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Abstract

Due to specific requirements for automotive applications, the design of an integrated antenna system able to guarantee the connection to several wireless services, i.e. GPS, GSM/GPRS and COSPAS-SARSAT, must be faced as an optimization problem. Starting from electrical and geometrical constraints, the design of the antenna must be faced considering, in addition to usual antenna design procedures, also interferences phenomena arising from the integration of antennas belonging to different classes in a single compact device. In the paper are described the design phases of the device and the experimental and numerical validation activity conducted on a prototype of the antenna.

Introduction

Nowadays several functions of great interest in automotive applications, as voice and data exchange, timing and localization, are offered at low costs by wireless networks, i.e. mobile phone and GPS systems. An automotive device exploiting such wireless functionalities needs of an antenna able to operate in different frequency bands in which wireless services operate and, due to the specific application in automotive environment, there are also some specific issues related to the coexistence of more than one antenna in a limited area, and related to limited weight and volume constraints. In this paper is described the integrated antenna developed in the framework of the AIDER (Accident Information and Driver Emergency Rescue) project1. The main objective of the AIDER project was the development of an accident management system able to obtain the reduction of the consequences of a road accident by optimising the rescue management in terms of operative time and effectiveness. To accomplish this task, AIDER vehicles are equipped with a sensor suite and data acquisition system to monitor the pre- and post-crash status of the vehicle and its occupants. The system is capable to automatically send to a control centre not only an emergency call but also full information (audio, video, sensors data) about the accident severity. To this end a highly survivable communication system, based on the integration of the functions of a cellular and a backup satellite communication link, is provided for information exchange between vehicles and rescue centers. Each vehicle is equipped with a GPS receiver in order to continuously monitor its current position, in particular when an accident occurs. The design of an integrated antenna able to guarantee all the necessary link to multiple wireless services must be accurately faced in order to solve mutual coupling problems arising when all the subsystem antennas have to be placed in a single limited volume.
The antenna design has been conducted by means of an optimization procedure, applied in two steps: first every antenna subsystem has been optimized as a stand alone device on a ground plane, and than the integrated antenna system, composed by the obtained antenna subsystems, has been optimized in order to solve interferences problems, and in order to maintain the compliance with project requirements. The employed optimization procedure is able to manipulate antenna subsystem parameters in order to make them comply with the required specifications for each antenna subsystems, and then, when applied to the three antenna subsystems placed together in a single device, it is able to modify their parameter in order to maintain the compliance with the project specifications.
A prototype of the resulting multi-function antenna has been built and tested, and in the last section of the paper are presented the results of the experimental verifications, compared with numerical simulations.

Integrated antenna design

For every antenna subsystem, related to a specific wireless service, a suitable class of antenna has been chosen in order to fill specifications, in particular gain values in the given angular ranges, assuming an infinite ground plane simulating the roof of a car. In order to guarantee reduced weight, dimensions and aerodynamic properties of the resulting antenna, only wire antenna structures have been considered. For COSPAS-SARSAT and for the GSM/GPRS systems a monopole antenna has been selected since such a structure presents the necessary gain behavior in the requested angular range. For the GSM/GPRS system a dual-band monopole antenna has been chosen and the multiple function has been obtained placing in a suitable position of the 930 MHz quarter-wave monopole an LC tuning device able to electrically detach the

[1] AIDER is an European project co-funded by the Information Society Technologies Programme within the initiatives of the 5th Framework Programme.

upper part of the monopole in order to obtain a quarter-wave monopole operating also in the 1850 MHz band. A more difficult issue was the selection of a proper antenna subsystem for the GPS function, since the possibility to exactly localize a vehicle in an after-crash status was one of most crucial requirements of the project, in order to optimize the rescue management in terms of time and effectiveness. A great number of commercial GPS receivers employ patch antennas, since they present radiation patterns with a broad lobe and they are low costs and light weight devices. However patch antennas are narrowband devices and their resonant frequency performance can vary depending on the ground plane size and depending on the dielectric loading due to, i.e., radome [1]. Other classes of antennas that provide circular polarization are the helical and the spiral antennas; they present a broad frequency band, they are relatively insensitive to mutual coupling phenomena [2] [3] and they present a wide hemispherical lobe and good performances for the cross polarization rejection ratio [4] [5] [6].
For the development of the optimisation procedure, for each single antenna the following quantities have been defined:

$$G_{SRS} = G_{SRS}\{l_{SRS}, d_{SRS}\} \quad (1)$$

$$VSWR_{SRS} = VSWR_{SRS}\{l_{SRS}, d_{SRS}\} \quad (2)$$

as the gain and the Voltage Standing Wave Ratio of the COSPAS-SARSAT antenna, where l_{SRS} is the length of the COSPAS-SARSAT monopole and d_{SRS} is the wire diameter. The same quantities have been defined for the dual-band GSM/GPRS monopole antenna for the two frequency bands:

$$G_{GSM/GPRS} = G_{GSM/GPRS}\{l_{GSM/GPRS930}, l_{GSM/GPRS1850}, L_t, C_t, d_{GSM/GPRS}\} \quad (3)$$

$$VSWR_{GSM/GPRS} = VSWR_{GSM/GPRS}\{l_{GSM/GPRS930}, l_{GSM/GPRS1850}, L_t, C_t, d_{GSM/GPRS}\} \quad (4)$$

where $l_{GSM/GPRS930}$ is the whole length of the dual-band monopole, $l_{GSM/GPRS1850}$ is the length of the lower part of the dual band monopole, L_t and C_t the values of the lumped components of the tuning circuit, and finally $d_{GSM/GPRS}$ the diameter of the wires. The same functions have also been defined for the two-arm conical Archimedean spiral antenna, in particular:

$$G_{GPS} = G_{GPS}\{x_{R1\,GPS}, y_{R1\,GPS}, x_{R2\,GPS}, y_{R2\,GPS}, h_T, h_B, S_{GPS}, d_{GPS}\} \quad (5)$$

$$VSWR_{GPS} = VSWR_{GPS}\{x_{R1\,GPS}, y_{R1\,GPS}, x_{R2\,GPS}, y_{R2\,GPS}, h_T, h_B, S_{GPS}, d_{GPS}\} \quad (6)$$

where $(x_{R1\,GPS}, y_{R1\,GPS})$ and $(x_{R2\,GPS}, y_{R2\,GPS})$ are respectively the coordinates of the lower spiral radius and of the upper spiral radius, h_T and h_B the heights of the top and of the bottom of the spiral above the ground plane, S_{GPS} the spacing between turns of the spiral and d_{GPS} the diameter of the wire.
Then for every antenna subsystem a cost function has been defined as:

$$\Im_i = \left|\frac{G_i - G_i^{SPEC}}{G_i^{SPEC}}\right|^2 + \left|\frac{VSWR_i - VSWR_i^{SPEC}}{VSWR_i^{SPEC}}\right|^2 \quad (7)$$
$$i = 1, 2, 3$$

where i stands for COSPAS-SARSAT, GSM/GPRS and GPS, G_i^{SPEC} and $VSWR_i^{SPEC}$ are the gain and the voltage standing wave ratio specifications for the three antenna subsystem operating in the three different bands. Some constraints regard maximum values of l_{SRS}, $l_{GSM/GPRS930}$, $l_{GSM/GPRS1850}$, L_t, C_t, $(x_{R1\,GPS}, y_{R1\,GPS})$, $(x_{R2\,GPS}, y_{R2\,GPS})$, h_T, h_B, and S_{GPS}. The diameters of the wires has been chosen among a discrete set of values corresponding to available standard values.
Also for the integration phase a cost function has been defined and antenna subsystems positions have been introduced among the design parameters, with reference to a global Cartesian coordinate system valid for all the antenna subsystems. So (1), (2), (3), (4), (5) and (6) has been rewritten as follow:

$$G_{SRS} = G_{SRS}\{x_{SRS}, y_{SRS}, l_{SRS}, d_{SRS}\} \quad (8)$$

$$VSWR_{SRS} = VSWR_{SRS}\{x_{SRS}, y_{SRS}, l_{SRS}, d_{SRS}\} \quad (9)$$

$$G_{GSM/GPRS} = G_{GSM/GPRS}\{x_{GSM/GPRS}, y_{GSM/GPRS}, l_{GSM/GPRS930}, l_{GSM/GPRS1850}, L_t, C_t, d_{GSM/GPRS}\} \quad 10)$$

$$VSWR_{GSM/GPRS} = VSWR_{GSM/GPRS}\{x_{GSM/GPRS}, y_{GSM/GPRS}, l_{GSM/GPRS930}, l_{GSM/GPRS1850}, L_t, C_t, d_{GSM/GPRS}\} \quad (11)$$

$$G_{GPS} = G_{GPS}\{x'_{R1\,GPS}, y'_{R1\,GPS}, x'_{R2\,GPS}, y'_{R2\,GPS}, h_T, h_B, S_{GPS}, d_{GPS}\} \quad (12)$$

$$VSWR_{GPS} = VSWR_{GPS}\{x'_{R1\,GPS}, y'_{R1\,GPS}, x'_{R2\,GPS}, y'_{R2\,GPS}, h_T, h_B, S_{GPS}, d_{GPS}\} \quad (13)$$

