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A New Generation of Fast and Low-Memory Smart Digital/ Geometrical Beamforming MIMO Antenna

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Abstract: Smart multiple-input multiple-output (MIMO) antennas with advanced signal processing algorithms are necessary in future wireless networks, such as 6G and beyond, for accurate space division multiplexing and beamforming. Such a MIMO antenna will yield better network coverage and tracking. This paper presents a smart MIMO antenna configuration with a highly innovative beamforming technique using several nonlinear configurations of dipole arrays. Phase delay factors are optimized at the transmitter to form a single beam and then to steer the beam towards a particular direction. A number of phase shifters are added in order to obtain maximum directional gain. This configuration also significantly increases the power gain of the MIMO antenna at a low cost and with operational simplicity. The paper also demonstrates how the beam width and beamsteering can be effectively controlled. Wolfram Mathematica software was used to generate the three-dimensional radiated beam patterns of the transmitter antenna. There are two approaches to configure the receiver antenna. In the first approach, the received signal magnitude is maximized by aligning the contribution of all elements of the receiver antenna to the same phase. With this approach, the field gain of the proposed system is 25.52 (14.07 dBi). The signal processing gain at the receiver is 64 (18.06 dBi). Therefore, the overall power gain for this proposed new digital/geometrical smart MIMO system is 32.13 dBi. In the second approach, the receiver beam is directed towards the transmitter by optimizing the phase delay coefficients of the receiver. Here, the overall gain of the system is found to be 134.56 (21.28 dBi). Even though the system gain in the second approach is lower, it has the advantage of low interference at the receiver side.

Keywords: MIMO systems; smart antennas; phase shifters; beamforming; beamsteering

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1. Introduction

The emerging 6G and beyond wireless networks will be equipped with accurate user tracking capability using dynamically steered, highly focused radio beams. This will enable enhanced location-based services in addition to space division multiplexing to improve the capacity. These sharply pointed beams will also effectively combat interference in highly crowded heterogeneous environments and efficiently exploit the additional capacity of millimeter wave (mmWave) bands [1,2]. Effective MIMO antennas are required to realize these advanced location- and movement-aware future networks. Such an effective, fast, and low-memory MIMO antenna technique is presented in this paper.

It is well known that MIMO systems use multiple antennas at both the transmitter and receiver to divide and conquer the hostile wireless channel. This can help reduce interference and improve signal quality [3,4]. The MIMO technique exploits multipath propagation, since signals received from multiple paths are intelligently combined at the receiver to reconstruct the original signal [5]. Minimizing interference is achieved by creating nulls in the beam (that is, radiation nulls). In the directions of the beam nulls, the signal is weak or non-existent.

However, the most significant advantage of the MIMO is its beamforming and beamsteering capabilities. Hence, MIMO offers a significant increase in channel capacity without additional bandwidth and it reduces power consumption. The MIMO technology is a key component of many modern wireless communication standards, such as 802.11n and 802.11ac Wi-Fi, and 5G and 6G cellular networks [2,4,6]. With the vast development of MIMO technology, smart MIMO antennas are being intensely researched to improve performance with low hardware and software complexity.

Smart MIMO antennas use advanced signal processing techniques for performance improvement. They have the ability to adapt to changing conditions in the environment, such as the level of interference, in addition to providing user tracking. A smart MIMO antenna can optimize its performance in real time and improve communication speed, capacity, and reliability [7].

Smart antennas are customarily categorized as either switched beam or adaptive array systems based on their operational modes. Switched beam antennas use a finite number of predefined, static, fixed radiation patterns and switch among them as needed. They do not usually use real-time feedback. On the other hand, in an adaptive array antenna system, an infinite number of patterns can be obtained, and these beams can be continuously steered by rapidly adjusting the signal phase angles of each antenna element. For instance, it can dynamically track different types of users, adapt to changing channel conditions, minimize interference, and maximize signal reception by adjusting its parameters in real time [3,8].

Smart antenna technology can spatially track mobile devices by adapting its radiation pattern to optimize both transmission and reception to/from each user's device [3]. Single beamforming and beamsteering can especially assist in avoiding problematic side lobe radiations.

In order to obtain effective and rotatable beams, signals from multiple elements of a nonlinear antenna array can be appropriately combined. This is achieved by organizing phase delays in the antenna array elements in specified patterns in space [7,9,10]. The use of advanced signal processing techniques and artificial intelligence algorithms allows for the optimization of the power and direction of the signal to/from each user, which in turn reduces interference and noise, thereby increasing the communication quality [11].

In this paper, a smart MIMO antenna system is proposed based on the antenna architectures described in [3]. The proposed smart MIMO antenna has the ability to maximize its directional gain by optimizing the phase delay factors of its elements. The validation of this proposed antenna architecture is achieved in a three-dimensional space using Wolfram Mathematica® software. The simulation results show a significant improvement of the directional field and power gains of the proposed system over existing systems. The technique proposed in this paper avoids the usual, costly exercise of adding additional hardware per antenna element (mixers, filters, power amplifiers, etc.) to obtain a high antenna gain. The very significant increase in the power gain is achieved by the smart geometrical arrangement of the MIMO antenna elements and their phase angle optimization. Another advantage of this new MIMO technique is its significantly higher power gain that circumvents the technological limitations and high cost of conventional mmWave electronics to obtain phase shift for every antenna element. Therefore, the technique proposed herein will reduce the cost as well as the complexity of the electronics required.

