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Research Article

A Comparative Performance Analysis of Two Printed Circular Arrays for Power-Based Vehicle Localization Applications

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A comparative study of the performance characteristics of a printed 8-element V-shaped circular antenna array and an 8-element Yagi circular array operating at 2.45 GHz for vehicular direction finding applications is presented. Two operating modes are investigated; switched and phased modes. The arrays were fabricated on FR-4 substrates with 0.8 mm thickness. Measured and simulated results were compared. Radiation gain patterns were measured on a 1 m diameter ground plane that resembles the rooftop of a vehicle. The HPBW of the Yagi was found to be about 3° narrower than its V-shaped counterpart when measured above a reflecting ground plane and operated in switched mode. The printed V-shaped antenna array offers 2.5 dB extra gain compared to the printed Yagi array.

1. Introduction

Increased usage of tracking devices in cars raised the need for the development of highly accurate position determination systems. One of the basic requirements for radio frequency (RF) vehicular localization is the accurate estimation of the direction of arrival (DOA) of the incoming RF signal [1]. Recent advances in smart antenna technologies—antennas with digital signal processing (DSP) equipment—enabled the enhancement of antenna coverage and efficient utilization of the transmitted power. In a bid to accommodate the maximum possible number of users, cellular service providers are utilizing smart antenna systems to shape the radiation patterns to focus their transmit power in a given region.

Traditionally, highly accurate DOA systems require the use of multiple receivers with separate antennas integrated with DSP algorithms like the multiple signal classification (MUSIC) and rotational invariance techniques (ESPRIT) [2, 3]. The use of multiple receivers dictated the size of the overall system to be large making it difficult to deploy for several applications. For increased practicality, microstrip antenna arrays are used nowadays to save space and to decrease the overall profile of the system. As the number of cars globally increases beyond the 1 billion mark [4], parking problems in densely populated cities have started to increase. Indoor, multistory parking lots are being considered as one of the most efficient ways of providing parking space for the available cars without interrupting the traffic flow. An emerging application of DF systems is for car localization in huge parking lots. The majority of modern cars are equipped with remote entry systems which can help in locating the car when the transmitter (key) is triggered within a specific distance from the receiver (car). Global positioning system (GPS-) based DF systems have proved their usefulness in open air parking lots [5] but in multistory covered parking plazas GPS-based solutions become ineffective.

