Design of a Beam-Steerable Antenna Array for 5G Applications Using a 3.7 GHz Butler Matrix

Capstone Report

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Abstract:

Within this project, a passive 4x4 Butler matrix-fed microstrip patch antenna array at 3.7 GHz is presented, simulated, and integrated for fixed-beamforming applications in the 5G mid-band. A single rectangular patch element was initially designed for a return loss of less than -30 dB and a gain of 5.5 dBi. As per this, four-element subarrays were built and optimized to increase impedance matching (S_{11} –36 dB) with limited gain. Then, using microstrip techniques, the Butler matrix was designed and included crossovers, 45° phase shifters, and miniature hybrid couplers. Each of the components' electromagnetic simulations showed good performance: crossovers showed decent isolation (S_{41}<–30 dB) and very minor phase error; phase shifters delivered S_{11}–40 dB with consistent 45° shifts; couplers showed –35 dB reflections, nearly ideal –3.4 dB insertion losses, and correct 90° quadrature. When integrated to the antenna subarrays, the assembled matrix maintained the necessary inter-port phase progression (–43° to –44°). Also, four distinct beam directions for respective input ports were verified through system integration simulations with an overall array gain of 11.7 dBi and efficiency of about 60%. So, the herein-proposed passive beamforming architecture is confirmed to be an energy-efficient and cost-effective solution to multi-beam 5G antenna systems.

Contents

Preface

The increasing need for advanced wireless communication systems, where antennas are key to providing efficient, high-speed connectivity, was the key motivation for this work. Innovative antenna solutions that provide compact, scalable, and outstanding performance are more important than ever as the world prepares for the launch of 5G and beyond.

The high-performance demands of the 5G network, in which efficiency, scalability, and miniaturization are critical, depend heavily on beam-steerable antennas. Through investigating Butler matrix's structure and array topologies for best beam-steering and gain, this project dove into antenna technology research. Through overcoming issues in contemporary communication networks and facilitating the advancement of future wireless technologies like 6G, this research sets the stage for future innovation in 5G antenna design.

Furthermore, the project enables the overall objectives of increasing worldwide connectivity and meeting the growing need for high-quality, high-speed communications systems. Further study and optimization of the submitted designs may result in new antenna scalability and effectiveness innovations, which would greatly advance the next-generation wireless systems.

I would like to express my deepest gratitude to my supervisors, Professor Mohammad Hashmi and Professor Sultangali Arzykulov, for their support, guidance, and professional advice throughout this project. In short, without the intelligent input and guidance of my supervisors, this project would not have been able to move as it stands today. Lastly, I would like to thank Professor Galymzhan Nauryzbayev for his critical feedback, constructive criticism, and overall support whilst this work was being built.

Nazarbayev University, April 24, 2025

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Chapter 1

Introduction

Wireless communications represent a fundamental field for supporting global connectivity, allowing people and devices to communicate free from physical infrastructure constraints, making it indispensable for applications ranging from mobile networks to the Internet of Things (IoT). As the world adopts next-generation technologies like 5G/6G, wireless communication is the foundation of future innovations, promoting efficiency and range across industries. Therefore, this Capstone Project is devoted to one of the essential parts of wireless communications – antennas. More precisely, an antenna array with beam-steering by a 3.7 GHz Butler matrix with reasonable gain and S-parameters is planned for design and fabrication.

The chosen operating frequency of 3.7 GHz is within the 5G mid-band radio spectrum, which offers the best potential trade-off between bandwidth and coverage. It is, thus, best applicable for urban and suburban deployments, with greater signal penetration capabilities compared to higher bands [1]. This is a suitable choice for academic prototyping with less complexity in fabrication and testing, yet still relevant enough to real-world application [2, 3].

Through an extensive literature review, different antenna design techniques were derived. As an outcome, this project employed an array of series-fed configurations of rectangular patch antennas. Every array starts with the design of a single element. It can be described this way: the ground plane is attached to the bottom of a substrate, and the main patch is attached to the top with a microstrip line leading to the input port [4, 5]. This structure will hold as a basis for all followed upgrades to arrays and antenna positioning. Indeed, there are other types of antennas, such as Quasi-Yagi, multi-layered antennas, etc. [6], but they were deemed as out of the scope for this project.

