A miniaturized antenna array for direct air-to-ground communication of aircrafts

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Abstract. In this paper, a miniaturized, high directivity low-cost antenna array is presented. The uniqueness of the proposed array (PA) exists in the feed mechanism designed using Dolph-Chebyshev non-uniform excitations. Authors simulated the designed antenna array using ANSYS EM 18.2 (HFSS) software and characterization is carried out in a fully established anechoic chamber. The simulated array antenna is operating at 2.4 GHz with a gain of 8.12 dB and a reflection coefficient of -28.45 dB having a bandwidth of 110 MHz. On contrast with the traditional array (TA), PA exhibits enhanced resonance characteristics by maintaining the same radiation characteristics. The bandwidth is increased by 37.5%, maintaining the same gain of 8.12 dB. In contrast, there is a remarkable reduction in the size compared to the traditional corporate feed array antenna with non-uniform excitation. The overall size of the PA antenna is 242.5 mm × 58.8 mm, which is 33.73% less compared to the TA.

1. Introduction

The recent advancements in the development of next-generation wireless communication equipment are creating a massive demand for low profile antennas. The main reason behind this is that the overall size of the communication equipment should be portable and must occupy a smaller area. At the same time, there should not be any compromise on the radiation and resonance characteristics of the antenna. Considering these aspects, the engineers must intelligently design antennas by selecting appropriate geometry, current distributions and the electrical dimensions of the radiating elements. In literature, a plethora of studies reported that are related to miniaturization of the antenna elements. The most prominent antenna miniaturization techniques published are into two categories: Material based and topology-based [1]. Some techniques that fall under the material based miniaturization are antennas with engineered substrates and Metamaterial (MTM) based techniques. In MTM based technology the antenna exhibits an inverse relationship between the size of the antenna and the refractive index. Several research results are reported based on the concept of inverse relationship. Saraswath et al. achieved the overall size reduction of 42.24% by loading metamaterial to a patch antenna [2]. In [3], Tanweer et al. designed a metamaterial slot antenna using rectangular Complementary Split Ring Resonators (RCSRR) which led to a miniaturization about 46.8%. Singh et al. developed a multiband microstrip patch antenna using metamaterial loading, which exhibited a size reduction of 68.3% [4]. In [5] Li et al. used a palisade-shaped metasurface (PSMS) for miniaturization. The use of high dielectric substrates is another way to miniaturize, but this method results in a reduction in radiation efficiency of the patch antenna. It also leads to difficulties in impedance matching and narrow bandwidth.
Several authors reported miniaturization by modifying the geometry and topology of the antenna. In this class, most commonly used techniques are engineered ground planes, reactive loading and distributed loading. Among engineered ground planes, Defected Ground Structures (DGS) and Electromagnetic Band Gap Structures (EBGS) are very popular. These methods redirect and displace the currents in the ground plane through the creation of slots that are comparable in size to the wavelength. The disadvantage of this technique is that it may develop unwanted clutter and noise due to coupling of the radiated signal from embedded slot to the neighbouring electronic devices. Hence a decrease in front-to-back radiation leading to reduced directivity.

In [6], Nashaat et al. presented a four-arm spiral DGS unit cell and its effect in miniaturization and multiband creation. Shah et al. reported a microstrip patch with H shaped slot integrated with U and L formed DGS and achieved 86% miniaturization [7]. In [8], Chetouah et al. made 66.8% miniaturization by creating L shaped defect in the ground plane. Mekimah et al. developed a partial ground antenna C shaped antenna with defects to achieve miniaturization [9]. In [10], Koga et al. presented a dipole slot antenna array with Coplanar Waveguide feed. Huang et al. miniaturized the conventional Vivaldi antenna to 38.05% by adding regular slot edges (RSE) [11]. Zhu et al. presented a Dielectric Resonator Antenna (DRA) Array with elements miniaturized to half of its original size [12]. Xiaopan et al. introduced a wang shaped left-handed metamaterial in the ground plane. Also the same metamaterial structure is placed on a metal reflector to achieve unidirectional radiation to improve the gain of the antenna array [13].

The motivation for this research is facilitating communication for airline passengers through an emerging technology known as DA2G communication. Since many business class people are frequent travellers and would like to connect to high-speed internet to complete their office work by transacting e-mails on the go. Authors initiated this research to develop high gain and miniaturized antenna array that are suitable for airline communication. In this paper, authors developed a unique non-uniform excitation feed with Dolph Chebyshev amplitude distribution to miniaturize the antenna array operating at 2.4 GHz. This antenna meets the requirements for Direct Air-to-Ground (DA2G) communication of aircraft, which needs a miniaturized high gain and directive antenna to establish links up to 42000 ft from the ground station with a 20 MHz of the contiguous band around 2.4 GHz. Hence this antenna can be used as an element along with a phase shifter network to develop a hybrid array for beam-steering in DA2G communication. In [14], Vondra et al. presented a detailed study on DA2G communication in terms of the standards used, antenna performance requirements and challenges toward the future DA2G.

