is a plot of the magnitude of the far-zone field strength versus position around the antenna, at a fixed distance from the antenna [14]. The antenna radiation patterns can be either plotted for the elevation plane \( \theta \) or for the azimuth plane \( \Phi \). Typically radiation patterns are measured in two dimensional and three dimensional graphs which show the generated field strengths away from antenna at a certain distance. Spherical \((r, \theta, \Phi)\), polar \((r, \Phi)\) or \((r, \theta)\) and rectilinear \((x, y)\) coordinate system are used to represent radiation pattern of the antennas. Radiation patterns generated by the antenna mainly depends on the geometry, material, physical size and its electrical characteristics. Antennas have isotropic, directional, omnidirectional radiation patterns.

2.2.6 Physical Size & Construction

Physical size and the construction of the antenna is one of the important parameters which effects the electrical characteristics and performance of the antenna. Size of the antenna mainly depends on the operating frequency. Normally at higher frequencies due to small wavelength size of the antenna decreases and vice versa. Antennas can be constructed in many different ways e.g. simple wire antennas, patch antennas, micro strip antennas, reflector antennas, aperture antennas, horn antennas etc. When considering antennas suitable at 2.320 GHz \((\lambda \approx 129\text{mm})\) frequency for the SDARS application a compact and light weight antenna is desired with high gain.

2.3 Automotive Antennas

The mobility by vehicles is indispensable for our personal lives as well as business activities. There have been strong requirements of safety, comfortable time & space, and convenience for the mobility by vehicles.

Initially AM radio reception was only available in vehicles. Several systems for these requirements have been gradually installed into vehicles with the growth of wireless technologies [15], [16]. FM radio and television (TV) programs can be currently received in vehicles by FM/AM, SDARS, DAB, DVB etc. Drivers can achieve information of own positions by Global Positioning Systems (GPS) and congestion information by Vehicle Information and Communication systems (VICS). Telephone can be used in vehicle and Bluetooth helps links between mobile terminals of driver and vehicle terminals. Laser radars and millimeter-wave radars have been installed as forward looking sensors [17].

Automotive antenna design technique is one of the key techniques to contribute the system realization very much. Automotive antennas generally need simple architectures and low cost due to consumer products, and compactness or low profile due to limited installation spaces of vehicle. Also, inclusion
of the vehicle body into the antenna design is needed, when antenna performance is strongly affected by the vehicle body.

The frequency bands used in automotive wireless systems range widely from AM band to the millimetre-wave band. The different frequency bands result in the different problems and difficulties of the development of antennas. The establishment of automotive antenna design techniques is needed in wide frequency range.

### 2.4 Satellite Radio Services for Automotives

With the increasing demand for connectivity anywhere and anytime, the satellite services market is contributing to improve the available services to the automotive market. The main automotive and mobile technologies today available, or under development, through the satellite providers are using L and S band, and are able to provide satellite internet access, satellite phone, satellite radio, satellite television and satellite navigation.

While different satellite services are used to deliver the mentioned technologies to end users, the following table 1 depicts some of the main services used for automotive, nautical or air markets in L/S band [18].

**Table 1: satellite technologies used in the automotive market [18]**

<table>
<thead>
<tr>
<th>Service</th>
<th>Operating frequency</th>
<th>Polarization</th>
<th>Orbit</th>
</tr>
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<tbody>
<tr>
<td>Thuraya or Inmarsat BGAN</td>
<td>Downlink: 1525 to 1560 MHz; Uplink: 1625 to 1660 MHz</td>
<td>Dual switchable SAT (LHCP or RHCP)</td>
<td>GEO (Geosynchronous orbit)</td>
</tr>
<tr>
<td>Global Navigation Satellite Systems (i.e. GPS and Galileo)</td>
<td>Downlink: 1575 MHz</td>
<td>RHCP</td>
<td>MEO (Medium earth orbit)</td>
</tr>
<tr>
<td>Iridium</td>
<td>Uplink /Downlink: 1610 to 1626 MHz</td>
<td>RHCP</td>
<td>LEO (Low earth orbit)</td>
</tr>
<tr>
<td>Globalstar</td>
<td>Downlink: 1610 to 1626 MHz. Downlink: 2484 to 2499 MHz</td>
<td>LHCP</td>
<td>LEO</td>
</tr>
<tr>
<td>DVB-SH</td>
<td>Downlink: 2170 to 2200</td>
<td>Dual switchable SAT</td>
<td>GEO</td>
</tr>
</tbody>
</table>
The data in the table show the frequencies used for each service, specifying the transmission from earth to satellite (uplink) and the transmission from satellite to earth (downlink) bands. For each service the polarizations required by the antenna specifications is specified, discriminating between the LHCP (Left Hand Circular Polarization), the RHCP (Right Hand Circular Polarization) and the LP (Linear Polarization).

