A Beam Steering System Design based on Phased Array Antennas

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Abstract- This paper presents a low-cost, compact, beam-steering phased array antenna (PAA) system based on a novel approach to integrating low-cost, high-performance phased shifters with their controlling boards within an antenna structure. Consequently, the system has been reduced to one structure for the antenna array and integrated phase shifters, rather than the sophisticated PAA with two separate boards which are connected by RF coaxial cables. The system has been achieved by the following stages; Firstly, the steering vector weights matrix was calculated by MATLAB. Then, four elements of uniform linear Microstrip patch antenna array with their feeding network power divider were designed and simulated in the CST simulation program. As a result, a practical model has been implemented. The designed RF-PCB for the 4-bit phase shifters MAPS_010143 were integrated within the antenna panel. The system works at a resonance frequency of (2.4 GHz), with (±45°) steering capability. The results are presented for the three models. The practical results match the simulation results very closely, fence proving the accuracy of the model and demonstrating a highly effective design.

1. Introduction
The use of steerable Phased Array Antenna (PAA) was started in military applications several decades ago. More recently, interest has been shown in PAAs to enhance the development of telecommunications for many commercial and industrial applications, such as military radar systems, weather surveillance radars, RFIDs, and late generation of cellular systems (5G), due to the significant performance advantage that they provide compared with traditional mechanical radars. PAAs usually required complex integration of high-cost solid-state and phase shifters. Thus, reduction in the complexity, cost, and size is the solution to facilitate their usage in wider areas [1-5]. One of the proposed approaches is to create several sub-arrays within the antenna. Each group is controlled by a phase-shifter. This will reduce the phase shifters in the structure as shown in figure 1. Each of these sub-arrays is controlled by a phase shifter. Each group is seen as a single element to another group. The total Array Factor of the system considers all the elements. However, the limitation of this idea is the increase in the side lobes and grating lobes, also the structure size issues [6-8].
Another approach is by using frequency control to achieve the beamforming [9-12]. These types of systems are not suitable for many applications because most of the applications require a fixed frequency. Beam steering of Microstrip Patch Antenna (MPA) was investigated by Thongsopa and Krairiksh in [13], where beam steering of a dual-feed patch antenna depends on the difference between the input feed frequencies. This idea did not achieve the steering effectively, having many issues with side lobes. Sangjun and Won in [14] presented a wearable patch antenna, where the main beam can be switched between $(0^\circ)$ and $(\pm30^\circ)$. It was proposed that the antenna should steer three beams in the same direction at the same frequency. However, the results show that the antenna has one beam and no practical results were presented. Attia and Ramahi in [15] proposed a novel method to steer the main lobe of an MPA by partially covering the single MPA with a high refractive index substrate. They achieved $(\pm25^\circ)$ overall steer. The steered beam had low-directivity due to the use of a single element. Indeed, the physical structure of the antenna is quite massive comparing with a single element antenna. Wenquan et al. in [16] have achieved a maximum beam steer of $(48^\circ)$ by introducing complementary split-ring resonators in the ground plane of the patch. The issue here is that the switching of rings is not accurate due to the use of switching diodes. Hussaini et al. in [17], have proposed a novel beam steering for a uniform circular six elements antenna by using a reactive loading and time modulated switching technique. They proposed a Genetic algorithm (GA) to optimize the results. The steering was effective, however, there were some issues in the return-loss of the antenna. In [18], a novel idea had been suggested based on a cascaded reconfigurable defected microstrip structure. PIN diodes were inserted in the defected area. Each stage performs $(\pm7^\circ)$ phase shifting. The proposed idea tries to steer the main beam of a four MPA around $(\pm20^\circ)$. Scott and Fusco in [19] have proposed a new method to perform the phase-shifting by integrating two parts of electronically phase shifters in series with the feeding lines. Two dipole array antennas have been used. The total achieved steering was $(\pm12^\circ)$ by changing the biasing voltages to the components. The total $(\pm12^\circ)$ has limited steering application. However, the idea was to find an alternative cheap way to perform the steering. As has been presented, all attempts tended to find alternative ways to replace the expensive phase shifters. Accordingly, low-cost, small-size, and high-performance phase shifters have been chosen for this project. Additionally, they can be integrated within the antenna panel which leads to eliminating the need to create two separate boards for the antenna array and the phase shifter. In contrast, limited to one compact PAA which has a multilayer board consisting of an antenna array, feeding network, and phase shifters with their controllers.

