Modeling of Phased Array Antenna for Data Transmission in Urban Environment

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Abstract

An article is devoted to modeling and optimizing an active phased array antenna (PAA) with parallel feeder excitation at 3.7 GHz 5G band using computer simulation in Matlab IDE for data transmission in urban environment.

Keywords

Modeling, Phased Array Antenna, Data Transmission, Urban Environment, Matlab IDE

1. Introduction

In today's world, where human needs and well-being are paramount, the problem of ensuring and improving the living standards and the efficiency of medical services is becoming increasingly urgent. One of the possible solutions to this problem is to use 5G mobile communication, which is expanding rapidly, especially in the n77 3.7 GHz 5G band (according to a recent report from Opensignal). However, in urban environments, a significant negative factor is the level of electromagnetic interference, which can adversely affect the operation of sensitive devices or equipment. The use of antenna arrays can partially minimize these negative factors by using the beam scanning technique [1].

Data transmission is essential process of sending and receiving signals and information between different devices or locations, such as wearable sensors, implantable devices, medical instruments, and remote servers. Data transmission can enable various applications, such as health monitoring, diagnosis, therapy, telemedicine, and biofeedback. However, data transmission also faces many challenges, especially in urban environments, where the wireless channel is often crowded, noisy, and multipath-rich. Therefore, it is important to design and implement efficient and reliable antennas for data transmission. A phased array antenna can offer many benefits for data transmission in urban environments, such as:

- High gain: A phased array antenna can achieve high gain by focusing the radiated power in a desired direction. This can improve the signal-to-noise ratio (SNR) and the link quality of the data transmission. A high gain can also reduce the transmit power and the interference to other users or devices.
- Beam steering: A phased array antenna can steer the beam direction dynamically to track the movement or location of the transmitter or receiver. This can enhance the coverage and reliability of the data transmission. Beam steering can also enable adaptive beamforming, which can suppress interference and multipath effects from undesired directions.
- Wide bandwidth: A phased array antenna can operate over a wide frequency range by using broadband elements or frequency scanning techniques. This can increase the data rate and capacity of the data transmission. A wide bandwidth can also support multiple frequency bands or standards for interoperability and flexibility.
- Small size: A phased array antenna can achieve a compact size by using miniaturized elements or integrated circuits. This can reduce the weight and volume of the antenna and make it suitable for

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wearable or implantable applications. A small size can also facilitate the integration and fabrication of the antenna with other components or devices.

However, designing and implementing a phased array antenna for data transmission is not trivial. It requires careful consideration of various factors, such as:

- Array elements: The array elements should have good radiation characteristics, such as high efficiency, low loss, wide bandwidth, and low cross-polarization. The array elements should also have low mutual coupling effects, which can degrade the performance of the phased array antenna. The array elements should also be compatible with the human body or environment, such as biocompatibility, safety, and conformability.
- Phase shifters: The phase shifters are devices that can adjust the phase of the signals at each array element to steer the beam direction. However, these requirements are often conflicting and difficult to achieve simultaneously.
- Feed system: The feed system is the network that distributes the signals from the transmitter or receiver to each phase shifter or array element. The feed system should have low loss, uniform amplitude and phase distribution, and easy integration with active components. However, it also has high complexity, large size, and limited bandwidth.

Data transmitting in urban environment using wireless systems of the 5G range are used. Phased Array Antennas (PAAs) are the basic link of such systems. Modelling process of PAAs as collections of antennas that can steer the beam direction electronically by adjusting the phase and amplitude of the signals at each element are cost-effective compare to in-vivo experiment [2]. PAAs have many applications in wireless communication, radar, sonar, and acoustic systems.

The main task of PAAs modeling is to analyze mathematically and computationally the array elements and their radiation patterns. The array elements can be wire antennas or aperture antennas, such as microstrip patch antennas or slot antennas. The mutual coupling effects are especially important for finite arrays, as they can influence the input impedance, bandwidth, efficiency, and scan performance of the array. Therefore, modeling and analyzing the mutual coupling effects are essential for the optimal design of phased array antennas.

Phased array antennas (PAAs) require modeling and analyzing the mutual coupling effects among the array elements. Several types of phase shifters can perform this task. One of the most popular methods is the method of moments (MoM), which numerically solves the integral equations for the unknown currents on the array elements. The MoM can handle arbitrary geometries and materials, but it needs a lot of memory and computation time for large data sets. Another method is the finite-difference time-domain (FDTD) method, which divides the Maxwell’s equations into discrete space and time domains and updates the electric and magnetic fields at each grid point using a simple algorithm. The FDTD method can handle complex structures and media, but it requires a high spatial resolution and a low time step to ensure numerical stability and accuracy.

Some examples of applying these methods for modelling and design to phased array antennas can be found in [3] and [4]. In [3], a novel FDTD method/algorithm is highlighted for analyzing microstrip phased array antennas on a finite substrate. The method/algorithm uses a subcell technique to model the thin metal patches and slots, and a conformal technique to model the curved edges of the substrate. The method/algorithm is applied to a two-element microstrip antenna phased array and compared with an existing method and experiments. In [4], a generalized formulation of array theory is presented, which includes mutual coupling effects and is appropriate for finite or infinite arrays of arbitrary wire elements or apertures in the presence of a conducting ground screen. The formulation is based on the reciprocity theorem and uses on MoM to apply it to wired and aperture arrays.

