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FACULTY OF PHYSICS AND TECHNOLOGY**

**DEPARTMENT OF ELECTRONICS, COMMUNICATIONS, AND INFORMATION  
TECHNOLOGIES**

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**DESIGN AND AUTOMATED TESTING OF THE PARAMETERS OF 5G  
ANTENNAS**

**A B S T R A C T**

**of a dissertation for the acquisition of an educational and scientific degree doctor (PhD)**

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**Doctoral program: Automation of Intangible Areas**

**(medicine, education, science, administrative activity, etc.)**

**SCIENTIFIC SUPERVISOR: ASSOCIATE PROFESSOR DR. NADEZHDA KAFADAROVA**

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The dissertation work has a volume of 154 pages, including 72 figures and 24 tables organized into an introduction, six chapters, conclusions, contributions, and a list of the author's publications. The literature cited section includes 74 titles in Cyrillic and Latin. The designations of the formulae, figures, and tables in the abstract match those in the dissertation work.

The dissertation was discussed and scheduled for defense at a meeting of the departmental council of the The ELECTRONICS COMMUNICATIONS AND INFORMATION TECHNOLOGIES Department at the UNIVERSITY OF PLOVDIV PAISIY HILENDARSKI on 28.02.2024, Minutes No. 61.

The dissertation defense will take place on 06/04/2024 at 11 a.m. in hall "BI 15", 21 "Kostaki Peev" street, at UNIVERSITY OF PLOVDIV PAISIY HILENDARSKI, at a meeting of the scientific jury.

The materials for the doctoral student's defense are available to those interested in the office of the Faculty of Physics and Technology at UNIVERSITY OF PLOVDIV PAISIY HILENDARSKI, Kostaki Peev street №21, floor 4, room 1.

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## INTRODUCTION

Mobile communications are constantly evolving and the sector has seen amazing progress over the past 70 years.

Like any other field of science and technology, mobile telecommunications require in-depth and constant research. This research mainly belongs to the category of applied studies. Applied research is business-driven, focusing on solving practical problems to obtain profit in the short to medium term. Basic science research, on the other hand, focuses on the long term where research is forward-looking, drives innovation, enables socio-economic prosperity and helps move from one generation of technology to another. In a more specific sense, research and development from academia is moving to industrial research laboratories and from there to standard development organizations. Standardization is followed by product development, and this leads to the development /implementation/ of telecommunication systems in the network.

Correct antenna and operating frequency selection can be essential to radio link quality and to improving the efficiency and reliability of wireless communication systems.

The present study aims to develop an innovative system for studying the directivity diagrams of various antennas in laboratory conditions. The system developed for this purpose includes an electromechanical device, ensuring the rotation of the antenna under investigation, hardware, and software part. In order to expand the possibilities and flexibility of the system, the software is designed so that real measuring devices can be used, which guarantees the accuracy of the results obtained. The proposed electromechanical device for the antenna rotating includes a rotary high-frequency coupler, which overcomes the problem of cable twisting. The research was conducted in the telecommunications laboratory of the Faculty of Physics and Technology of Plovdiv University Paisii Hilendarski.

## **Aim of the dissertation and tasks for its achievement:**

**The aim of the dissertation work is to design 5G antennas and develop a system for automated parameters testing of their directivity diagrams.**

To achieve the goal of the dissertation, it is necessary to perform the following research tasks:

1. To survey the existing state-of-the-art approaches for studying the parameters of antennas for mobile applications. To carry out a critical theoretical analysis of the literature in the field of scientific research.
2. To design and create a working prototype system for 5G antenna directivity pattern research. To select appropriate modules for creation the prototype system.
3. To analyze the obtained results of the measurements carried out by the developed system prototype. To outline the main shortcomings of the prototype based on the critical analysis carried out.
4. To make a selection of the main functional nodes which build the working system used for automated testing of the parameters of the antennas directivity pattern.
5. To develop a working system for 5G antenna directivity pattern research. To develop an electromechanical functional unit for the implementation of rotational movement of the antenna under investigation. To develop software for synchronizing the work of the individual executive mechanisms that make up the system, as well as for researching the main parameters of the antennas' directivity pattern.
6. To develop a methodology for carrying out study of the antennas directivity pattern using the developed system.
7. To conduct research on different types of 5G antennas and build their directivity diagrams using the developed system.
8. To design, create and study an antenna for 5G. The study should be carried out using the created system for automated testing of the parameters of the directivity patterns.

## CHAPTER ONE

### Overview of modern approaches to parameter study on antennas for mobile applications

#### 1.1. Cellular Mobile Communication Systems - 5G Scenarios and Services

The high-frequency 5G spectrum provides the expected leap, not only in speed, but also in capacity, low latency and high quality. Existing 5G services can be categorized into broadcast, intelligent, autonomous and public 5G services. The International Telecommunication Union - Radiocommunication Sector (ITU-R) has defined three scenarios for the use of 5G [2]. These include Enhanced Mobile Broadband (eMBB), Ultra Reliable and Low Latency Communications (URLLC) and Massive machine type Communications (mMTC). The extension of 5G from eMBB to mMTC and URLLC comes from the observed demand for high-data-rate streams for both mission-critical applications and connectivity to large numbers of low-power, low-cost devices. Based on end-user experience, current 5G services are categorized into broadcast, smart, autonomous, and public 5G services [2]. Table 1.1 summarizes the five service categories of 5G. The vision of 5G is to provide an ultra-low-latency, fibre to the home user experience with more than 100 billion connected devices with improved energy and cost efficiency.

*Table 1.1: Summary of the five categories of 5G services*

<i>Categories</i>	<i>Services</i>
Broadcast 5G services	Massive content streaming Virtual Augmented Reality Telepresence
Smart 5G services	Serving a crowded area User-oriented computing Edge/FOG Computing
Ubiquitous 5G services	Smart Personal Devices/Health Smart Building / Network Smart City / Smart Factory systems
Autonomous 5G services	Smart Transport/Teleoperation 3D drone-based connectivity Robot-based service
Public 5G services	Private security and public safety Disaster monitoring Emergency

## **1.2 Types of antennas for mobile applications**

Printed antennas are a type of antenna that are manufactured using planar microwave technologies such as microstrip, patch lines, coplanar waveguide, and custom printing techniques. These antennas can be classified into different categories depending on the different characteristics and parameters of their radiating elements and feeding methods. Depending on their characteristics, we can find different classifications. In the first chapter, the characteristics of antenna types are discussed in detail.

## **1.3 Main characteristics of antennas**

Key characteristics of antennas that must be considered when designing wireless systems are radiation directivity diagram, frequency, gain, bandwidth, impedance, return loss, half power beam width (HPBW), number of side beams, polarization, cross-polarization, and voltage standing wave ratio (VSWR) [3-7].

## **1.4 Antenna measurements**

Testing and evaluation of antenna parameters are performed under certain conditions. Outdoor tests are not protected from environmental conditions, while indoor testing is limited by spatial features. Indoor studies use isolation chambers which are lined with signal-absorbing material to eliminate reflections from the walls. There are two main forms of chambers: rectangular and conical insulation chambers. Rectangular chambers are generally used for frequencies above 1 GHz, while conical chambers are used for frequencies below 1 GHz. There are various methods to study the antenna parameters described above, such as: radiation directivity pattern (radiative pattern), gain and polarization. The study of antennas is directly related to the occurrence of errors. The first chapter also discusses the types of errors made when carrying out measurements, namely: RF reflections, mechanical and system errors. In this category we can also identify the following errors: errors in the installation and adjustment of the antenna and errors from the environmental influence. Incorrect antenna setting or mounting can lead to undesirable influences on experimental results. For example, the incorrect antenna position can lead to reflections that compromise measurements. Factors such as electromagnetic interference from other devices, atmospheric conditions or meteorological phenomena can cause external effects on the antenna and also lead to errors in measurements.