There are different crucial parameters that determine the sustainability of antenna design: s-parameter, z-parameter, efficiency, far-field, beam-steering accuracy, and gain. Improving the latter two characteristics is one of the top priorities of the project. Some antenna designing techniques, aimed at increasing gain, that are worth mentioning: the practice of multi-element antenna designs, introduced a compact MIMO antenna for wideband applications, as well as a MIMO antenna [7, 8]. These designs provided valuable insight into the potential for further optimization of multi-element configurations. Consequently, the idea of converting the single patch into a multiple antenna array was established at this stage.

As it was learnt, beam-steering in antenna arrays can be accomplished using a variety of methods, such as phase shifters, digital beamforming, parasitic arrays, reconfigurable intelligent surfaces (RIS), and passive networks like the Butler matrix [9, 10, 11]. Due to the low active component count, high efficiency, and straightforward structure the a 3.7 GHz Butler matrix was selected for this project. Unlike active beamforming systems, the Butler matrix eliminates the need for complex control circuitry, which significantly reduces its power consumption and cost [12]. Generally, the matrix represents a specific configuration of hybrid couplers, phase shifters, and crossovers to distribute input signals to output ports with fixed phase differences. This way, distinct radiation beams are generated when connected to an antenna array, each corresponding to a particular steering direction [13]. The passive architecture is especially useful for applications that call for multiple fixed beams without active phase control, making it preferable to digital/analog beamforming techniques. Thus, the main benefits matrix provides: lower insertion loss, lower power consumption, and easier implementation using common microwave components [14]. Despite its advantages, the Butler matrix also presents several challenges that must be addressed during the design and implementation phases. Firstly, even the smallest mismatches can degrade beam-steering performance and disrupt phase and amplitude balance across all signal paths [15, 16]. Secondly, with more ports, the Butler matrix's physical layout gets more complicated, which could result in larger circuit dimensions and possible transmission line coupling [17, 18]. That is why these constraints require careful electromagnetic simulation and optimization to ensure reliable operation and desired beam coverage. Several of design techniques can be used to mitigate the challenges involved with implementing the Butler matrix. The first step in guaranteeing exact phase and amplitude balance is to accurately model each component, including phase shifters and hybrid couplers, using electromagnetic simulation tools such as Advanced Design System (ADS) by Keysight. Then, maintaining the intended phase relationships and minimizing mismatch are made possible by strict control over fabrication tolerances, particularly substrate permittivity, line widths, and spacing [19]. As for more conceptual approaches, a symmetrical and small PCB layout can be used to reduce crosstalk and fight layout complexity [20]. Otherwise, methods like well-isolated microstrip lines or grounded coplanar waveguides can also aid in reducing mutual coupling [21]. However, in this work's case, the mismatches were eliminated through the implementation of curved transmission lines (tracks), allowing for preserving relatively compact dimensions and adjusting the phase difference of around 45°between the ports. So, in the frameworks of this project, a 4×4 Butler matrix was designed and implemented at 3.7 GHz to feed a patch antenna array, achieving accurate, reliable beam-steering.

1.1 Ethical and Professional Responsibilities

- **Ethical Responsibility:**
  Actually, there are a number of ethical concerns to be addressed while designing the beam-steerable antenna array for 5G systems. Specifically, privacy and safety concerns. Additionally, wireless communication systems using higher frequencies have risks about radiation exposure. Although the broad 5G band (3.3 – 3.8 GHz) has poor penetration by the human body, the likelihood of exposure to this technology over a long period in urban cities necessitates scrupulous research to ensure that standards of safety are met. Beyond doubt, the project must be guided by rules of international safety guidelines such that limits of exposure to electromagnetic radiation are maintained in order to conserve public health.

