Electronic phase-controlled beam steering for moving target tracking using a linear antenna array for DOA application

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Abstract. In this paper, an algorithm that can be implemented using MATLAB software is proposed to calculate phase shifts of antenna array elements depending on a desired angle. The obtained values of phase shifts are sent automatically to CST Microwave Studio through the COM interface to analyze the antenna radiation pattern and gain. The whole scheme of dynamic beam steering and interaction between MATLAB and CST Microwave Studio software is shown in the graphical abstract Fig. 1. The presented method can be used to achieve dynamic beam steering of the antenna arrays by automatic transmission of phase values without any human intervention.

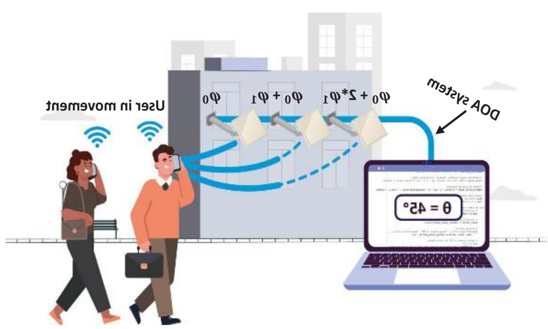

Fig. 1. Graphical abstract

For each angle of steering, the algorithm calculates the necessary phase shift and sends them to CST to analyze the radiation pattern of the antenna array with these conditions. The simulation results prove that the calculated phase shifts result in a directivity of beam with total gain of the antenna array approximately equal to 14 dBi. This method verifies the efficiency of the suggested phase controller and the interface created between MATLAB and CST for Direction of Arrival (DOA) applications.

Keywords: Beam Steering, Patch Antenna, DOA.

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1 Introduction

The necessity to monitor and estimate the location of the moving target in the process of communication has recently become especially acute [1]. The use of beam-tracking technology is vital for providing high-quality communication to mobile users, as it entails dynamically orienting the antenna array beam towards the target [2]. It becomes crucial for the maintenance of a stable connection in highly mobile environments. Direction-of-arrival (DOA) estimation is one of the most important technologies underlying beam steering. DOA systems calculate the angle of the arrival of the signal by estimating the phase differences between several received signals on the antenna elements [3]. In turn, the phase difference arises due to the spatial distance between the antennas and becomes the key to the calculation of the accurate angle of the signal arrival, allowing for its targeting [4]. Besides, operation with frequencies like 5.8 GHz makes it possible to create small-sized phased arrays with the high angular resolution required for precise beam orientation [5]. The advantages of the beamforming at the same frequency include high directionality, low interference, efficient spectrum utilization that makes this method highly appropriate for 5G, radar, wireless power transmission, and autonomous systems [6,7]. Thus, MATLAB-phase control used in CST simulations becomes a reliable tool for modeling, analyzing, and validating beam tracking systems in realistic conditions [5]. In this paper, we present an antenna array designed for beam steering applications.

Phase delay is one way that beam steering can be accomplished [8]. The array is characterized by high directional gain across different phase angles, making it well-suited for detecting signals from moving targets with precision. Operating in the 5.74–5.88 GHz band with the proposed frequency of 5.8 GHz, the antenna exhibits a peak gain of 14.6 dBi. Additionally, a MATLAB-based algorithm is implemented to calculate the appropriate phase shift for each antenna element, tracking a moving target using beam steering. Therefore, in this work, we propose an automated beam steering framework based on real-time phase control and MATLAB–CST integration, focusing on simulation-based tracking of a moving target. Unlike previous studies, our system dynamically adapts the beam direction to follow a sinusoidally varying target angle.

2 Phased array beam steering simulation

2.1 Beam steering and phase control for target tracking

In this first paragraph, we will describe tracking of a moving target by a technique known as beam steering. This is based on an antenna array, where there is exact control over the direction of the beam that is radiated without actual mechanical movement. Beam steering is achieved electronically through application of phase shifts between the individual elements of the antenna array. By phase-shifting the signal at every antenna element, the overall array radiation pattern can be directed to a desired responsiveness and accuracy continuously. Beam-steering (BS) aims at directing the signal toward its intended recipient with the least possible interference. High-gain electronically steered antennas are common in wireless power transmission, satellite communications, and 5G wireless mobile communications [9].