## CHAPTER TWO

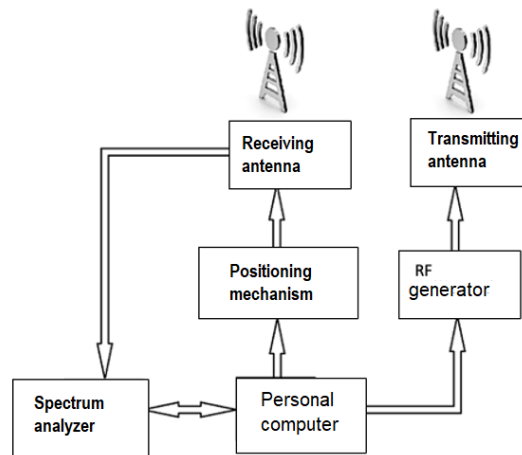
### Design of an antenna research system

One of the biggest challenges in the design of the system is related to the operating frequencies of the radio channel (the radio frequencies in use) on which the operation of the network depends. For this reason, an accurate analysis of the main characteristics of antennas at different operating frequencies and environmental conditions (vibrations, changes in temperature, electronic noise etc.) is necessary to predict and optimize the radio coverage. In this case, the adequate design and manufacture of 5G antennas is crucial to ensure the required quality and reliability of coverage and cost redistribution in different deployment scenarios of the base station or 5G devices and communication systems.

Before developing the antenna research system, a working prototype was designed and manufactured to evaluate the viability and effectiveness of the device concept which leads to saving time and effort by avoiding potential problems and failures at an early stage. Detecting problems in the prototype results in making the necessary corrections before the final version of the system.

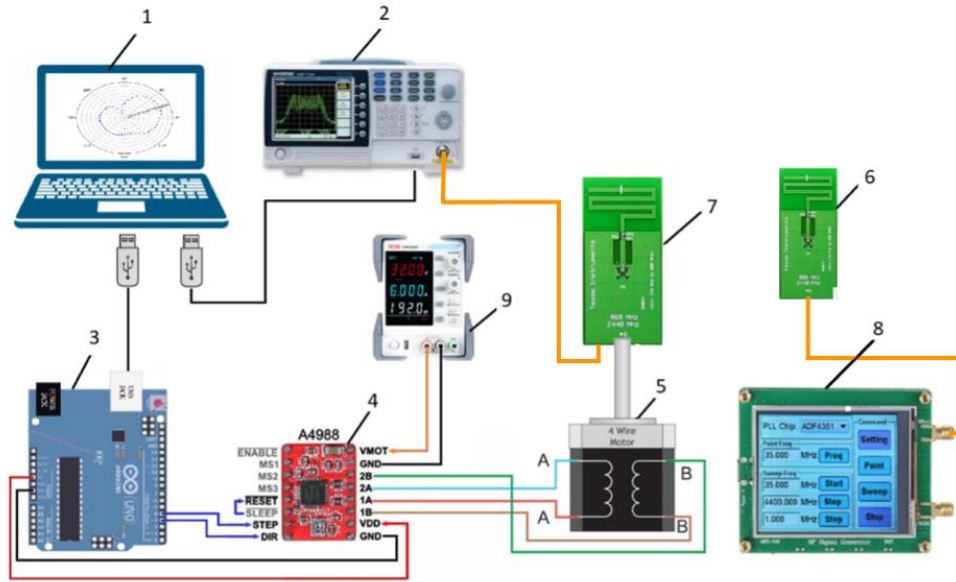
#### 2.1. Design and creating a working prototype of a 5G antenna research system.

As a result of the analysis, a decision was made about the modules to be used in the construction of the designed system such as: transmitting module with antenna, measurement module to which the investigated antenna is connected, positioning system, data recording and processing module. The block pattern of the entire system is shown in Figure 2.1.



*Figure 2.1. Block diagram of the designed system for measuring the radiation pattern of antennas*

The diagram of the experimental setup is shown in figure 2.2. The experimental setup consists of the following components: 1 personal computer, 2 spectrum analyzer GWINSTEK GSP-9300, 3 microcontroller Arduino UNO, 4 stepper motor driver A4988, 5 stepper motor, 6 stationary (transmitting) antenna, 7 tested (receiving) antenna, 8 high frequency generator, 9 power supply.



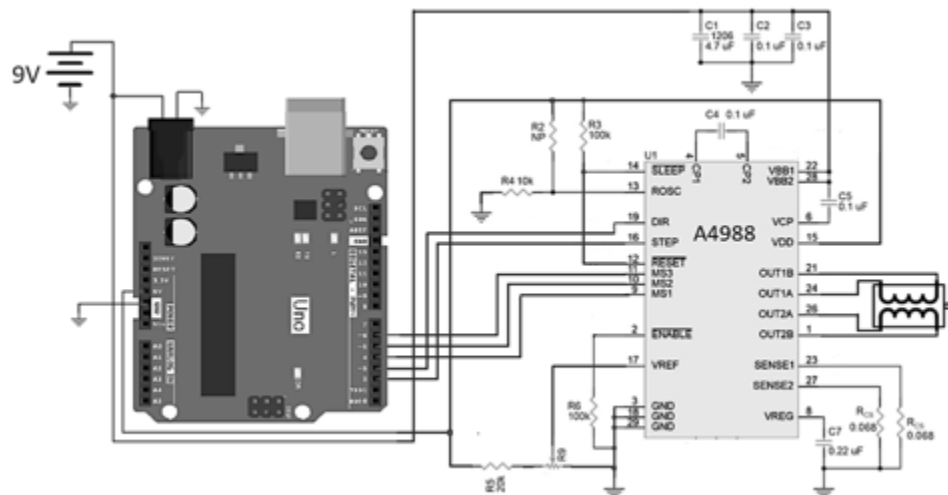
**Figure 2.2. Experimental setup for investigation of 5G antenna**

Obtaining a graphic image of the directivity pattern is performed by rotating the antenna at 3600, periodically measuring the power of the received signal (in dBm). For this purpose, the signal from the transmitting antenna, to which a high-frequency radio generator operating at constant power is connected, is transmitted to the receiving antenna under investigation. The transmitting antenna is stationary and is located at a certain distance from the receiver. The receiving antenna is connected to the rotor axis of the stepper motor, which is mounted on a specially designed tripod [31]. The movement is carried out in steps of a fixed value, each changing the angular position of the investigated antenna relative to that of the transmitter. The power of the received signal in dBm is measured after establishing the current position of the antenna. The antenna movement and signal measurement are synchronized with customised software for a personal computer. A bipolar stepper motor with a step size of 1.80 was chosen for the rotary motion. The motor is controlled by a hardware driver and an Arduino Uno microprocessor board. The stepper motor driver used for this purpose is the A4988 integrated circuit. This driver was chosen because it enables the use of stepper motors operating over a wide range of supply voltages



and operating currents. This makes it possible to use a wide range of engines which greatly facilitates the development of the prototype. Also, the driver allows easy change of the step angle of the electric motor when operating in microstepping mode, thus allowing for more precise angular positioning of the antenna when using less expensive motors. The driver allows the limitation adjustment of the of the operating current flowing through the motor. The maximum permissible value of the output current of the driver is 1A, and when additional cooling is used it can reach 2A. The supply voltage for the logic part of the circuit can be in the range of 3 - 5.5V VDD and from 8 - 35V for the motor supply voltage VMM. The A4988 integrated circuit allows the motor to be controlled in microstep mode, thus increasing the resolution of the angular positioning of the antenna [32].

When testing heavier antennas, it is necessary to increase the torque of the motor to ensure the correct movement of the antenna at a certain speed. This can be achieved to some extent by increasing the motor supply voltage within certain limits, as a result of which the rate of change of current through the windings increases. To ensure safe operation of the motor, the option of active current limiting is used, which is supported by an integrated circuit A4988 [33]. Changing the angular position of the antenna by one step is carried out by applying a pulse to the STEP input of the integrated circuit A4988, the logic level of the DIR input determines the direction of rotation. Setting the microstep mode is done in software through the inputs MS1, MS2, and MS3, which are connected to the Arduino Uno development board. The motor control hardware wiring diagram is shown in Figure 2.4.



**Figure 2.4. Wiring diagram of the motor control hardware**

### **2.1.1. System software**

The movement of the antenna and the measurement of the signal are synchronized by customized software that is installed on a personal computer. The software allows the user to configure the parameters necessary to rotate the antenna during the measurement. The software sets the addresses of the communication ports to which the spectrum analyzer and the Arduino Uno development board are connected, as well as the step size of the motor and the resulting graphs are scaled. To improve the quality of the measurements, experiments were carried out using various digital filtering software algorithms to eliminate unwanted noise.