All of the above mentioned systems rely on a buzzer to guide the user to the car location. The buzzer might not be heard, not to mention that this solution will never work for hearing impaired people. An alternative approach is a system that determines the actual location of the car and sends a signal to the user that will show on a key fob (controller with lights and buttons) with his/her key chain pointing him/her to the correct direction of the location of the car. Reference [6] have proposed the design of a DF system based on a four
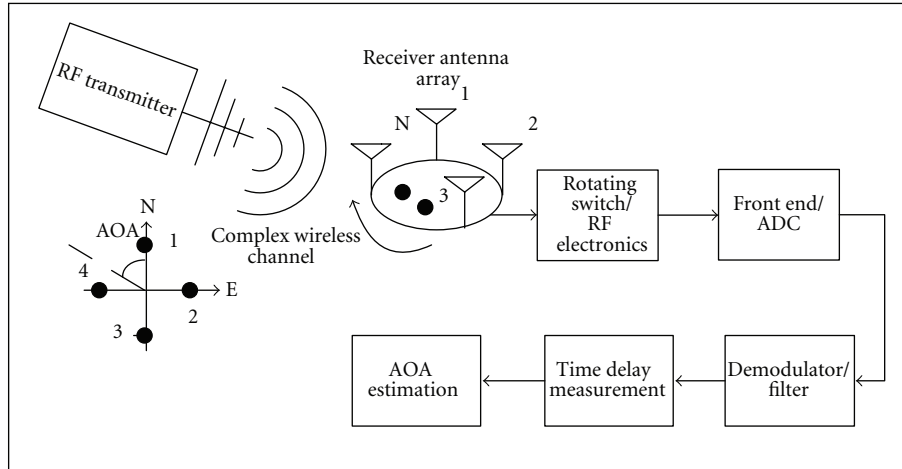
Figure 1: Block diagram of a single channel car localization system.
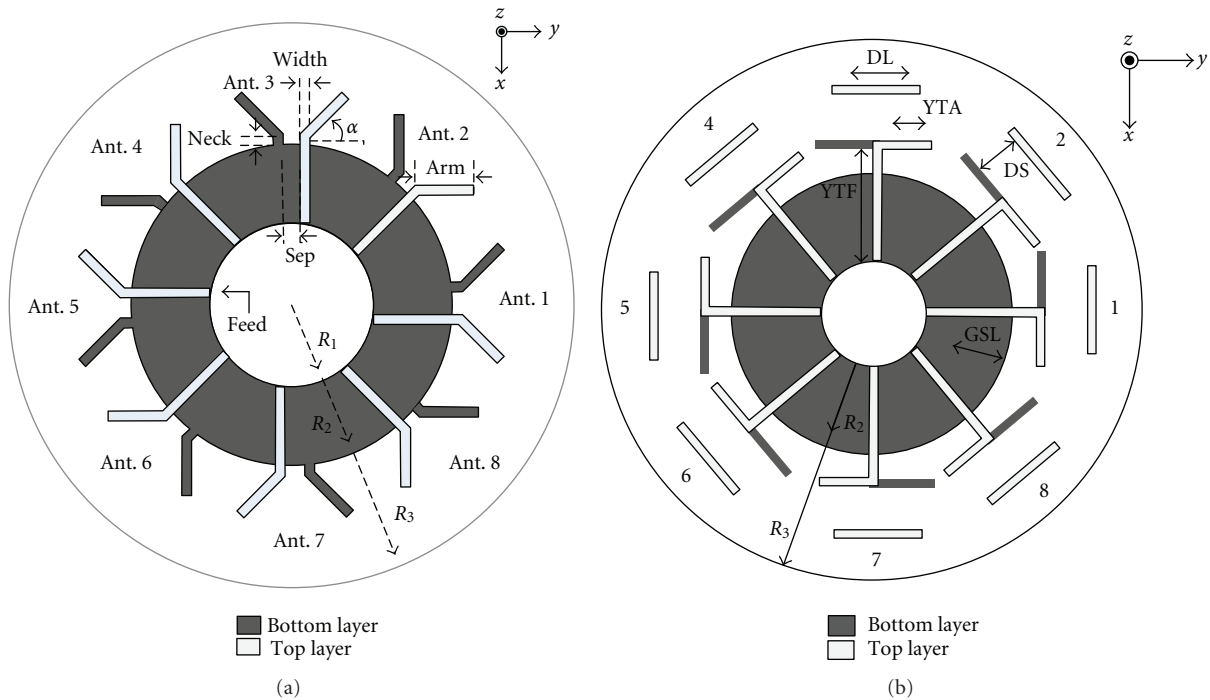

Figure 2: Designs for the printed arrays (a) 8-element V-shaped circular array and (b) 8-element Yagi circular array.

element linear array antenna with phase shifters for beam scanning. The beam scanning ability of this system is highly limited by the linear nature of the array and thus cannot scan more than 180° in the azimuth plane. Considering a large-covered parking lot where the position of the car is not known, accurate localization requires the onboard DF system to be able to scan 360° so that signals from the transmitter are received regardless of its position with respect to the receiver. In [7], the performance of an 8-element circular Yagi antenna array with two slightly different ground (GND) plane designs was proposed and analyzed. Since the application of this antenna requires hoisting it on top of a car, the roof of the car acts as a large ground plane and has a significant effect

on the radiation pattern of the antenna. The authors did not take the effect of the ground plane into consideration. Moreover, the half power beamwidth (HPBW) offered by the circular Yagi array was much wider than needed for accurate localization. The block diagram of a single channel car localization system similar to that in [8] is shown in Figure 1. The work presented in this paper focuses solely on the antenna array section.

V-shaped wire antennas are known for their directive patterns when operated in pairs [9]. The design and characterization of printed V-shaped antenna elements is not found in literature. In this work we present the design, fabrication, and characterization of a V-shaped printed antenna array

TABLE 1: Simulated and measured center frequency, $-10\,\mathrm{dB}$ matching bandwidth, and $|S_{11}|$ for the Yagi and the V-shaped antennas.