2. Design, Simulation and Characterization of the PA Antenna

2.1. Design and Simulation

As a part of the designing a 1 × 4 array antenna, excitation coefficients are calculated and developed an inset fed corporate feed network, as shown in Figure 1. In this design, the gap between feed and patch of individual elements of the array is varied as there is a variation in the impedance at respective feed points. Elements 1 and 4 maintain 0.921 mm gap between patch and feed, whereas elements 2 and 3 maintain 2.954 mm. The impedances of each microstrip line used in the feed network is obtained by considering input power as 1 Watt and source impedance as 50 Ω. FR4-Epoxy ($\varepsilon_r = 4.4$) with 1.6 mm thick is used in the design.
The final design is simulated using Ansys EM 18.2 (HFSS) software to study the performance of the array antenna. Figure 2 depicts the geometry of the proposed miniaturized array antenna created using the feed mechanism shown in Figure 1. The top portion of the figure is the full view of the PA and bottom portion is the zoomed version of a portion to indicate design parameters. The design parameters of the PA antenna are presented in Table 1.

![Figure 1. Proposed 1 × 4 array antenna feed network](image)

2.2. Fabrication and Measurement
The prototype of the proposed design is fabricated and characterized in a fully established anechoic chamber. Figure 3 shows the fabricated prototype view of PA. The experimental set up is presented in Figure 4. The E plane and H Plane radiation patterns are measured at the desired frequency of 2.4 GHz. A Double ridge broadband horn antenna operating at 1 to 18 GHz is used as a reference antenna during the measurements. The reflection coefficient of the proposed array is measured using the VNA.
model Anritsu Site Master S820E. Figure 4(a) and (b) represents the measurement of the reflection coefficient of PA antenna and the TA antenna, respectively.

**Table 1. Parameters of the PA antenna**

| Parameter | Value (mm) | Parameter | Value (mm) |
|-----------|------------|-----------|------------|
| Lg        | 59.5       | L1        | 15.4       |
| Wg        | 242.5      | L2        | 13.4       |
| Lp        | 29.5       | L3        | 31.9       |
| Wp        | 35.8       | L4        | 30.8       |
| W1        | 1.8        | L5        | 3.6        |
| W2        | 3.9        | L6        | 43.02      |
| W3        | 5.9        | L7        | 14.8       |
| W4        | 2.9        | L8        | 7.4        |
| W5        | 0.7        | L9        | 3.32       |
| Lins1     | 10         | S         | 29.8       |
| Lins2     | 8          | G1        | 0.92       |
| X         | 4.8        | G2        | 1.95       |

**Figure 3.** View of fabricated prototype PA antenna
3. Results and Discussion

The simulated and measured reflection coefficient characteristics are plotted, as shown in Figure 5. The measured and simulated results are found corroborating. Contrasting the results plotted, we can infer that the PA antenna is showing least reflections with a reflection coefficient of -28.45 dB. The TA has a -10 dB bandwidth of 80 MHz whereas the PA antenna shows an improved 110 MHz bandwidth.
Figure 5. Comparison of Reflection Coefficient

The impedance matching of the TA and PA antennas is compared in Figure 6. From the traces, it is evident that both designs show an acceptable impedance match around the desired frequency.

Figure 6. Impedance characteristics of TA and PA
The 2D radiation (E Plane and H Plane) characteristics of the TA and the PA at 2.4 GHz are compared in Figure. 7 (a) and (b). From the traces of E plane radiation pattern, one can notice that the gain of the array is maximum at $\theta = 0^\circ$. Also, there is no variation in the total gain observed for both TA and PA antenna. Similarly, the H plane pattern shows a maximum gain of 8.12 dB at $\theta = 0^\circ$. It can also be noted that both arrays follow uniform shape in the upper hemisphere of the radiation patterns.

![Figure 7. Comparison patterns of TA and PA (a) E plane (b) H Plane](image)

The gain characteristics of the TA and PA are compared in Figure. 8. in the span of frequencies between 2 to 3 GHz. There is a good agreement between the simulated and measured gain pattern. Some minor deviations noticed in the characteristics may be due to factors such as fabrication process, the uncertainties in the experimental setup or the soldering techniques adopted for SMA connector to the array antenna.

![Figure 8. Gain characteristics of TA and PA](image)
The gain characteristics of the TA and PA are compared in Figure. 8, in the span of frequencies between 2 to 3 GHz. There is a good agreement between the simulated and measured gain pattern. Some minor deviations noticed in the characteristics may be due to factors such as fabrication process, the uncertainties in the experimental setup or the soldering techniques adopted for SMA connector to the array antenna.

4. Conclusion
A low profile antenna array for 2.4 GHz is fabricated and characterized. The optimized feed network incorporated in this work has resulted in miniaturization of size without compromising the radiation and resonance characteristics. Table 2. provides the performance of antenna TA and PA antennas.

| Characteristic     | TA         | PA         |
|--------------------|------------|------------|
| Gain (dB)          | 8.13       | 8.12       |
| $S_{11}$ (dB)      | -21.08     | -28.45     |
| Bandwidth (MHz)    | 80         | 110        |
| Directivity (dB)   | 11.6       | 11.4       |
| Size (mm)          | 254.5mm×84.56mm | 242.548mm×58.77mm |

From the tabulated results we can observe that there is a Bandwidth enhancement from 80 MHz to 110 MHz and the overall size is reduced by 33.73%. Since the PA meets the requirements of Direct Air-to-Ground Communication of aircraft. As a future work authors are utilizing the PA as an element along with a proper phase shifter network to further develop an hybrid array to establish aircraft communication from air to base station.

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