### **2.1.2. The measurement procedure**

Once the measurement procedure starts, the computer sends a command to the Arduino Uno development board to move the antenna. The communication between the two devices is carried out through a USB serial interface. After receiving the command, Arduino Uno sends the corresponding control signals to the A4988 driver and sends information to the computer about the end of the action. For the realization of these processes, specialized firmware was developed and installed in the Atmega 328 microcontroller on the Arduino Uno board. As soon as the antenna is moved, a procedure to measure the signal strength received by the antenna is started. For this purpose, a spectrum analyzer GW Instek GSP9300 to which the antenna under study is connected is used. The analyzer has a frequency range of 9KHz – 3GHz. To control the spectrum analyzer, the PyVISA Python library is used, which allows control of all types of measuring devices, regardless of the interface (eg GPIB, RS232, USB, Ethernet).

Test measurements of a dipole antenna operating at 2.5 GHz were performed by the created prototype. The measurements were performed at 200 steps per stroke (1.80), since the transmitting and test antennas are located in one plane at a distance of  $10\lambda$ , where  $\lambda$  is the length of the electromagnetic wave. The signal is measured in dBm by GW Instek GSP930 spectrum analyzer. Radiation patterns are obtained in Cartesian and polar coordinates. The radiating properties of the antenna are recorded in the E and H planes of the radio wave. For a linearly polarized antenna, the planes E and H are defined as the planes containing the electric and magnetic field vectors, respectively.

## **2.2 Selection and analysis of the main functional units making up the active antenna research system**

Based on the developed prototype of the antenna research system, a working system with improved characteristics was created. The main drawback of the prototype was twisting of the feeder RF cable of the antenna under study. The developed construction that allows the investigated antenna to rotate without causing mechanical tension in the cables leads to overcoming this shortcoming. Another disadvantage of a measuring system with a connecting fixed cable between the measured rotating antenna and the spectrum analyzer is the need to return the element to which the antenna is attached to its initial positions, i.e., to rotate in the opposite direction by 360 degrees after the measurement is completed. The movement of the holder in two opposite directions can cause errors in the angular positioning of the antenna for the next measurement. This error is usually caused by looseness in the actuator. This shortcoming was noticed in the working of the prototype. A disadvantage of the prototype system was also the limited range of possibilities for determining the number of steps of the stepper motor, which limits the step resolution of the antenna rotation. It was necessary to increase the number of steps in a precise study of the antennas, when the visualization of small deviations in the radiation pattern was aimed. In addition, the use of the A4988 driver in the prototype development limits the use of stepper motors with small operating current to 1A. This is a serious limiting factor in the investigation of heavy antennas where greater torque is required.

### **2.2.1 Stepper motor driver**

After a thorough study of existing methods and devices for control of stepper motors in the setting up of the measuring system the DM556 driver was selected [34]. The device is designed on the basis of an advanced DSP algorithm, through which the movement of the rotor is controlled. Thus, optimal torque in a wide range of operating revolutions during the operation of the motor is ensured. The driver offers the possibility to implement micro step mode with 16 different resolutions at: 400, 800, 1600, 3200, 6400, 12800, 25600, 51200, 1000, 2000, 4000, 5000, 8000, 10000, 20000, 40000 steps per revolution. The input voltage can be varied over a wide operating range of 24-80 Vdc. The peak current limiting mode through the coils can be selected to: 2.40 A, 3.08 A, 3.77 A, 4.45 A, 5.14 A, 5.83 A, 6.52 A, 7, 20 A. The control inputs are TTL compatible and galvanically isolated with optocouplers.

The repetition frequency of the pulses that are applied to the step change input is up to 200 KHz. The idle current is automatically limited, which reduces the heat dissipated by the motor while it is positioned at a certain step angle. The driver is suitable for controlling both 2-phase and 4-phase motors. Overvoltage and overcurrent protections were implemented. When constructing the system, a vertical positioning of the DM556 driver was chosen.

To extend the applicability of the antenna research system and provide greater flexibility during measurements, its construction is designed to be able to analyze the performance of antennas with different geometrical characteristics, which necessitates changing the value of the motor torque depending on the weight and geometry of the antenna under study. Another important parameter of the system that can be changed is the time to perform the analysis, which in turn is related to the speed of rotation of the engine. Therefore, the choice of the value of the supply voltage depends on how much torque is needed at certain revolutions of the motor.

### **2.2.2 Communication interface between the computer and the spectrum analyzer**

As a result of the development of the various interfaces, a strong motivation to unite the software interfaces, the VXIplug & play Alliance introduced the VISA (Virtual Instrument Software Architecture) standard arose. It is a standard communication API (application programming interface) for controlling instruments and measuring devices. VISA allows program development to be independent of the device communication bus [35,36]. Using the VISA libraries allows communication with many interfaces such as GPIB, USB and Ethernet. The VISA standard is currently maintained by the IVI Foundation. For the LAN interface, the TCP/IP based protocol is known as VXI-11. Later, its improved version appeared called HiSLIP (High Speed LAN Instrument Protocol). The last addition concerns the USB interface support. The USB device class initially supported by VISA is called USB-TMC (Test and Measurement Class).

The Python programming language can be used to call functions from the VISA shared library (.dll,.so,.dylib), allowing direct use of standard implementations. Implementing the VISA standard in Python can be used to directly access most interface buses used by tools. The GW INSTEK 9300 spectrum analyzer is controlled using SCPI commands [39]. They have a tree-like structure organized into nodes. Each level of the command tree is a node that represents a keyword in the SCPI command. Each keyword (node) in the SCPI command is separated by a colon (:).

