Performance Enhancement of Low-Profile Wideband Multi-Element MIMO Arrays Backed by AMC Surface for Vehicular Wireless Communications

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ABSTRACT A low-profile printed dipole antenna (PDA) backed by broadband rhomboid artificial magnetic conductor (AMC) is introduced for vehicular wireless communications. Firstly, a suggested PDA with a pair of the microstrip E-shaped dipoles is fed by an E-shaped microstrip feedline to expand the bandwidth in the measured range of 5.5-6.96 GHz ($S_{11} \leq -10$ dB). Then, the suggested rhomboid AMC reflector is inserted into the PDA to gain improved radiation efficiency up to more than 90%. The PDA loaded by the 3×3 rhomboid AMC array with the size of 48 mm×48 mm×6.8 mm exhibits -10 dB measured impedance bandwidth from 4.48 to 7 GHz (almost 44%) for wireless local area network (WLAN) and worldwide interoperability for microwave access (WiMAX) applications. The suggested PDA with AMC compared to the PDA without AMC exhibits a size reduction of 42.3%, enhanced gain up to 8.4 dBi, and excellent impedance matching (at least -20 dB) with uni-directional radiation patterns. The novel AMC unit cell is realized based on the recognized method as rhomboid coupled parasitic patches. The rhomboid AMC design operates at 6.20 GHz with an AMC bandwidth of 5.10-7.18 GHz (34%). Also, by loading 3x4 and 5x5 AMC reflectors into the two-element and four-element array of PDA, low-profile wideband structures with enhanced radiation properties are achieved. The measured S-parameters show the broad bandwidth from 4.48 to 7.12 GHz in C-band with enhanced gains and efficiencies (more than 90%) of multiple elements. Besides, the suitable isolation between the array elements of more than 30 dB for multiple-input multiple-output (MIMO) systems is achieved by applying various polarized directions of PDAs and loading periodic AMC reflectors.

INDEX TERMS Artificial Magnetic Conductor (AMC), Electromagnetic Band Gap (EBG), Printed Antenna, MIMO, Wideband, WLAN/WiMAX.

I. INTRODUCTION

Vehicular communication plays a major role in the development of transport systems by considering diverse daily problems, such as pollution, traffic jams, and accidents. It includes the standard technology to enable fast and secure vehicle-to-vehicle and vehicle-to-infrastructure communications (see Fig. 1). By increasing the development of wireless communication systems, wideband antennas have been considered for vehicular wireless networks [1]. Microstrip antennas can be nominated to provide high-quality signals for vehicular wireless networks due to the prominent features like low-profile, light weight, and ease of implementation [2] and [3]. In these structures, compact wideband microstrip antennas are applied for smart wireless devices and intelligent transport systems. Nowadays, Intelligent Transportation Systems (ITS) will significantly influence diverse aspects of life as its applications for traffic safety and efficiency. Vehicular communication plays an important role in the realization of these applications as it enables direct information exchange between vehicles. In the past decade, extensive efforts have been performed into the research on the applications, architectures, protocols and channel models of vehicular communications [4]-[6].

FIGURE 1. Vehicular wireless communications.
Low-profile wideband microstrip antennas can be considered for vehicular mobile communications owing to minimized interference, high data rate transmission, and limited space and coverage multipath environment [7]-[10]. For this purpose, compact low-profile multiple-input multiple-output (MIMO) antennas are becoming more interesting for vehicular wireless base station systems [8]. In the last decades, the growth of wireless networks has concluded the extensive use of MIMO technology. The MIMO systems use printed antennas like microstrip antennas due to their charming specifications, like a low profile structure, light weight and simple implementation [11] and [12]. Although a low impedance bandwidth of the microstrip antennas is considered a significant challenge in most discussions. A compact MIMO antenna with the operating bandwidth of 3.33-3.67 GHz for 5G mobile terminals is studied in [11]. In recent literatures, there are various techniques to reduce the mutual coupling of array elements [13]-[16]. In previous studies of [14]-[16], various designs of microstrip arrays by using meta-surface are introduced to improve the isolation between elements. For example, the 2x2 patch array with improved isolation and a wide bandwidth of 8-9.25 GHz (14.5%) for MIMO and SAR applications is reported in [15]. Diverse approaches in previous studies are introduced to ameliorate the bandwidth of microstrip antennas [17] and [18].

In most studies, electromagnetic band-gap (EBG) structures have been employed in many wireless networks and a wide variety of electromagnetic equipment due to their unique and remarkable characteristics [19]. They exclude the surface wave’s propagation in a determined frequency gap. It is known, the artificial magnetic conductor (AMC) structures introduce a privilege like a perfect magnetic conductor with in-phase reflection response entire a certain range. Based on this, multiple low profile antennas and mode prevention designs are applied AMCs as diverse surfaces to augment the distinguishing features [20]-[29]. Among these works, a mushroom-shaped AMC structure as a beneficial approach is usually applied for diverse arrangements to achieve the low profile structures with a higher efficiency [24]. In the recent work, an EBG mushroom surface with a dual-layer is reported to attain a size reduction of more than 60% for multiple patch microstrip antennas [28]. This study is designed to present diverse two and four-element patch antennas at 2.5 GHz for MIMO systems. It is noted that a narrow AMC bandwidth in designing broadband microwave technologies and antennas is a drastic drawback [30]. Therefore, there are few types of research for broadening the bandwidth of AMC structures [31]-[33]. In [33], a bandwidth of 4.4% at the resonance of 6.2 GHz is demonstrated to acquire a compact AMC unit cell with relatively acceptable angular stability.