This paper presents a novel, low-cost and compact size PAA beam steering system. The system has high beam steering performance and the novelty is to use low-cost digital phase shifters, which have been integrated into the antenna panel. The results show a compact PAA system, working at a resonance frequency of $(2.4$ GHz$)$, with $(\pm60^\circ)$ steering capability. Besides, there is a reduction in the cables that feed the PAA system, i.e., only one RF cable and the controlling lines, instead of the sophisticated traditional PAA systems in which the phase shifters board is separated from the antenna array panel, and RFs coaxial cables are used to feed each element in the antenna array. The system methodology is explained in section two. While the results and the discussion illustrated in section 3. Finally, the conclusion is presented.

2. System Design Methodology
The proposed system has been achieved by the following steps; Designing and implementing a uniform linear array (ULA) of four elements MPA starting with a single MPA. Then, designing the
corporate feeding network based on Wilkinson Power Divider, to feed the antenna array elements. After that, designing a Radio Frequency Printed Circuit Board (RF-PCB) for the phase shifters and then integrate the RF-PCB with the antenna array structure. Finally, developing a MATLAB code to calculate the steering vector weights matrix and test the system performance.

2.1 Design and implement a ULA

The radiation pattern of a single element antenna is wide and has relatively low-directivity [20-23]. To meet the demands of a long communication link, it is recommended to design an antenna with high directivity. This can be achieved by modifying the electrical size of the antenna which leads to enhancing the directivity. An alternative way to meet high directivity is to design an antenna with an assembly of elements that can be designed in a suitable geometrical and electrical configuration. This type of antenna is known as an Array. Array’s elements are usually identical [20]. The total array field is equal to the multiplication of the single element positioned at the center by a factor which is known as Array Factor (AF) and can be generalized as:

\[ AF = \sum_{n=1}^{N} e^{i(n-1)\psi} \]  

Where \( \psi = kd \cos \theta + \beta \)

The antenna array main lobe can be steered by controlling the excitation of the phase or amplitude, or both, of each element in the array [2]. Assuming that scanning pattern within \( \theta_0 (0^\circ \leq \theta \leq 180^\circ) \), this can be performed by adjusting the \( \beta \) among the array elements as in equation (2).

\[ \psi = kd \cos \theta + \beta |_{\theta=\theta_0} = kd \cos \theta_0 + \beta = 0 \rightarrow \beta = -kd \cos \theta_0 \]  

This is the basis of scanning PAA. Generally, the PAA performance increases when the number of elements increases in terms of directivity, HPBW, and scanning capability.

2.2 MPA Array Design

The project has been designed to work at (2.4 GHz) which falls in ISM unlicensed band. The single MPA (2.4 GHz) was designed and simulated in CST. FR-4 substrate with permittivity of (4.3) and a thickness of (1.6 mm) was chosen for the design. Antenna array design depends on the single MPA.

The initial space was chosen to be (0.5λ) which is equal (62.5 mm) for (2.4 GHz), then optimized. It is worth pointing out that the radiation pattern of the antenna array will differ when the feeding lines are constructed. The differences occur due to the mutual coupling among the feeding lines and the radiated elements. The antenna array structure of four MPA with spaces of (0.5λ) is shown in figure 2 and table1.

![Figure 2. Antenna Array (A): Front View. (B) Back View, CST](image)

| Table 1. Antenna dimensions |
|-----------------------------|
| Parameter | W | W1 | L | L1 | L2 | L3 | L4 | L5 | PW | PL |
| Value (mm) | 250 | 2.88 | 139 | 10.85 | 30.6 | 27.4 | 122.11 | 16.78 | 41.8 | 28.8 |
2.3 Antenna Feeding Networks and Power Divider

The feeding network (power divider) should have high performance and be compact. This network should have a special shape to fit the integration of the phase shifters as will be seen later. The corporate feeding network has been designed based on the Wilkinson power divider (WPD). The straight structure of the WPD was expanded from (2:1) to (4:1) splits as shown in figure 2.