MIMO beamforming falls under the following categories: analog beamforming, digital beamforming, hybrid (analog/digital) beamforming, and lens-based hybrid beamforming [12]. Analog beamforming is used to improve the signal at the RF level, while digital beamforming is used to improve the signal at the baseband level. The technique presented herein may be the beginning of a new category of MIMO beamforming, which we like to classify as digital/geometrical beamforming. This new digital/geometrical MIMO system can increase the capacity and coverage of wireless links by using a number of beams that can be directed to almost any direction [13]. We assume that this new approach can help overcome some of the following challenges of mmWave 5G and 6G networks: point-to-point predominantly line of sight (LOS) communication, high data rates requiring high network overheads, mobility support, and high user density. With radio networks consuming about 80% of the electric power supplied to mobile networks, the MIMO antenna presented herein is also highly energy efficient, making it an attractive tool in MIMO technology, since MIMO antennas do present an energy consumption problem.

The approach presented in this paper is a novel method of beamforming that utilizes non-numerical optimization techniques to achieve the desired beam. Specifically, the method uses a phase shift technique to manipulate the signal propagation and receiving, allowing for the rapid movement of the beam to new positions without the need for repeated numerical optimizations. This approach offers a significant advantage over traditional methods of beamforming, which rely on probabilistic signal processing techniques that can be time consuming and computationally intensive. By using this innovative technique, the proposed method enables efficient and effective beamforming, making it an important contribution to the field of wireless communication systems.

In Section 2, we describe the specific construction of the new digital/geometrical MIMO system, both at the transmitter end and the receiver ends, and the geometrical model of the proposed MIMO system. This section also explains how the nonlinearly positioned MIMO antenna in space can be used to form and steer beams by merely shifting the geometric angles of the positions of the elements relative to each other. Since this requires no additional computations, the beams may be steered rapidly. In addition, when the dipole antenna elements are parallel to each other in the MIMO transmitter or receiver, the current elements are parallel to each other, and the vectors of the currents do not come into play. However, in future work, the relative tilt of the transmitter MIMO system with respect to the receiver MIMO system needs to be accounted for.

In Section 3, details of the beamforming and beamsteering approach in the new digital/geometrical MIMO system are given. These equations form the basis of the computer code that is developed to carry out both beamforming and beamsteering. The paper focuses on the generation of a single beam, and not multiple beams, although this technique may be readily extended to multiple beams. In Section 4, the results of a single beam formed using the new digital/geometrical MIMO system are presented. These results ensure pinpoint accuracy, fast steering, low computational burden, and low memory, enabling the system to be able to cater to fast-moving mobile users in low-latency future wireless networks.

2. Digital/Geometrical Hybrid MIMO Beamforming Method

2.1. Proposed Smart MIMO System Architecture

Figures 1 and 2 illustrate the MIMO system architecture, which has multiple antennas at both the transmitter and the receiver. Phase shifters can perform beamsteering and beamforming very quickly with a much higher directional gain. In this MIMO system, the transmitter and the receiver are bidirectional and interchangeable.

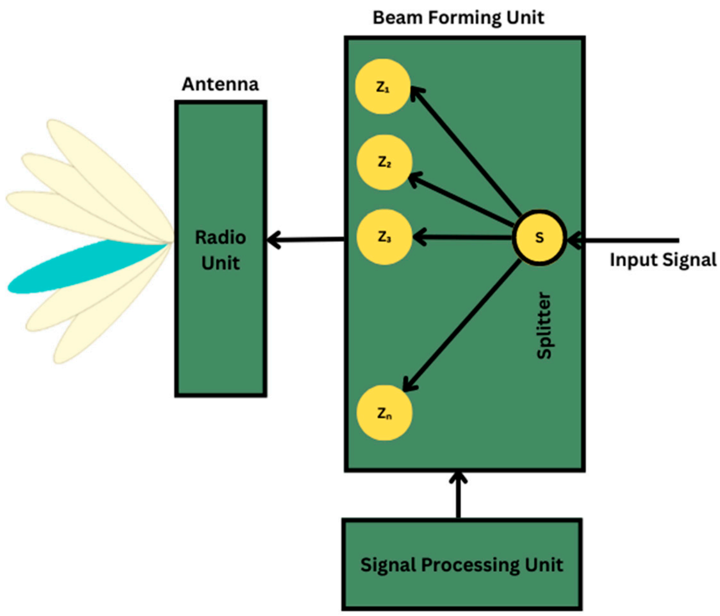

Figure 1. Transmitter antenna of the proposed MIMO system.

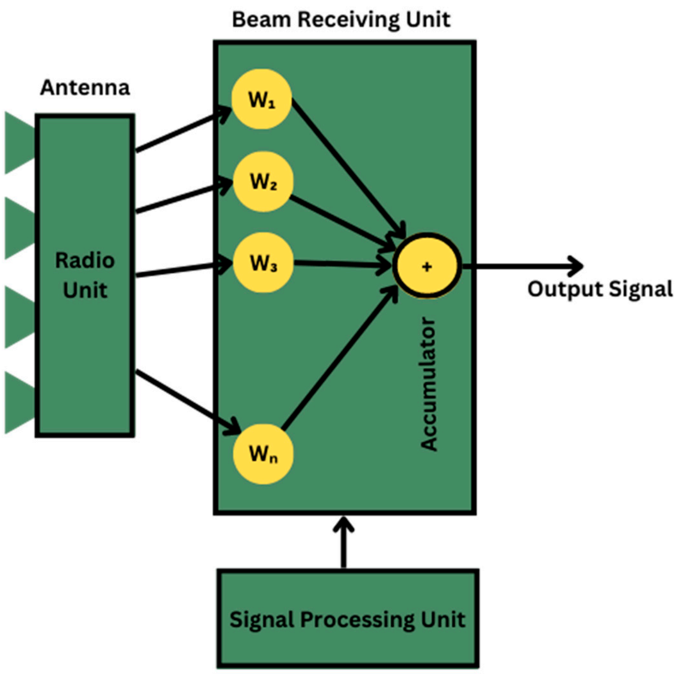

Figure 2. Receiver antenna of the proposed MIMO system.