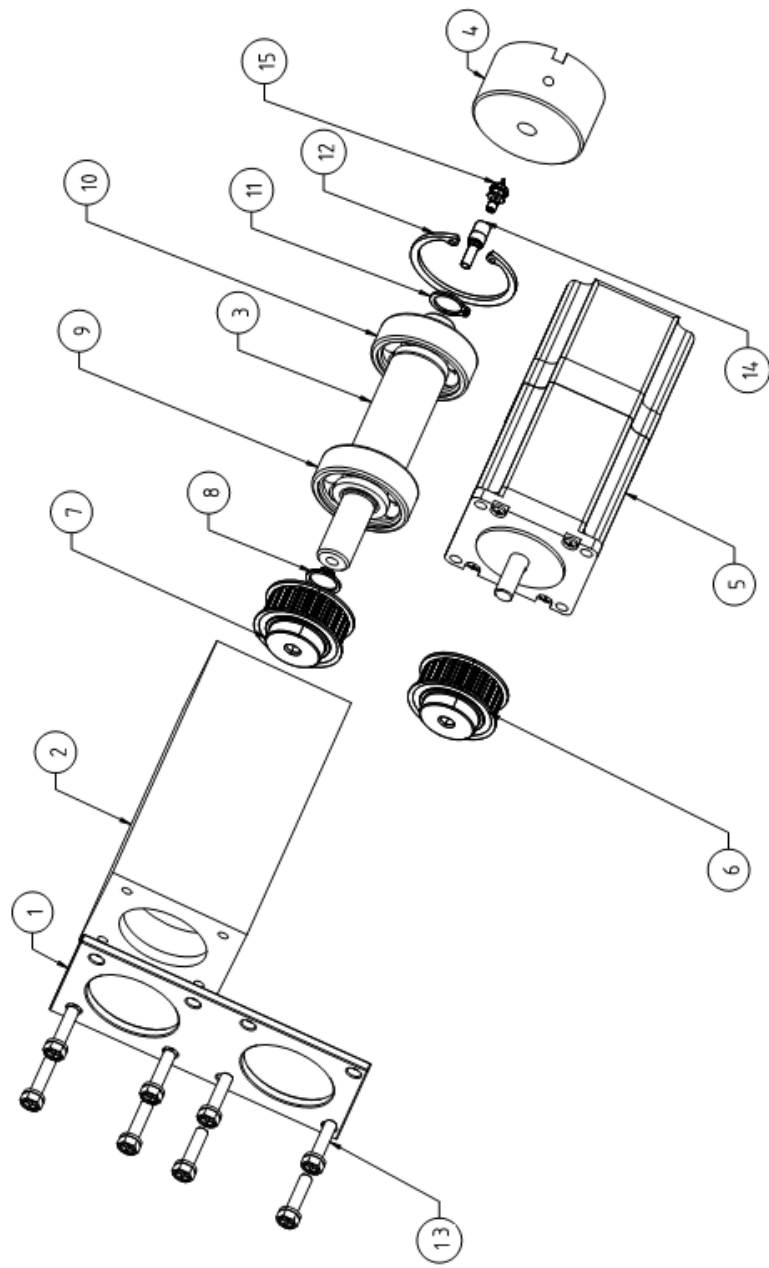
## **CHAPTER THREE**

### **Development of a functioning system for the study of the directivity pattern of antennas**

#### **3.1. Development of the electromechanical functional unit**

The main disadvantage of many of the antenna directivity testing systems is that the antenna under test must perform a rotational movement while the measuring equipment to which it is connected is stationary. This leads to twisting of the connecting coaxial cables between the antenna and the measuring devices. To reduce the bending radius, some manufacturers use coaxial cables of greater length and smaller diameter. Nevertheless, this design of the system leads to a significant reduction in the life of both cables and connectors, as well as antenna displacement. To overcome this shortcoming, a design was proposed that allows the antenna under study to rotate without causing mechanical tension in the cables. In this case, an SMB connector is used to connect the antenna to the measuring equipment, which has a special connection retention mechanism that allows precise positioning of the male to female connector. The SMB connectors used are from the Amphenol company and meet the requirements of MIL-C-39012, and the interface is in accordance with MIL-STD-348.

The schematic diagram of the mechanical part of the antenna research system is given in figure 3.2.

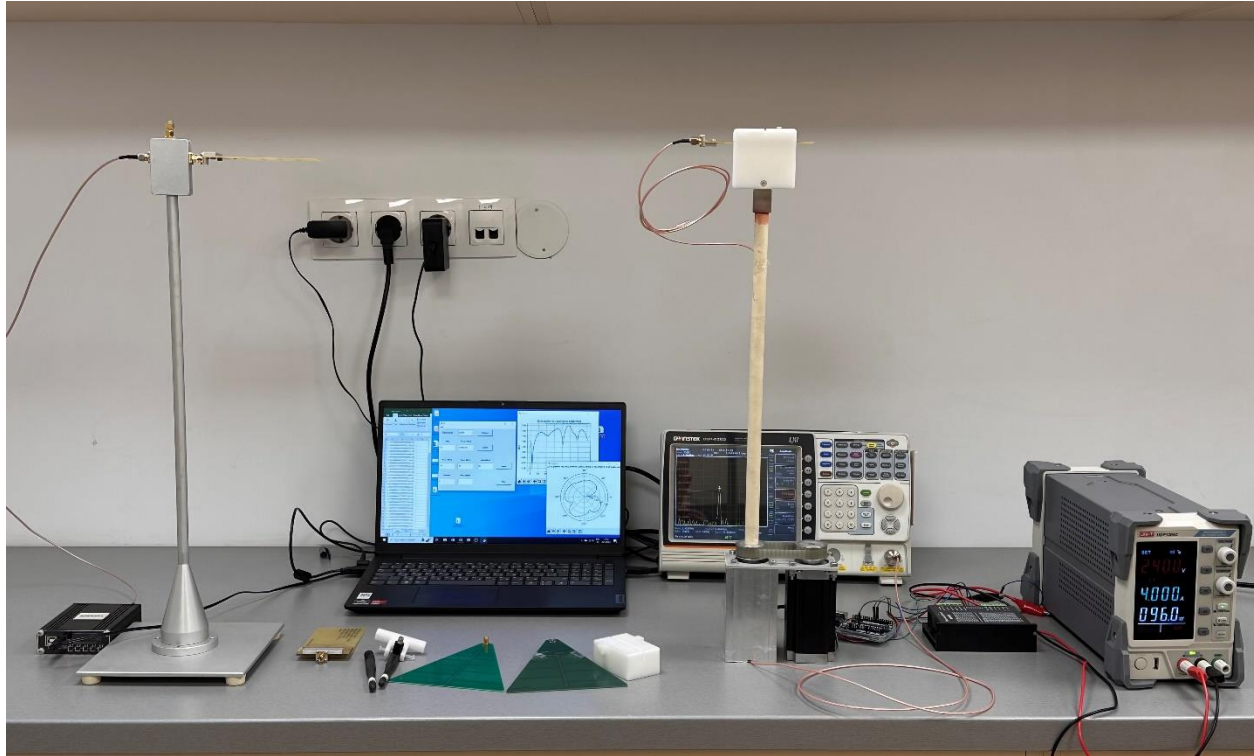


**Figure 3.2** *Assembly drawing of the device*

The rotational movement of the antenna is carried out by the stepper electric motor SM57STH111-404 (position 5). The motor shaft has a diameter of 8 mm, and the the toothed-belt pulley (position 6) is clamped to it. It is fixed to the motor axis by means of a locking screw M3 x 10. This toothed belt pulley is made of aluminum AW2017A, has 22 teeth with a pitch of T5, profile 1F, and is designed to work with a belt with a width of 10 mm.

The antenna under test is clamped stationary by a fixing device to shaft 3. Toothed-belt pulley 7 is mounted on shaft 3 which has the same parameters as that of the motor. The torque of the stepper motor is transmitted to shaft 3 by means of a reinforced flat belt with teeth on the inner side whose profile is the same as the teeth of the belt pulleys. Belt teeth mesh with corresponding grooves on timing belt pulleys. A large pretension of the belt is not necessary for proper operation of the belt drive, and the pulling capacity is not significantly affected by the angle of contact and the center distance [41], which allows belt drives to be designed with smaller dimensions and large velocity ratios. The belt drives have great wear resistance and the ability to work without additional maintenance, as the elasticity of the belt and its teeth significantly reduce dynamic loads. The implementation of belt drive allows achieving good kinematic accuracy and precise positioning of the antenna at the respective angular positions. Also, due to the possibility of realizing the toothed-belt drive with a small center distance by design a significant reduction in the dimensions of the entire mechanical unit is achieved. The shaft is hollow, and along its length a hole with a diameter of 5 mm is drilled. The coaxial cable that connects to the antenna passes through this hole. A female SMB connector fits into a 6.6mm diameter 10mm deep hole which is bored at the bottom of the shaft. The bearing housing is made from an aluminum profile with a square section of 60mm x 60mm. In it, two holes with a diameter of 42 mm are bored. The holes are the bearing sockets in which the outer rings of the ball bearings (positions 9,10) are mounted. A technological release in the form of a hole with a diameter of 43 mm and a length of 55 mm is formed between the holes which allows easier installation of the assembled bearings with the shaft in the body itself and facilitates the turning operation of boring the bearing sockets. To limit the axial movement of the bearings and shaft, a hole with a diameter of 38mm is bored at the upper end of the body. Thus, a technological step with a height of 4mm is formed, and a seeger ring groove is formed under the lower bearing. In order to restrict the axial movement of the bearings and shaft, a hole with a diameter of 38mm is bored at the upper end of the body. Thus, a technological step with a height of 4mm is formed, and a seeger ring groove is formed under the lower bearing.

Figure 3.7 shows a photograph of the experimental setup for studying the main characteristics of the directional pattern of antennas.



*Figure 3.7. Experimental setup for the study of the main characteristics of the antenna's directivity pattern*

### **3.2. Antenna study software**

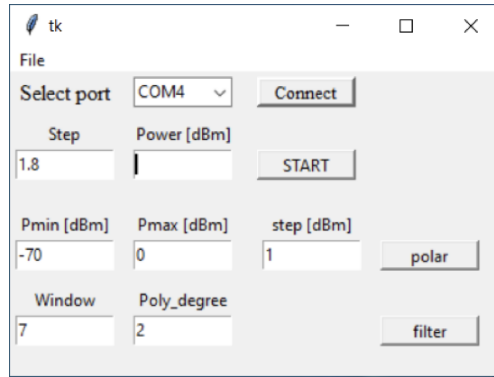
The operation of the measuring system is controlled by specialized software that is installed on a personal computer. The TkInter library was used to create the user interface.

The “Selected port” drop-down menu is provided for selecting a USB port to which the Arduino UNO development board is connected, and the board sends the necessary signals to the stepper motor control hardware.

The information about the size of the step of the motor is recorded in the text field *Step*. This value is entered by the user in accordance with the settings of the driver controlling the motor [43-45].

