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Conformal Multifunction Antenna for Automobiles

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1. Introduction

The development of a conformal automobile antenna having more than three functions began in 1993 at Wang Electro-Opto Corporation (WEO, formerly Wang-Tripp Corporation) [1-5]. It was an internally funded effort to develop a rooftop-mount multifunction antenna that can simultaneous handle six functions: AM and FM radios, remote keyless-entry, cell phone, satellite communications and satellite geolocation (GPS and GLONASS). The design was soon selected by a major U.S. automobile manufacturer for possible integration into a new passenger car model.

Unfortunately, the prototype development effort funded by that auto manufacturer was short-lived. First, the RF performance requirements established for the analog world was overly, and unnecessarily, demanding. Second, the auto manufacturer's "body people" were still in a denial mode against the cavity that must be cut out on the car to accommodate the antenna being designed. Indeed, the development effort was way ahead of both real market needs and technology maturity.

Over the last fourteen years, rapid growth of wireless services has led to a proliferation of antennas on automobiles. As a result, there are now serious efforts to develop conformal multifunction automobile antennas to reduce the antenna counts on cars [e.g., 6-7]. This paper discusses some key design issues and the latest approaches at WEO.

2. Wireless Systems on Modern Automobiles

Table 1 summarizes wireless systems on the automobile. This table is by no means complete, as more and more wireless systems are appearing, such as various mobile satellite communications systems, UWB (ultra-wideband) systems, etc. Nor is the table consistent with all the conventions, some of which change with time or vary with geographical locations.

Table 1: Wireless Systems onboard Automobiles

System	Freq (MHz)	Pol	Pattern	Sat/Ter	Tx/Rx
AM Radio	0.526-1.607	VP	Omni	Ter	Rx
FM Radio	87-108	HP	Omni	Ter	Rx
Keyless entry	350	VP	Omni	Ter	Rx
Dig. Video Broad-T	470-862	VP	Omni	Ter	Rx
Misc. Anal. Mobile	450-900	VP	Omni	Ter	Tx/Rx
GSM 900/1800	890-960/1710-1880	VP	Omni	Ter	Tx/Rx
PCS (low band)	901-941	VP	Omni	Ter	Tx/Rx
PCS (high band)	1850-1990	VP	Omni	Ter	Tx/Rx
Dig. Aud Broad-T	1452-1492	VP	Omni	Ter	Rx
GPS L1/L2	1563-1587/1164-1188	RHCP	Unidirect.	Sat	Rx
GLONASS L1/L2	1593-1610/1239-1254	RHCP	Unidirect.	Sat	Rx
Galileo	1164-1591 (6 bands)	RHCP	Unidirect.	Sat	Rx
DECT	1880-1900	VP	Omni	Ter	Tx/Rx
UMTS	1885-2200	VP	Omni	Ter	Tx/Rx
Satellite Radio	2400-2460	RHCP	Unidirect.	Sat	Rx

The omnidirectional pattern is generally required for terrestrial services, and the unidirectional pattern of broad beam width (with hemispherical coverage) is required for satellite

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services. For terrestrial services, the polarization is not crucial (due to multipath propagation); however, generally VP (vertical polarization) is specified, CP (circular polarization) is preferred, and HP or slanted LP (linear polarization) is also acceptable.

3. Can a Single Multifunction Antenna Handle All Wireless Needs on an Automobile?

To handle all the functions in Table 1, using a single conformal multifunction antenna, is obviously very difficult. The antenna has to cover such a wide range of frequencies, differences in pattern and polarization, and to be conformal to and compatible with the metallic or non-metallic surface of the automobile. Therefore, it is significant to note Toyota's plan, revealed in a recent interview article with its CEO, that "Toyota cars may achieve over the next decade the ultimate goal of just one antenna for a car…. Currently, dozens perform that task" [7].

Although the ambitious Toyota goal is consistent with the U.S. military's JTRS (Joint Tactical Radio System) being developed, it is worth noting that the antenna solution for similar JTRS clusters still remains largely elusive, even after 20 years of research including its predecessor SPEAKEASY program. Furthermore, Toyota's multifunction antenna is more difficult to design than the JTRS's if the antenna includes AM and FM radios. Nevertheless, this author shares the Toyota vision under the premise that Toyota's "one antenna" refers to an "antenna structure" using a "shared aperture" approach.

Indeed, the fundamental design approach, supported by measured data, was already in place and reported more than a decade ago [1-5]. The multifunction antenna employed the newly invented SMM (spiral-mode microstrip) antenna [2], which has multioctave (in fact, over 10:1) bandwidth and multimode, both omnidirectional and unidirectional, radiation patterns for terrestrial and satellite services, respectively. The SMM antenna and a coupled loop antenna were placed on the rooftop of a car, simulated with aluminium screen and plates, inside a metallic cavity approximately 1-inch (2.54 cm) thick and 2 ft × 2.5 ft (61 cm × 76 cm) in area. The breadboard antenna functioned fairly for AM/FM radios and remote keyless entry. It also worked for satellite communications and geolocation using the mode-1 operation of the SMM antenna, which has a unidirectional pattern. However, its mode-0 (with omnidirectional pattern) performance was not good enough.