2.2. Mathematical Modeling of the Smart MIMO System

The proposed new digital/geometrical smart MIMO antenna scheme of this paper can be illustrated using Figure 3 in the XY coordinates system. The transmitter (Tx) has N number of multiple antenna elements, with each element positioned in the XY coordinates plane at (x_1,y_1), (x_2,y_2), (x_3,y_3), …, (x_n,y_n). The receiver (Rx) has M number of antenna elements, with each element positioned in the UV coordinates plane at (u_1,v_1), (u_2,v_2), (u_3,v_3), …, (u_n,v_n). r is the distance between the reference points of the transmitter antenna and the receiver antenna elements.

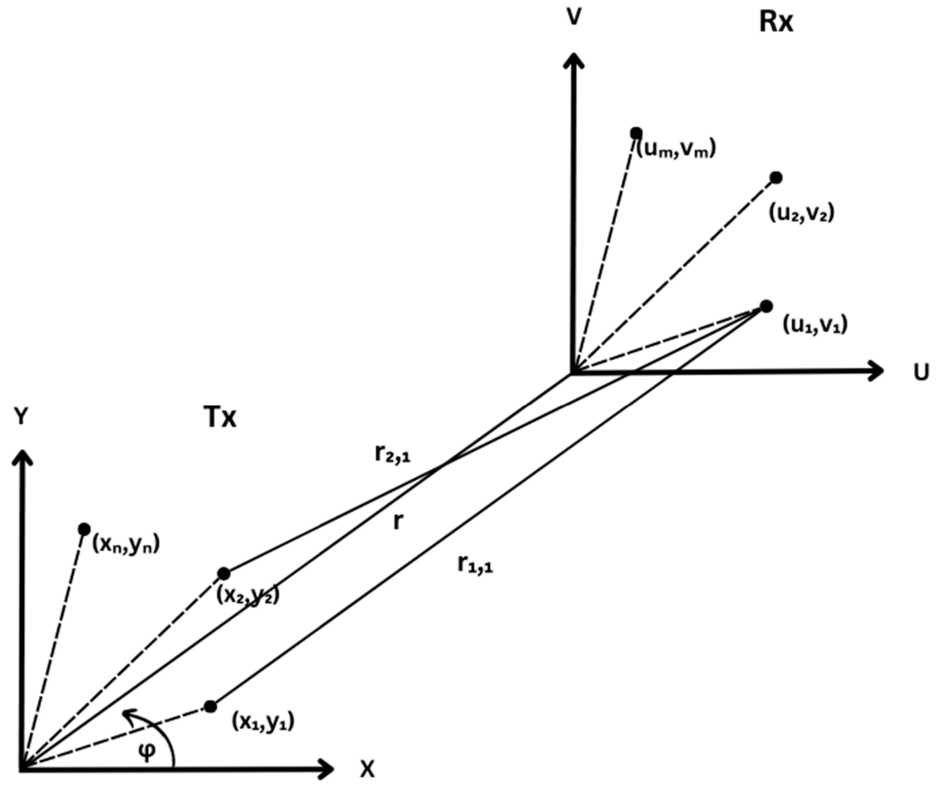

Figure 3. Schematic diagram of the MIMO antenna on XY and UV coordinate planes.

Referring to Figure 3, the distance between the first antenna element of the transmitter and the first antenna element of the receiver can be written as

$$r_{1,1} = r - x_1\cos(\varphi) - y_1\sin(\varphi) + u_1\cos(\varphi) + v_1\sin(\varphi)$$

The distance between the second antenna element of the transmitter and the first antenna element of the receiver can be written as

$$r_{2,1} = r - x_2\cos(\varphi) - y_2\sin(\varphi) + u_1\cos(\varphi) + v_1\sin(\varphi)$$

Similarly, the distance between the n^{th} antenna element of the transmitter and the m^{th} antenna element of the receiver can be written as

$$r_{n,m} = r - x_n\cos(\varphi) - y_n\sin(\varphi) + u_m\cos(\varphi) + v_m\sin(\varphi)$$