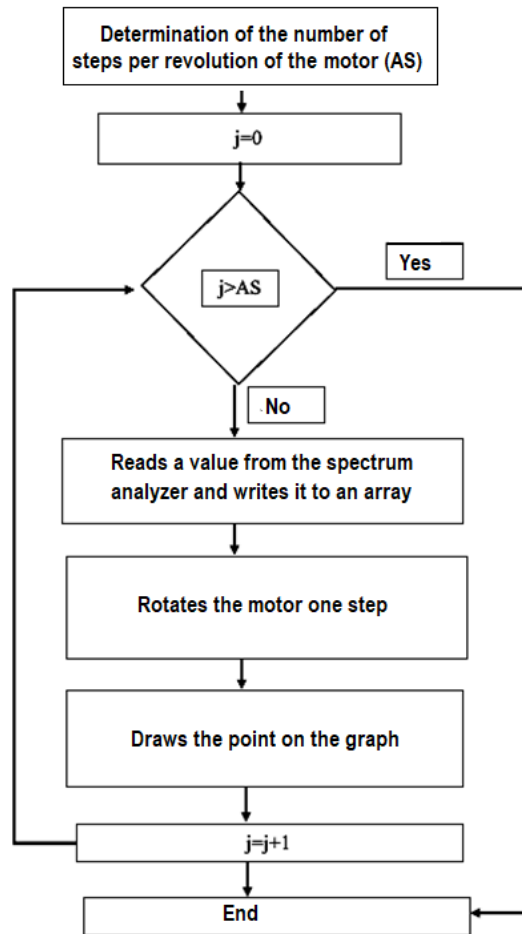
During the measurement, the current value of the signal power is continuously displayed in the “Power[dBm]” text field.





**Figure 3.9** User interface

The algorithm of the measurement procedure has the following form:

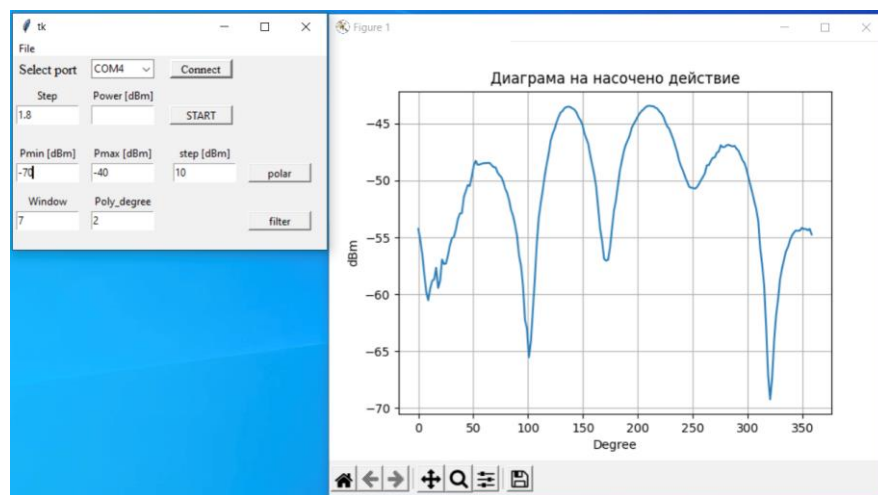


**Figure 3.10** Algorithm of the measurement

First, the global variables  $x$ ,  $y$ ,  $i$ ,  $j$  and the required number of steps the motor must make in one revolution to rotate the antenna  $360^0$  are defined.

The variables  $x$  and  $y$  are assigned two empty one-dimensional arrays, in which the numeric values containing the coordinates of the points are stored. The  $x$  array consists of values from 0 to 360 that change by the step that is set in the *Step* field. The  $y$  array contains the values for the power measured with the spectrum analyzer for each of the steps [46]. The  $y$  array contains the power values for each of the steps measured with the spectrum analyzer [46]. The  $j$  variable represents a step counter by initializing it with a value of 0. To plot the graph in Cartesian coordinates the following steps are performed. A command to the spectrum analyzer is given and the signal power value is read. This value is written to the  $y$  array and displayed on the screen with  $x$  and  $y$  coordinates. A command to the Arduino Uno microprocessor board which controls the stepper motor driver is then given. It rotates in one step, which changes the angular position of the antenna. The value of the variable  $j$  increases by 1. It must be checked whether the value of  $j$  is greater than the value of  $AS$ . As long as the value of  $j$  is less than or equal to the value of  $AS$  the steps are performed in the described sequence. When the value of  $j$  becomes greater than  $AS$ , the above described steps stop.

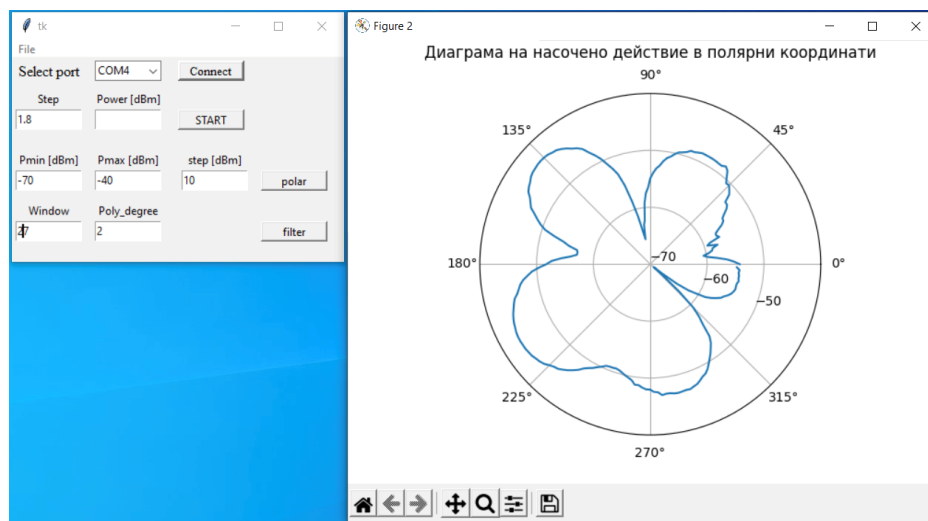
After performing the procedure, the directivity pattern of the measured antenna is visualized on the screen in a Cartesian coordinate system, which is shown in figure 3.11.



*Figure 3.11 Directivity pattern in a Cartesian coordinate system*

In addition to being presented in Cartesian coordinates, the graph can also be presented in polar coordinates, which is adopted in the study of the radiation characteristics of antennas. It is possible to set the limits of the graph when drawing it, which changes the scale. This is done to better visualize the graph in different dynamic ranges of the measured power. Thus, it becomes possible to see small details in the graphs. This is done using the fields in the user interface Pmin [dBm], Pmax [dBm], step [dBm].

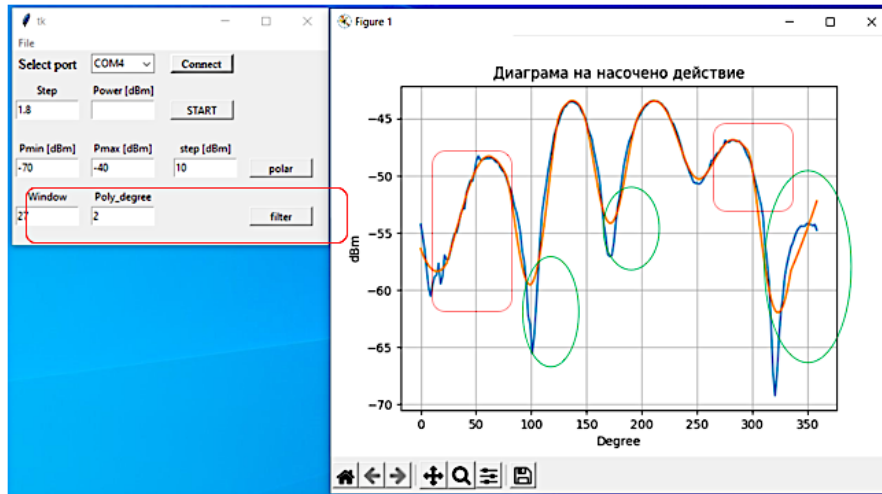
After performing the procedure, the directivity pattern of the measured antenna is visualized on the screen in a polar coordinate system, which is shown in figure 3.12.