where (x_{SRS}, y_{SRS}), $(x_{GSM/GPRS}, y_{GSM/GPRS})$ are the coordinates of the base of the two monopole antenna subsystems and (x_{GPS}, y_{GPS}) the position on the ground plane of the axis of the conical spiral antenna. Now for the conical Archimedean spiral $(x'_{R1\,GPS}, y'_{R2\,GPS})$ and $(x'_{R2\,GPS}, y'_{R2\,GPS})$ are the coordinates of the lower spiral radius and of the upper spiral radius with reference to a local Cartesian coordinate system having the z-axis coinciding with the axis of the conical spiral.
Also for the integration of three antenna subsystems a global cost function has been defined exploiting the cost functions already defined in (7) for each antenna subsystem:

$$\Im^* = \sum_{i=1}^{3} \Im_i, \quad i = 1, 2, 3 \quad (14)$$

with the following additional constraints: the coordinates of the antenna subsystem (x_{SRS}, y_{SRS}), $(x_{GSM/GPRS}, y_{GSM/GPRS})$ (x_{GPS}, y_{GPS}) must be chosen in a restricted domain ($-\tilde{x} \le x \le \tilde{x}, -\tilde{y} \ge y \le \tilde{y}$); there can't be any electrical contact between parts of the monopole antennas and of the conical spiral. The optimum design of the three antenna subsystems as stand alone devices has been achieved by minimizing (7) for the three antenna subsystems as stand alone devices, and by minimizing (14) for the integrated multi-function antenna. The employed minimization procedure is based on a customized particle swarm optimizer (PSO) described in details in [7].

Numerical and experimental assessment of the antenna design

In this section are presented the experimental results obtained with a prototype of the optimized integrated antenna and, in order to do an assessment of the antenna performance and of the design procedure, they are compared with the simulation results obtained by means of two different numerical method, i.e. the Method of Moment (MoM) and the Finite Difference Time Domain (FDTD).

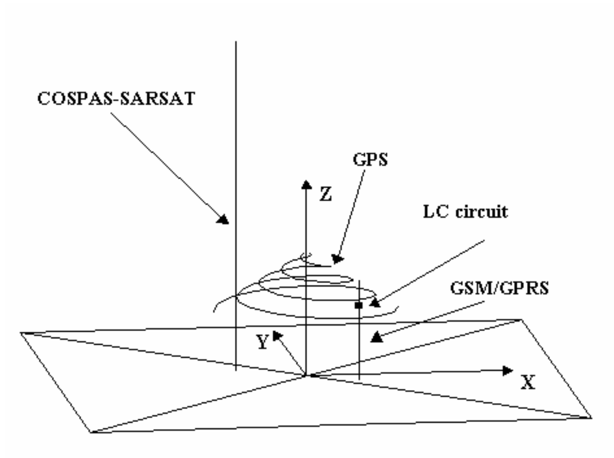

Figure 1. Geometry of the integrated multi-function antenna

In figure 1 is shown the geometry of the resulting integrated multi-function antenna as obtained after the last phase of the optimization procedure; as can be observed the two monopole antennas has been placed by the optimization procedure among the turns of the conical Archimedean spiral, according to the constraints related to maximum allowed volume of the multifunction antenna. Moreover, in order to minimize mutual coupling phenomena in the required frequency bands, the procedure has placed the monopole antennas in two diametrically opposed positions. The resulting maximum vertical dimension is due to the SARSAT monopole height (175 mm), while the remaining part of the antenna has the shape of a small sized conical volume, having a maximum height equal to about 65 mm over the ground plane, containing GPS spiral antenna and the double band GSM/GPRS monopole.

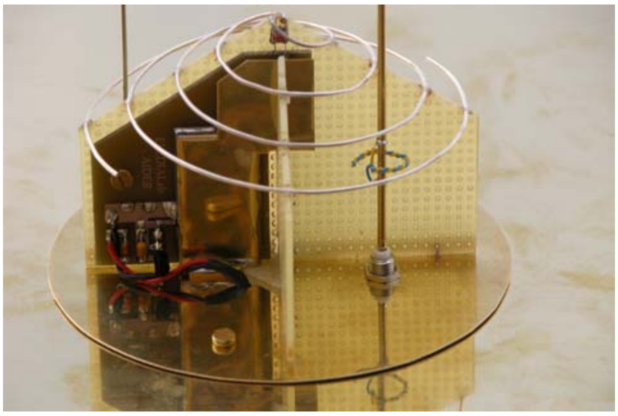

Figure 2. A photograph of the integrated multi-function antenna

In the photograph in figure 2 are shown some details of a prototype of the multifunction antenna. With a prototype have been done both gain and VSWR measurements inside an anechoic chamber in order to assess the antenna performances. In figures 3(a), 3(b), 3(c) and 3(d) are shown the results of the simulated gain for all the frequency bands of the optimized multi-function antenna and their comparisons with the experimental data and with the specifications in the given angular ranges. All the comparisons show the compliance of the measured results with the specifications in all the frequency bands; only for the lower elevation angles ($\theta \cong \pm 90°$) in the upper GSM/GPRS band gain values are apparently under the specifications, due to limited size of the ground plane of the multifunction antenna prototype. However the gain performance has been considered compliant with project specifications since the given value equal to –2.0 dBi was intended as a minimum linear average in all the elevation range (measured linear average equal to $\cong$ - 2 dBi).
Also for the GPS band at the specified elevation angle ($\vartheta = \pm 70°$) the gain is about 6 dB under the specifications; this result is to be considered compliant to the specifications since a pre-amplification of about 28 dB has been considered, as requested, in the optimization constraints.