With the assumption that all of the transmitter antenna elements have the same length and the same current distribution function along the dipole elements, the vertical plane radiation function $f_{tx}(\theta)$ for all of the transmitter elements are the same. Here, θ is the angle that the observation point makes with the vertical axis of the dipole element. Similarly, with the same assumption, we can also say that the vertical plane radiation function $f_{rx}(\theta)$ of the receiver antenna elements remains same for the receiver elements. Therefore, the entire electric field (E) at the receiver can be written as follows, by incorporating the transmitter and receiver models shown in Figures 1 and 2:

$$\begin{aligned} E = \Bigg\{ f_{tx}(\theta) f_{rx}(\theta) & \left[\frac{e^{-j\beta r_{1,1}}}{r_{1,1}} Z_1 W_1 + \frac{e^{-j\beta r_{2,1}}}{r_{2,1}} Z_2 W_1 + \cdots \frac{e^{-j\beta r_{n,1}}}{r_{n,1}} Z_n W_1 \right] \\ & + \left[\frac{e^{-j\beta r_{1,2}}}{r_{1,2}} Z_1 W_2 + \frac{e^{-j\beta r_{2,2}}}{r_{2,2}} Z_2 W_2 + \cdots \frac{e^{-j\beta r_{n,2}}}{r_{n,2}} Z_n W_2 \right] + \cdots \\ & + \left[\frac{e^{-j\beta r_{1,m}}}{r_{1,m}} Z_1 W_m + \frac{e^{-j\beta r_{2,m}}}{r_{2,m}} Z_2 W_m + \cdots + \frac{e^{-j\beta r_{n,m}}}{r_{n,m}} Z_n W_m \right] \Bigg\} \end{aligned} \quad (1)$$

where β is the phase constant of the radiating wave, W_j are the phase delay factors of the receiving antenna, and Z_i are the phase delay factors of the transmitting antenna. Here, the dipole current I_i is replaced with phase delay factors $Z_i = AI_i$ and A is the constant related to the respective current vectors I_i with the respective phase delay factors Z_i. The vertical plane radiation function of a dipole antenna $f(\theta)$ is given below [14].

$$f(\theta) = \frac{\cos\left(\frac{\beta l}{2}\cos(\theta)\right) - \cos\left(\frac{\beta l}{2}\right)}{\sin(\theta)} \tag{2}$$

where l is the length of the dipole element.

Substituting the expressions for the distances in Equation (1) and rearranging the equation by assuming that all of the distances are equal to r for the amplitude component of the far electrical field, we obtain

$$E = \frac{e^{-j\beta r}}{r} f_{tx}(\theta) \sum_{i=1}^{N} Z_i \, \mathrm{e}^{j\beta(x_i cos\varphi + y_i sin\varphi)} \left(f_{rx}(\theta) \sum_{j=1}^{M} W_j \, \mathrm{e}^{-j\beta(u_j cos\varphi + v_j sin\varphi)} \right) \tag{3}$$

In order to maximize the directional gain at the receiver, we need to obtain

$$E = \left|\frac{e^{-j\beta r}}{r}\right| \left| f_{tx}(\theta) \sum_{i=1}^{N} Z_i e^{j\beta(x_i cos\varphi + y_i sin\varphi)} \right|_{max} \left| f_{rx}(\theta) \sum_{j=1}^{M} W_j e^{-j\beta(u_j cos\varphi + v_j sin\varphi)} \right|_{max} \tag{4}$$

Expressing the phase delay factor as $W_j = e^{j\beta(u_j cos\varphi + v_j sin\varphi)}$, which is the conjugate value of each receiving antenna element weight, and multiplying each individual term with its conjugate, the maximum directional gain can be achieved.

$$|E|_{max} = \left|\frac{e^{-j\beta r}}{r}\right| \left| f_{tx}(\theta) \sum_{i=1}^{N} Z_i e^{j\beta(x_i cos\varphi + y_i sin\varphi)} \right|_{max} f_{rx}(\theta) M \tag{5}$$

where M is the number of receiving antenna elements.

At the transmitter, the directional beam is to be maximized towards the receiver. In order to obtain $\left(\left|\sum_{i=1}^{N} Z_i e^{j\beta(x_i cos\varphi + y_i sin\varphi)}\right|_{max}\right)$, we enhanced the single beamforming and beamsteering towards receiver direction by optimizing the phase delay coefficients Z_i.

The directivity of an antenna is defined as the ratio of the power radiation intensity in a given direction from the antenna to the power radiation intensity averaged over all directions around the antenna. The directivity D of an antenna in a specified direction is defined from its definition, as below:

$$D = \frac{Power\ Density\ at\ the\ specified\ Direction}{\frac{Total\ Radiated\ Power}{The\ surface\ area\ of\ a\ sphere\ enclosed}}$$

Based on the above definition, we derived Equation (6) for the directivity of the transmitter antenna.

$$D = \frac{2}{\pi} \frac{\left[|f_{tx}(\theta)|^2 \left|E_\varphi\right|^2 \right]}{\frac{1}{PQ} \sum_{i=1}^{P} \sum_{j=1}^{Q} |f_{tx}(\theta)|^2 \left|E_\varphi\right|^2 sin\theta} \tag{6}$$

where $E_\varphi = \sum_{i=1}^{N} Z_i e^{j\beta(x_i cos\varphi + y_i sin\varphi)}$. The overall power gain G can be calculated for the system described in Equation (5) as per Equation (7) given below.

$$G = D_{Tx} \times M^2 \times R \tag{7}$$

where D_{tx} is the directivity of the transmitter antenna, M^2 is the signal processing power gain at the receiver antenna, and R is the directivity obtained from the $f_{rx}(\theta)$ function.

The receiving antenna can also perform beamforming and direct the beam towards the transmitter direction. In that case, the overall gain of the system described in Equation (4) can be determined as given in Equation (8).

$$G = D_{Tx} \times D_{Rx} \tag{8}$$

where D_{Rx} is the directivity of receiver antenna. Having beamformed the transmitter and the receiver by steering the transmitter and receiver beams towards each other, the interaction noise received at the receiver is minimized.