<table>
<thead>
<tr>
<th></th>
<th>MHz; Uplink: 1980 to 2010 MHz</th>
<th>(LHCP or RHCP) and TER (LP)</th>
<th>SDARS Downlink: 2320 to 2345 MHz</th>
<th>Dual SAT (LHCP) and TER (LP)</th>
<th>GEO, LEO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SDARS</strong></td>
<td></td>
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</tr>
</tbody>
</table>
| **2.5 SDARS Antenna**

SDARS (satellite digital audio radio service) is a satellite service used to provide digital radio to end users. Starting from its first requirements release ([19] [20]), it was underlined that the circularly polarized satellite signal should reach the users in the open areas, being further supported by terrestrial transmitters providing the necessary coverage especially in the urban environment, where the satellite signal could be obstructed by buildings or other constructions.

Since several years, SDARS is available in USA and Canada [21], and the service is in operation in the S-band (from 2320 to 2345 MHz), employing dual transmission broadcast format: LHCP signals provided by satellites and LP signals radiated by terrestrial stations. Currently SiriusXm is using a network of five satellites including two GEO and three LEO satellites. GEO is a very common Geosynchronous orbit at the altitude of 35,786km from the Earth whereas LEO is a small low earth orbit with an altitude less than 2000km above the Earth [14]. The network of the satellites operates in such a way that for complete 24 hours of the day, at least one satellite is visible to the SDARS receiver antennas. Unlike global positioning system (GPS) which has a large network of satellites with at least satellite availability of 5 to 6 at a time for its customers. SDARS network of satellite can provide about 2 to 3 satellites in most of the time in a day except a small interval of time when only one satellite is visible to the SDARS receivers. This is why SDARS antenna needs strict gain requirements for high performance and to provide the satellite digital radio service available every time for the users.

Operating satellite system by SiriusXm, for SDARS, uses right hand circularly polarized (RHCP) antenna for the uplink communications whereas for the downlink communications SDARS antenna element uses left hand circularly polarized (LHCP) radiation pattern. To enhance the reliability, overall throughput of the system and performance circularly polarized antennas are required.
The automotive SDARS antennas implement such as dual polarized system either with two separate antennas (dual-arm solution), one optimized for the LP terrestrial reception and the other for the LHCP satellite one; or with a single antenna (single-arm solution) receiving both signals. However now a days antenna element for satellite communication is main topic of interest in SDARS application due to its high performance, quality and complexity instead of terrestrial antenna.
3 Design and Results

An overview of the measurement and simulation tools is given in the beginning in the chapter. Some important proposed antenna elements and their performance issues are discussed in detail here. A comparison of the proposed designs is given and finally the simulation and measurement results for the best selected design are analysed and discussed in detail.

3.1 Numerical Simulations

Computer simulation technology (CST) provides the 3D electromagnetic field simulation tool CST Microwave Studio (MWS). A full-wave electromagnetic field simulator such as CST models and computes the interaction of electromagnetic fields with the physical object and environment. The software efficiently uses Maxwell's equations to calculate antenna performance, electromagnetic compatibility, radar cross section and electromagnetic wave propagation, etc. [13]. It offers the different solvers such as Time and Frequency domain solvers.

In the presented work CST MWS is used for the numerical simulations of the designed antenna elements. Broadband calculations for operating frequency, S-parameters and the radiation patterns were analysed and optimized by CST MWS. CST MWS gives the possibility to optimize the design for the defined goals or optimize and analyse the individual design parameter by setting parameter sweep. Both tools parameter sweep and optimization tool, in CST MWS, are efficiently used thought out the project work for the in depth analysis of the designed antenna models. All simulated results were well verified by the real time measurements of the prototypes.