  Ethical responsibilities also involve making the technology accessible and inclusive. So, this literally means designing the antenna in a way that it is adoptable by different categories of users, ranging from urban telecommunications carriers to rural communities. Therefore, making an effort to ensure that the technology is accessible to all social groups regardless of their location or economic ability is most important in preventing the creation of a technology divide. In addition, there is an ethical consideration in the environmental dimension, where the materials employed and the energy consumed by the antenna system must be environmentally friendly (sustainable).

  Another ethical aspect is transparency and decision-making is crucial: full disclosure of the design, testing procedures, and potential risks must be provided to independent evaluators. Addressing these issues responsibly involves adhering to the principles of ethical engineering, ensuring that the technology is deployed safely and that its benefits do not compromise public well-being. It is believed that throughout the development, clear communication with users about possible risks and the responsible use of the antenna system will uphold ethical standards.

- **Informed Judgments:**
  Undoubtedly, throughout the project, well-informed decisions must be made via combining technical expertise and societal considerations. Obviously, literature reviews on 5G technologies and antenna designs will guide the development process. For instance, the decision to use Butler matrix arises from their ability to enhance beam-steering accuracy, as documented in various studies mentioned above. However, potential challenges, such as the increased complexity of design and higher manufacturing costs, will be weighed against these benefits.

  In fact, societal aspects are of the utmost priority. Through the incorporation of knowledge from health and environmental experts, the design will be simulated as efficient and safe for public consumption. Moreover, in an effort to demonstrate the flexibility of the design to various locations and user demands, scalability and accessibility of the project must be taken into consideration.

Not to forget, that ethical considerations also play a role in making informed decisions. In other words, it must be emphasized that technology is transparent and its deployment does not exacerbate the digital divide. Hence, both urban and rural application scenarios and low-income communities are not excluded from accessing advanced communication networks. Truly, balancing technical innovation with societal responsibility will be crucial in the decision-making process.

Last but not least, the documentation and testing play an important role in informed judgment. IN other words, through scrupulous documentation of each design iteration, potential challenges, and their resolutions, traceability and accountability is promised. Of course, this practice will not only enhance the project's credibility but also provide valuable insights for future developments.

- **Global Context:**
  Since wireless communications are worldwide, the 5G antenna array has repercussions far beyond the local frameworks. It forms the core of international connectivity, and the project can be applied to other regions of the world with varying difficulties in the deployment of 5G and 6G networks. For example, the compact and scalable nature of the antenna array can be applied to both urban cities in developed nations and rural villages in developing countries.

  Besides, 5G technology is of critical significance in addressing global challenges such as the increasing demand for high-speed communication in densely populated areas. The improved data rates supported by 5G antennas allow for global innovations such as smart cities, IoT devices, and self-driving cars, so the design of this project serves as one of many stepping stones for future technologies.

  Apart from that, different regulatory environments across the globe must also be considered. Since nations have different spectrum allocation policies, some of which restrict or heavily regulate certain frequency bands. Therefore, the design must be flexible enough to support those regional variations, and facilitate antenna's effective use in any market.

  Worth mentioning: the project also holds potential for advancing global sustainability initiatives. By using energy-efficient components and reducing the environmental footprint of communication infrastructure, the antenna design can contribute to reducing global energy consumption, a key goal in international sustainability efforts. Thus, this global perspective makes the project not just a technical solution but a socially responsible one, addressing challenges that transcend borders.

- **Economic Impact:**
  As for the economic impact of the project – it has both short-term and long-term expectations. In the short term, the development of the 5G antenna array requires significant investment in design, testing, and manufacturing. Also, the choice to use Butler matrix induces that the project remains cost-effective by improving performance without adding unnecessary complexity. This approach helps minimize initial production costs and makes the design more affordable for industries in telecommunications and IoT device manufacturers.

  Regarding the long-term aspect, the antenna's ability to enhance beam-steering accuracy and optimize frequency usage will reduce the infrastructure needs of 5G and 6G networks. So, by improving spectrum efficiency, the project can help reduce the number of base stations required, ultimately lowering network deployment and maintenance costs.