In order to achieve Beam steering and target tracking, high gain antennas are critical components in facilitating long distance communication, including satellite communication, radar, deep space exploration, and earth to earth communication links. [10]. It is well known that parabolic reflector antennas, lens antennas, and phased arrays are some examples of high gain antennas which are used widely. Despite their good gain performance, the practicality of these types of antennas is sometimes restricted because of structural complexity, complicated feed system design, and costly production process. Hence, considerable work has been done in the development of economical and high-gain antennas [11]. That is why we chose to use a high gain planar phased array antenna. Such an antenna is characterized by many benefits including low profile, minimum loss, lightweight nature, inexpensive cost, common aperture, lower insertion loss, multi-beam coverage, and easy to manufacture.

2.2 Beam steering simulation on MATLAB

A MATLAB script was developed to demonstrate a 4-element phased antenna array operating at 5.8 GHz, tracking a moving target by calculating and setting the phase for each element. The system computes exactly four phase shifts one for each antenna element, at each timestep ensuring that each element receives a unique phase value.

The phase shift $\Delta\varphi$ between adjacent elements in a phased array antenna is caused by the extra distance

$$L = d \sin \theta \tag{1}$$

that a wavefront traveling at an angle θ must cover to reach the next antenna element spaced by d. This path difference creates a time delay:

$$\Delta t = \frac{L}{c} = \frac{d \sin(\theta)}{c} \tag{2}$$

Since one full wavelength λ corresponds to a phase change of 2π radians and a period $T = \frac{\lambda}{c}$ the phase shift can be expressed

$$\Delta\varphi = 2\pi \times \frac{\Delta t}{T} \tag{3}$$

In case one wishes to aim the beam in the direction which is at an angle of θ as shown in Figure 1, the phase difference ($\Delta\varphi$) between each radiator is determined as follows from Equation (4) [10]:

$$\Delta\varphi = \frac{2\pi d}{\lambda} \sin(\theta) \tag{4}$$

Which ensures that signals from all elements combine constructively in the desired direction θ, steering the beam electronically without mechanical movement.

For an array of N antennas, the phase shift for the n-th antenna is calculated as

$$\varphi_n = -\frac{2\pi d \sin \theta}{\lambda} \cdot n \tag{5}$$

Where φ_n is the phase of the n-th element, d = 50 mm is the element spacing, λ=0.05m is the wavelength, and θ is the angle to the target. Target angle will be described using the below equation:

$$\theta(t) = 30^\circ + 10^\circ \sin(0.2\pi t) \tag{6}$$

Thus, the target angle is a sinusoidal function that oscillates between 20° and 40°. MATLAB calculates these phase shifts and applies them to the CST parameters (Phase Element 1 to Phase Element 4) via the COM (Component Object Model) interface, triggering project rebuilding and electromagnetic simulations to generate radiation patterns. These patterns visualize antenna gain across different angles, verifying beam alignment with θ(t). The CST software rebuilds and runs the project to verify the result of the beam tracking in real time. This example, inspired by phased array theory [12] demonstrating how differently delayed phases between antenna elements can be used to steer the beam without mechanical movement.
For a given theta, the phase shifts generated by MATLAB were automatically applied in CST, and the resulting radiation pattern of the proposed antenna array is discussed in the following section. Unlike manual tuning, the phase control is performed dynamically using MATLAB's COM interface to control CST simulations in real time.

3 Tracking a moving target using beam steering on CST

3.1 Antenna design on CST

The construction of the antenna array is the first step in the beam steering tracking of a moving target procedure. The unit cell level, which serves as the phased array's basic building element, is where this process begins. A rectangular microstrip patch antenna is constructed in this study to function at 5.8 GHz, a frequency often utilized in contemporary wireless communication systems and industrial, scientific, and medical (ISM) applications.