Several types of phase shifters modelling methods have been introduced in the scientific works [5] and [6] in particular, such as mechanical, ferrite, diode, transistor, MEMS, optical, liquid crystal, metamaterials, etc. Modelling of the phase shifter take into account at 10 GHz with 360 degrees phase shift range and 1 dB insertion loss. In scientific work [6], a model of novel optical phase shifter based on silicon photonics is presented with parameters of frequency 28 GHz with 360 degrees phase shift range and 2 dB insertion loss.

Another important aspect of phased array antenas is the modelling, design and implementation of the phase shifters and the feed system that can adjust the phase of the signals at each array element for steer the beam direction. PAAs modeling by the specified methods is not taken into account the optimality of parameters, in particular: low loss, wide bandwidth, high linearity, low noise, high power handling capability.

One of the possible solutions to overcome these challenges is to use printed circuit board (PCB) technology for designing and implementing phased array antennas for data transmission. PCB technology is a well-established and low-cost technique that can create complex circuits and structures on a thin substrate using conductive traces and vias. PCB technology can offer several advantages for phased array antennas for data transmission, such as:

- Integration: PCB technology can integrate both passive and active components on a single substrate using flip-chip or wire-bonding techniques. This can reduce the size and complexity of the phased array antenna and improve its performance and reliability.
- Flexibility: PCB technology can create various shapes and geometries of the phased array antenna using different types of substrates, such as rigid, flexible, or conformal. This can enable different applications and scenarios of data transmission, such as on-body, in-body, or off-body.
- Scalability: PCB technology can produce large quantities of phased array antennas with high precision and consistency using automated processes. This can lower the cost and increase the availability of phased array antennas for data transmission.

Some examples of PCB-based phased array antennas for data transmission in urban environments can be found in [7], [8], [9], and [10]. In [7], a 16-element W-band phased-array transceiver chipset with flip-chip PCB integrated antennas is presented for multi-gigabit wireless data links. The chipset is manufactured in a 0.18-μm SiGe BiCMOS technology and is flip-chipped onto a low-cost organic PCB with integrated antenna arrays. The chipset can achieve a maximum wireless data rate of 30 Gb/s using 64-QAM modulation at a distance of 1 m. In [8], a novel PCB design technique for dual-polarized 5G phased array antenna is proposed for LMDS band operation. The antenna array uses a modified Butler matrix to achieve beam scanning in both azimuth and elevation planes. The antenna array can achieve a gain of 14.0 dBi and a bandwidth of 1 GHz. In [9], a FR-4 PCB process-based mm-wave phased array antenna using planar high-impedance surfaces is designed for 60 GHz band operation. The antenna array uses a planar high-impedance surface to enhance the gain and bandwidth of the antenna elements. The antenna array can achieve a gain of 13.5 dBi and a bandwidth of 8 GHz. In [10], a multi-band 16–52-GHz transmit phased array employing 4 × 1 subarrays with tapered slot Vivaldi antenna array is presented for wireless communication applications. The subarrays are designed in a SiGe BiCMOS process and flipped on a PCB. The subarrays can achieve a gain of 18 dBi and a bandwidth of 36 GHz.

Phased antenna arrays are also called antenna arrays (AA), the direction of maximum radiation or reception, the corresponding directional pattern shape is changed by changing the phase of radio signals in the radiating elements

The use of an antenna array with parallel feeder excitation [11] makes it possible to increase the bandwidth of the antenna because it does not have the effect of accumulation of phase instabilities and the use of low-power phase invertors is possible. The advantages of a parallel scheme are:

- a higher efficiency factor and a higher level of permissible radiation, because with N phase rotators, only the Nth part of the total radiation power passes through each of them;

high scanning accuracy due to the fact that the errors of any of the phase shifters affect the operation of only one element of the grid.

2. Mathematical description of the main technical characteristics of PAAs

Active phased antenna arrays are described [1] by the directional pattern, the width of its main lobe, the level of the side lobes, the magnitude gain coefficient (Ga), the coefficient of directional action, the reflection coefficients of the elements, the potential A and the specific spectral density of the noise power Q. For PPA, the potential is equal to:

$$\mathrm{A} = G_a \mathrm{A}_\Sigma = \mathrm{K_a} P A_0 N_e \tag{1}$$

where G_a gain coefficient is the amplification factor of the active phased array antenna (numerically equal to the product of the useful effect factor by the directional effect factor);

P_0 - radiation power of a single element;

N_e - the number of single elements;
A_Σ is the total potential of all single elements.

For the receiving PAA, the specific noise power spectral density is equal to:

$$Q = h_{\varpi}/S_{eff} \tag{2}$$

where h_{ϖ} is the noise power spectral density at the output of the PAA;
S_{eff} is the effective surface of the antenna.

The three-dimensional directivity diagram of the PAA $f(\theta,\varphi)$ in the general case has the form:

$$f(\theta,\varphi) = \frac{1}{MN}\left|\frac{\sin[M\pi d_x(\sin\theta\cos\varphi)/\lambda]}{\sin[\pi d_x(\sin\theta\cos\varphi)/\lambda]}\right| \times \left|\frac{\sin\left[N\pi d_y(\sin\theta\sin\varphi)/\lambda\right]}{\sin\left[\pi d_y(\sin\theta\sin\varphi)/\lambda\right]}\right| \tag{3}$$

where M is the number of elements along the length of the antenna array;
N - the number of elements across the width of the antenna array;
d_x - distance between emitters in the azimuth plane;
d_y - distance between emitters in the angular plane;
λ - is the working wavelength of radiation;
θ - azimuth;
φ - seat angle.