  On the other hand, there are potential challenges to consider as well. For instance, the high-frequency nature of 5G technology requires precision in manufacturing, which may require more precise and expensive facilities (leading to an increase in production costs). Furthermore, global economic fluctuations, such as changes in material prices or labor costs, could affect the overall affordability of the antenna array. Addressing these risks requires careful planning and partnerships with manufacturers to keep production costs manageable.

  Overall, the long-term economic impact of the project is linked to its sustainability. Simply put, by designing an energy-efficient antenna operational costs over time will be reduced. This is crucial in industries where energy consumption is a significant part of operating expenses, such as in large-scale wireless networks. As a result, the design contributes to not only short-term cost savings but also long-term economic planning, making it a competitive solution for various markets.

- **Environmental Impact:**
  Frankly, the environmental impact of the project primarily revolves around resource efficiency, energy consumption, and material sustainability. The use of effective Butler matrix design leads to a reduction in the power required for signal transmission, thereby lowering the overall energy consumption of

wireless communication systems, which is particularly important in cities.

Besides, the choice of materials used in the antenna's construction plays a vital role in minimizing its environmental footprint. Indeed, the selection of eco-friendly materials and reducing the size and weight of the antenna would allow the project to limit resource use and reduce the environmental impact of manufacturing. Since, the compact and scalable nature of the design requires fewer materials compared to larger, more complex antenna systems.

Moreover, the reduction in infrastructure requirements due to enhanced beam-steering accuracy has a positive environmental impact too: fewer base stations will be needed to cover the same area, which reduces the need for extensive physical infrastructure, thus lowering land use and minimizing disruption to natural ecosystems. Certainly, this is particularly important for a countryside or sensitive environmental areas where large-scale construction could cause ecological damage.

Energy efficiency is another key consideration. Because of focusing on reducing signal loss and improving the antenna's operational performance, the project contributes to minimizing the energy required to operate 5G/6G networks. Thus, this aligns with the aforementioned global sustainability goals, such as reducing greenhouse gas emissions and energy consumption in the telecommunications sector, which is known for its high energy demands.

Generally, the project's design must also consider the end-of-life disposal of the antenna components. If the materials used are recyclable or biodegradable this can significantly reduce the environmental impact of discarded antennas. Doubtlessly, implementing a design that promotes easy recycling or reuse of materials contributes to the circular economy, minimizing waste and promoting healthier product life cycles.

- **Societal Impact:**
  In terms of enhancing communication networks and improving access to advanced technology, the societal impact of the 5G antenna array project is profound. It would not be an overstatement to say that this project has the potential to provide faster, more reliable internet services to users, from urban professionals to rural communities with the help of improving the efficiency of wireless networks.

  Specially, the project can help bridge the digital divide by making high-speed communication networks more accessible to underserved areas. Communities out of bigger cities often lack the infrastructure for reliable internet, limiting their access to resources, such as education and economic opportunities. That is why developing a cost-effective and scalable antenna solution is necessary, consequently allowing this project to contribute to expanding network coverage in these areas, and improving social and economic inclusion.

Furthermore, the societal impact extends to the enhancement of public services. As an example, governments and institutions could leverage improved wireless networks for smart city initiatives, public safety, and emergency response systems. With reliable high-speed communications, populated areas can manage infrastructure more efficiently, respond faster to emergency events, and enhance the quality of life for their residents.

It has to be acknowledged that the antenna structure also has the potential to foster innovation and economic growth. Most definitely, the antenna array can enable new industries and technological advancements that rely on fast, reliable wireless communication due to providing the necessary infrastructure for technologies like the Internet of Things (IoT), smart grids, and autonomous vehicles. That being so new job positions and markets will emerge, bringing widespread benefits to society.