Antenna type	Antenna number	Center frequency (GHz)		$-10\,\mathrm{dB}$ Bandwidth (MHz)		$|S_{11}|$ (dB)	
		Sim	Meas	Sim	Meas	Sim	Meas
Yagi	1	2.347	2.41	365	297	-21.4	-35.8
	2	2.397	2.41	369	290	-22.6	-28.7
	3	2.397	2.41	365	310	-22.1	-32
	4	2.397	2.41	362	296	-21.6	-24.2
	5	2.399	2.40	365	334	-21.6	-36.7
	6	2.397	2.41	360	292	-22.5	-26.3
	7	2.393	2.41	358	298	-21.6	-34.5
	8	2.399	2.41	369	310	-22.9	-32.2
V-Shaped	1	2.5	2.51	304	240	-17.3	-25.7
	2	2.5	2.51	300	238	-17.0	-25.3
	3	2.5	2.51	300	240	-17.1	-25.6
	4	2.5	2.50	301	235	-16.9	-26.3
	5	2.5	2.51	300	233	-17.1	-26.2
	6	2.5	2.51	302	240	-17.7	-25.6
	7	2.5	2.50	301	235	-17.2	-25.2
	8	2.5	2.51	301	238	-17.8	-25.8

operating at 2.45 GHz. In addition this work provides a comparison between the performance of a printed 8-element circular Yagi antenna array and the proposed 8-element circular V-shaped antenna array for single channel vehicular direction finding applications. Simulation results for the HPBW, $-10\,\mathrm{dB}$ matching bandwidth, and the effect of the ground plane are presented and a comparison between the two array types is made. In addition, the antennas were fabricated and the gain patterns were measured at an outdoor antenna range facility at Oakland University, Michigan, USA. The arrays were excited under switched as well as phased modes of operation to allow for proper use in power based RF-DF applications.

The rest of the paper is organized as follows: Section 2 presents the modeling and designs of the two antenna arrays, Section 3 shows the comparative study of the simulated and the measured quantities for the two antennas without the presence of the ground plane and when a ground plane is inserted beneath the antenna arrays, and finally the paper concludes with Section 4.

2. Antenna Array Designs

The geometries of the printed V-shaped and the Yagi circular antenna arrays are shown in Figure 2. Both arrays were designed to operate in the 2.45 GHz band.
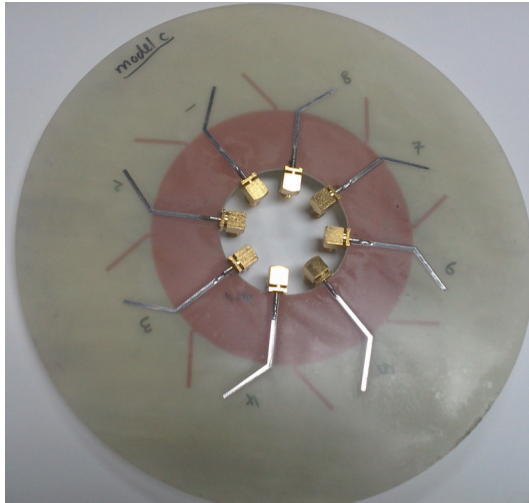
The printed V-shaped circular antenna array (Figure 2(a)) was designed on an FR-4 substrate with $\epsilon_r = 3.8$ and 0.8 mm thickness. The dimensions of the V-shaped antenna array were (in mm) $R1 = 25$, $R2 = 45$, $R3 = 100$, Arm = 20, neck = 3, Width = 1.5, Sep = 7, and $\alpha = 30°$. A parametric study via simulations was conducted to investigate the effect of the printed V-shaped antenna parameters on its resonance and operating bandwidth. An increase in α as well as *neck* increases both the center frequency as well as the $-10\,\mathrm{dB}$ matching bandwidth. An increase in *arm* on the other hand, decreases the resonance frequency and decreases the offered bandwidth as well. Increasing *sep* decreases the resonant frequency while it increases the offered bandwidth. These parameters were tuned using HFSS. The dark elements and the circular ground plane are on the bottom side of the PCB while the white/light colored arms are on the top side.

For the printed Yagi antenna array, an FR-4 material with $\epsilon_r = 4.0$ and a thickness of 0.8 mm was used; the dimensions of the design in mm (Figure 2(b)) were $R1 = 25$, $R2 = 51$, $R3 = 100$, YTF = 43, YTA = 26, DL = 32, DS = 10, and GSL = 19. These values were optimized using a 3D full wave field simulator (HFSS). The feeder length (YTA) affects the resonance frequency as well as the operating bandwidth. If its length is increased both the resonance frequency and operating BW decreases. The distance between the director and the feeder affects the input matching of the feeder, and should be kept at least 10 mm away from the feeder. Increasing the director length decreases the HPBW while increasing the back lobe levels. The dark elements and the circular ground plane are on the bottom side of the PCB while the white/light colored arms are on the top side. Note that the antenna elements have been numbered arbitrarily from 1 to 8 and the same naming scheme is used in the following sections.