The optimal choice of the dimensions [11] of the antenna array is chosen according to the analytical dependence in the form:

$$\begin{cases} d_x \le \dfrac{\lambda}{1+\sin(\theta_{\max}^{x})} \\ d_y \le \dfrac{\lambda}{1+\sin\left(\theta_{\max}^{y}\right)} \end{cases} \tag{4}$$

where $\theta_{\max}^{x}$, $\theta_{\max}^{y}$ - the maximum aperture angles of the directional diagram in the azimuth and elevation directions, respectively.

The active PAA module in the time domain can be described by the following system of equations in the operator form:

$$\begin{cases} u_{in} = L_{\text{in}}(e, i_{\text{in}}) \\ u_{\text{out}} = L_{\text{out}}(i_{\text{in}})' \end{cases} \begin{cases} i_{\text{in}} = F_{\text{in}}(u_{in}, u_{\text{out}}) \\ i_{\text{out}} = F_{\text{out}}\,(u_{\text{in}}, u_{\text{out}})' \end{cases} \tag{5}$$

where u_{in}, u_{out}, i_{in}, i_{out}, - voltages and currents at the input and output of the antenna module, respectively;
e - normalized vector;
F_{in}, F_{out} - non-linear in the general case integrodifferential linearly independent operators describing the active element;
L_{in}, L_{out} - linear integrodifferential operators describing the input and output circuits of an active element (vacuum lamp, bipolar or field-effect transistor) and are determined by a system of equations in the form:

$$\begin{cases} L_{\text{BX}} = \sum\limits_{m=0}^{M} a_m^R \dfrac{d^m}{dt^m} + \sum\limits_{n=0}^{N} b_b^R \iint \ldots \int dt^n, \\ L_{\text{Вих}} = \sum\limits_{m=0}^{M} a_m^F \dfrac{d^m}{dt^m} + \sum\limits_{n=0}^{N} b_b^F \iint \ldots \int dt^n, \end{cases} \tag{6}$$

where $\mathrm{R}, \mathrm{F}, \mathrm{n}, \mathrm{m}$ are dimensionality indices of the operator space; a, b- weighting coefficients.

3. Design of PAA and simulation results

On the basis of input data and theoretical calculations, the geometric dimensions of single antenna element of the active phased array antenna with parallel feeder excitation at 3.7 GHz were obtained as shown in the Figure 1.

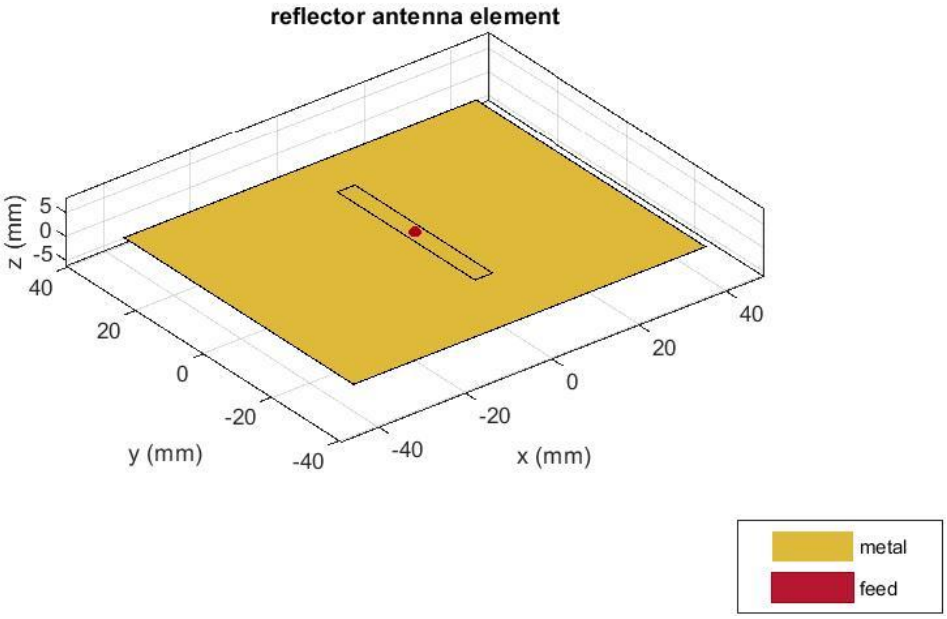
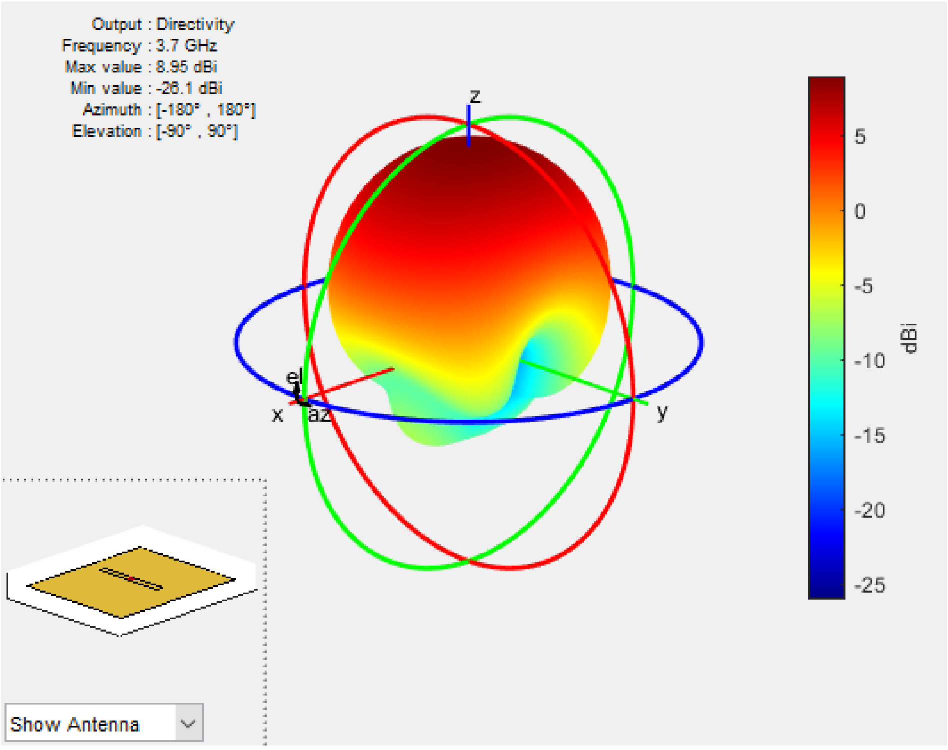