3.2 Measurement Setup

MiDAS 4.1 system by Orbit/FR is used for the real time 3D far field radiation pattern measurements of the designed antennas. MiDAS system has the capability to measure real time 3D, 2D and 1D far field radiation patterns for the antenna elements. It has the capability to measure vertical, horizontal and circularly polarized (LHCP, RHCP) antenna elements. By control module of the MiDAS system the test antenna can be rotated in the six different axes. In the measurement scenario test antenna is placed about 20m away and 7m high from the transmit antenna as shown in fig. 1.2. Transmit antenna has the capability to transmit circular (LHCP, RHCP) and linearly (Horizontal, Vertical) polarized waves within a frequency range of 1 to 18 GHz [17]. Transmit antenna throughout the measurements, remain fixed at the lower end directed towards the receiver. Before the measurement starts transmit and receive antennas are aligned in their LOS and then control
module automatically adjusts the position of the test antenna to -90 degrees. It is possible to control the rotation and movement of the axes either manually or automatically.

![MiDAS 3D far field test setup](image)

**Fig.1.2: MiDAS 3D far field test setup**

MiDAS system calculates the receive power (dBm) by rotating the test antenna from -90 degrees to +90 degrees with the step of 5 degrees on axis 3 (elevation plane). On each 5 degree step the test antenna is rotated about its axis 4 (phi-plane) by 360 degrees. To measure more accurate and detailed radiation patterns, the step on the elevation plane can be reduced to 1 degree. In these measurements hemispherical 3D radiation pattern is obtained for the test antenna which gives the information for the received signal power at the test antenna.

### 3.3 Antenna Mounting Positions in Car

Most challenging task of this project is to make a compact SDARS antenna element which fits well into the small space of the car mounting position. There are many different antenna mounting positions in the car for different antenna services as shown in fig. 1.3(a). However for the SDARS element the desired mounting positions are 7, 4 and 3 as shown in fig. 1.3(a).
Fig.1.3: Antenna mounting position (a) in car (b) Top roof position.

### 3.3.1 Top Roof Position

Third possible position for mounting the SDARS antenna element in the car is at top roof as shown in figure 1.3(b). This position is the most suitable place for mounting the antenna element on the car to get best possible quality of receive signal. It is because at the top roof, antenna element has no cavity and no edges near to it also a big ground plane is available around the antenna by the metal roof of the car. In this position the available cavity dimension is 50*50*20 mm³.

### 3.3.2 Windscreen Position

The most desired mounting position was just below the wind screen, inside the car. At this position maximum possible space for the complete SDARS antenna element is 41*42*20 mm³ with a tilt of 10 degree towards the driving direction. In this position distance between the wind screen glass and the antenna mounting position is only 5.6mm. To avoid wind screen glass of the car and its effects on the antenna performance, at maximum the antenna element is allowed to have only 2.5mm space out of the cavity. The car cavity for this position is shown in figure 1.4. In this project work windscreen position is considered initially for the antenna measurements due to its strong requirement and effects
3.3.3 Spoiler Position

Second position for the antenna mounting is in the spoiler of the car as shown in the figure 1.5. The spoiler has no cavity but there are high edges of about 7mm quite near to the antenna element which can affect the performance of the element. As compare to the wind screen position, spoiler position has no deep cavity however the surface around the antenna is not smooth, unparalleled with edges and holes near to antenna element which affects a lot the performance of the antenna. The available space for antenna element in the spoiler is limited to 55*60*20 mm³.

3.4 Reference Antennas for the Measurements

All proposed antennas were manufactured and measured antennas and compared with the reference antenna to analyse and optimize the performance of the antenna. It is required to make a left hand circularly polarized antenna element. So a LHCP cross dipole reference antenna, see fig. 1.7, is used during the measurements of all circularly polarized antennas. However for the linearly polarized antenna elements a primitive quarter wave monopole is used as shown in figure 1.6.
During all measurements the reference antenna is placed on a 1m circular ground plane without car cavity. However the test antennas are measured in the three different car positions. As all measurements during this project were done in an open air environment so for each test antenna measurement, reference antenna is measured in the same weather environment to make exact comparison. At 2320MHz 3D far field radiation patterns for the reference antennas were measured, see Appendix A.