Recently, by ameliorating the variety of integrated circuit technologies, the broadband AMC surfaces in the low-profile microstrip antennas are impressively utilized with improved features [34]-[43]. In [35], a low profile circular polarized dipole antenna with the AMC surfaces like a reflector plate is reported to provide a broadband antenna with a higher gain. This antenna loaded by AMC with the total size of 240 mm×240 mm includes the impedance bandwidth in 1.19–2.37 GHz with the axial ratio (AR) bandwidth of 1.25–1.97 GHz.

The present study reports a detailed discussion of the new suggested PDA using broadband AMC design for vehicular wireless systems. At first, a low profile broadband PDA with microstrip E-shaped dipoles is introduced. For this purpose, two radiating E-shaped dipoles fed by the E-shaped feedline broaden the impedance bandwidth in C-band. In the following, a rhomboid AMC is introduced to resonate at 6.20 GHz (5.1-7.18 GHz) for broadband application in C-band. Then, a 3x3 rhomboid AMC reflector array is developed under the PDA to obtain the ameliorated radiation efficiency. It presents the measured -10 dB impedance bandwidth in 4.48-7 GHz for WLAN/WiMAX and Vehicular base station systems. Also, the proper impedance matching at least -20 dB over the band and excellent compactness with enhanced gain are achieved. Meanwhile, the performance of the AMC surface inserted in PDA is studied by introducing two-element and four-element arrays of the suggested design with improved radiation properties for MIMO systems. For this purpose, the PDAs with different polarized directions are considered to investigate the isolation between the antenna elements for achieving low-profile wideband MIMO arrays.

II. SUGGESTED PRINTED DIPOLE ANTENNA WITH BROADBAND AMC REFLECTOR

3D view and top view of suggested PDA backed by planar AMC surface are drawn in Fig. 2. Two radiating dipoles with E-shaped arms are placed on the Taconic TLT substrate with a size of 48 mm×48 mm, \( h_2=0.8 \) mm thickness, \( \varepsilon_r=2.55 \) and loss tangent of 0.0006. The 3x3 periodic patch array of the rhomboid AMC surface is placed underneath the PDA as a reflector. It is made from substrate thickness (FR4) of \( h_3=3 \) mm to couple the energy to the top layer. The Styrofoam layer is embedded between the AMC reflector and PDA as an air gap to achieve the optimum wideband performance. The optimum value of \( h_2=3 \) mm selects as the air gap distance. The PDA as a top layer includes two printed E-shaped dipoles on the top side and an E-shaped microstrip feedline on the backside. One dipole is fed by the coaxial probe and the other dipole couples by applying the E-shaped feedline. The second dipole leads to better impedance bandwidth and more symmetrical radiation patterns due to symmetric structure.

The proposed PDA is introduced based on an E-shaped patch with unequal arms for achieving different resonances [20]. The length, width and position of slots into the E-shaped patch with the multi-arms result in a broad bandwidth. By incorporating multiple parallel slots into the patches with unequal resonance arms, various resonances occur and thus the impedance bandwidth can be broadened.
The conventional microstrip patch antenna is modelled as a simple resonant circuit \( L_1 C_1 \), as seen in Fig. 3 (b) with the presented lumped elements [18] and [20]:

\[
C_1 = \frac{\varepsilon_r \varepsilon_0 L_w}{2h} \cos^{-1}\left(\frac{\pi f_0}{L_e}\right)
\]

\[
L_1 = \frac{1}{(2\pi f_0)^2 C_1}
\]

\[
R_1 = \frac{Q}{\omega C_1}
\]

\[
Q = \frac{\sqrt{\varepsilon_r f_0}}{4 f_0 h}
\]

where \( f_0, L_e, f_c, h \) and \( \varepsilon_r \) are the distance of feed point from the edge, the effective length of the patch, the frequency of operating band and substrate characteristics, respectively. When two slots incorporate into the patch as E-shape, an additional series inductance \( \Delta L \) and an additional capacitance \( \Delta C \) as a gap capacitance between the middle and side arm of the E-shaped patch can be modelled as shown in Fig. 3 (c). Two E-shaped arms with the centre arm are coupled with \( C_c \) (see Fig. 3(d)). Thus, different inductive and capacitive couplings in the proposed patch design result in a wide impedance bandwidth with multiple resonances.

On the basis of the transmission line model for the rectangular radiating patch, the basic width (\( W \)) and length (\( L \)) of the patch at the resonant frequency are determined using equations (5)-(8) [18]:
\[
W = \frac{\lambda_0}{2\sqrt{\varepsilon_r + 1}}
\]
\[
L = \frac{c}{2f_0 \sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L
\]
\[
\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1 + \varepsilon_r - 1}{2}\left(1 + \frac{1}{1 + 12\frac{h}{W}}\right)
\]
\[
\Delta L = 0.412h \left(\frac{\varepsilon_{\text{eff}} + 0.3}{\varepsilon_{\text{eff}}} - \frac{0.258}{\varepsilon_{\text{eff}}} + 0.264\right)
\]

Where, \(\varepsilon_{\text{eff}}, h\) and \(\Delta L\) are effective permittivity coefficient, thickness and additional length due to fringing fields, respectively. Similarly, the basic width and length of the printed microstrip dipole antenna are designed based on the equations (5)-(8) for given operating frequency at C-band. In this case, dielectric constant substrate, \(\varepsilon_r=2.55\) is considered. The optimum sizes of the proposed PDA such as different lengths and the total height of the patch are optimized by full-wave simulator with the parametric study.