Figure 1: Geometric dimensions of single antenna element of the active phased array antenna

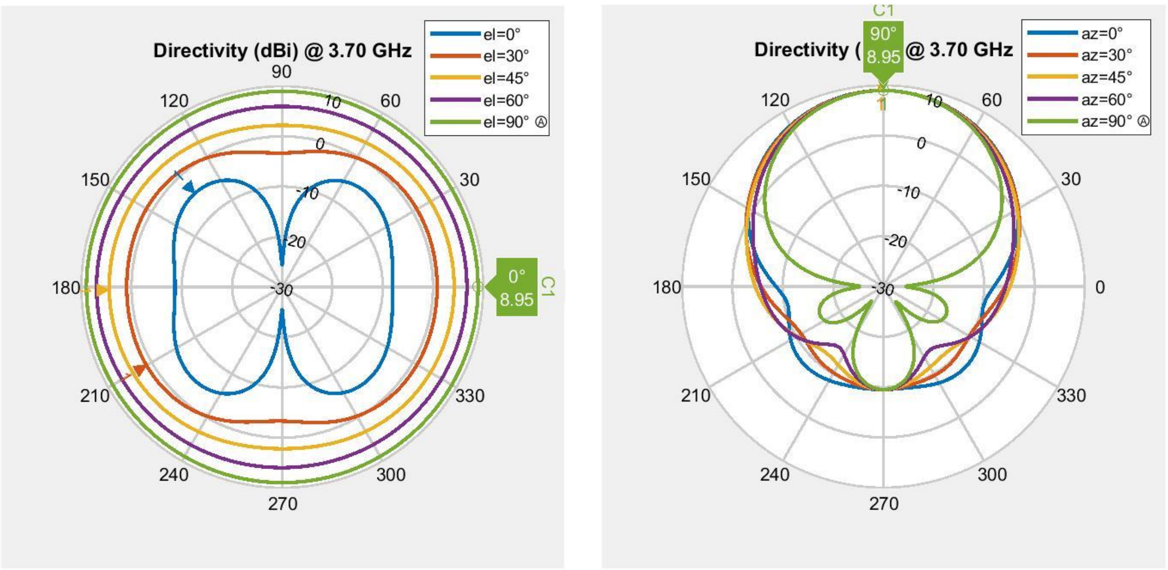
Using Matlab Integrated Development Environment [12], the directivity diagram of phased array antenna element in 3-dimensional coordinates [13] is built as shown in the Figure 2.



Output : Directivity
Frequency : 3.7 GHz
Max value : 8.95 dBi
Min value : -26.1 dBi
Azimuth : [-180° , 180°]
Elevation : [-90° , 90°]

Figure 2: Directivity diagram of phased array antenna element plot in 3-dimensional coordinates

Azimuth (a) and elevation (b) cut of directivity at 0, 30 45, 60 and 90 degrees elevation/azimuth, assuming 3,7 GHz operating frequency in 2-dimensional coordinates with few slices [14] is built as shown in the Figure 3.



(a) (b)

Figure 3: Azimuth (a) and elevation (b) cut of directivity at 0, 30 45, 60 and 90 degrees elevation/azimuth

Use the Phased Array System Toolbox to design a 5-by-9 rectangular array of antenna elements on a PCB on FR4 substrate. The spacing between the elements should be 0.5 times the wavelength. Specify that the array should be normal to direct radiation in the same-parallel direction to generate maximum coverage in the geographic azimuth. The type of single antenna element to use is a reflector-backed dipole antenna element. Due to the relatively high (0.1 Watt) transmitter power, the influence of steel roof covers of buildings and their primary horizontal polarization, it is advisable to create a horizontally oriented phased antenna array.

The directivity diagram [13] of phased array antenna in 3-dimensional coordinates is built as shown in the Figure 4.