3. Results and Discussions

A snapshot of the two-fabricated antennas is presented in Figure 3. An Agilent HP8510C network analyzer was used to carry out the measurements of the two arrays in the microwave laboratory in the EE Department at KFUPM. Each of the eight ports of the array were excited individually while all other ports were terminated with $50\,\Omega$.
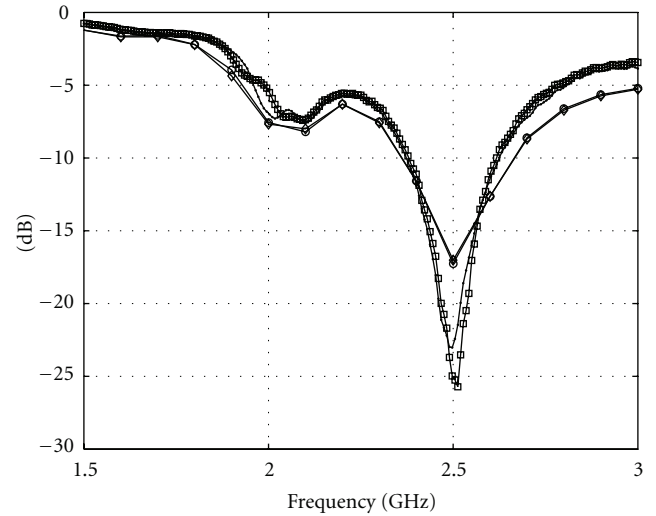
(a)
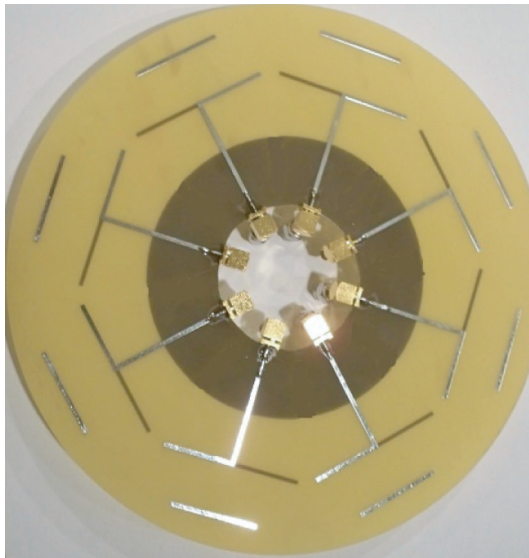
(b)

FIGURE 3: Fabricated printed antenna arrays: (a) 8-element V-shaped circular array and (b) 8-element Yagi circular array.

(a)

(b)

FIGURE 4: Simulated and measured reflection coefficient for elements 1 and 2 for (a) V-shaped antenna array and (b) Yagi antenna array.
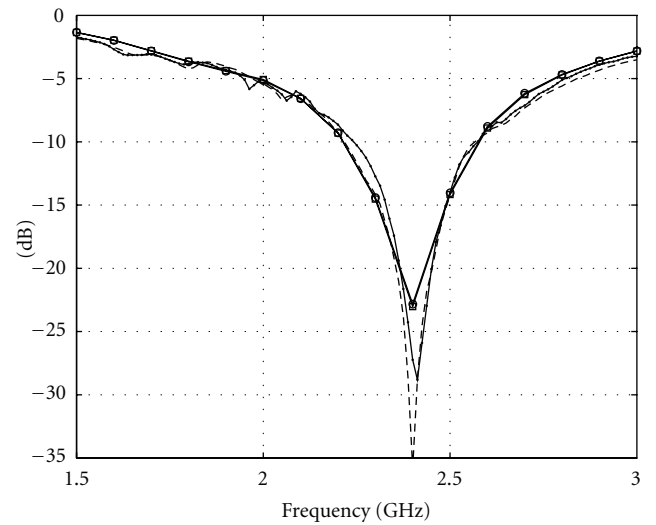
Table 1 presents the measured (meas) and simulated (sim) values for the resonance frequencies, HPBW, and $|S_{11}|$. Figure 4 shows the measured and simulated values of the reflection coefficients for elements 1 and 2 for both the V-shaped and the Yagi arrays. Good agreement is observed from the results.