**Figure 3.12 Directivity pattern in polar coordinates**

To improve the quality of the measurements, it is possible to filter the measured signal digitally, which eliminates unwanted noise. Filtering is carried out, by means of the Savitzky–Golay filter, with the possibility to change its main parameters, which are: window size and polynomial order [47]. This type of filter works on the basis of polynomial approximation of individual frames (windows) of the input signal using the minimum squared error criterion [48].

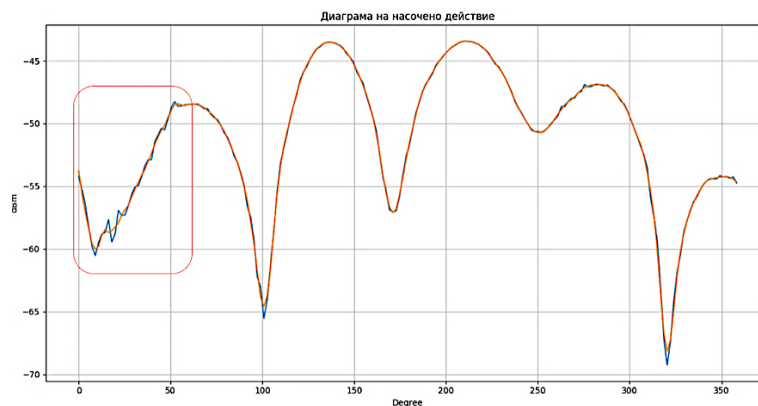
Figure 3.13 shows the user interface and the resulting directivity diagram. The diagram contains two graphs. The first graph (in blue) is the actual directivity pattern and the second (in orange) is the directivity pattern after applying the filter.



**Figure 3.13** Directivity pattern obtained without filtering (in blue) and after applying filter (in orange) with parameters window size 27 and second order polynomial.

As can be seen from the figure, the high-frequency components are well filtered (the areas outlined in red), but the graph obtained after filtering is significantly different in shape from the actual one, which is due to the large width of the window and the low order of the polynomial (especially strongly expressed in the areas outlined in green).

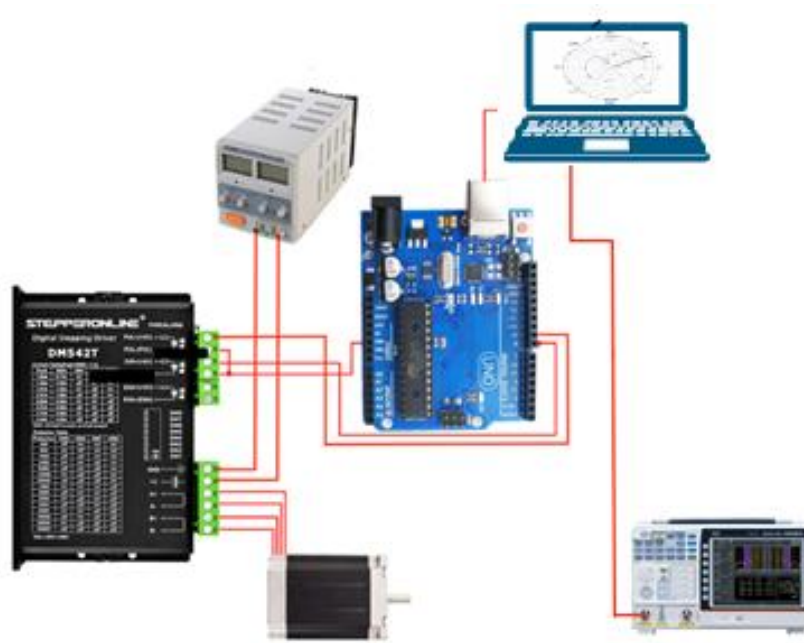
Figure 3.14 shows the same signal applied to a filter with reduced window width 7 and a second-order polynomial. The figure shows a much better correspondence between the graphs before and after filtering the signal than those of Fig. 3.14 at window width 27 values.



**Figure 3.14** Directivity pattern without filter (in blue) and after applying filter (in orange) with parameters window size 7 and second order polynomial.

To obtain the directivity diagrams of the antennas, the developed software synchronizes the operation of the spectrum analyzer and the stepper motor. The functional components that make up the system are shown in Figure 3.20.

The DM 556[53] driver is used to control the stepper motor (model - SM57STH111-4004). The parameter needed to make the antenna rotate is the number of steps that the stepper motor must take. It is then fed as a command to the Arduino Uno microprocessor board, which is connected to the stepper motor driver.



***Figure 3.20 Functional components of the measuring system***

The power supply of the driver is provided by a laboratory power supply unit and in this case has a value of 24V. Communication between Arduino Uno and DM 556 is done through the DIR, PUL terminals. DIR sets the direction of rotation of the motor. Each pulse applied to the PULL input increases the angular displacement of the motor rotor by one step. Therefore, when the Arduino Uno receives the value for the total number of steps (that the motor needs to take) on its serial port, it starts sending pulses to the PUL terminal of the DM556.

## **CHAPTER FOUR**

### **Methodology for carrying out the study of antennas**

A methodology for carrying out the research on the directivity pattern of antennas for 5G mobile communications was developed. This methodology includes the steps described below.

The radiating antenna is clamped on the fixed stand, and on the rotating side the studied antenna is placed. The radiating antenna is connected to a high frequency generator and the investigated antenna to the input of the spectrum analyzer. After starting the generator, the radiating antenna begins to generate electromagnetic waves with a certain frequency, which reach the antenna under study.

The received signal enters the input of the spectrum analyzer. For its measurement, the following settings of the spectrum analyzer must be made:

1. Setting the center frequency
2. Adjustment of the frequency range for the respective measurement
3. Cursor positioning
4. Creating a link between a spectrum analyzer and a personal computer
5. Starting the PC software after completing the spectrum analyzer settings
6. Starting the corresponding USB port to which the Arduino Uno development board is connected
7. Pressing the START button of the software after which the measurements begin

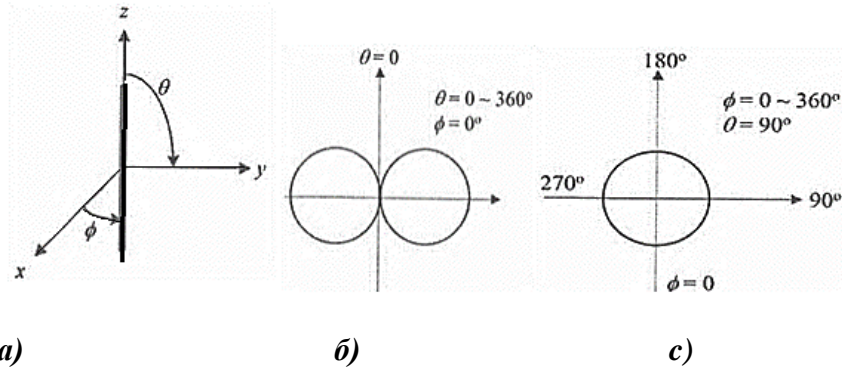
## **CHAPTER FIVE**

### **Construction of antenna directivity pattern for 5G using the developed system**

In order to study the working capacity and efficiency of the developed antenna test system, numerous measurements of different types of antennas were performed. The research was conducted in the "Telecommunications" laboratory at the Faculty of Physics and Technology of Plovdiv University. The dissertation work presents the research results of the following antennas: a dipole antenna for a frequency of 2.45 GHz, a yagi antenna for a frequency of 2.45 GHz and a log-periodic antenna operating in the frequency range 850 MHz – 6500 MHz [62].

- Dipole antenna for a frequency of 2.45 GHz.

The theoretical directivity pattern of a dipole antenna in the planes E(x,z) and H(x,y) in a polar coordinate system is shown in figure 5.4.