3. Beamforming and Beamsteering

Any arbitrary set of dipoles arranged in a uniform linear array produces a symmetrical radiation pattern on both sides of the plane on which the dipoles are placed. However, this arrangement cannot generate a single beam and steer it over the entire space surrounding the antenna. The proposed antenna [3] is a dipole antenna array that can form a single beam and steer the beam in any direction using the optimized phase delay factors. Many research studies show different types of techniques [15–17] used for optimizing the phase shifters. Among them, machine learning and artificial intelligence-based techniques are significant in the optimization process. However, these models require high computational power and memory. This paper presents a system that uses a simple mathematical model to optimize the phase delay factors.

Referring to Figure 4, the radiated electric field at a particular point can be written in terms of antenna element current vectors I_1, I_2, I_3, …, I_n for the N number of dipoles.

$$E = P_0 I_1 e^{-j\beta r_1} + P_0 I_2 e^{-j\beta r_2} + \cdots + P_0 I_n e^{-j\beta r_n} \tag{9}$$

where $P_0 = Af_{tx}(\theta)$. Substituting for spherical coordinate distances r_1, r_2, and r_n by Cartesian X-Y coordinate distances, Equation (9) can be written as follows, recollecting that $AI_i = Z_i$:

$$E = f_{tx}(\theta)\begin{pmatrix} Z_1 e^{j\beta(x_1 cos\varphi + y_1 sin\varphi)} + Z_2 e^{j\beta(x_2 cos\varphi + y_2 sin\varphi)} + \cdots \\ + Z_n e^{j\beta(x_n cos\varphi + y_n sin\varphi)} \end{pmatrix} \tag{10}$$

where Z_1, Z_2, and Z_n are the complex weights that are proportional to the complex current vectors I_1, I_2, and I_n, respectively. To achieve the objective of forming a resultant single beam, the values of the complex weights Z_1, Z_2, and Z_n need to be optimized such that the resultant radiated field must match a desired single beam function $f(\varphi)$. In order to optimize the phase delay factors to obtain a steerable single beam, a desired single beam function $f(\varphi)$ is selected, as shown in Equation (11).

$$f(\varphi) = Z_1 e^{j\beta(x_1 cos\varphi + y_1 sin\varphi)} + Z_2 e^{j\beta(x_2 cos\varphi + y_2 sin\varphi)} + \cdots + Z_n e^{j\beta(x_n cos\varphi + y_n sin\varphi)} \tag{11}$$

The optimization of complex weights Z_1, Z_2, and Z_n may be achieved either analytically or iteratively [16]. Since the number of dipole elements will be limited to as few as possible, an analytical optimization method is more appropriate.

Complex weights Z_1, Z_2, and Z_n can be optimized by multiplying the equation by its complex conjugates and integrating the φ over the limit from 0 to 2π. Here, the first term is multiplied with the $e^{j\beta(x_1 cos\varphi + y_1 sin\varphi)}$ and integrated with respect to the angle φ over the limits from 0 to 2π. Thus,

$$\begin{aligned} \int_0^{2\pi} f(\varphi) e^{-j\beta(x_1 cos\varphi + y_1 sin\varphi)} d\varphi &= Z_1 \int_0^{2\pi} d\varphi + Z_2 \int_0^{2\pi} e^{j\beta[(x_2 cos\varphi + y_2 sin\varphi) - (x_1 cos\varphi + y_1 sin\varphi)]} d\varphi \\ &+ \cdots + Z_n \int_0^{2\pi} e^{j\beta[(x_n cos\varphi + y_n sin\varphi) - (x_1 cos\varphi + y_1 sin\varphi)]} d\varphi \end{aligned} \tag{12}$$

Similarly, multiplying Equation (11) with the complex conjugates of the second term and integrating over 0 to 2π, we obtain Equation (13),

$$\int_0^{2\pi} f(\varphi)e^{-j\beta(x_2cos\varphi+y_2sin\varphi)}d\varphi = Z_1\int_0^{2\pi} e^{j\beta[(x_1cos\varphi+y_1sin\varphi)-(x_2cos\varphi+y_2sin\varphi)]}d\varphi + Z_2\int_0^{2\pi} d\varphi + \cdots + Z_n\int_0^{2\pi} e^{j\beta[(x_ncos\varphi+y_nsin\varphi)-(x_2cos\varphi+y_2sin\varphi)]}d\varphi \tag{13}$$

and repeat up to the *n*th term.

$$\int_0^{2\pi} f(\varphi)e^{-j\beta(x_2cos\varphi+y_2sin\varphi)}d\varphi = Z_1\int_0^{2\pi} e^{j\beta[(x_1cos\varphi+y_1sin\varphi)-(x_ncos\varphi+y_nsin\varphi)]}d\varphi + Z_2\int_0^{2\pi} e^{j\beta[(x_2cos\varphi+y_2sin\varphi)-(x_ncos\varphi+y_nsin\varphi)]}d\varphi + \cdots + Z_n\int_0^{2\pi} d\varphi \tag{14}$$