2.4 Phase Shifter (MAPS_010143)

The project aim is to perform the beam steering by changing the phase shifter weights which are integrated within the antenna panel. The challenge is to use accurate and low-cost phase shifters. MACOM Technology Solution Company has produced a phase shifter with interesting specifications. The MAPS-010143, figure 5, is a 4-bit phase shifter that has an integral CMOS driver build in a (4 mm) PQFN-SMD packet, 24-pins which perform high phase-shifting accuracy with minimum losses [23].

![Figure 3. 4-bit Phase Shifter PQFN SMD[23]](image)

The phase shifter has low-DC power consumption and minimal attenuation variation over the phase shift range. It provides a phase shift from (0°) to (360°) in (22.5°) steps. It has two controlling modes: serial and parallel [23]. The serial mode is designed to connect the phase shifter circuit to a computer system to perform the clocking and change the phase. In the parallel mode, control can be achieved by connecting the four controlling bits to a normal 4-bit switch. The small size of these phase shifters can be exploited by integrating them with the antenna panel, which is one of the project’s aims.

2.4.1 Phase Shifters’ RF-PCB Design

Phase shifters’ RF-PCB controlling circuit has been designed by using a modeling program (Proteus). PCB is fabricated from a substrate such as epoxy/glass-fiber plate and the conducting layer which is usually copper of a thickness of (35/70) μm. PCB may have single-side or double-sided layers and this depends on the design requirements, in some cases more than one layer can be used. This is called multilayer board such as computers mainboards. It is possible to connect the layers by using Vias. For this project, a single layer of RF-PCB board was used to mount all the components. The design started by modifying a 24-Pin SMD (4x4 mm) footprint and made it compatible with the IC configuration. For the practical model, it was decided to have separate parts of RF-PCB for each phase shifter, to allow more flexibility in integration with the antenna array panel. The design has the specification of an RF-PCB, in terms of substrate type and lines dimensions. The substrate was chosen to be FR-4. Each of the phase shifters has its feeding power and control switches on the board as shown in figure 4.

![Figure 4. RF-PCB for MAPS-010143 Phase Shifters, (A) Proteus, (B) Fabricated Model](image)
2.5 *Beam Steering Vector Weights Matrix Calculation*

The PAA can be controlled electrically to steer the main beam towards a specific direction. Beam steering is performed by changing the elements phase weights in the antenna array, however, there is no full control of the pattern shape, in terms of HPBW, nulls positions, and side lobes numbers and levels. The vector weights matrix calculation for beam steering in this project has been calculated by developing a MATLAB code. The main idea is based on AF derivation. The AF of ULA can be given as in equations (1 and 2). Where \( \beta \) represents the phase shift differences among the elements, and the main beam of the antenna array can be steered by changing the phase of the adjacent elements. The phase shifters that are used for the design give (16) phase shift of a step of (22.5\(^\circ\)). The MATLAB code asks for the required angle to be entered to steer the main beam towards it. Then, it will start calculating the exact phase weight for each element in the array. Theoretically, the maximum achievable beam steering is (±60\(^\circ\)), i.e. (120\(^\circ\)). The system can perform the steering of (10\(^\circ\)) steps from (0\(^\circ\)) to (45\(^\circ\)) with very high accuracy. Above (45\(^\circ\)) to (60\(^\circ\)) this accuracy decreases in terms of the maximum main lobe peak pointing angle. The phase shifter was chosen to work in parallel mode; thus, the phases are changed digitally by switches. Each combination of digits gives a corresponding phase shift. Table 2 shows the combination of the switches to perform the (16) phases steps. \((D_4)\) is the LSB and \((D_1)\) is the MSB.