With a relative permittivity of εr = 2.55 and a thickness of h = 1 mm, the dielectric substrate on which the antenna is printed provides a balance between performance and size. The patch's width (Wp) and length (Lp) were especially determined to be in resonance at f_r= 5.8 GHz. A microstrip line feed is used to excite the antenna, designed with a characteristic impedance of Z_0 = 50 Ω, ensuring proper impedance matching with standard RF systems. The mathematical equations were used to obtain the initial values of the dimensions of the rectangular microstrip patch used to design the antenna element.

The geometry of the planned rectangular patch antenna, as simulated by CST, is shown in Fig. 2, while Fig. 3 shows its reflection coefficient (S11), which displays a reflection coefficient well below -10 dB, confirms that it operates at 5.8 GHz, indicating appropriate impedance matching and negligible return losses. The antenna's achieved gain of 8.297 dBi permits effective radiation in the intended direction, and its directivity of 8.795 dBi demonstrates that it can concentrate energy more efficiently than an isotropic source.

The design guarantees a considerable portion of the input power is radiated with comparatively minimal losses in the substrate and conductors, thanks to an overall radiation efficiency of 89.65%.

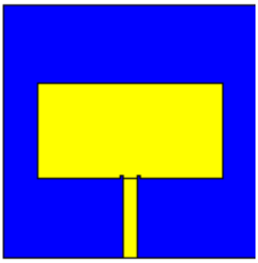


Fig. 2. Antenna design

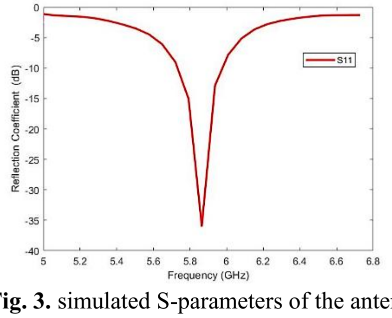


Fig. 3. simulated S-parameters of the antenna

Because of these features this single-element design will later be replicated and arranged into a linear array configuration, forming the basis for beam steering through controlled phase shifts.

3.2 Phased antenna array design

Once the unit cell is validated, the next step involves constructing a linear antenna array to enable beam steering capabilities. Phased array antenna is one of the examples of a directional antenna that consists of number of driven elements located in front of plane that reflects radio waves in a certain direction [13].

In this study, the antenna array demonstrated in Fig. 4, consists of a four-element linear array designed using identical microstrip patch antennas operating at 5.8 GHz. The arrangement of the elements is done along the x-axis, keeping the distance between each element as 50 mm, which is close to half of the wavelength at the operating frequency. This spacing is chosen to ensure a good compromise between directivity and avoiding grating lobes.

The designed antenna array operates efficiently at the targeted frequency. Simulation results confirm that the array is well matched to the desired frequency band, ensuring minimal reflection and maximum power transfer as illustrated in Fig. 5. The antenna array has a high level of directivity of 14.65 dBi and gain of 14.6 dBi as depicted in Fig. 6, making it suitable for applications that require focused energy transmission and enhanced signal strength in specific directions (DOA).