3.5 Proposed Antenna Elements

During the project work different antenna elements such as cross dipole, PIFA, patch antennas, ring antenna, dielectric resonator antennas etc. were designed for the required objectives. Few important designs are discussed in this report. Following designs were simulated and measured with the prototype design. Finally by comparison the best suitable design was selected. Mainly radiation pattern, circularity and gain of the proposed designs were focused for the initial results which are presented here. Manufactured prototypes of the proposed designs and their measured results with SDARS gain specifications are shown in Appendix B.

![Fig.1.8: Proposed designs (a) L-shaped patch antenna (b) Z-element (c) single T-slot](image)

Initially L-shaped patch design shown in fig. 1.8 (a) is tested and verified by the MiDAS system. However the simulated and measured results for L-shape patch design has shown that the design does not fulfil the SiriusXm gain requirements.

Another design with a Z-element surrounded by four T-slots is simulated and tested. The simulation results fulfils the requirement however the measured design for the T-slot has less as compare to the simulated result. Also the complete design is complex to manufacture with five ports which also makes this design expensive.
3.5.1 Ring Antenna Design

The proposed design is a primitive circularly polarized ring antenna element as shown in fig. 1.9. The designed ring element has 19mm of outer radius with 2mm height from the ground plane. The ring element is 5mm high and 1mm thick. It has two ports at an angular distance of 90 degrees. All the simulated and measured results presented for the DRA element are at 2320MHz.

The designed ring gives a good circular polarized radiation with good impedance match. The radiation pattern has maxima at null position with a gain of 7dBi in the simulated design. However the measured ring element has good gain but the beam width is not wide as in the simulated results. It is possible to obtain right hand circular polarized or left hand circular polarized just by changing the order in the phase shift of the ports.

Fig.1.9: Ring antenna (a) simulated design in cavity (b) ring element in space

3.5.2 Circular Microstrip Patch Design

The four-port circular microstrip patch antenna is a simple patch antenna with compact dimensions as shown in fig. 1.10. The designed antenna has a circular patch on FR4 substrate of \( \varepsilon_r = 4.5 \). The outer radius of the circular patch is 17mm whereas the inner radius is 12mm. The structure of the antenna is made on the substrate of the AD1000 Arlon which has the \( \varepsilon_r = 10 \).

The overall thickness of the antenna is about 4mm. A feeding network for four ports is designed using CST Design Studio and Ansoft Designer which is manufactured on FR4 as shown in Appendix B.

The benefit of this design is its compact thickness of 4mm. The antenna element can be placed out of the cavity when mounting in wind screen position of the car where 2.5mm space is available out of cavity. In this situation the antenna has a good performance with a ground plane of 1m².

The designed antenna has a gain of more than 5dBi with a good impedance match in the simulated design. The designed antenna becomes non-symmetric with a small ground plan along with cavity. It is because of the high edges near the antenna. Measured results of the circular patch
3.5.3 Dielectric Resonator Antenna Design

Dielectric resonator antenna (DRA) is a two port cylindrical element with a radius of 13mm and height of 10mm. Two metal strips are used with the width of 1mm and height of 9mm spaced with 90 degree angular distance around the DRA as shown in the fig. 1.11. DRA element has broad beam and strong circularity with a gain more than 6dBi. Due to cavity walls in the mounting position the DRA had reduced a little its performance. To remove the wall effects a parasitic element 1mm above the DRA is used which improves the radiation pattern. Detailed result and analysis for the DRA element are presented later in the chapter.

Fig. 1.11: Dielectric resonator antenna (DRA)
3.6 Comparison & Analysis of Proposed Designs

The proposed antenna elements were finally analysed & discussed to select the best possible solution considering the performance, compactness, ease of manufacturing and cost effectiveness of the design. As discussed before L-shaped patch element is not a good solution because it is much sensitive to the walls of the car cavity. Also the design does not fulfil the gain requirements in all directions of the azimuth both in simulation and measured results.

The second design consisting of separate horizontal and vertical components performs quite good in the simulations and full fills the requirements. However the measured design is not satisfying the simulated results. Measured z-element has quite good resemblance to the simulated results but the measured T-slots element has about 2dB less gain than the simulated design. With some optimization the performance of the T-slot element can be improved but on the other hand the proposed design is non-compact, difficult to manufacture and also expensive.

Another design was a primitive ring element which is circularly polarized with a peak gain of 7Bi at the null position. The ring element fulfils the requirements in the simulated design but the manufactured design has less broad beam radiation pattern.