The feedline system with the E-shape is recognized as a feeding method to attain better coupling and thus a proper impedance matching achieves in the input port. For this purpose, the parameters of \(P_1, T_1, \) and \(P_2\) for feedline are optimized, according to Fig. 2 (b). The dimensions of the width and length of one dipole are 16 mm \(\times\) 8.9 mm, and they etch on the substrate by sizes of 48 mm\(\times\)48 mm. The feeding system of PDA for 50- \(\Omega\) input impedance is utilized by using a long coaxial probe, as seen in Fig. 2 (d). The coaxial probe connects to the first printed dipole and it is coupled to the second dipole branch by E-shaped feedline on the rear side of the substrate. The main design parameters select as thicknesses \(h_1=0.8\) mm, \(h_2=3\) mm, and \(\varepsilon_r=4.4\) and \(\tan\delta=0.02\) for FR4 substrate. The arrangement of the 3\(\times\)3 AMC periodic ground plane is developed below the PDA as the reactive coupling to conclude a broader bandwidth and enhancement of radiation properties. The sizes of the suggested structure with AMC are listed in Table I.

Fig. 4 demonstrates the geometry of a suggested rhomboid AMC unit cell. The regular patches are combined with a center square patch. It is noted that the proposed AMC is achieved based on the AMC in [22] with some modifications of parasitic elements to operate in C-band for broadband wireless applications. It can be modified and optimized based on the size of \(m\) and \(n\) and the electrical specification. By studying the reflection properties of the infinite AMC unit cell, an acceptable wideband performance in C-band is achieved. The relative permittivity and thickness of \(\varepsilon_r=4.4\) and \(h=3\) mm, respectively are selected to realize on an FR4 substrate. The dimension of the unit cell is equal to \(m=10.5\) and \(n=7\) mm and the size of the ground plane is selected 16\(\times\)16 mm\(^2\).

The electrical and structural specifications of the rhomboid AMC are the main factors on obtaining the enhanced bandwidth. The structural specification of the broad AMC bandwidth acquires from the reactance couplings for arms, slots and parasitic patches. The optimum AMC bandwidth is gained by choosing the suitable electrical specification as \(h\) and \(\varepsilon_r\). Based on this, the angular stability should remain without variation for broadband applications. Indeed, various parts with slots insert into the rhomboid AMC design, lead to an extra inductance and capacitance and an extensive AMC bandwidth is obtained [18].
The mushroom-type EBG structure is formed by a via-loaded metal patch which can be characterized by an equivalent parallel LC resonator with a resonant frequency \( f_r = 1/(2\pi\sqrt{LC}) \). The inductance \( L \) is obtained by the current path between the patch surface and ground plane through via. Besides, the capacitance \( C \) represents the gap effect between two adjacent patches. The values of LC resonator and the frequency band gap in terms of the EBG parameters can be determined by the following formulas [24]:

\[
C = \frac{W_{ebg} \varepsilon_r (1 + \varepsilon_r)}{\pi} \cosh^{-1}\left(\frac{2W_{ebg} + g}{g}\right)
\]

(9)

\[
L = \mu_0 h
\]

(10)

\[
BW = \frac{1}{\eta} \sqrt{\frac{L}{C}}
\]

(11)

where, \( \varepsilon_r \) and \( \mu_0 \) are the permittivity and permeability of free space, respectively. Also, \( \eta \) is the free space impedance which is \( 120\pi \).

The electromagnetic properties of the suggested AMC are analyzed based on the finite element method (FEM) for periodic arrangements. As shown in Fig. 4, an infinite model is fulfilled with a periodic boundary condition (PBC) at the surrounding faces. It helps to model the infinite conditions of the unit cell to investigate the reflection properties for different incident angles with various polarization angles.

III. EXPERIMENTAL AND SIMULATION RESULTS

An investigation of reflections responses of the infinite AMC array is discussed in this section. Also, a printed antenna backed by the rhomboid AMC surface is tested to achieve a low-profile broadband antenna.

The finite element method based on the Floquet theory is utilized in Ansoft High-Frequency Structure Simulator (HFSS) to simulate the AMC design. Fig. 5 plots the reflection magnitude and phase of the suggested AMC by radiating the perpendicular TE/TM waves (\( \theta=0^\circ \)). The simulated result of \( \pm90^\circ \) reflection phase for TE/TM waves includes 5.10-7.18 GHz (34%) with a resonance of 6.20 GHz. Also, Fig. 5 (b) plots the phases and magnitudes of the reflection response of the rhomboid AMC for diverse inclined incident waves \( \theta=0^\circ \) to \( 45^\circ \) in two polarization angles of \( \phi=0^\circ \) and \( 90^\circ \). Moreover, symmetric AMC leads to the same results in both polarization angles of \( 0^\circ \) and \( 90^\circ \). Fig. 5 (a) plots the reflection magnitudes with little losses around the resonance. As compared to the known researches [24] and [31]-[33], the suggested AMC expresses the acceptable characteristics. It indicates the symmetric unit cell design with the same response for TE/TM waves and considerably broader bandwidth (more than 2 GHz) with acceptable stability over the AMC bandwidth for broadband application in C-band. Based on this, the good angular stability attains for broadband applications.

FIGURE 5. Magnitude and phase of TE/TM responses of rhomboid AMC for indirect incident waves in \( \phi=0^\circ \) and \( 90^\circ \).