Comparing the simulated and the measured results in Table 1, good agreement is observed. The -10 dB matching BW of the measured antenna is lower than the corresponding simulated one. One of the possible reasons for this deviation can be the effect of the fabrication process and the presence of SMA connectors used to feed the antenna elements. Although great attention was paid while soldering the SMA connectors to the antenna arms, one can never achieve absolute accuracy while soldering by hand; this might also be a possible reason for the difference between the measured

and the simulated values. The difference between the $|S_{11}|$ values is believed to be attributed to the difference between the simulated and fabricated feed excitation mechanisms, the former was a feeding strip like a probe feed while the latter was a regular SMA connector.

3.1. Switched and Phased Modes of Operation without a Reflecting Ground Plane. In order to measure the radiation

FIGURE 5: Antenna range at Oakland university.

FIGURE 7: Normalized simulated directivity patterns for the V-shaped antenna array without ground plane—dotted markers for switched mode and diamond markers for phased mode.
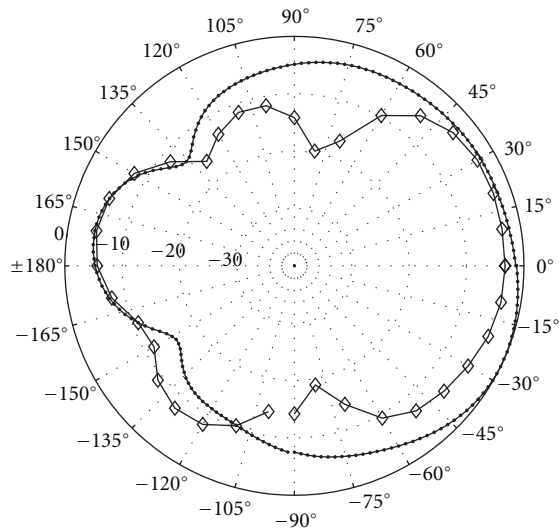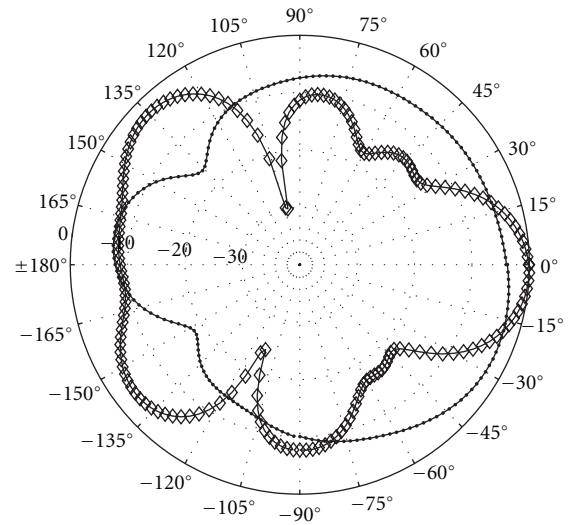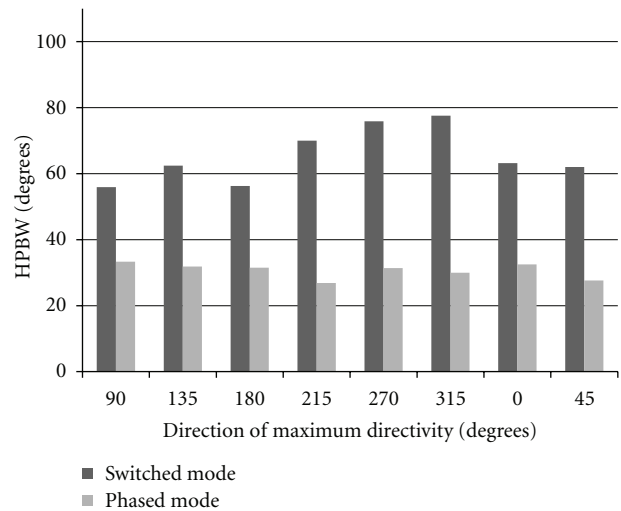

FIGURE 6: Normalized simulated directivity pattern comparison for the antennas without ground plane—dotted markers for V-shaped and diamond markers for Yagi pattern.