Conclusions

In the paper the design of an integrated multi-function antenna for automotive applications has been presented. The applied design methodology, based on a minimization procedure, has been validated by means of numerical simulations and experimental measurements. The comparisons of the obtained results confirm the effectiveness of the procedure and future activities will be devoted to the integration of different kind of antennas operating in different wireless service frequency bands.

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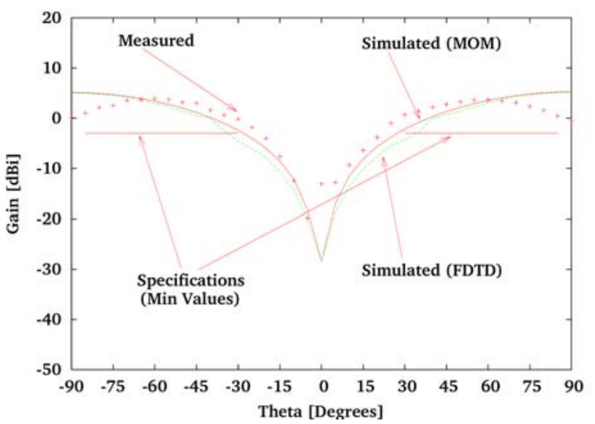
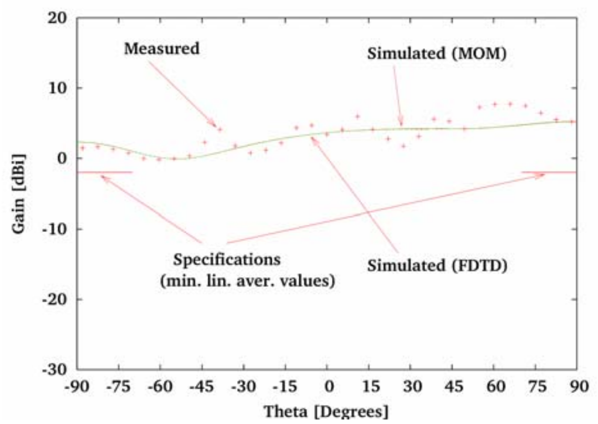
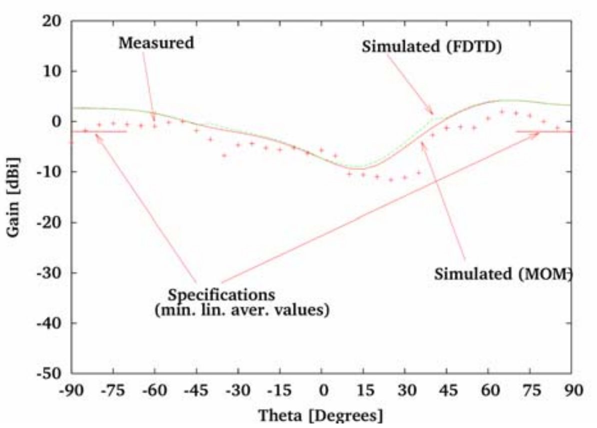


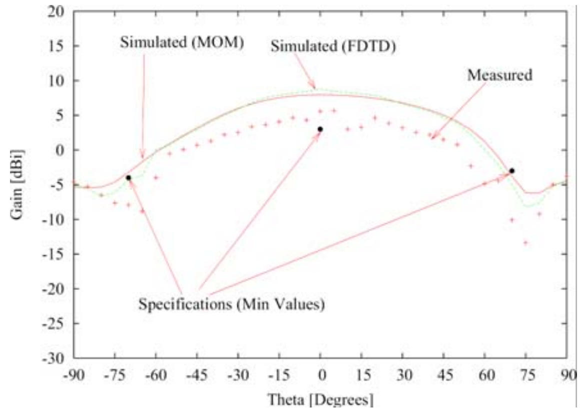
(a) COSPAS-SARSAT band



(b) GSM/GPRS lower (930 MHz)



(c) GSM/GPRS upper band (1850 MHz)



(d) GPS band

Figure 3. Measured and simulated gain of the optimized multi-function antenna (a) COSPAS-SARSAT band, (b) GSM/GPRS lower band, GSM/GPRS upper band and (d) GPS band.