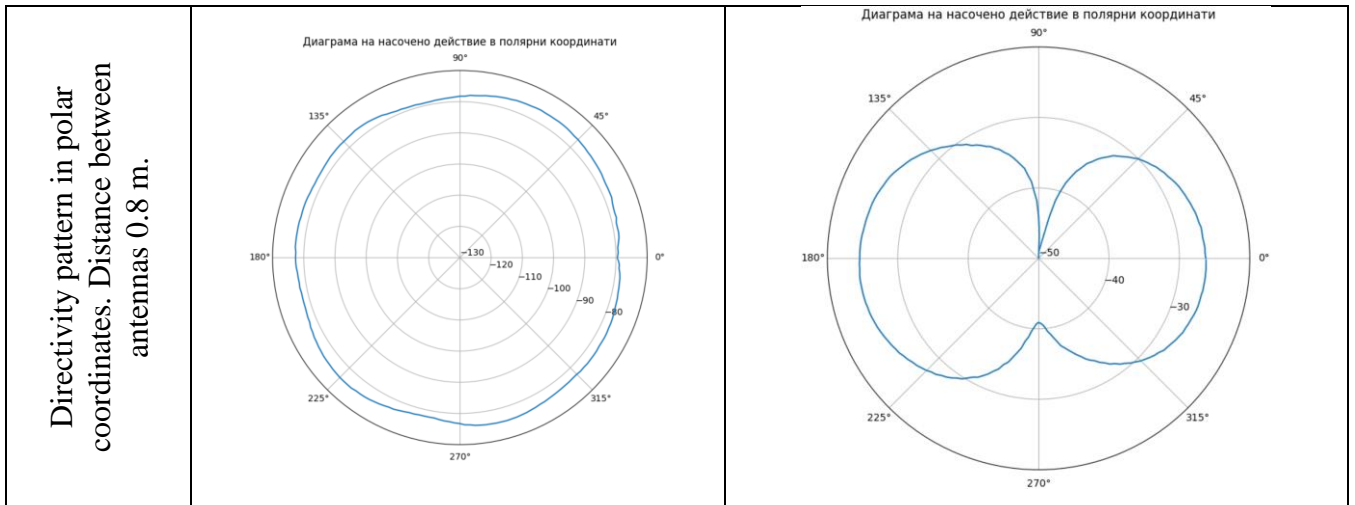


**Figure 5.4** Directivity pattern of a dipole antenna presented in a polar coordinate system.  
 a) dipole antenna in the coordinate system; b) measurement in the E(x,z) plane; c) measurement in the H(x,y) plane

Table 5.1 shows the resulting directivity diagrams in the H and E planes, respectively, of a dipole antenna designed at an operating frequency of 2.45 GHz. The diagrams for different distances between the receiving and transmitting antennas are shown in Cartesian and polar coordinate systems. The transmitting antenna in this case is again a dipole with the same characteristics.

**Table 5.1** Directivity patterns of a dipole antenna

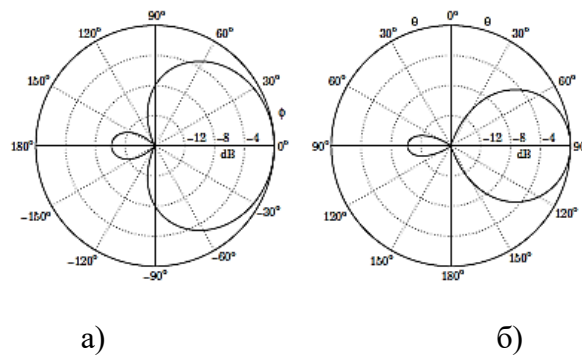
	Directivity patterns of a dipole antenna in the H plane	Directivity patterns of a dipole antenna in the E plane
Directivity pattern in Cartesian coordinates. Distance between antennas 0.8 m.		



Directivity patterns in the E and H plane for all measurements remain close to those theoretically defined for the dipole antenna.

- **Yagi-Uda antenna for frequency 2.45 GHz.**

The theoretical directivity pattern of a two-element Yagi antenna in the H(x,z) and E(x,y) planes in a polar coordinate system is shown in Figure 5.5.

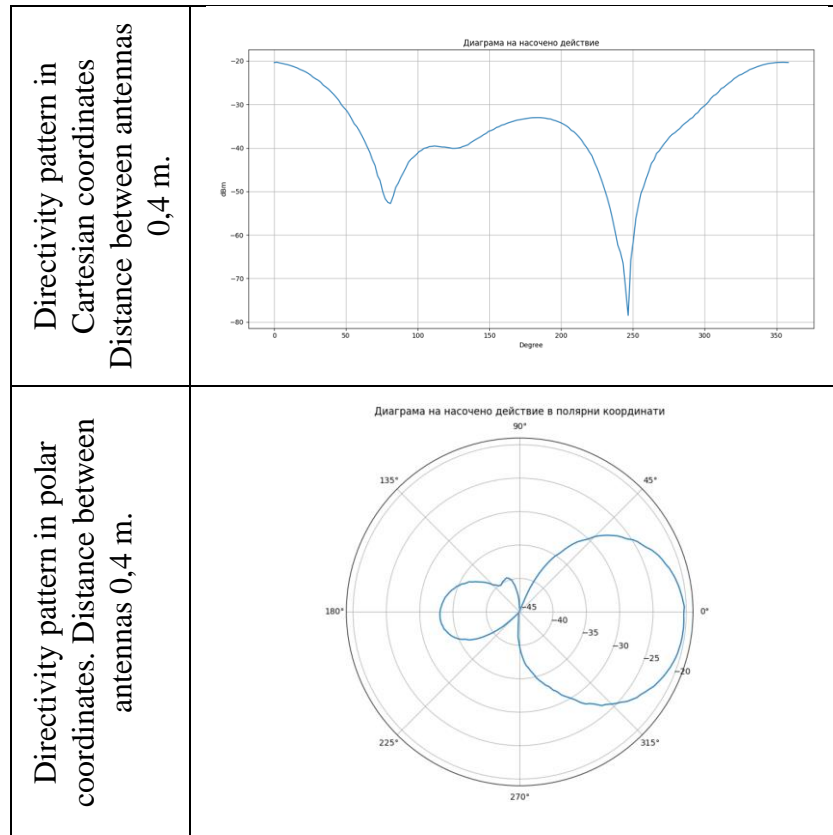


**Figure 5.5 Directivity patterns in a) the H- plane and b) the E- plane of Yagi-Uda antennas**

The resulting directivity patterns in the H plane of a Yagi antenna designed for an operating frequency of 2.45 GHz are shown in Table 5.3. The diagrams for different distances between the receiving and transmitting antennas are presented in Cartesian and polar coordinate systems. The transmitting antenna in this case is a Yagi antenna with the same characteristics.



**Table 5.3 Directivity pattern of a Yagi antenna in the H plane**



Directivity diagrams in the H plane for all measurements remain close to the theoretically defined ones for the Yagi antenna. The studies of the antenna in the E plane are not shown, as they are similar, but with a shifted maximum of the received signal at  $90^0$  according to the radiation theory of the Yagi antenna. The main elements (position of the main maximum and width) of the directivity pattern of the investigated antenna in E plane and H plane respectively for frequency 2.45 GHz are determined.

- **Log-periodic antenna operating in a frequency range 850 – 6500 MHz.**

Using the developed antenna research system, the directivity diagrams in the H plane and the E plane of a log-periodic antenna for frequencies 2.45 GHz and 900 MHz for different distances between the receiving and transmitting antennas were obtained in Cartesian and polar coordinate systems. The transmitting antenna is a Yagi antenna. The main features (position of the main maximum and width) of the directivity pattern of the investigated antenna in the E and H plane respectively for frequency 2.45 GHz are determined. Table 5.4 shows the resulting directivity

diagrams in the H and E planes, respectively, of a log-periodic antenna designed at an operating frequency of 2.45 GHz.

**Table 5.4 Directivity pattern of a log-periodic antenna**

	<i>Directivity pattern of a log-periodic antenna in the H plane</i>	<i>Directivity pattern of a log-periodic antenna in the E plane</i>
Directivity pattern in Cartesian coordinates. Distance between antennas 0.8 m		
Directivity pattern in polar coordinates. Distance between antennas 0.8 m		

## CHAPTER SIX

### Design, manufacture and research of an antenna for 5G

#### 6.1 Antenna design for 5G

In this chapter, for the purposes of the dissertation, a rectangular patch antenna which operates at a resonant frequency of 2.45 GHz was designed. The design of the antenna includes analytical calculation of the geometric dimensions, design of the antenna using the specialized HFSS software, obtaining the directivity diagram, as well as developing a physical prototype. The prototype was tested experimentally for a real evaluation of the properties of the designed antenna with and without filter.

To ensure that its performance meets the desired specifications, designing a patch antenna involves several steps. The main algorithm of the design process includes the following steps: defining the main characteristics of the antenna, choosing the type of patch antenna, calculating the dimensions of the antenna, determining the radiation pattern, making a prototype and testing, optimization, and documentation. The rectangular patch is separated from the ground plane by an FR-4 dielectric pad. The feed line of the proposed antenna is a microstrip transmission line with the impedance of 50  $\Omega$ .