FIGURE 8: HPBW simulations comparison for the V-shaped antenna array placed over a ground plane.

characteristics for the switched mode of operation of the V-shaped and the Yagi circular antenna arrays, the fabricated antennas were measured at an outdoor antenna range at Oakland university, Michigan, USA. Figure 5 shows the measurement set-up.

Since there are eight array elements spanning an azimuthal plane of 360°, it is designed such that each element provides directive radiation pattern along its azimuthal direction (ϕ) covering a sector of 45°. The antenna array is to be mounted on the car rooftop, the main region of interest in our work is the azimuth (ϕ) plane. All the measurements presented in the following Sections consider the azimuth plane patterns. For accurate localization in a switched mode operation of the array where only one element is excited at a time, it is required that the HPBW of each of the antenna elements of the array be as narrow as possible so that a clear distinction between signals received at adjacent antenna elements can be made in a power based RF-DF system. The switched mode of operation does not require complex electronics, only an RF switch/MUX along with a

power measurement IC (received signal strength indicator—RSSI), and a microcontroller are needed. In the comparison between the normalized azimuthal directivity patterns of the Yagi and the V-shaped antenna presented in Figure 6, we observe that the V-shaped antenna array provides higher HPBW when operated under switched mode. The HPBW for the Yagi was 100° whereas that for the V-shaped array was found to be 120°. Antenna 7 (towards $\phi = 0°$) was excited for both arrays. The gain of the V-shaped array was approximately 2.5 dBs higher than the Yagi array.

Unlike the switched mode of operation, phased mode requires exciting all the antenna elements simultaneously with equal excitation coefficients but varying phases. Analytical expressions to calculate the relative phases required
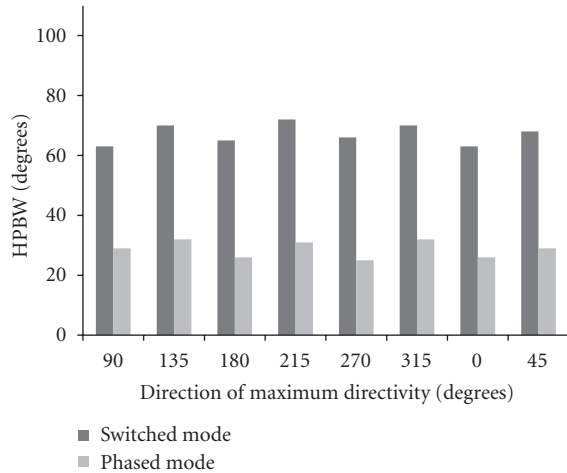
FIGURE 9: HPBW simulation comparison for the Yagi array placed 5 cm over the ground plane.

(a)

(b)

FIGURE 10: Simulated switched mode beams overlayed for the v-shaped antenna (a) elements 1 to 4 and (b) elements 5 to 8. Solid (elements 1 and 5), dots (elements 2 and 6), dashes (elements 3 and 7), and circles (elements 4 and 8).

to achieve maximum gain/directivity in a given direction are found in [9]. Figure 7 shows the simulated azimuthal patterns V-shaped antenna when operated under switched and phased modes of excitations; the HPBW for the switched mode was found to be approximately 100° and for the phased mode was 34°. In addition, gain improvement of about 3 dB was observed. This improvement came at the cost of higher hardware complexity.

3.2. Switched and Phased Modes of Operation with a Reflecting Ground Plane.

As mentioned in Section 1, the application of our antenna designs require that they are installed on the car roof. The roof, being made of metal, tends to reflect the energy radiated by the antenna array in the downward direction hence increasing the power radiated upwards and affecting the azimuthal patterns. In order to correctly model the effect of the car's roof on the performance of the antenna array, we have simulated the array models by placing a large conducting plane (1 m in diameter) at a height of 5 cm below the array. These simulations mimic the behavior of the car roof on our antenna's performance and provide a much closer insight to their behavior. In addition to the simulations, the antenna arrays were measured by placing them over a 1 m diameter rolled edge ground plane at a height of 5 cm to measure the actual radiation patterns.