FIGURE 6. Measurement and simulation results of S-parameters of the suggested PDA over AMC and without the reflector and effect of simple square AMC reflector.
FIGURE 7. Simulation results of S-parameters of the suggested PDA with AMC for different heights of the air gap.

The measured and simulated S-parameters of the suggested PDA design over AMC and without the reflector are illustrated in Fig. 6. The PDA without AMC surface includes the measurement range of 5.5-6.96 GHz (23.4%) for $S_{11} < -10$ dB. It presents a broadband printed antenna for wireless applications in C-band. As seen from Fig. 6, the suggested PDA with the rhomboid AMC reflector indicates the -10 dB measured bandwidth of 43.90% in 4.48-7 GHz in C-band. The proposed design with obtained bandwidth is considered a proper candidate for WLAN/ WiMAX and MIMO systems. It is concluded that the PDA with the 3x3 AMC reflector presents the bandwidth enhancement of almost double that of the PDA without the AMC reflector. On the other hand, the decrease in the operating frequency leads to suitable miniaturization. As an interesting note, at the PDA with AMC reflector an impedance matching of -45 dB occurs over the obtained bandwidth. The suggested PDA with AMC reflector in comparison with the PDA without AMC has an excellent matching of at least -20 dB. Therefore, it results in a low-profile antenna with improved radiation properties and enhanced broadside gain. Moreover, the proposed design loaded by simple square AMC reflector with unit cell’s size of 14x14 mm$^2$ covers 5.28-6.85 GHz, according to Fig. 6. It is concluded that using novel idea of rhomboid AMC design results in a wider bandwidth and more size reduction with better impedance matching.

The total dimensions (width x length x height) of the PDA without AMC reflector are $0.88\lambda_L$, $0.88\lambda_L$, and $0.015\lambda_L$, respectively ($\lambda_L$ is the wavelength at the lower frequency). Whereas, the total dimensions of the PDA with the rhomboid AMC surface are $0.71\lambda_L$, $0.71\lambda_L$, and $0.101\lambda_L$, respectively. Thus, by introducing the rhomboid AMC reflector in the suggested structure, a size reduction of 42.3% gains compared with the PDA without the AMC.

Fig. 7 illustrates the effect of the height of the air gap, $h_2$, between the printed antenna and the AMC reflector. It is obviously seen that for $h_2=3$ mm, an optimum result of S-parameter is attained for wide bandwidth with excellent impedance matching. With an increase in the air gap, the bandwidth enhances until $h_2$ reaches the optimum value. By passing from $h_2=3$ mm, the impedance matching is decreased.

FIGURE 8. Simulation results of S-parameters of the suggested PDA with AMC for variations of $m$ and $n$.

FIGURE 9. Simulated and measured gains of the suggested design with and without AMC reflector.

The simulated S-parameters of the suggested PDA with 3x3 AMC reflector for variations of $m$ and $n$ in the rhomboid unit cell are provided in Fig. 8. Indeed, it describes the design process of the suggested antenna to gain an optimum result. For $m=10.5$ mm and $n=7$ mm, optimum performance is achieved compared to the other sizes of AMC unit cell. In this status, the return loss of the proposed structure reaches less than -21 dB. The maximum gain of the suggested PDA with rhomboid AMC surface within the operational bandwidth is 8.4 dBi, as seen in Fig. 9. Thus, the gain of the structure is impressively increased over the obtained impedance bandwidth up to more than 4 dBi with slight variations and good stability. Besides, it is seen that the gain in the backside direction for the suggested design with AMC reflector is considerably reduced to -20 dB compared to the PDA without the reflector. For this purpose, a low profile structure with directional radiation patterns is achieved for wideband wireless operation.
Fig. 10 plots the surface current density on the printed dipole antenna and AMC reflector at various resonant frequencies. As seen from Fig. 10 (a) at the lower resonance of 5.25 GHz of the suggested design, a current distribution dominates on the feed place for the first dipole branch which is directly connected to the E-shaped feedline. It also concentrates on the sections of the AMC unit cells that are located under the feed line, especially the center unit cell. It is obtained that in Fig. 10 (b) at the higher resonance of 6.6 GHz, the current density distributes on the long arms of the first E-shaped dipole that is connected directly to the E-shaped feedline and second coupled E-shaped dipole. Also, at this resonance, the current density focuses on most unit cells of the AMC and around the central section of the structure.

Also, the co-polarization and cross-polarization of radiation patterns for the proposed design are plotted in Fig. 11. It illustrates the acceptable cross-pol level of at least -25 dB and -40 dB in both XZ and YZ-planes, respectively at three frequencies of wide operating band.

**FIGURE. 10.** Surface current density on the suggested PDA with AMC at (a) 5.25 (b) 6.6 GHz.

**FIGURE. 11.** Radiation patterns of the suggested PDA with the AMC surface for co and cross-polarizations (a) XZ-plane and (b) YZ-plane.
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Table II. Comparison of suggested design with other studies