A compact design of four port circular patch element is tested which fulfils the requirements on the big ground plane. However the design does not give good performance with the decreased ground plane. Another disadvantage of the design is four ports and the design does not perform well with the four port network. However with optimization the design can be improved.

Dielectric resonator antenna (DRA) which is quite simple to manufacture and also has quite broad beam radiation pattern is a good solution to the SDARS applications. The measured DRA element has shown the similar results as obtained in the simulated design. Latter a parasitic element is introduced which helps to keep the radiation pattern of DRA symmetric within the car cavity. The parasitic element is also helpful to improve the broadness of the beam and the resonant frequency of the DRA can also be adjusted up to 350MHz by changing the size, thickness and height of the parasitic element.

It is observed from the results the measured DRA element fulfils the SiriusXm gain requirements. So finally the dielectric resonator antenna (DRA) element with the parasitic element is selected due to its high sustained performance within the car, simplicity and compactness. The DRA fulfils the gain requirements of the SiriusXm in the car cavity.

Table 2: A comparison of the proposed antenna designs

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<thead>
<tr>
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<tbody>
<tr>
<td>L-shaped patch</td>
<td>3.5</td>
<td>-12</td>
<td>7</td>
<td>39<em>39</em>11(l<em>w</em>h)</td>
</tr>
<tr>
<td>Z-element with T-slots</td>
<td>4.67</td>
<td>-10</td>
<td>6</td>
<td>20<em>20</em>20(l<em>w</em>h)</td>
</tr>
</tbody>
</table>
3.7 Results of Dielectric Resonator Antenna

The designed and measured results for the dielectric resonator antenna are presented in the following subsections. Effect of the different parameters of DRA on the performance of DRA are presented and discussed in detail here.

3.7.1 Return Loss of DRA

Dielectric resonator antenna is designed for the desired SDARS frequency range (2320-2345MHz). The designed DRA shows high impedance match both in simulation and measured results, see fig. 1.120 and 1.31. As can be seen that a -19.6dB of return loss is measured for the designed DRA with an overall value of at least -17dB over the whole 25MHz frequency band.

![Simulated return loss of DRA](image)

Fig.1.12: Simulated return loss of DRA
3.7.2 Axial Ratio of DRA

In all simulated and measured designs about 10dB difference between the cross and co-polarizations is obtained, at the peak gain position. Therefore an axial ratio of less than 3dB is achieved on the peak gain position of the DRA as shown in fig. 1.14 and fig. 1.15. For the measured DRA element, axial ratio is obtained using the eq. 4, by using the measured difference between the cross and co-polarizations of DRA.
3.7.3 Effect of Parasitic Element

DRA has very good performance on the 1m ground plane but when the DRA is put into the car cavity it reduces its gain and also axial ratio increases. So to reduce the cavity effects a circular parasitic element above the DRA is placed. There is a significant influence on the DRA performance due to the parasitic element. By changing the size of the p-element it is observed that the resonant frequency of DRA can be adjusted up to 350MHz. It is observed that for 1mm change in the radius of circular p-element the resonant frequency of the DRA shifts by about 25MHz. By changing the thickness of the parasitic element the resonant shifts about 10MHz and the gain of the DRA also changes. If the distance between the DRA and parasitic element is increased the beam broadness and circularity of the antenna is disturbed with a small shift of frequency.

The highest performance with a broad beam, at the operating frequency of 2320MHz, is achieved by placing p-element of diameter 26mm and 0.2mm thickness 1mm above the DRA.
Fig.1.6: Measured effects of p-element on the DRA

3.7.4 Optimization of the DRA

The designed DRA element is optimized by changing all possible parameters. As the car cavity is very small so all proposed elements had so much effect of the cavity walls and edges. For the DRA element much less effects are observed and DRA sustained its good performance even in the cavity. It is because of the strong concentrated fields around the DRA element. It is observed that the resonating frequency of the DRA can be adjusted by changing the permittivity, height, diameter and the parasitic element. There is not much effect on frequency due to the two feeding strips.

It is seen the DRA radiation pattern gets broader if the parasitic element is placed parallel to the car cavity hole. Also the circularity of the DRA increases in this case.