Figures 8 and 9 present a comparison between the simulated HPBW for the two excitation modes of the V-shaped array and the Yagi antenna array, respectively. For both the antenna arrays, a sharp decrease in the HPBW is observed when operated under the phased mode of excitation. The presence of ground plane reduced the HPBW by approximately 45° on average for the V-shaped array (Figure 8), and approximately 35° for the Yagi array (Figure 9) when operated in switched mode. In addition, the maximum gain for both arrays was reduced by a couple of dBs when operated in this mode. The HPBW for the phased mode of operation was not affected as much by the presence
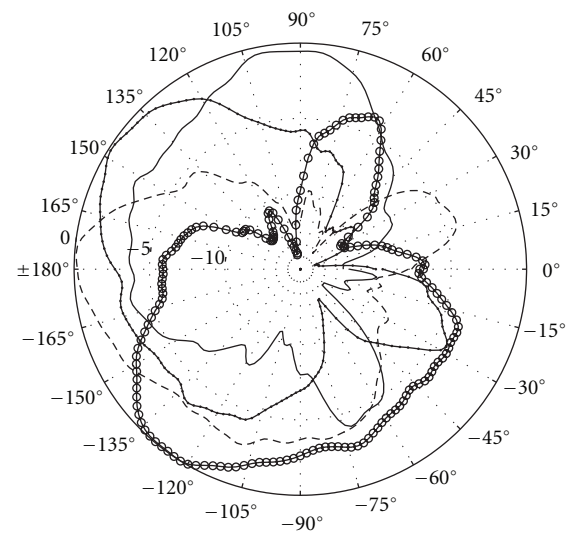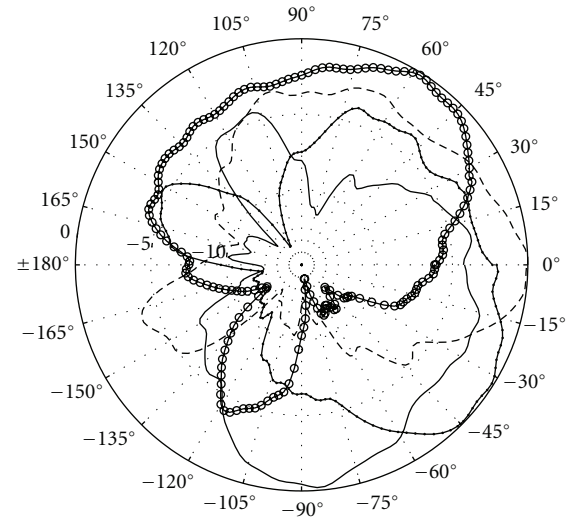
of the ground plane. This was expected albeit at the expense of higher cost electronics.

The switched mode beams for multiple elements of the V-shaped array with a GND plane (5 cm below) are shown in Figure 10. Figure 10(a) shows the beams of the first 4 elements, while Figure 10(b) shows the beams of the remaining 4-elements. Please observe that some overlap will occur due to the larger than 45° HPBW. But with proper electronics, the correct sector can be correctly chosen using the simple and cheap switch mode operation of the array (a quadrant rather a narrow sector). Figure 11 shows the simulated gain values as a function of frequency for the Yagi and V-shaped arrays. The V-shaped array offers
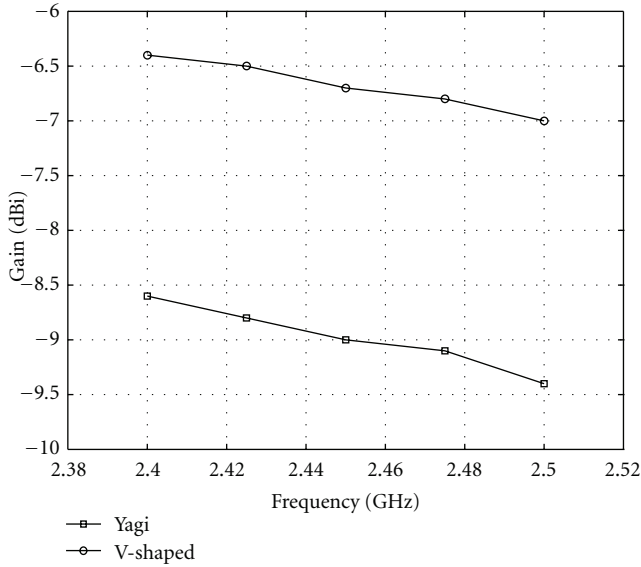
FIGURE 11: Simulated Gain values versus frequency for the V-shaped and Yagi arrays 5 cm over a 1 m diameter GND plane.