| Proposed design | Measured Impedance bandwidth (5 ≤ ε ≤ 10 dB) and Applied substrate | Size of antenna (Width x Length x Height) and Applied substrate | Type of used AMC and AMC bandwidth | Utilized Techniques and Measured isolation | Maximum Gain and Efficiency | Practical Applications | Height of the overall antenna |
|-----------------|---------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------|-----------------------------------------|-----------------------------|--------------------------|--------------------------|
| Suggested PDA with AMC | 4.48-7 GHz (43.9%) Minimum impedance matching: -45 dB 48x8x6.8 mm$^3$ 0.71$\lambda_x$ x 0.71$\lambda_y$ x 0.101$\lambda_z$ | Rhomboid AMC unit cell 5.10-7.18 GHz | Diverse polarizations of PDA with 3x4 AMC array (Isolation> 31 dB) | 8.4 dBi 94% | WLAN/ WiMAX, MIMO Systems | 6.8 mm |
| MIMO antenna [11] | 3.33-3.67 GHz (9.7%) Minimum impedance matching: -20 dB 70x140x0.8 mm$^3$ 0.177$\lambda_x$ x 1.55$\lambda_y$ x 0.009$\lambda_z$ | Substrate: εr=4.3 | - Decoupling techniques using two-port feed network (Isolation> 15 dB) | 6 dBi 78% | 5G Mobile | 0.8 mm |
| 1x2 array with EBG- MTM in [14] | 8.7-11.7 GHz, 11.9-14.6 GHz Minimum impedance matching: -40 dB 37x70x1.6 mm$^3$ 1.07$\lambda_x$ x 2.03$\lambda_y$ x 0.053$\lambda_z$ | Substrate: εr=4.3 | - Inserting a fractal isolator between the radiating elements (Isolation> 20 dB) | 9.15 dBi 72%-95% | MIMO and RFID Applications | 1.6 mm |
| 2x2 array with EBG in [15] | 8.9-25 GHz (14.5%) Minimum impedance matching: -15 dB 96x96x1.6 mm$^3$ 2.56$\lambda_x$ x 2.56$\lambda_y$ x 0.043$\lambda_z$ | Substrate: εr=4.3 | Metamaterial based on fractal EBG closely-packed patch arrays based on decoupling structure of fractal cross-shaped EBG surface (Isolation > 17 dB) | 7 dBi 89% | X-band, MIMO and SAR Applications | 1.6 mm |
| antenna with AMC in [30] | 3-4.1 GHz (31%) Minimum impedance matching: -30 dB 75x75x12.7 mm$^3$ 0.75$\lambda_x$ x 0.75$\lambda_y$ x 0.127$\lambda_z$ | Substrate: εr=4.3 | Simple square AMC unit cell 3.1-4 GHz | 7.1 dBi 88% | MIMO Systems | 12.7 mm |
| Printed antenna with AMC in [34] | 2.37-2.50 GHz (5.34%) Minimum impedance matching: -27 dB 100x125x7.5 mm$^3$ 1.02$\lambda_x$ x 0.82$\lambda_y$ x 0.63$\lambda_z$ | Substrate: εr=3.44 | Simple square AMC unit cell 2.28-2.64 GHz | Printed slot antenna with wideband 3x5 AMC array | 10.3 dBi 88% | WLAN Application | 7.5 mm |
| Bow-tie antenna with AMC in [38] | 1.64-1.94 GHz (16.8%) Minimum impedance matching: -25 dB 50x70x25 mm$^3$ 0.27$\lambda_x$ x 0.38$\lambda_y$ x 0.137$\lambda_z$ | Substrate: εr=4.4 | Simple circular AMC 1.3-2.7 GHz | Bow-tie printed antenna with 6x9 fractal AMC array | 6.5 dBi 85% | Communication Systems | 25 mm |
| antenna with AMC in [39] | 6.9-7.9 GHz (13.5%) Minimum impedance matching: -25 dB 76x76x7 mm$^3$ 1.75$\lambda_x$ x 1.75$\lambda_y$ x 0.160$\lambda_z$ | Substrate: εr=2.2 | Mushroom-type AMC 7.05-9 GHz | Near-Zero-Index Metamaterial Lens Combined With AMC | 13 dBi 90% | Aerospace Applications | 7 mm |
| antenna with AMC in [40] | 2.2-2.72 GHz (18%) Minimum impedance matching: -30 dB 67.5x67.5x4.5 mm$^3$ 0.51$\lambda_x$ x 0.51$\lambda_y$ x 0.032$\lambda_z$ | Substrate: εr=3.5 | Jerusalem Cross AMC 3.6-3.8 GHz | M-shaped antenna based on 3x3 Jerusalem Cross AMC array | 5 dBi 90% | Telemedicine Applications | 4.5 mm |
| Dual-band Antenna with AMC in [36] | 3.14-3.83 GHz (19.8%) and 4.40-5.02 GHz (13.2%) Minimum impedance matching: -30 dB 79.6x79.6x10 mm$^3$ 0.93$\lambda_x$ x 0.93$\lambda_y$ x 0.13$\lambda_z$ | Substrate: εr=4.4 | Square AMC with slots 2.9-3.7 GHz 4.5-5.2 GHz | Crossed dual-polarized dual-band bowtie dipoles and a dual-band AMC reflector | 7.1 dBi 91% | Sub-6 GHz 5G applications | 10 mm |
| Dual-band Antenna with AMC in [42] | 1.42-1.6 GHz (12%) and 2.44-2.60 GHz (7.6%) Minimum impedance matching: -25 dB 85.5x85.5x5.62 mm$^3$ 0.68$\lambda_x$ x 0.68$\lambda_y$ x 0.043$\lambda_z$ | Substrate: εr=4.4 | Square AMC with slots 2.4-2.5 GHz | Textile antenna with dual-band and dual-sense with 3x3 AMC reflector | 2.1 dBi 83% | GPS and WBAN/WLAN applications | 5.62 mm |
The performance of the suggested design for measured bandwidth, impedance matching and maximum gain is compared in Table II. It clearly describes the prominent features of the suggested structure including considerable size reduction, wider bandwidth and enhanced maximum gain. The proposed structure is considered a following design process to show an acceptable performance:

- Suggesting a novel wideband AMC design in 5.10-7.18 GHz (34%) for C-band operation and investigation of their properties in the infinite condition.
- Designing a novel broadband printed dipole antenna using E-shaped dipoles and suggested feeding network in C-band (5.5-6.96 GHz) for WLAN/WiMAX operation.
- The combination of the low profile broadband printed antenna backed by the wideband planar AMC surface for broadband wireless and MIMO applications with improved Radiation and impedance performance.