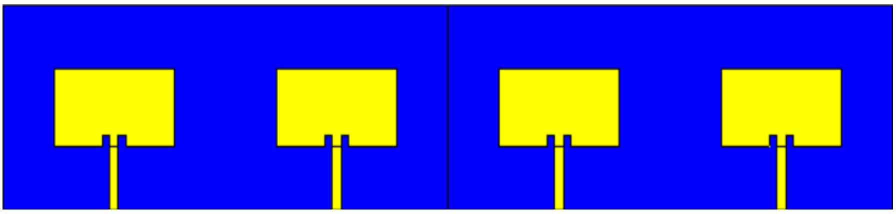


Fig. 4. Antenna array design

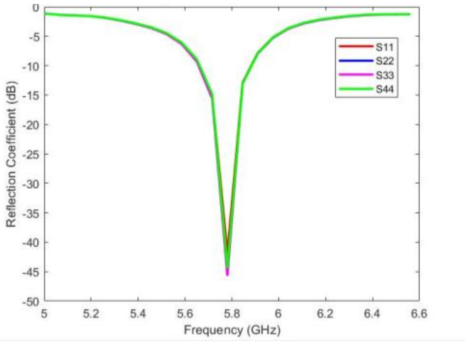


Fig. 5. Simulated S-parameters of the antenna array

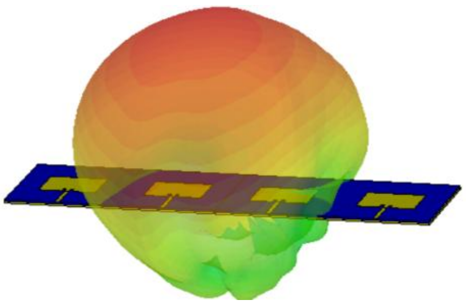


Fig. 6. Radiation pattern of the antenna array.

3.3 Beam steering principle based on phase

The principle behind the operation of the beam-steering in transmit arrays is based on the electromagnetic waves (EM) emitted from a feed antenna and propagating through a planar array of periodically placed unit cells with period "d". Each particular unit cell having index n (n=0,1, ...) will cause a certain phase shift φ_n, which can be found according to Equation (7) [9].

$$\varphi_n = K_0 n \Delta s + \varphi_0 \tag{7}$$

where $K_0 = \frac{2\pi}{\lambda_0}$ is the propagation constant in free space. The term Δs refers to the difference in paths traveled by two neighboring elements, n_{th} and (n + 1th) elements, after the wave passes through the transmit array. The path difference for a transmitted wave steered at an angle θ can be written as Δs=d.sinθ, where d is the periodic distance between two neighboring elements. Hence, the necessary phase shift is [9]:

$$\varphi_n \quad = \varphi_{n+1} - \varphi_n \tag{8}$$

$$\Delta\varphi = K_0 \Delta s = \frac{2\pi}{\lambda_0} .d.sin\theta \tag{9}$$

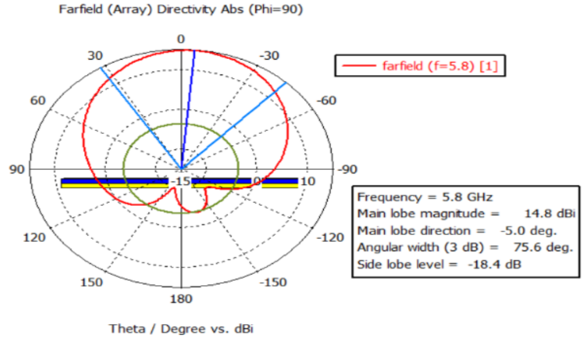
$$Sin\theta = \frac{\lambda_0}{2\pi d}. \Delta\varphi \tag{10}$$

The phase distribution for the transmitarray depends on the angle at which we would like to deflect the beam. For this purpose, Equation (10) is utilized to find the required phase shift. Equations (8) and (9) are used to define the relationship between the steering angle and phase compensation [9].

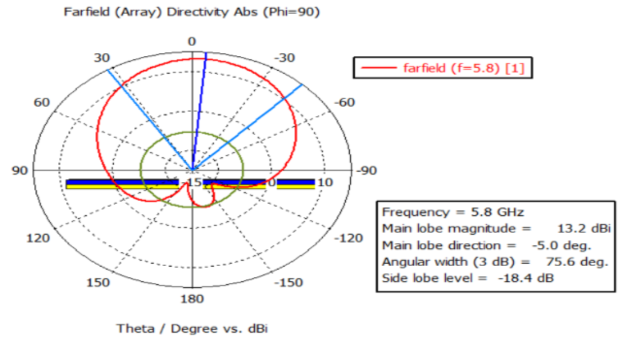
3.4 Emulating target tracking via phase variation

The Farfield Array Factor tool in CST was used to apply progressive phase shifts between the elements of the antenna array, enabling the main lobe of the radiation pattern to be electronically steered toward different directions without physically rotating the array.