FIGURE 13: Measured HPBW comparison for the Yagi and the V-shaped array placed 5 cm over a ground plane operated under switched mode.
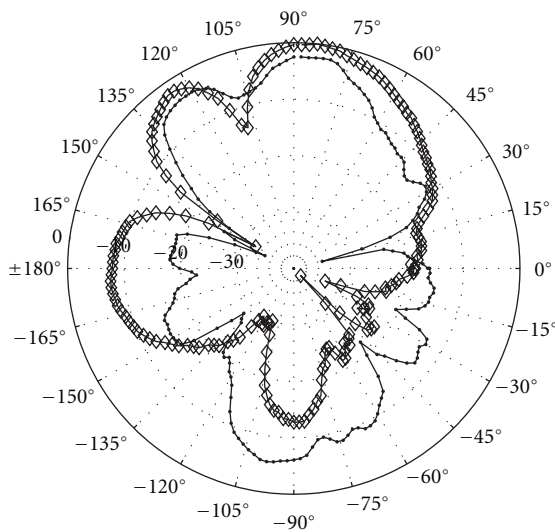

FIGURE 12: Normalized measured gain patterns for switched mode operation with ground plane-dotted markers for Yagi and diamond markers for V-shaped.

approximately 2.5 dB higher gain than the Yagi array. Please note that the gain values are low because the main beam is directed upwards due to the presence of the GND plane beneath the array. Gain values were taken at the elevation angle of 90° representing the roof of a vehicle.

The normalized-measured gain patterns for the switched mode of operation and when element 1 is excited are shown in Figure 12 for both the Yagi and the V-shaped arrays when placed 5 cm above a 1 m diameter ground plane. While the Yagi elements provided better HPBW, the V-shaped elements provided higher gain values. In Addition the back lobe gain
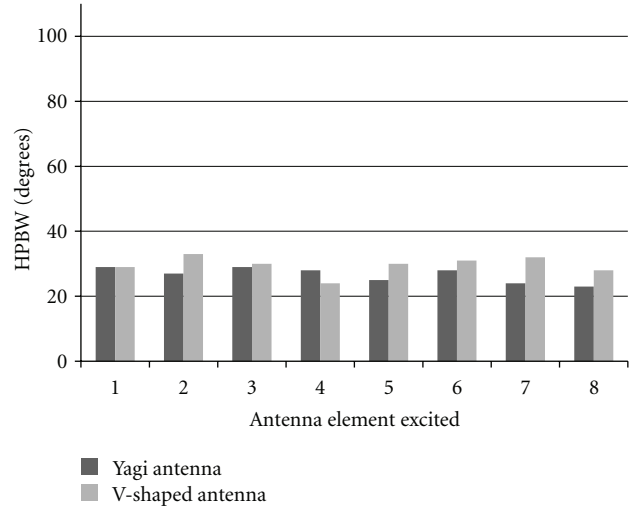
of the Yagi array was 5 dB higher than the backlobe gain of the V-shaped array.

The presence of the ground plane showed a sharp decrease in the HPBW of the antennas as compared to the case without a ground reflector for both arrays in the switched mode of operation. Figure 13 presents the measured HPBW comparison between the Yagi and the V-shaped antenna array operated under the switched mode and in the presence of the ground plane. It is clear that the Yagi array provides a narrower HPBW by an average of 3° than the V-shaped array. The measurements show that the HPBW are 50% less than their simulated counterparts; this is due to the presence of a sharp dip in the main lobe (Figure 12) that might be attributed to the mounting set-up of the antennas. The mounting set-up consisted of duct tape as well as wooden bars to raise the antenna array above the GND plane and hold it in its place. The duct tape (considered as a new dielectric medium) might have affected the radiation characteristics and might have contributed to the dip observed. What is important here is that the presence of a GND plane below the arrays had resulted in narrower HPBW (since the maximum of the pattern was pushed upwards) that allows them to be used in power-based-direction finding applications at lower cost.

4. Conclusion

A comparative performance analysis of two printed circular antenna arrays of V-shaped and Yagi elements has been presented in this paper. Both arrays were designed to operate at 2.45 GHz. Switched and phased modes of excitation were simulated for both antenna designs. The arrays are intended for use in power-based RF DF applications. Measurements under the switched mode reveal that the HPBW is lowered by the presence of a reflecting ground plane, this is of great

importance for enhancing the sectorial resolution for such an application.

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