Indeed, our aim was designing low-profile wideband printed antennas with a high stable gain and efficiency with uni-directional pattern and reduced backside direction over wide bandwidth. For this purpose, the suggested design compared with the previous research works with planar AMCs like [11], [15], [30], [34], and [38]-[40] introduces a bandwidth of 8-9.25 GHz (14.5%) and maximum gain of 8.4 dBi with enhanced impedance matching over the operating bandwidth until -45 dB. For example, in [11] a MIMO antenna with the size of 70x140x0.8 mm$^3$ (0.77λd×1.55λd×0.009λd) indicates a narrow bandwidth of 3.33-3.67 GHz (9.7%) and maximum gain of 6 dBi. The reported MIMO array with metamaterial based on fractal EBG in [15] introduces a bandwidth of 8-9.25 GHz (14.5%) with 96x96x1.6 mm$^3$ (2.56λd×2.56λd×0.043λd) and high gain of 7 dBi. It includes closely-packed patch arrays based on decoupling structure of fractal cross-shaped EBG surface with isolation of larger than 17 dB. Also, the proposed MIMO array loaded by simple square AMC reflector in [30] with the size of 75x75x12.7 mm$^3$ (0.75λd×0.75λd×0.127λd) indicates a wide bandwidth of 3-4.1 GHz and maximum gain of 7.1 dBi. It shows shorted V-shaped patches coupled by a bowtie dipole with 5x5 AMC array and larger isolation of 25 dB. In [36], dual-polarized dual-band bowtie dipoles and a dual-band square AMC reflector is operated in 3.14-3.83 GHz (19.8%) and 4.40-5.02 GHz (13.2%) with total size of 79.6x79.6x10 mm$^3$ (0.93λd×0.93λd×0.13λd) and maximum gain of 7.1 dBi. Thus, it can be concluded that the propose design introduces a compact wideband antenna with enhanced gain for MIMO systems.

IV. Multi-element Array of Suggested PDA Design

In this section, the performance of AMC surface developed in two-element and four-element arrays of PDA is studied by investigating S-parameters, isolation and radiation properties.

A. Two-element MIMO array

The two-element array of the suggested PDA is shown in Fig. 12 for wireless and MIMO applications. This structure can be arranged for PDA with different polarized directions to control the mutual coupling between the elements of the antenna array. Fig. 12 displays a 1x2 array with a 3x4 AMC reflector with the size of 48 mm×64 mm and orthogonal direction for the second element (element 2). The distance between two printed dipoles is considered d=6.5 mm to attain proper isolation between two elements. The measured and simulated S-parameters of the PDA array with AMC surface are provided in Fig. 13. Based on this, the measured range of $S_{11}$ for element 1 in 4.55-6.90 GHz is obtained which covers WLAN (5.2/5.8 GHz) and WiMAX (5.5 GHz). Moreover, the reflection coefficient of $S_{22}$ for element 2 covers the measured range of 4.48-7.12 GHz for WLAN/WiMAX applications. These results show almost the same frequency response for two elements of the PDA array. The measured $S_{12}$ parameter shows the isolation larger than 31 dB over the operational band and it reaches 40 dB over the bandwidth. Therefore, the suggested printed array loaded by AMC can be considered for MIMO communication systems.

Fig. 14 provides the various configurations of PDAs in the orthogonal and horizontal positions with the AMC surface. The simulated $S_{21}$ of the suggested designs with different polarized directions is plotted in Fig. 15. For status (a) the isolation is at least 31 dB. Whereas, in statuses of (b) and (c) with horizontal and orthogonal polarizations for both PDAs, the isolations of at least 14 and 20 dB, respectively are obtained. The distance d is a key parameter to determine good isolation due to the mutual coupling between the elements. For statuses of (b) and (c), d parameter is chosen 6.5 mm and 9.75 mm, respectively. According to the obtained results, optimum status (a) with d=6.5 mm leads to lower mutual coupling and wideband performance with better impedance matching. On the other hand, due to the linear polarization of the suggested PDA,
the status (a) results in the diverse polarizations of the antenna array. The Images of the fabricated cases of the PDA array backed by AMC reflector are shown in Fig. 23.

FIGURE. 13. S-parameters of the suggested array of PDA with rhombic AMC reflector.

FIGURE. 14. Three different configurations of PDAs with AMC reflector; (a) horizontal and orthogonal polarized directions (b) horizontal polarized directions and (c) orthogonal polarized directions.

FIGURE. 15. Simulated isolations (S21) of the suggested arrays introduced in Fig. 14.

FIGURE. 16. (a) Simulated and measured gains of two elements (b) Simulated and measured efficiencies of two elements of the suggested array.
The measured maximum gains of two elements 1 and 2 in the horizontal and orthogonal polarized directions for the suggested array with AMC reflector within the operational bandwidth are about 8.4 dBi, as seen in Fig. 16 (a). The gain of the structure shows a slight variation and good stability. The measured radiation efficiencies of the MIMO array indicate approximately the same outputs for two elements, as seen in Fig. 16 (b). Thus, it is concluded that a low profile array with directional radiation patterns is achieved for wideband MIMO operation.