| Phases | 0  | 22.5 | 45  | 67.5 | 90  | 112.5 | 135 | 157.5 | 180 | 205.5 | 225 | 247.5 | 270 | 292.5 | 315 | 337.5 |
|--------|----|------|-----|------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|-----|-------|
| D1     | 0  | 0    | 1   | 0    | 1   | 1     | 0   | 1     | 0   | 0     | 1   | 1     | 0   | 0     | 0   | 1     |
| D2     | 0  | 0    | 1   | 1    | 0   | 1     | 1   | 0     | 1   | 0     | 1   | 1     | 0   | 0     | 0   | 1     |
| D3     | 0  | 0    | 0   | 0    | 1   | 1     | 1   | 0     | 0   | 0     | 1   | 1     | 1   | 0     | 0   | 0     |
| D4     | 0  | 0    | 0   | 0    | 0   | 0     | 0   | 1     | 1   | 1     | 1   | 1     | 1   | 0     | 0   | 0     |

Five steering cases were chosen of a step of (10\(^\circ\)) from (15\(^\circ\) to 45\(^\circ\)) and a (60\(^\circ\)), to illustrate the steering trends. All the cases show both, positive and negative steering directions.

Table 3 illustrates the phase weight of each element in the array and the corresponding combination of the digital switches for an example of a steering case towards +15\(^\circ\).

| Element 1 Phase | Element 2 Phase | Element 3 Phase | Element 4 Phase |
|-----------------|-----------------|-----------------|-----------------|
| Element 1 Phase | Element 2 Phase | Element 3 Phase | Element 4 Phase |
| 315              | 270             | 225             | 180             |
| D1               | D2              | D3              | D4              |
| 0                | 1               | 1               | 1               |
| D1               | D2              | D3              | D4              |
| 0                | 0               | 1               | 1               |
| D1               | D2              | D3              | D4              |
| 0                | 0               | 0               | 0               |
| D1               | D2              | D3              | D4              |
| 0                | 0               | 0               | 0               |

2.6 *Integration of RF-PCB with Antenna Structure*

Phase-shifters were integrated within the antenna array structure by fitting them on the antenna back panel. \((RF_{in})\) and \((RF_{out})\), for each RF-PCB were connected to the antenna elements’ feeding lines. The connections were made by Vias of (0.7 mm) through the substrates of the RF-PCB and antenna array. All Vias have the same length to avoid any phase differences among the antenna array elements. The antenna array ground plane was connected to the RF-PCBs ground-plane, as in figure 5, which gave more stability for the phase shifter performance.
Figure 5. (a) PAA Design Front Panel. (b) Phase Shifter Integrated with the Antenna Array Back-Panel.

The Reflection coefficient \((S_{11})\) of the PAA after integrating the phase shifters is shown in figure 6. The figure compares the \((S_{11})\) for the three models, MATLAB, CST and practical model.

Figure 6. \((S_{11})\) for PAA Matlab, CST, and Practical

The effects of integrating phase shifters within the antenna array feeding lines are clear on the \((S_{11})\), however, the antenna still resonates at (2.4 GHz).

3. Beam Steering Results and discussion
The PAA has been implemented practically according to the CST design. The vector weights matrix was applied. The practical model was tested in the anechoic chamber as shown in figure 7.

Figure 7. PAA testing in the Anechoic Chamber

The results were as expected and verified the MATLAB and CST results. figure 8 to figure 13 show the selected steering cases.
Five steering cases were chosen in a step of (10°) from (15° to 45°) and a (60°), to illustrate the steering trends. The practical model results were close to the MATLAB results and CST, which is the benchmark. Figures 8 to 13 show a comparison of the three models, MATLAB, CST, and practical model steering results. It is clear from the figures that there are minor differences between the MATLAB pattern and CST. These differences are to be expected because MATLAB results are based on mathematical equations, however, CST is closest to actual results and takes into consideration all the effects such as mutual coupling among elements, the substrate effects, and the ground plane effects. Thus, CST is considered the benchmark for practical model beam steering results. The mismatch losses of the phase shifters and the antenna array were expected. This problem is critical and is considered to be the main cause for any degradation in the system performance for two reasons; firstly, the phase shifter IC should be matched at the (RFin) to ensure that it is receiving the suitable operation level value. Secondly, the (RFout) matching, to ensure that it is matched with feeding lines without any reflections. The phase shifter has a characteristic impedance of (50Ω). Consequently, the antenna array feeding lines were designed to be as (50Ω) at the places where the...
phase shifters were fitted. The Microstrip line width for this is (2.88 mm), according to the design specifications. However, when fitting the phase shifters on the back panel of the antenna array, the connection Vias (RF\textsubscript{in}) and (RF\textsubscript{out}) were (0.7 mm) through the two substrates, RF-PCB and antenna array respectively. Nevertheless, the results have the same shape and trends, which leads to concluding that the mismatches are as minimal as possible, the phase shifters are performing the steering correctly in all cases and the steering matrix is correct and it is suitable to use for the practical model.