Finally, n number of equations can be obtained where n is equal to the number of dipole elements present in the MIMO antenna. Hence, these equations can be written in the following matrix form:

$$\begin{bmatrix} P_{11} & P_{12} & \dots & P_{1n} \\ P_{21} & P_{22} & \dots & P_{2n} \\ \dots & \dots & \dots & \dots \\ P_{n1} & P_{n2} & \dots & P_{nn} \end{bmatrix} \begin{bmatrix} Z_1 \\ Z_2 \\ \dots \\ Z_n \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ \dots \\ q_n \end{bmatrix} \tag{15}$$

where

$$P_{ij} = \int_0^{2\pi} e^{j\beta[(x_jcos\varphi+y_jsin\varphi)-(x_icos\varphi+y_isin\varphi)]}d\varphi \tag{16}$$

and

$$q_i = \int_0^{2\pi} f(\varphi)e^{-j\beta(x_icos\varphi+y_isin\varphi)}d\varphi \tag{17}$$

Thus, the optimized coefficients can be obtained from Equation (15), as given below:

$$\begin{bmatrix} Z_1 \\ Z_2 \\ \dots \\ Z_n \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1n} \\ P_{21} & P_{22} & \dots & P_{2n} \\ \dots & \dots & \dots & \dots \\ P_{n1} & P_{n2} & \dots & P_{nn} \end{bmatrix}^{-1} \begin{bmatrix} q_1 \\ q_2 \\ \dots \\ q_n \end{bmatrix} \tag{18}$$

where the matrix elements P_{ij} and q_i are numerically calculated.

Once the phase delay coefficients are obtained for a selected angle of beamsteering, the electrical field can be evaluated using the expression obtained in Equation (10).

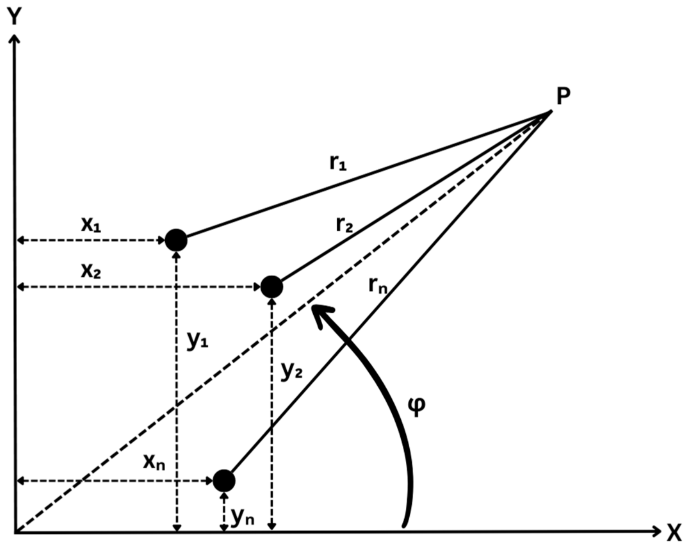

Figure 4. Schematic diagram of dipole placement in XY coordinate plane.

4. Numerical Evaluations

The optimization of the phase delay factors is carried out as per Equation (18) obtained in this paper. MATLAB® programing language is used to evaluate the phase delay coefficients. Unfortunately, MATLAB® does not have an effective way to display three-dimensional solid shapes. Therefore, Wolfram Mathematica® is used to model the relevant three-dimensional solid beam pattern. Initially, the phase delay coefficients are calculated using the developed software code. Subsequently, these coefficients are used to display the azimuthal plane and three-dimensional solid shape radiation patterns.

4.1. Beamforming to a Desired Direction

The proposed eight-element dipole antenna configuration from our previous single beam work [3], shown in Figure 5, is used as the transmitter and is optimized to form a beam in arbitrarily selected directions. This antenna can steer the beam to any direction (from 0° to 360°). These outcomes are already validated in our previous work [3] and will not be repeated herein considering space and similarity concerns. However, the radiation patterns are tested to steer the beam towards random angles 0°, 5°, 15°, 27°, 42°, 55°, 73°, 88°, 135°, 152°, 177°, 213°, 245°, 260°, 305°, and 340° by optimizing the phase delay coefficients, as shown in Figure 6.

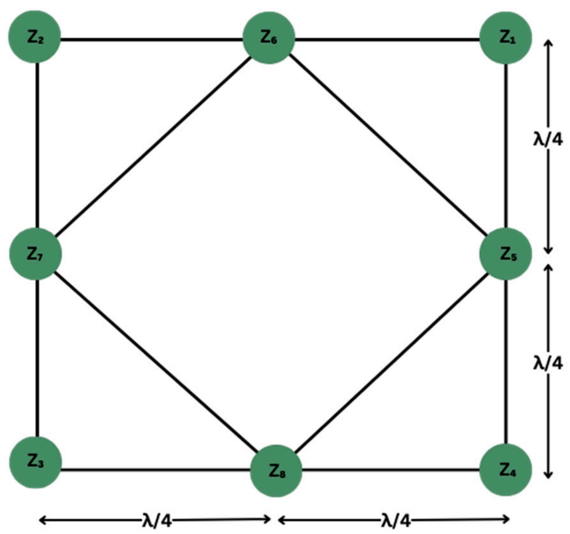

Figure 5. Proposed eight-element dipole antenna.

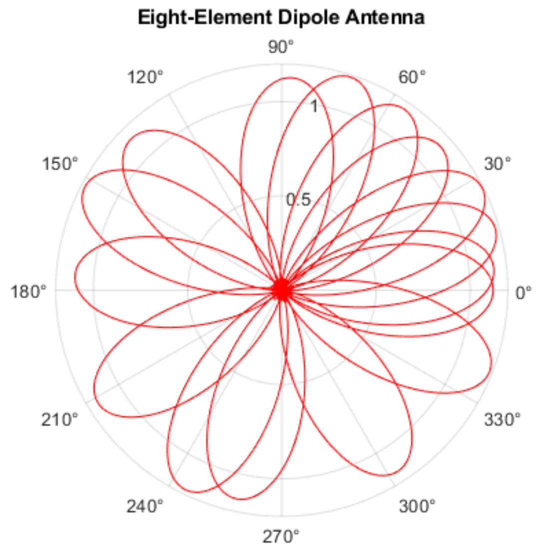

Figure 6. Radiation pattern for arbitrarily steering beams.