The calculated envelope correlation coefficient (ECC) in terms of far-field radiation patterns is provided in Fig. 17. Due to the good isolation between the elements and high efficiencies and gains, the ECC level reaches less than 0.01. For access point antenna diversity, the acceptable envelope correlation coefficient is less than 0.7 [44]. Also, the measured ECC based on the measured S-parameters and efficiencies is obtained in Fig. 17. It is important to note that the measured ECC between elements i and j based on the far-field radiation parameters are calculated using the following formula [44]:

\[
\rho_{i,j} = \left| \frac{\int_{0}^{2\pi} \int_{0}^{\pi} (XPR_{E_{\theta},E_{\phi}} P_{\theta} + XPR_{E_{\theta},E_{\phi}} P_{\phi}) \sin(\theta) d\theta d\phi}{\prod_{i=1}^{N} \int_{0}^{2\pi} \int_{0}^{\pi} (XPR_{E_{\theta},E_{\phi}} P_{\theta} + XPR_{E_{\theta},E_{\phi}} P_{\phi}) \sin(\theta) d\theta d\phi} \right|
\]

(12)

where \( E_{\theta i} \) and \( E_{\phi j} \) are the electric field components in the elevation angle direction while \( E_{\phi i} \) and \( E_{\phi j} \) are the components in the azimuthal angle direction for antennas i and j. XPR is the cross-polarization discrimination factor that shows the difference between horizontal and vertical polarizations of the incident wave. \( P_{\theta} \) and \( P_{\phi} \) are the power densities for elevation and azimuth angles. Equation (12) can be simplified by assuming that XPR equals 1, and the angular power densities are uniform.

\[
\Gamma_{a} = \left( \sum_{i=1}^{N} |a_i|^2 \right) \left( \sum_{i=1}^{N} |b_i|^2 \right)^{-1}
\]

(13)

In addition, to evaluate the radiation performance, the total active reflection coefficient (TARC) is considered. The TARC provides a more meaningful and complete characterization measure of MIMO efficiency because it contains the effect of mutual coupling. TARC is defined as the ratio of the square root of total reflected power divided by the square root of total incident power [44]. The TARC at the port antenna can be described as

\[
CCL = -\log_2 \det(\psi^R)
\]

(14)

where \( \psi^R \) is the receiving antenna correlation matrix:

\[
\psi^R = \begin{pmatrix}
\rho_{1,1} & \cdots & \rho_{1,N} \\
\vdots & \ddots & \vdots \\
\rho_{N,1} & \cdots & \rho_{N,N}
\end{pmatrix}
\]

(15)
The capacity loss increases due to spatial correlation between receive antennas. The elements of the correlation matrix can be obtained by the following equations [45]:

\[ \rho_{ii} = 1 - \left( |S_{ii}|^2 + |S_{jj}|^2 \right) \]  
\[ \rho_{ij} = -\left( S_{ij}^* S_{jj} + S_{ji}^* S_{jj} \right) \]

The calculated CCL for the proposed two-element MIMO array is shown in Fig. 19. As shown in Fig., CCL illustrates the proper behavior in operating bandwidth below 0.4 bits/s/Hz. Ideally, CCL should be less than 0.4 bps/Hz within the entire operating band. Thus, the proposed MIMO array proves that good impedance matching and isolation between the two antenna elements lead to low capacity loss.

The Mean effective gain (MEG) is defined in terms of the following equation [45]:

\[ MEG = 0.5 \times \left( 1 - \sum_{i=1}^{N} |S_{ii}|^2 \right) \]

The MEG values of the MIMO array are given in Fig. 20. The values for MEG-1 and MEG-2 are almost identical and the difference of MEG between the two ports is less than 3 dB. The ratio of MEG-1 with MEG-2 (MEG-1/MEG-2) is close to 1 which satisfies the equality criterion for the two elements.

The measurement and simulation results of radiation patterns in the XZ-plane and YZ-plane for two elements of the PDA array with AMC reflector are provided in Figs. 21 and 22. It is understood that suitable accordance with the results is obtained. Meanwhile, the suggested design presents acceptable unidirectional radiation patterns at three frequencies for wireless operation. Also, it is observed that the radiation patterns for two elements of 1 and 2 have a slight difference due to their positions and polarized directions. The arrangement of the 3x4 AMC array reflector is effective on the gain of elements. It results in more symmetrical patterns in the YZ-plane for element 2 compared to element 1. On the other hand, it is comprehended that element 2 is in the polarized direction of element 1. Thus, it considers as a director of element 1 and results in the gain of element 1 towards Y-direction, as seen in Fig 18, in the YZ plane. The Y-inclined pattern of element 1 results in that the gain of element 2 is slightly more than the gain of element 1 over the most bandwidth, according to Fig. 16 (a).
FIGURE 22. Measurement and simulation results of radiation patterns of element 2 of the suggested array with the AMC surface for gain in XZ and YZ-planes.

FIGURE 23. Images of fabricated cases of the PDA array backed by rhomboid AMC reflector.

FIGURE 24. Structure of the suggested four-element array of PDA backed by the broadband 8×8 AMC reflector (a) 3D view (b) top view (c) feeding system by SMA connectors.
B. Four-element MIMO array

In this section, the performance of the four-element array loaded by rhomboid AMC is studied by investigating S-parameters, isolations, and radiation properties.

