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Transparent and conformal wheel-shaped fractal antenna for vehicular communication applications

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ABSTRACT

In this article, a low cost, compact conformal antenna is proposed for vehicular communications applications. The concept of fractal geometry is applied in this design to make the model more attractive in its appearance as well as to attain desired bands in the vehicular communication spectrum. It is fabricated on a transparent and flexible poly vinyl chloride material of size 55 mm × 40 mm × 3 mm. The proposed antenna is intended to operate in GSM-1800/1900, Digital Communication System (DCS-1800), Personal Communication Service (PCS-1900), Universal Mobile Telecommunications System (UMTS), Long-Term Evolution (LTE2600), Industrial, Scientific, and Medical radio band (ISM 2.4G), Wireless local area network (WLAN), Bluetooth, World Interoperability for Microwave Access (WiMAX), IEEE802.11p protocol based Vehicle-to-everything, Dedicated short-range communications (DSRC) and Wireless Access in Vehicular Environments (WAVE) communications bands. The prototype of the antenna in its planar and conformal versions exhibit the wideband characteristics and their measured results show good agreement with that of obtained simulation results. The virtual analysis of platform mounted characteristics of the proposed antenna at two different locations of the vehicle (vehicle rooftop and on side-view mirror) are performed in ANSYS Savant simulation tool and the corresponding far-field radiation performance is characterized.

1. Introduction

Day by day the applications in the vehicular technology is growing rapidly to establish safe and efficient communication systems. The advanced mobile communication techniques will be integrated into the automotive systems to provide accurate information and road-safety precautions to the driver at faster data rates. This could strengthen the driver to aware of the current road-traffic conditions as well as internal conditions of the vehicle and thereby improve the vehicular traffic safety [1]. Most of the earlier studies on vehicular antennas deal with hidden, glass-based antenna systems for FM reception [2], but the present scenario is drifting towards the microwave spectrum which is gaining attention with additional features that can be provided to the vehicle in terms of both safety and entertainment purposes like HD-Radio, Digital Video Broadcasting (DVB), GPS, GLONASS, GALILEO, Remote Vehicle Access, Bluetooth and Tyre pressure monitoring [3]. On the other hand, development of the network protocols and miniaturized electronics in conjunction with vehicular communication modules are getting their significance in the automotive industry. These simultaneous things are initiating the researchers around the world to work on the deployment of sophisticated modules, which include design of a suitable antenna with well-maintained operating performance characteristics. Design of modern antennas to fulfil the vehicular application requirements such as impedance bandwidth, gain and radiation performance altogether is a quite challenging task to the antenna engineers.

Since few decades, the antennas field has received much attention on developing compact systems with aerodynamic compatibility for integration and mounting on vehicles. There are several techniques that are available in literature for the antenna miniaturization, among which fractals have gained much interest. The self-similar and space filling properties offered by fractal structures [4,5] usually provide multi-band operation, and also makes the antenna smaller in size. The mathematical morphology of fractal geometries has been applied in various domains of interests such as electromagnetics and mechanics in determining the travelling wave solutions [6–9]. Moreover, design of antennas on new kind of substrate materials is emerging nowadays, in which the major focus is on the transparent substrates with flexible characteristics with high efficiency. In [10], a method of applying high conductive coating to selective regions of high current density is proposed to increase the efficiency of the antenna, which is designed to operate at 2.2 GHz. The multiband characteristics of antenna are

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illustrated by using a crescent shaped patch and the defected ground structure in [11]. The antenna with CPW feeding uses Cantor set fractal as radiating element and the T-shaped tuning stub produces the notch band in the antenna as mentioned in [12]. In [13], a fractal antenna is designed with Γ-shape radiating structure to operate in mobile communication bands which is fractalized by rotating the duplicated parts in quadrature angles and achieved the bandwidth enhancement. A transparent antenna is fabricated on a PET substrate and AgHT-8 as conducting media with CPW feeding [14]. The trapezoidal shape radiating patch and the rectangular slotted ground enables this antenna to work in dual band. Design of H-shaped slot antenna on a transparent material 1737 Corning glass substrate is demonstrated [15] in which the silver grid layer serves the purpose of conductive layer and this antenna operate from 1.83 to 2.23 GHz with a stable gain of nearly 5 dBi across the operating band. In [16], a defected microstrip structure band stop filter is embedded in the feeding structure and the inverted-π slot is introduced to achieve the notch band performance within a wideband response. A circular slot antenna designed in [17] with reconfigurable dual-notch response, which is realized by incorporating a pair of open-ended T-shaped stubs and inverted-F stub-loaded rectangular resonator etched in the CPW feeding structure. A coplanar waveguide fed antenna is designed in [18] to operate in dual band, which uses the two conducting strips and bow-tie shaped slots. The gap coupled modified square fractal is used in [19] to overcome the narrow band performance of the antenna and achieved 85.2% impedance bandwidth at 1.844 GHz resonant frequency. A transparent and flexible antenna is proposed in [20] to operate from 5.18 to 5.32 GHz WLAN service for the usage in laptop computers. In this design, the multilayer film named IZTO/Ag/IZTO is used in the prototyping of the model. Another transparent multilayer film-based antenna is presented in [21] fabricated on a polyimide substrate to operate at 1260 MHz frequency. The Sierpinski fractal carpet structure is used as the ground plane of the antenna presented in [22] and in turn dual-band operating spectrum is obtained. An antenna with the applications in designing smart windows, transparent mobile devices, etc. is presented in [23] which uses the metal mesh (MM) for enabling the transparency feature and operating from 2.4 to 2.5 GHz.