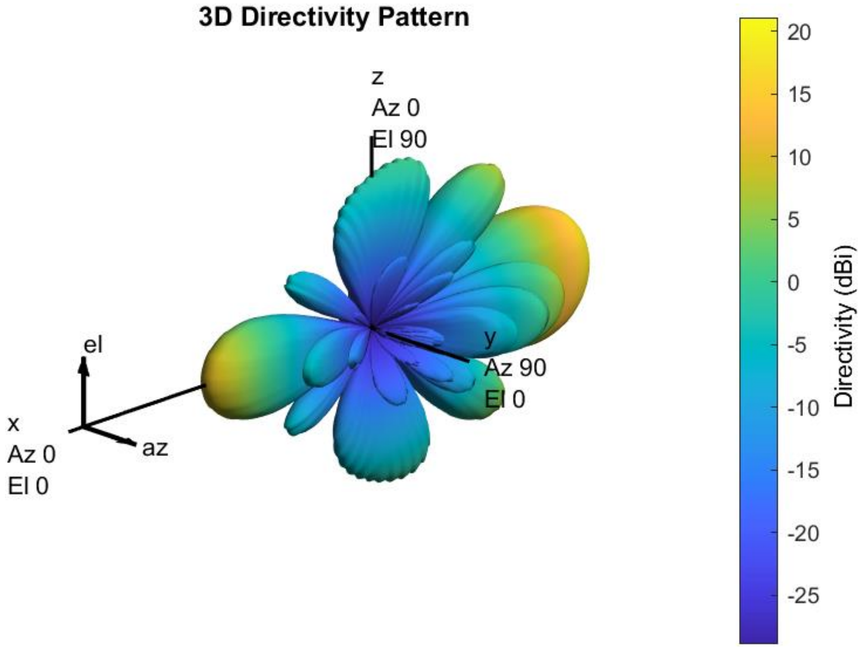
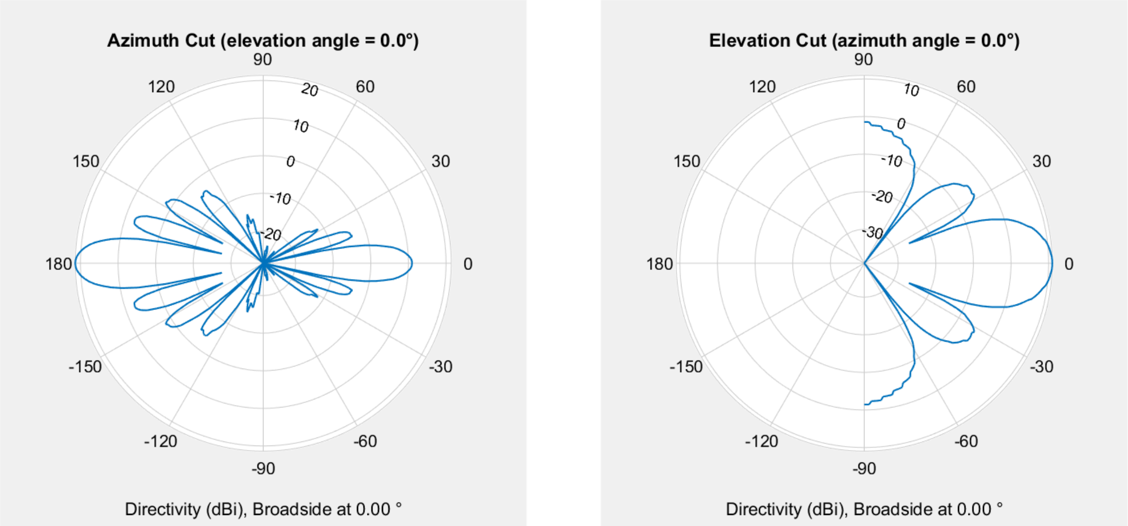


Figure 4: Directivity diagram of 5-by-9 phased array antenna in 3-dimensional coordinates

A 2-dimensional coordinate system [14] is used to build an azimuth cut of directivity at 0 degrees elevation and an elevation cut of directivity at 0 degrees azimuth for a 5-by-9 phased array antenna operating at 3.7 GHz as shown in the Figure 5.



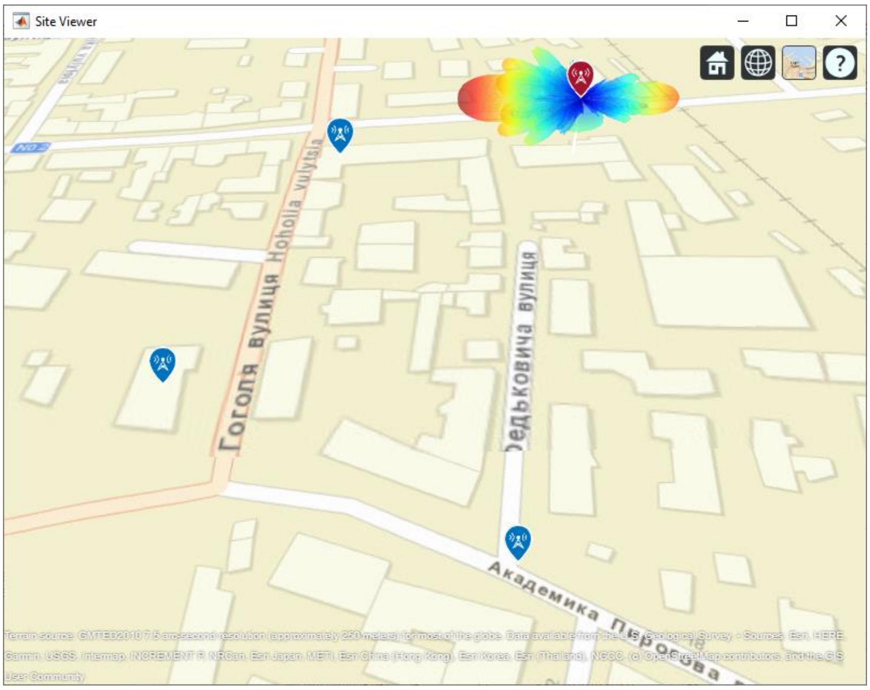
(a) (b)