The four-element array of the suggested PDA is shown in Fig. 24 for wireless and MIMO applications. This structure can be arranged for PDA with different polarized directions to control the mutual coupling between the elements of the antenna array. It displays a 2x2 array with the 5x5 AMC reflector with the total size of 80 mm×80 mm. The distances between the printed dipoles are considered $d_{12} = 16$ mm, $d_{13} = 16$ mm, $d_{24} = 16$ mm, and $d_{34} = 16$ mm to attain good isolations between four elements. On the other hand, due to the linear polarization of the suggested PDA, the suggested four-element array results in the diverse polarizations of the antenna array. The four elements are separately fed by long coaxial probes, as seen from Fig. 24 (c).

The measured and simulated S-parameters of the four-element array with the AMC surface are provided in Fig. 25 (a). Based on this, the measured range of $S_{11}$ for element 1 in 4.55-6.95 GHz is obtained which covers WLAN (5.2/5.8 GHz) and WiMAX (5.5 GHz). Moreover, the reflection coefficients of $S_{22}$, $S_{33}$, and $S_{44}$ for elements 2, 3, and 4 cover the measured ranges of 4.47-6.92, 4.54-6.96 and 4.48-6.93 GHz, respectively for WLAN/WiMAX applications. These results show almost the same frequency response of the four-element MIMO array for WLAN and WiMAX base station systems.

According to Fig. 25 (b), the measured isolations between the four elements show good isolations at least 30 dB and a maximum of 67 dB over the operational bandwidth. At least isolations of $S_{12}$, $S_{13}$, $S_{14}$, $S_{23}$, $S_{24}$, and $S_{34}$ are 30, 36, 30, 30, 33 and 34 dB, respectively and they reach 52, 67, 55, 52 and 44 dB, respectively.

The measured gains of four elements 1, 2, 3 and 4 in the orthogonal and horizontal polarized directions for the four-element MIMO array are provided in Fig. 26 (a). The gains of elements show maximum gains of elements 1, 2, 3, and 4 are more than 8.7 dBi within the operational bandwidth. The measured radiation efficiencies of the MIMO array indicate approximately the same outputs for four elements, as seen in Fig. 26 (b).
The measured envelope correlation coefficient (ECC) in terms of far-field radiation patterns is plotted in Fig. 27. Due to the good isolation between the elements and high efficiencies and gains, the ECC level reaches less than 0.01 between four ports. The measured TARC, CCL and MEG for the proposed MIMO array are shown in Fig. 28. It indicates that TARC, CCL and MEG have acceptable values for the four-element MIMO array.

The measurement and simulation results of radiation patterns in the XZ-plane and YZ-plane for four elements of the PDA array with the AMC reflector are provided in Fig. 29. It is understood that suitable accordance with the results is obtained. Meanwhile, the suggested design presents acceptable unidirectional radiation patterns at three frequencies for wireless operation. The Images of the fabricated cases of the PDA arrays backed by the rhomboid AMC reflector are shown in Fig. 30.

To completely describe and emphasize the originality of the proposed work, following outputs are listed for MIMO arrays backed by AMC reflectors:

- Size reduction of more than 42%
- Bandwidth enhancement up to 21%
- Low-profile printed antenna; $0.71\lambda_L \times 0.71\lambda_L \times 0.101\lambda_L$
- Good impedance matching over the wide operational band
- Gain enhancement of more than 4 dBi
- High stable gain around 8 dBi for all elements over the wide bandwidth
- High efficiencies of more than 90%
- High isolations of larger than 30 dB between elements
- Various polarized directions of MIMO elements (horizontal and orthogonal polarized directions)
- Uni-directional radiation patterns with reduced backside direction
- The Measured ECC less than 0.5 over the wide operational band
- The Measured acceptable TARC over the wide operational band
- The Measured CCL less than 0.4 bits/s/Hz over the wide operational band
- The measured ratio of MEGs close to 1 for all ports
- Utilizing as a suitable candidate for vehicular communication systems, WLAN/WiMAX operation and Vehicular base station systems

![Figure 28](image_url)
V. Conclusion

The novel design of the AMC unit cell is introduced to provide a broadband response in C-band operation. It is composed of the rhomboid parasitic patches for including 5.10-7.18 GHz (34%). This AMC design indicates the distinguished properties with proper stability within the AMC bandwidth. The suggested PDA with E-shaped arms backed by AMC reflector introduces the low-profile broadband antenna for wireless communications systems. By loading the 3x3 rhomboid AMC surface into the PDA the -10 dB impedance bandwidth of 4.98-7 GHz (43.9%) is achieved. The extraordinary impedance matching until -45 dB, excellent compactness and broader bandwidth were obtained from the suggested PDA with AMC compared with the PDA without the reflector. Besides, the unidirectional radiation patterns with a higher gain up to 8.4 dBi are obtained. From experimental results, the acceptable efficiency is reported and it is concluded that the suggested design can be used for broadband wireless systems such as WLAN/WiMAX. Finally, the performance of the two-element and four-element arrays of the PDA is studied by utilizing the 3x4 and 5x5 MC reflectors. For this purpose, three configurations for different polarized directions are investigated to attain good isolation of larger than 31 dB between the elements of two-element array. It is concluded that the compact MIMO antenna array with high gains (more than 8.4 dBi) and efficiencies for elements can be used for vehicular wireless applications.
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