In this article, a novel transparent material-based fractal antenna is presented. The entire work is divided in different sections as per the operational convenience. In Section 2, the design aspects of the antenna with mathematical formulation, planar and flexible iterations of the proposed antenna are discussed. Section 3 illustrates the simulation and measured results of the proposed fractal antenna using Anritsu MS2037C VNA Master followed by the brief parametric optimization of critical geometrical variables used in the design. The radiation performance of the free-standing antenna in its planar and flexible configurations and surface current distribution characteristics are presented. Later, the far-field characteristics of the antenna is analyzed by placing antenna on the vehicular body. The performance of the proposed antenna is compared with the existing literature, and finally concluded the suitable vehicular application-oriented analysis in Section 4.

2. Antenna design

An area of metallization which is supported above a ground plane and fed against the ground at an appropriate point or points forms a generic microstrip patch antenna structure. The layout of the proposed transparent antenna is shown in Fig. 1. The antenna is designed on the transparent PVC substrate material with relative permittivity of 3.0, dielectric dissipation factor of 0.02 and thickness of 3 mm. The modified version of circular patch is used in this structure for which the signal is launched through coplanar waveguide (CPW) feeding. Fractal geometry is considered for the modified version of circular patch.

2.1. Materials and methods

The substrate is an important entity in the microstrip patch antennas which serves the purpose of holding the sensitive metallic layers and thus gives physical support, strength to the antenna. In this design, a thermoplastic polymer material named clear poly vinyl chloride (PVC) is used as substrate in the flexible form. Some plasticizers doped in this material to impart the softness and transparent colour with slight blue tint which possesses refractive index ranging from 1.54 to 1.56. Its attractive features such as chemically inertness, water resistant, corrosion resistant and weather resistant, thermal and electrical insulation, self-extinguish towards flammability are influenced to use this material as substrate in the antenna design.

The 3D electromagnetic analysis of the proposed antenna is performed in ANSYS HFSS simulation tool which uses the finite element method (FEM) for analysing the antenna geometry and obtaining the fundamental characteristics such as reflection coefficient and radiation patterns. The platform mounting analysis of the antenna is performed in the simulation tool ANSYS Savant, which is based on an asymptotic (high-frequency) method of Shooting and Bouncing Rays (SBR).

2.2. Structure and design

The evolution of the proposed antenna is demonstrated through several structural alterations in the circular patch with the iterations shown in Fig. 2 (see Table 1).

In the first iteration, a circular ring shape radiating element is used with CPW feed as shown in the Fig. 2(a). The input (feed) line of width 'W_f' and length 'L_f' is fed against the upper ground plane of dimensions '$L_g \times W_g$' fulfils the coplanar waveguide feeding. The advantage of using this feed is to minimize the cross-polarization and mutual coupling [24]. A gap of 'g' is maintained between the feed line and the ground conductors for impedance matching. The width of the circular ring is $(R_1 - R_2)$ where R_1 and R_2 are the outer and inner radius of circular ring. One of its interesting features is that, the size of the circular ring is substantially smaller than that of the circular patch when both are operated in the lower operating band. This circular ring structure is expected to create a resonating response owing to its sufficient electrical length, which could correspond to low frequency between 1 and 2 GHz. In the second iteration, a circular disc is placed concentrically to the circular ring. This could improve the resonant behaviour of the antenna due to the annular slot formed in the resultant antenna structure as shown in the Fig. 2(b). In iteration-3, the annular slot is filled with eight circular elements with radius of $(a_1 + t_1)$ as displayed in Fig. 2(c). The center of these individual circular elements is located at 'd_1' distance from the center of the patch. Filling the gap between the circular ring and concentric circular element is expected to minimize the reflection losses across its operating band. In the iteration-4, a total of eight circular elements with radius 'a_1' are etched from previously filled circular elements of radius $(a_1 + t_1)$. In the further iterations of 5 and 6 the scaled version of circular cuts used in iteration-4, are engraved from the remaining conductive portion which is existing in the radiating patch. For obtaining this type of fractal geometry, the scale factor 'sf' is considered and this is used for downscaling of corresponding circular cuts made in the radiating patch. The mathematical considerations are presented in the following section.

2.3. Mathematical formulation

The circular ring element in the iteration-1 with outer radius 'R_1' and inner radius 'R_2' placed on a material of relative permittivity 'ε_r' then the effective relative permittivity 'ε_e'is given by [25] is

$$\varepsilon_e = 0.5(\varepsilon_r + 1) + 0.5(\varepsilon_r - 1)\sqrt{(1 + 10t/W)} \quad (1)$$

where

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