Over the next ten years, research at WEO gradually enhanced the performance of the mode-0 SMM antenna, resulting in excellent ultra-wideband (instantaneous bandwidth over 10:1) [8-12]. It is also worth noting that this approach has been investigated comprehensively by Gschwendtner and Wiesbeck [6] with operation practically over 470-2200 MHz for mode-0, and 1300-2200 MHz for mode-1. In their work, the antenna is placed in a circular metallic cavity, 40-cm in diameter and 4-cm deep, on the top of the trunk lid of a small sedan. As a comparison, the smaller cavity in [6] restricted the spiral antenna to operations at frequencies much higher than those in [1], which had cavity 3.7 times larger in area. **Today, it is indeed technically feasible to develop a single conformal multifunction automobile antenna as envisioned in [7].**

4. Room and Location for Mounting Automobile Antenna

In the preceding section, we established the feasibility of a single conformal multifunction antenna for automobiles. In the process we also exposed the real issues at stake. It is not whether a multifunction antenna can be designed to handle all the functions on a car, but how large the antenna will be and how well it can perform, and whether or how its presence can be tolerated by the "body people" within the automobile manufacturer.

The room and location allowed for antenna installation are based on complex tradeoffs among performance, cost, aesthetic appeal, customer taste and fashion, etc. In early 1990s, a cavity 61 cm × 76 cm in area and 3-cm in depth was electronics engineers' specification objected by the "body people" [1]. Today, even with the mandate of the CEO, it is questionable whether they would accept a cavity size 40-cm in diameter and 4-cm in thickness, as chosen in [6]. Indeed, **a cavity 30-cm square and 3-cm thick, to the senior author's best knowledge, appears to be the upper bound acceptable to "body people" at major automobile manufacturers worldwide.**

To reduce the antenna size below 30-cm diameter, an interim solution was taken, in which AM/FM radios and keyless entry were excluded. Fig. 1 shows two multifunction antennas, protected by a radome about 20-cm in diameter, mounted on the rooftop of two passenger cars, which handled terrestrial and satellite services from around 800 MHz up to 5 GHz.. Field tests conducted sporadically over the years on GPS and local cell phone services showed satisfactory performance. To expand the operating frequencies down to 300 MHz, and perhaps even 80 MHz, new techniques are now being pursued, which will be discussed in a latter section.

Figure 1. Multifunction SMM antennas mounted on rear rooftop of two passenger cars.

As for the location of the antenna, both the rooftop [1, 3] and the trunk lid [6] were considered acceptable. In general, rooftop mount offers better performance, easily by 3 dB or more, than trunk lid mount because of its unobstructed field of view, higher antenna height, and a larger conducting surface that is the real radiating antenna at lower frequencies.

5. Antenna Feed Network

The feed network of a multifunction antenna includes multiplexing and/or switching circuits which can perform each function simultaneous or selectively. For each function, adaptive diversity can also be employed to enhance performance. Today, multifunction and MIMO (Multiple-Input Multiple-Output) are generally treated as different and independent architectures for wireless systems, with different requirements for the antenna employed. With the proliferation of wireless systems, the automobile multifunction antenna, as an end-user equipment, must be upgradable, scalable, affordable, and reliable, and its role will extend into the MIMO architecture. However, the antenna system per se, including its feed network, is best to be so transparent that it does not have to be reconfigurable, or systems specific.

6. Performance Enhancement, Size Reduction, and Fabrication/Cost Issue

The long-standing and unproductive efforts in reducing the size of the antenna had been doomed for over half a century by the classical theory on the limitation of antenna gain-bandwidth by its electrical size. In 2005 and 2006 [13], the senior author pointed out the deficiencies in applying the theory to real-world antennas, in particular that a travelling-wave antenna mounted on a platform is not subject to the rigid classical physical limitation on gain bandwidth. As a result, performance enhancement and size reduction have become much more feasible today, and thus the unique broadband and multimode features of the spiral antenna can be exploited to enhance performance, as well as add new features, for automobile multifunction antennas.

To reduce the size of travelling-wave antennas, the senior author and his colleagues had conceived the magneto-dielectric antenna [14] and the miniaturized slow-wave antenna [15]. However, these techniques have been hampered by the lack of practical low-loss high permittivity/permeability materials at high RF frequencies.

During the past decade, practical low-loss high-permittivity/permeability materials are becoming more and more available. With the advent of LTCC (low-temperature co-fired ceramic), LCP (liquid crystal polymer), and high-permeability ceramic materials, etc., research in antenna size reduction has become very active, and promising results have been reported. In particular, magneto-dielectric materials for frequencies up to 1 to 3 GHz are recently reported to be available. The use of magneto-dielectric materials with equal relative permittivity and permeability (ε_r and μ_r), for $\varepsilon_r = \mu_r = 2.0, 4.0, 5.0$, etc. at another laboratory was observed to achieve antenna size reduction without significant degradation in performance [16], as envisioned in [14-15]. It is certain that new materials will be developed in the next 3-10 years from vigorous research in metamaterials, artificial materials, nanotechnology, etc. For the time being, research in antenna size reduction at WEO is being conducted using commercial-off-the shelf (COTS) electromagnetic materials.

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