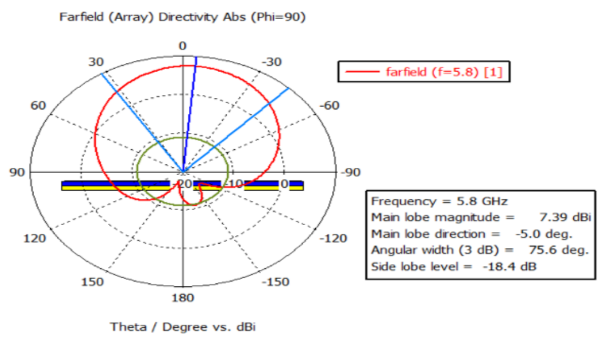
To simulate this beam steering behavior, a series of phase shifts were applied in fixed increments across the antenna elements. By gradually increasing the phase shift from 0° to 60°, the direction of the main lobe in the far-field radiation pattern was effectively controlled. Each phase shift value corresponded to a new beam direction and hence gain, making possible the tracking of a moving target along a known path. For instance, the radiating patterns of the phased array antenna at 5.8 GHz frequency level for three different phase shifts are presented in Fig. 7. The phase shift levels considered for Fig. 7(a), (b), and (c) were 0°, 30°, and 60°, respectively. The corresponding realized gains were 14.8 dBi, 13.2 dBi, and 7.39 dBi, respectively. From these results, it can be said that the concept of beam steering was successfully achieved as there was dynamic change of the main lobe direction for different phase shifts applied to the array elements. This has also been confirmed by the high gain levels realized for the steering angles 0° and 30°. Nevertheless, the main lobe magnitude was observed to reduce as the steering angles increased. This was caused by increased phase mismatch, sidelobe effect, and low efficiency of the array at high off-axis angles.



(a)



(b)



(c)

Fig. 7. Far Field Radiation Patterns of Phased Antenna Array at (a) 0º, (b) 30º and (c) 60º Phase Shifts

In summary, the results obtained above confirm the theoretical principles of phased arrays and show that even a simple four-element phased antenna array is capable of imitating target tracking through the use of the phase control method. Moreover, the increased number of elements in a phased antenna array greatly enhances the effectiveness and performance of this array. The increased size allows one to increase gain and decrease the beamwidth, which in turn provides for an improvement in the effectiveness of transmission or reception of signals over long distances with increased accuracy. In particular, this property makes phased antenna arrays suitable for tracking moving targets within complex and large areas such as open fields, urban environment, or any other area where target tracking is needed. Another important aspect associated with the increase of the number of elements in phased antennas is an improved angular resolution, which is important for DOA estimation. The gradual gain reduction observed at higher steering angles is due to increased side lobes and reduced main lobe efficiency, common in small arrays.

3.5 Simulation Validation

Two techniques were applied to enhance the reliability of the simulation results. Firstly, the theoretically computed steering angles, calculated using the phase-shift equation in Equation (4), as referenced from Balanis [5], were compared against the far-field beam directions obtained by the CST simulator. It has been found that the predicted beam directions matched perfectly with the theoretical estimations for each of the three phase angles, 0°, 30°, and 60°. This verifies the accuracy of the phase controlling algorithm implemented in MATLAB code. Secondly, the gain value of 8.297 dBi obtained for the element antenna from CST simulation was compared against theoretical gain estimation of a rectangular microstrip patch with a dielectric constant of ε_r=2.55, which usually results in gain values within a range of 7 to 9 dBi as published in [5, 9].

4 Conclusion

This work introduces a planar antenna array formed by an array of resonant unit cells periodically placed in a two-dimensional planar structure. This configuration enables dynamic beam steering capabilities. However, the proposed approach demonstrates how phase control can be leveraged to simulate the real-time tracking of a moving target by steering the beam. We confirmed the array's capacity to create a high-gain directional beam fitting the target position by means of design and simulation in CST Studio. The results confirme that the effectiveness of this technique in dynamically manipulating the radiation pattern has been proven to be effective, which is crucial in advanced applications like Direction of Arrival (DOA). In addition to the tracking capabilities, this technique makes it possible to capture the incoming signal from an unspecified direction, meeting some important requirements of the next-generation DOA system. The future plan will be the validation of this method by means of implementing it in hardware and in large-scale antennas.

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