The feeding network of the DRA gives the possibility to switch the polarity of the antenna from left hand circular polarization to right hand circular polarization if the order of the phase shift between the ports is changed. It is also observed that the axial ratio goes bad if the phase shift between the ports is more or less than 90 degrees. Width of the feeding strips has minor effects on frequency shift and radiation pattern of the DRA.

The dimensions of DRA have much effect on the gain, radiation pattern, circularity and impedance matching of the developed antenna. It is observed that by increasing the height of the DRA element from 8mm to 12mm, gain and broadness of the beam increases with a shift to lower frequency. Increasing the height of the DRA also affects the circularity of the DRA element. If the radius of the DRA is increased the overall gain of the element increases but due to the cavity wall effects the circularity is not so good.
3.8 DRA Simulation Results

The simulation results for the DRA element obtained using CST microwave studio are presented here. As can be seen radiation pattern is quite broad with an axial ratio of less than 3 dB in the peak gain directions. The DRA element is initially simulated on a 1m ground plane. As the results on the 1m ground plane are very good so the DRA is simulated within the simple car cavity. Results obtained in all three different car positions were simulated which are discussed below.

3.8.1 Roof Top Position

Initially the DRA element is simulated on 1m circular ground plane buried in a cavity with a tilt of 10 degree as shown in fig. 1.17. This is the most suitable position for the DRA with an available space of 50*50*20 and with no edges around the DRA element. In real life top roof position of the car has more than 1m metal roof which serves as the ground plane for the DRA which further improves the DRA performance.

The simulated results show the gain of 5.33dBi is achieved with a wide beam width. The difference between the LHCP and RHCP of the DRA is more than 9 dB which gives an axial ratio of less than 3dB at the peak gain position.

![Simulated design of the DRA in the top roof position](image_url)

Fig.1.17: Simulated design of the DRA in the top roof position
Fig. 1.18: Simulated co-polarization of the DRA in the top roof position

### 3.8.2 Windscreen Position

At the windscreen position the complete DRA element has the available space of 41*42*20 mm³. The designed DRA element is buried in cavity as shown in fig. 1.19. The result obtained from the simulated design is shown in fig. 1.20. Here it is required to hide the antenna within the cavity in such a way that the antenna is not out of the cavity more than 2.5mm. At this position high gain of the antenna is observed but the beam width decreases a little as compare to top roof position. It is due to the near edges and the limited height available out of the cavity at this position. In the radiation pattern cuts at different elevation angles shows the effect of the cavity wall and edges around the DRA element.

Fig. 1.19: Simulated design of the DRA in the windscreen position
3.8.3 Spoiler Position

At the spoiler position the complete DRA element has the available space of 55*60*20 mm³. The designed DRA element is place in spoiler with high edges of about 8mm around it as shown in fig. 1.21. The result obtained from the simulated design is shown in fig. 1.22. At this position good gain of the antenna is observed but the beam width decreases a little as compare to top roof position. The radiation pattern shows some cuts which are the effects of the side edges in the spoiler position.


3.9 DRA Measurement Results

After successful simulation results of the DRA element a prototype is measured using vector network analyser and MiDAS 4.1 for the far field radiation pattern measurements. The measured results are similar to the simulated results. The developed SDARS antenna is tested for all three positions.

3.9.1 Roof Top Position

For the realization of the top roof position a circular ground plane of 1m diameter is used as shown in fig. 1.23. The measured DRA element at this position shows very good performance with a high gain at desired elevation angles as shown in fig. 1.24. Both LHCP and RHCP of the DRA are measured in this position. An axial ratio of less than 2dB is observed at this position. It is observed that DRA element has about 1.5 dB higher gain than the reference cross dipole antenna.
The wind screen position is the most desired position for SDARS antenna from the automotive industry but on the same time this position has huge effects on the performance of the antenna. For the developed DRA element the 3D far field radiation patterns are measured using MiDAS setup. A cavity is used for the measurements to realize the original car mounting position as shown in fig. 1.25. For the DRA LHCP and RHCP are measured at this position. The DRA element has about 0.5 dB more gain than the measured reference antenna, with a little less beam width as shown in fig. 1.26. In the radiation pattern cuts on the different elevation angles are observed similar to the simulated results due to the cavity edges.
Fig. 1.27: Measured co-polarization of the DRA in the windscreen position

3.9.3 Spoiler Position

A spoiler of an old car is used in this measurement for the realization of the spoiler position as shown in fig. 1.27. The measured DRA element at this position has a little less gain than the measured reference antenna element as shown in fig. 1.28.