Figure 5: Azimuth (a) and elevation (b) cut of directivity diagram of 5-by-9 phased array antenna in 2-dimensional coordinates

For instance, we can place [12] a 0.1 Watt transmitter with an antenna on top of the Ternopil Ivan Puluj National Technical University main building, which is 25 meters above the ground, equivalent to the height of an 8-floor building. The phased antenna arrays pattern in 3-dimensional coordinates appears as shown below, with reference to the terrain as shown in the Figure 6.

Just for example, let place [12] receivers at places:

- library;
- building #8;
- the roadcross of Fedkovych and Pirogov Streets.

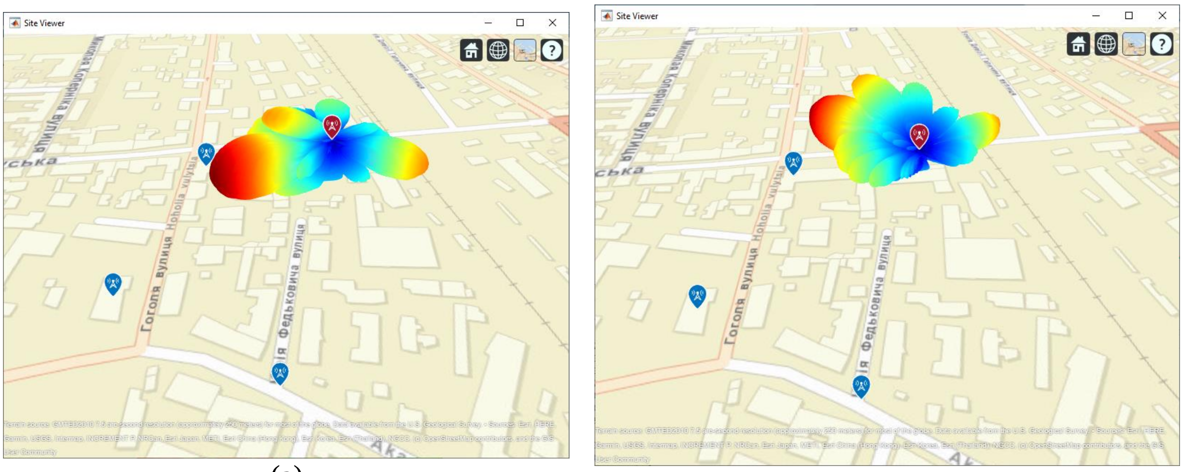


Terrain source: GMTED2010 7.5 arc-second resolution (approximately 250 meters) for most of the globe. Data available from the U.S. Geological Survey. • Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

Figure 6: Receivers allocation at 3 places

Scan the antenna beam by applying a taper for an angle of -30, 0 and +30 degree. GHz as shown in the Figure 7. In active phased array antenna with parallel feeder excitation system, each antenna element is connected to a separate feed line, which is excited by a single source, such as a transmitter or receiver. The signals from each feed line are then combined using a beamforming network, which adjusts the phase and amplitude of the signals to create a directional beam that can be steered in different directions.

The beam scanning mechanism allows the antenna system to scan the beam across a wide range of angles, allowing it to detect and track targets at different locations. This is achieved through the use of a mechanical or electronic scanning system that adjusts the phase of the signals fed to each antenna element, creating a sweeping motion of the beam.



(a) (b)

Figure 7: Antenna beam scanning by applying a taper for angles -30 and +30 degree in 3-dimensional coordinates

Let project [12] the directional pattern of the antenna onto the terrain surface.

Scan the antenna beam by applying a taper for an angle of -30 degree as shown in the Figure 8.

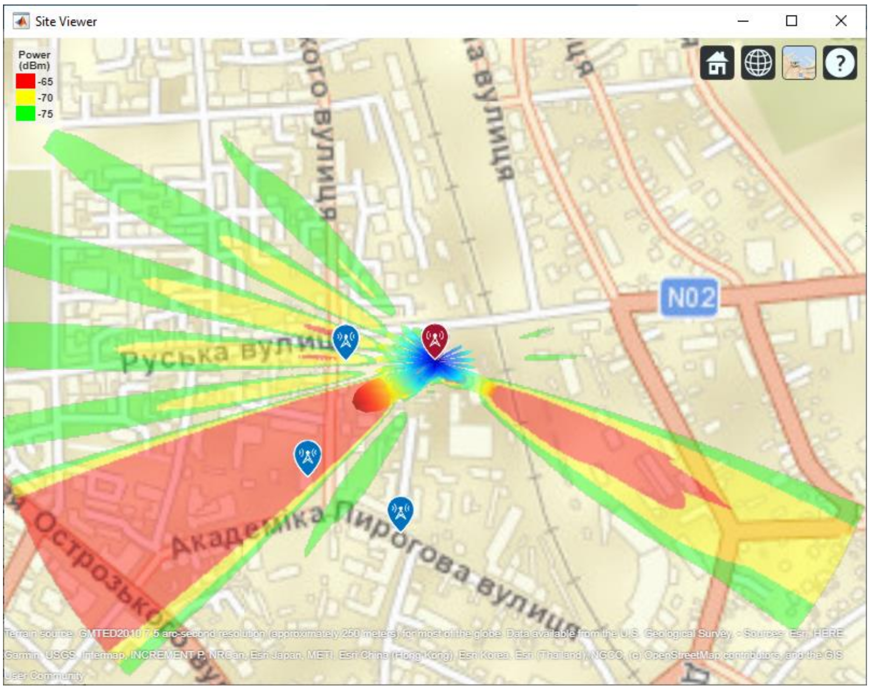


Figure 8: Antenna beam scanning by applying a taper for an angle of -30 degree (projection onto the terrain surface)

Scan the Scan the antenna beam by applying a taper for an angle of 0 degree degree as shown in the Figure 9.