We were able to steer a single beam to almost any direction while retaining its shape. The directivity was varied with an accuracy of 0.1°. Thus, the performance of steerable single beamforming is well proven with high accuracy.

The beam presented in Figures 7–10 was created to study the three-dimensional radiation pattern. This was carried out considering the dipole elements as half-wave dipoles and a randomly selected angle of 30°. The 3D space views of the obtained beam are presented in Figures 7–10 with the different positions.

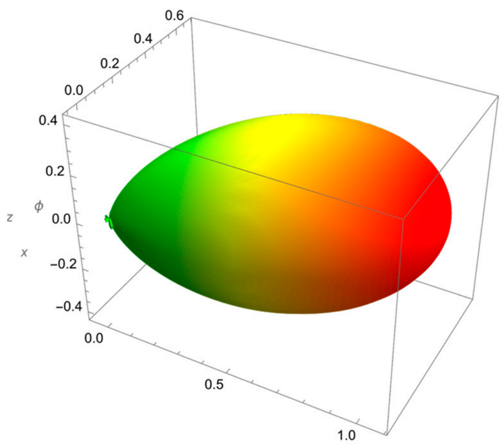

Figure 7. Three-dimensional view of the single beam formed at 30^0 when the transmitter antenna elements are half-wave dipoles.

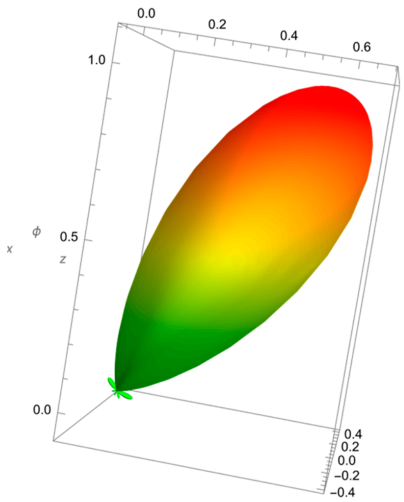

Figure 8. Azimuth view of the formed narrow beam.

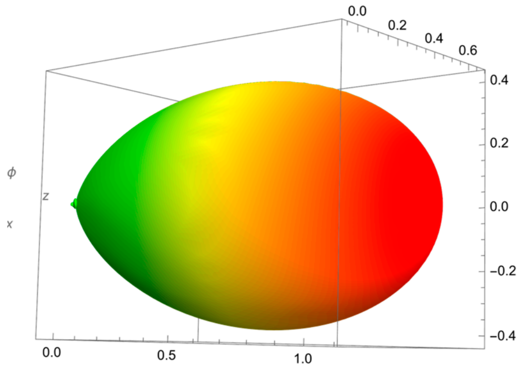

Figure 9. Vertical view of the formed narrow beam.

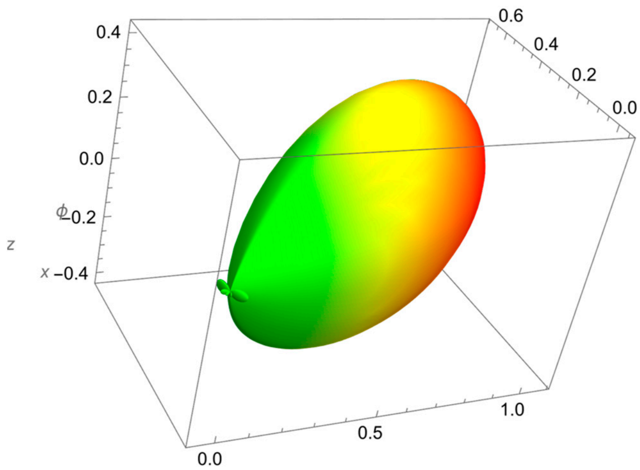

Figure 10. The same beam is shown at an angle for a better view of the side lobes. The side lobes have negligible energy.

Seven different space vectors occur in an eight-element antenna structure. The beam is guided in the desired direction by the contributions of phase shifters from each space vector. Eight phase delay shifters, combined with proper dipole placement positions, are sufficient to precisely guide the beam toward any desired angle between 0° and 360°. The shape of the beam is very narrow and highly focused. Moreover, the energy wastage is negligible due to the negligible side lobes, which illustrates that this antenna is highly energy efficient.

4.2. Performance of Proposed Smart MIMO System

Compared to an isotropic antenna, the directivity of the new digital/geometrical MIMO is very high. This means that it can precisely transmit or receive signals in a specific direction. The directivity of an antenna is expressed as a ratio of the power transmitted or received in a particular direction to the average power radiated or received by an isotropic antenna and is usually measured in decibels (dB). According to the numerical calculation, the directivity of this transmitted beam of the new digital/geometrical MIMO for the example presented above is 11.6 (10.65 dBi), while the obtained side lobe reduction is 0.05. When we use a similar antenna as the receiver end of this system, the eight-element dipoles proved to be a highly directive receiving side. On the receiving side, the directivity of the vertical plane of half-wave dipole antenna affects the overall antenna gain. According to the calculations performed, this value is 2.2 (3.42 dBi) for the proposed MIMO receiver system. Hence, the overall antenna gain for this proposed system is 25.52 (14.07 dBi). Moreover, the signal processing gain at the receiver antenna contributes to the overall power gain of the system. The signal processing gain at the receiver is 64 (18.06 dBi). Therefore, the overall power gain of the proposed new digital/geometrical smart MIMO system, calculated using Equation (7), is 1633.28 (32.13 dBi).