Fig. 1.27: Measured design of the DRA in the spoiler position
Both LHCP and RHCP of the DRA are measured in this position. An axial ratio of less than 3dB is observed at this position. It is observed that DRA element has about 1.5 dB lower gain than the reference cross dipole antenna.

3.10 Discussion

Different designs were presented for the SDARS applications. All presented antennas show very good performance on the ground plane without cavity. However, it is observed that each of the presented antenna elements have strong influence of the different car mounting positions. The presented antenna...
elements can be a good solution for the SDARS applications on a big ground plane such as top roof position whereas for the use in the cavity and non-smooth ground planes, the antenna elements should be optimized further. The newly developed DRA element for the SDARS application shows very good performance. All simulated results were well verified by the measured results using MiDAS setup. A high impedance match and less axial ratio is observed. The developed DRA performs best on the 1m ground plane whereas it has some effects of the car cavity on the windscreen and spoiler position. It can be seen that DRA element has high gain at the top roof and windscreen position. A comparison of the DRA gain performance is shown in the fig. 1.29. It can be seen that the DRA element fulfils the SiriusXm gain requirements of 4dBic at the top roof position and the windscreen positions. The DRA performance degrades a little in the spoiler position due to the high edges and bends around the antenna. Each position of the car has its own effects on the gain, operating frequency and circularity of the antenna which needs to be optimized accordingly. Measured DRA is compared with a reference circularly polarized cross dipole antenna. A comparison graph for all three possible positions is shown in Appendix C. It can be seen that the DRA fulfils the SiriusXm gain requirements at the high elevation angles. For the low elevation angles the element has little less gain but for satellite communication gain at the high elevation angles specifically between 50 – 70 degrees must be achieved. For the top roof and windscreen position DRA element has gain more than the reference element.
4 Conclusions and Future Work

This thesis work presents the research and development of the antenna element for the SDARS applications. During the project work different designs were presented and it is observed that each element has a strong influence of the car body on its performance. However the proposed designs can be a good solution for the SDARS applications on a big ground plane such as top roof position whereas for the use on a non-smooth ground planes the antenna elements should be optimized further. Finally the newly developed DRA is presented which has a high gain of more than 6dBi with an axial ratio of less than 3dB at the peak gain position. Return loss, less than -19dB is measured. The DRA element shows best performance on the circular ground plane of 1m diameter. It is observed that the DRA element has broad beam with high gain, if a parasitic element is used above the DRA. The parasitic element helps to tune the resonating frequency of the DRA without changing the dimensions of the DRA.

Rectangular or spherical shaped DRA elements can be optimized for this application resonating at higher modes. It is also observed to have better response by placing the parasitic element directly on the DRA which can be further investigated. All proposed designs can be optimized to improve their performance on the non-smooth ground planes. Circular patch designs should be further optimized with a better feeding network; z-element can be combined with another antenna element to give a better theta element.
References


Appendix A: Measured reference antennas

Fig.A.1: Measured LHCP for cross dipole at 2.32GHz

Fig.A.2: Measured vertical component of quarter wave monopole at 2.32GHz
Appendix B: Measured proposed antennas

Fig.B.1: L-shaped patch measured design in windscreen car cavity
Fig. B.2: Measured Z-element design

Fig. B.3: Measured horizontal component of Z-element design

Fig. B.4: Measured T-slot element design
**Measured Vertical Component of 4-Slot element**

**Fig. B.5**: Measured vertical component of T-slot element design

**Fig. B.6**: Measured ring antenna design
Fig. B.7: Measured co-polarization of the ring antenna at 2320MHz

Fig. B.8: Measured circular patch antenna design (a) top view (b) bottom view
Fig B.9: Measured co-polarization of the circular patch antenna
Appendix C: Measure DRA in comparison to reference antenna

Fig.C.1 Comparison of the measured reference antenna and DRA at Top roof position
Fig. C.2: Comparison of the measured reference antenna and DRA at windscreen position

![Comparison of the measured reference antenna and DRA at windscreen position](image)

Fig. C.3: Comparison of the measured reference antenna and DRA at spoiler position

![Comparison of the measured reference antenna and DRA at spoiler position](image)