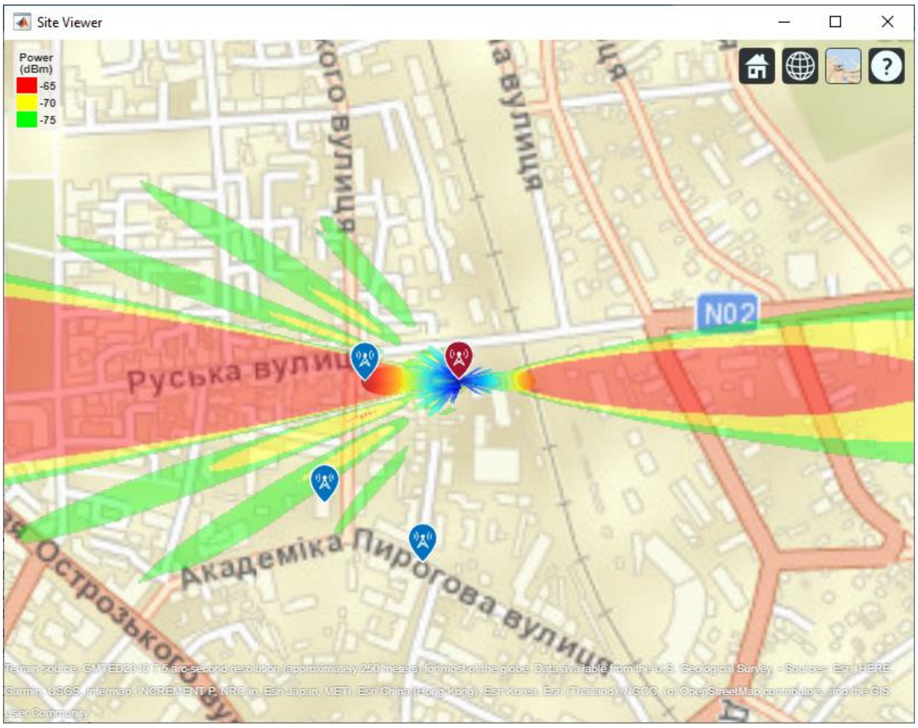


Figure 9: Antenna beam scanning by applying a taper for an angle of 0 degree (projection onto the terrain surface)

Scan the Scan the antenna beam by applying a taper for an angle of +30 degree degree as shown in the Figure 10.

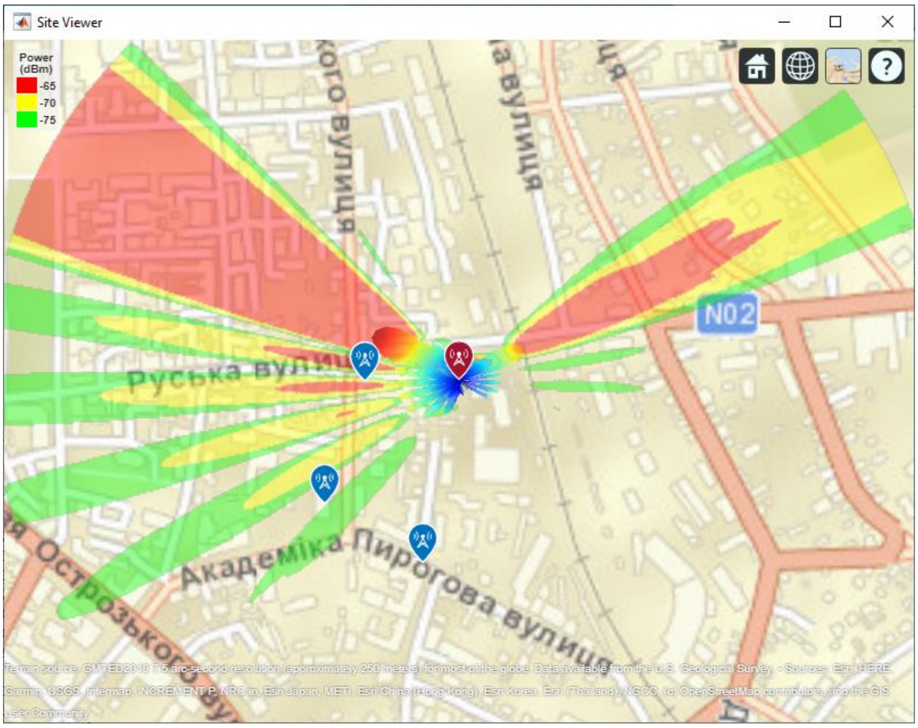


Figure 10: Antenna beam scanning by applying a taper for an angle of +30 degree (projection onto the terrain surface)

The experiment results in the virtual environment are as follows (sensitivity of each receiver is - 75 dB) as shown in the Table 1:

- strong signal -65;
- medium signal -70;
- weak signal -75.