3.1 Steering Accuracy
Theoretically, the maximum achievable beam steering is (±60\textdegree), i.e. (120\textdegree). The system can perform the steering of (1\textdegree) steps from (0\textdegree) to (45\textdegree) with high accuracy and with sidelobe levels around (-10 dB). Above (45\textdegree) to (60\textdegree) this accuracy decreases, in terms of steering the maximum of the main lobe peak pointing angle and sidelobe levels. There is more than one reason behind the decline in performance. For instance, the antenna array aperture size, the number of elements in the array, and the PAA steering concepts of changing only the phase or phase and the amplitude of each element in the array. These reasons will be discussed in the following sections.

3.2 Pattern Shaping and HPBW
HPBW is considered an important beam steering performance parameter. The narrower beam leads to better performance. However, as mentioned before, more than one factor can affect the antenna array HPBW. table 4 and figure 14 to figure 17 show a comparison of the HPBW of the main lobe for all steering cases in CST and practical model, also, the practical antenna gain taking into account the substantial sidelobes present at large steering angles.

| Steering Angle (Deg) | 0  | -15 | 15 | -25 | 25 | -35 | 35 | -45 | 45 | -55 | 55 | -60 | 60 |
|----------------------|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|
| HPBW Simulation (Deg)| 24.8 | 25.7 | 25.7 | 26.9 | 26.9 | 28.9 | 28.9 | 30.3 | 30.3 | 31.4 | 31.4 | 31.6 | 31.6 |
| HPBW Practical (Deg) | 24.8 | 26.1 | 26.9 | 27.3 | 27 | 29.2 | 29.5 | 30.6 | 30.2 | 31.5 | 31.2 | 32 | 31.8 |
| Antenna gain(dB) | 8.39 | 5.6 | 5.73 | 5.07 | 5.07 | 4.2 | 4.33 | 3.6 | 3.53 | 2.5 | 2.26 | 2.1 | 1.58 |

**Table 4. HPBW and gain for CST and Practical**

![Figure 14. HPBW for CST and Practical (Positive Steering)](image1)

![Figure 15. HPBW for CST and Practical (Negative Steering)](image2)
It is clear that the values of steering for both the practical model and CST are close to each other. The noticeable change is that when increasing the scan angle, the HPBW angle increases which leads to broadening the antenna main lobe and at the same time increases the side-lobes numbers and levels decreases antenna gain and creates the grating lobes. The decrease in the main lobe level is expected because the power is lost in the increasing side lobes and grating lobes.

4. Conclusion
This paper presents a novel approach of beam steering system based on phased array antennas. The project aimed to build a novel, low-cost, and compact PAA. The system has been achieved by the following stages; Firstly, the steering vector weights matrix $w$ as calculated by Matlab. Then, four elements of uniform linear Microstrip patch antenna array with their feeding network power divider were designed and simulated in the CST simulation program. A prototype model has been implemented. Then, the specially designed RF-PCB for the 4-bit phase shifters MAPS_010143 were integrated within the antenna panel. The system has been tested and the results have been compared with the simulation results. The system has high beam steering. The result presents a compact PAA system, working at a resonance frequency of (2.4 GHz), with (120°) steering capability, reducing the cables that feed the PAA system and limiting them to only one RF cable and the controlling lines, instead of the sophisticated traditional PAA systems in which the phase shifters board is separated from the antenna array panel and RFs coaxial cables are used to feed each element in the antenna array.

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