Using Equation (8), we calculated the overall power gain of the MIMO system when both the receiving and transmitting antennas were pointing at each other. This was 134.56 (21.28 dBi).

5. Discussion

MIMO technology has become a key component in modern wireless communication systems, enabling higher data rates, improving reliability, and providing better coverage in challenging environments. This developed antenna system is a novel digital/geometrical MIMO dipole antenna architecture that has high-speed beamsteering capability, which allows the beam to be steered in any direction (0°–360°) with high directionality and low complexity due to the optimization of the phase delay factors.

According to Figures 7–9, the radiated beam is very narrow in all of the three-dimensional planes, proving a high directionality, low interference from/to other sources, and high energy efficiency in a desired direction. Due to these advantages, this new digital/geometrical MIMO system can significantly benefit future wireless communication using 6G and beyond [3].

Furthermore, the directivity of the transmitter is approximately 11.6 (10.65 dBi). Compared with other types of MIMO antenna systems, this directivity value is higher. For instance, in patched-type [18–22] antenna systems, the directivity is between 3 dBi and 10 dBi. Moreover, the patched-type antennas work at a limited frequency band. According to the study and findings of [23], the beam directivity can be increased to 15 dBi using structurally larger and heavier horn-type antennas. However, this beam cannot be steered easily. Furthermore, it requires a considerable amount of energy to form a beam. As we can observe from the radiation patterns of the antenna in [23], much energy is wasted on the intermediate side lobes. Another study on a spiral-dipole antenna elaborated that the power gain of the antenna transmitter is between 0 dBi and 3 dBi. Another MIMO dipole antenna shown in [24] reached the maximum power gain of 4.7–4.9 dBi. A microstrip antenna using metamaterial yielded a maximum power gain value of 15 dBi in [25]. However, the radiated beam is not steerable in all directions, and the energy wastage is high. By comparing the antennas mentioned above, this proposed smart new digital/geometrical MIMO system has several advantages and is a competitive antenna design for future wireless communication systems.

At the receiver side, there are eight dipole elements that are connected to the phase delay factors. Hence, the signal processing gain of the receiver antenna is 64 (18.06 dBi).

This gain value contributes to the increase in the overall power gain of the new digital/geometrical MIMO system. Due to the directivity of the vertical plane for a half-wave dipole antenna at a specified angle, the overall power gain value at the receiver-side antenna is $64 \times 2.2 = 140.8$ (21.48 dBi). Therefore, this proposed system has a very high directional power gain at its receiver end. This will increase the quality of the signals [26] and provide the ability to detect very weak signals from long distances.

The overall power gain of the entire smart MIMO system is 1633.28 (32.13 dBi), which is a very high value when compared with the other types of MIMO systems. However, when we calculated the overall directivity by forming the beams to a specified direction at the transmitter and at the receiver, the overall power gain value only reached 134.56 (21.28 dBi). There is a significant difference between these two values because, when we used the first approach, more noise was generated at the receiving side due to multiple receiving signals. Hence, the SNR of that system was low. However, when the beams were formed to specified directions at the transmitter and receiver, the effect of the noise was very low, leading to a higher SNR value.

One of the advantages of this system is that the transmitter can work as a receiver, and the receiver can work as a transmitter. Even though the directional power gains change with the transmitter or receiver, the overall power gain of the entire system remains the same and will only be changed by inadvertent environmental factors, such as rain or buildings.

6. Conclusions

For the next-generation wireless networks, massive MIMO is the essential enabling technology, combining the antenna arrays at the transmitter and the receiver to offer exceptional spectral and energy efficiency. This paper elaborates on the overall performance of the proposed smart MIMO antenna system, namely, the new digital/geometrical MIMO. According to the mathematical formulation of the signal processor, software code implementation, and calculations, the overall gain of the proposed system is 25.52 (14.07 dBi). The signal processing gain at the receiver is 64 (18.06 dBi). Therefore, the overall power gain for this proposed new digital/geometrical smart MIMO system is 1633.28 (32.13 dBi). When we calculate the overall directivity by forming the beams towards a selected direction at the transmitter and the receiver, the overall power gain value increased to 134.56 (21.28 dBi).

The proposed system has several advantages that make it suitable for use in M2M and IoT applications. It can radiate very narrow beams with low energy consumption, and it can form and steer beams in any desired direction. The phase delay shifters can optimize the beamforming to reduce side lobes and improve the overall directivity.

The paper suggests future developments of the work, such as adjusting the transmitter weights to further increase the power gain of the transmitter, improving the performance of the receiver, and eliminating spatially distributed noise by beamforming at the receiver. The implementation of the physical antenna structure is planned to evaluate and fine tune its hardware performance, making it readily available for use in 5G and 6G wireless systems and beyond.

Overall, the proposed digital/geometrical MIMO system shows promising results for achieving high spectral and energy efficiency in wireless networks, and its potential applications in M2M and IoT make it an interesting technology to watch in the future.

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