Table 1
The results of virtual experiment

Receiver #	Beam Scan Angle, degree	Signal strength, dB	[Receiver's sensitivity - received power], dB
1	-30	- 68.86	6.14
2	-30	- 62.54	12.46
3	-30	- 92.64	17.64
1	0	- 48.78	26.21
2	0	- 91.96	16.97
3	0	- 89.90	14.90
1	+30	- 66.33	8.66
2	+30	- 77.86	2.86
3	+30	- 87.80	12.80

The obtained results of the experiment in a virtual environment confirm the phased antenna array design efficiency and the possibility of a real prototype manufacturing with minimal financial costs.

4. Discussion

The proposed approach for designing phased array antennas using a combination of meta-materials and artificial magnetic conductors by a printed circuit board (PCB) process-based fabrication method offers several advantages over traditional designs. Firstly, the use of meta-materials allows for the creation of thin, lightweight, and compact antennas that can be easily integrated into various platforms, including unmanned aerial vehicles (UAVs) and small satellites. This is particularly useful for applications where size and weight are critical factors, such as in satellite constellations where launch costs are directly proportional to the mass of the payload which will be the subject of future research.

Secondly, the use of artificial magnetic conductors enables the antenna to operate effectively in diverse environments, including those with high levels of electromagnetic interference (EMI). This is especially important in urban areas where there are numerous sources of EMI, such as buildings, cars, and other electronic devices. By suppressing the impact of these interferers, the proposed antenna design can provide more reliable and consistent performance, which is essential for applications such as search and rescue missions or disaster response.

Thirdly, the proposed approach allows for the integration of multiple frequencies and beamforming capabilities, enabling the antenna to transmit and receive signals simultaneously across different frequency bands. This feature is particularly useful in scenarios where multiple communication channels need to be maintained simultaneously, such as during natural disasters when different emergency responders may be operating on different frequency bands.

Finally, the proposed antenna design has the potential to overcome some of the limitations associated with traditional phased array antennas. For example, the use of meta-materials and artificial magnetic conductors can help reduce the impact of mutual coupling between adjacent elements, which can improve the overall efficiency and directivity of the antenna. Additionally, the proposed design can potentially mitigate the effects of environmental factors such as rain, fog, and dust, which can degrade the performance of traditional phased array antennas.

Despite these advantages, there are still some limitations to the proposed approach that should be acknowledged and addressed in future research. One of the primary limitations is the influence of the urban environment on the antenna's performance. Elements such as steel roof covers, building surfaces, and landscape features can all affect the signal strength and directionality of the antenna, and these effects need to be carefully studied and accounted for.

Another limitation is the cost and complexity of manufacturing meta-materials and artificial magnetic conductors, which can be prohibitively expensive and require specialized expertise. Therefore, there is a need to explore alternative materials and fabrication techniques that can achieve similar results without incurring excessive costs or requiring extensive knowledge in advanced material science for data transmission through telecommunication channels and networks is vital for many applications, especially for transmitting biosignals [15,16] and biosensors in cyberphysical systems [17-20] for remote monitoring what will be highlighted in future research. This can improve the health and quality of life of individuals and society, as well as create new opportunities and challenges for research and innovation.

In conclusion, the proposed approach for designing phased array antennas using a combination of meta-materials and artificial magnetic conductors offers significant advantages over traditional designs, including improved compactness, durability, and multi-frequency capability. While there are still some limitations to be addressed, the potential benefits of this approach make it an exciting area of research that could have far-reaching implications for various industries and applications. Future studies should focus on exploring the effects of urban environments on the antenna's performance and identifying cost-effective alternatives to meta-materials and artificial magnetic conductors.

5. Conclusions

In this article, we develop and present a model of a phased array antenna (PAA) for data transmission in urban environment using Matlab IDE.

We provide the mathematical descriptions of the potential, the specific noise power spectral density, and the directivity diagram of PAAs.

We design a 5-by-9 rectangular array from a reflector-backed dipole antenna element, and simulate its performance in urban environment. We show how the antenna beam can be scanned by applying a taper for different angles, and how the directional pattern can be projected onto the terrain surface.

We also conduct a virtual experiment with three receivers at different locations, and measure their signal strength depending on the beam scan angle.

The benefits of using computer simulation over experiment in vivo for phased antenna arrays are:

- Computer simulation is faster, cheaper, and more flexible than experiment in vivo. It can simulate a large number of scenarios and environments without the need for physical setup and measurement. It can also easily modify and optimize the design and parameters of phased antenna arrays to achieve the desired performance;
- Computer simulation is safer and more ethical than experiment in vivo. It can avoid the potential risks and harms of exposing humans, animals, or equipment to high-frequency electromagnetic radiation from phased antenna arrays. It can also reduce the environmental impact and waste generation from experiment in vivo.
- Computer simulation is more comprehensive and informative than experiment in vivo. It can provide detailed and visualized data and analysis on the behavior and performance of phased antenna arrays from different perspectives and dimensions. It can also help identify and solve potential problems and errors before implementing them in experiment in vivo. The obtained results of the experiment in a virtual environment confirm the phased antenna array design efficiency and the possibility of a real prototype manufacturing with minimal financial costs. Such design of phased antenna array is technological and cost-effective. cost-effective.

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