For the purpos of correct design, a known methodology for calculating the main parameters of a patch antenna is applied. Table 6.1 shows the calculated values of the design parameters of the antenna.

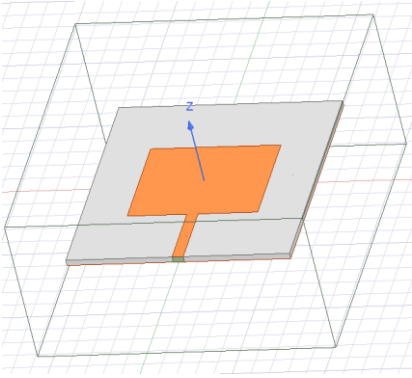
***Table 6.1. Parameters of the designed patch antenna***

Parameters	Values (mm)
h	1.5
Length of the pad	55
Width of the pad	60
Length of the patch element	30.93
Width of the patch element	34.2

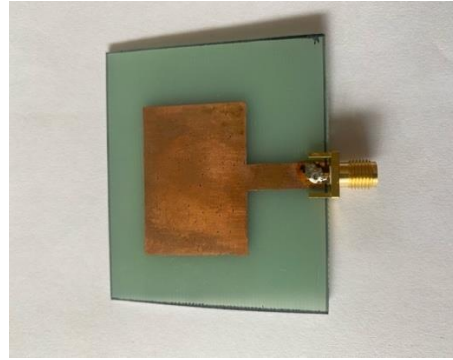
### **6.3 Antenna design and simulation results with the ANSYS HFSS software product**

To design a patch antenna and its characteristics, a 3D electromagnetic field simulator for RF and wireless design Ansys HFSS was used [74].

Figure 6.3 shows the design of the antenna under study obtained using the HFSS software, in which the results of the analytical calculations are embedded.



**Figure 6.3** *The design of the rectangular microstrip antenna, using HFSS software*

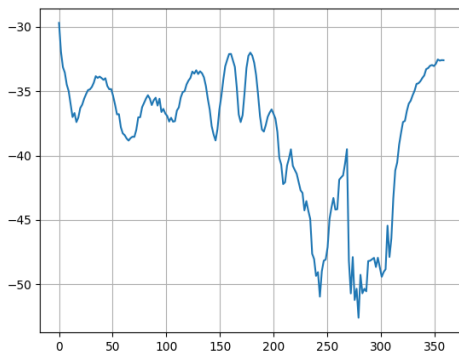


**Figure 6.8** *The manufactured patch antenna*

To verify the obtained performance parameters of the antenna using the HFSS simulation software, a prototype of the designed antenna was created. In the prototype, the design dimensions of the pad and the radiating element are exactly preserved. Figure 6. 8 shows a photograph of the manufactured prototype.

#### **6.4 Measurements and results**

Test measurements on the fabricated antenna for received signal frequency of 2.45 GHz were performed. Measurements are made using the established antenna probe system at 200 steps per stroke (1.80). Figures 6.9 and 6.10 show the directivity diagrams without signal filtering in Cartesian and polar coordinate systems, respectively.



**Figure 6.9** *Radiation pattern without filtering in Cartesian coordinates*



**Figure 6.10.** *Radiation pattern in polar coordinates*

It was found from the experimental measurements of the patch antenna prototype that the designed antenna offers sufficiently good efficiency for the selected resonance frequency and can be used in a wide range of WLAN applications.

## **CONCLUSION**

Based on the analysis of existing approaches for antenna parameter research, focused on mobile applications, a decision was made to develop a prototype antenna research system for 5G. Experiments which were conducted aimed at identifying the main shortcomings of this prototype

Within the dissertation, a special high-frequency rotary connector module which prevents the connection cable from twisting between the rotating antenna and the spectrum analyzer was designed and manufactured.

Customized software for a personal computer that coordinates the actions of the executive mechanisms of the system was created. This software has a user interface for managing measurements and presenting results numerically and graphically. During the measurement, a database of signal power values depending on the angular position of the antenna is created, and a signal filtering algorithm is also built in. In addition, customized firmware for the Arduino Uno microcontroller board which provides control of the stepper motor driver and communication with the PC has been developed.

Different types of 5G antennas were investigated and their directivity diagrams were built. Also, the main parameters of these diagrams corresponding to the known theoretical antenna directivity models were determined.

A patch antenna for 5G was designed and manufactured. Its radiation properties are simulated using the specialized HFSS software and verified using the author's measurement system.

## **CONTRIBUTIONS OF THE DISSERTATION WORK**

### **Scientific and applied contributions:**

1. A critical theoretical analysis of the existing state-of-the-art approaches for studying the parameters of antennas for mobile applications is performed.
2. A working prototype of a 5G antenna study system was created. Experiments were conducted to define the main shortcomings of the prototype. Based on the analysis of the shortcomings of the prototype, structural changes were introduced in some of the main functional units that make up the system. New components are proposed to create the system.
3. A working antenna study system for 5G was designed and manufactured. A customized high-frequency rotary connector module was designed and build, which prevents twisting of the connecting cable between the examined rotary antenna and the spectrum analyzer.
4. Customized software for a personal computer was created, which synchronizes the actions of the executive mechanisms of the system, performs signal filtering, visualizes the obtained results in digital and graphic form (in Cartesian and polar coordinate systems), creates a database of the values of the power of the signal received by the tested antenna depending on its angular position.
5. A specialized firmware was developed for an Arduino Uno development microcontroller board, through which the control of the stepper motor driver and communication with the personal computer is carried out.
6. Various types of 5G antennas were investigated and their directional action diagrams were constructed. The main parameters of these diagrams are determined, which are consistent with the known theoretical directivity models of these antennas.
7. A patch antenna for 5G was designed, fabricated and studied.

## LIST OF PUBLICATIONS ON THE DISSERTATION

1. S. S. Sotirov, N. M. Kafadarova and T. T. Lovchaliev, *Embedded System for Radiation Pattern Measurements of Antennas*. 2022 XXXI International Scientific Conference Electronics (ET), Sozopol, Bulgaria, 2022, pp. 1-4, doi: 10.1109/ET55967.2022.9920288. (Proceeding indexed in Scopus)
2. N. V. Vakrilov and T. T. Lovchaliev. *Design, Fabrication and Measurements of Microstrip Patch Antenna at 2.66 GHz*. 2022 XXXI International Scientific Conference Electronics (ET 2022), Sozopol, Bulgaria. pp. 1-4, doi: 10.1109/ET55967.2022.9920324. (Proceeding indexed in Scopus)
3. N. Kafadarova, T. Lovchaliev, N. Vakrilov, S. Sotirov (2022). *Research of Antennas for the 5G First Frequency Range with Application in Education of Engineering Students*. 9th International Conference on Education & Education of Social Sciences (SOCIOINT 2022). pp. 178-182. ISBN: 978-605-06286-6-1.
4. N. Vakrilov, N. Kafadarova, T. Lovchaliev. 2021. *Teaching 5G principles to students in a pandemic*. Proceedings of ICERI2021 Conference, 2021, pp. 9193-9197. ISBN: 978-84-09-34549-6
5. Tihomir Lovchaliev (2021). *Cellular Mobile Communication Systems – 5G Scenarios and Services*. Scientific works of the Union of Scientists in Bulgaria - Plovdiv. Series C. Technique and technologies. Volume XIX, ISSN: 1311-9419 (Print); ISSN 2534-9384 (Online), 2021. Scientific Works of the Union of Scientists in Bulgaria - Plovdiv. Series C. Technics and Technologies. Vol. XIX, ISSN 131 -9419 (Print); ISSN 2534-9384 (Online), 2021.
6. Tihomir Lovchaliev (2022). *Investigation of Waveguides from Different Materials for 5G Applications*. Scientific works of the Union of Scientists in Bulgaria - Plovdiv. Series B. Technique and technologies. Volume XX, ISSN 1311 -9419 (Print); ISSN 2534-9384 (Online), 2022. Scientific Works of the Union of Scientists in Bulgaria - Plovdiv. Series C. Technics and Technologies. Vol. XX, ISSN 1311 -9419 (Print); ISSN 2534-9384 (Online), 2022.