Chapter 2

Methodology

2.1 Choice of Materials

The choice of materials plays a pivotal role in achieving the desired performance and reliability for the designed antennas and Butler matrix. For this project, Rogers RO4003C was selected as the substrate material due to its moderate dielectric constant of approximately 3.55, which supports efficient signal propagation at given frequency. As for the substrate's thickness, 1.52 mm is enough to balance between mechanical stability and minimized substrate losses. Meanwhile, the patch and ground plane are made of copper with a thickness of 0.017 mm, the choice was made in favour of its superior electrical conductivity, which reduces resistive losses and enhances antenna efficiency. Altogether, these materials support the high-frequency and precise performance requirements of 5G applications.

2.2 Antenna Design

2.2.1 Antenna Geometry

A suitable antenna array must be developed to evaluate and optimize beam-steering capabilities. The first step in this process is to design a single-element rectangular patch antenna.

The next step would be to upscale the latter antenna configuration to a series of 4 rectangular antennas. Theoretically, the series should consist of 2 antennas of original design in the center and 2 smaller versions on their sides. The dimensions of the smaller ones can be determined through optimization in ADS.

The final stage of antenna development included the creation of an antenna array based on the mentioned patch series. Since the antennas are placed parallel to each other, the only variable parameter is the distance between antenna series. The ADS optimization tool has proven to be a great tool for finding said distance.

2.2.2 Antenna Characteristics

The methodology aimed to identify an optimized design that meets the performance requirements for modern 5G applications. Thus, throughout the design and simulating process for the antenna, significant focus was placed on several critical parameters:

- S_{11}: Ensuring a satisfactory reflection coefficient (S_{11} < -25 dB) at the target frequency of 3.7 GHz was prioritized to guarantee effective impedance matching and minimal power loss.
- Gain: Maximizing the antenna's gain was critical to improving signal strength and achieving directional radiation patterns suitable for 5G communication.
- Efficiency: High radiation efficiency was targeted to minimize power losses.
- Beam-Forming: The ability of the antenna to direct energy in specific directions was evaluated using array configurations and parasitic elements, optimizing the design for practical beam-steering applications.
- Beam-Steering: The precision of beam-steering was assessed by observing the shift in the main lobe direction in response to excitation of different ports of the Butler matrix. This analysis informed design improvements to achieve better control over beam direction without increasing complexity.

2.3 Butler Matrix Design

Designing the Butler matrix is relatively more intricate than a simple rectangular patch antenna, since it consists of more components and more sensitive to sight changes in geometry.

2.3.1 Matrix Components Development

- Designing a designated 90°hybrid coupler operating at 3.7 GHz. Main characteristics include the S_{11} less than -30 dB and 90° phase difference between output ports;
- Designing a designated 3.7 GHz crossover with S_{11} less than -30 dB, no phase difference between output ports, and it has to be able to transfer signal from the input to the output;
- Develop a phase shifter that will have a phase difference of 45°and S_{11} of around -40 dB, when transporting the signal;

2.3.2 Structure Assembly

The created components are assembled into a Butler matrix. Since the end result was required to have -45° between adjacent ports, all inaccuracies were eliminated after optimization. However, in order to match the inputs of the antenna array, additional transmission lines were added to the outputs of the structure.

2.3.3 Fabrication

In order to verify the performance of the final Butler matrix design, it was fabricated. The S-parameters and phase differences were measured with a Vector Network Analyzer.

2.4 Phased Antenna Array

After the two main parts of the project were ready, the antenna array and the Butler matrix, they could be connected together. The final structure is a phased antenna array beam-steerable with a 3.7 GHz Butler matrix, that is capable of providing 4 distinguishable radiation beams with -45° phase difference. The performance of the whole assembled structure was simulated and verified in ADS.

Overall, in case of 5G base stations, satellite terminals, or radar systems, this beam-steerable array can be used for dynamic coverage adaptation. In multi-path environments, it improves signal reliability, capacity, and interference mitigation by electronically shifting beams without the need for mechanical movement. Meanwhile, before physical testing, the ADS validation ensures that the design satisfies real-world performance benchmarks. Future research could include integration with control algorithms for real-time beam tracking and measured pattern validation in anechoic chambers.

Chapter 3

Results and Discussions

3.1 Results

3.1.1 Single Element Rectangular Patch Antenna

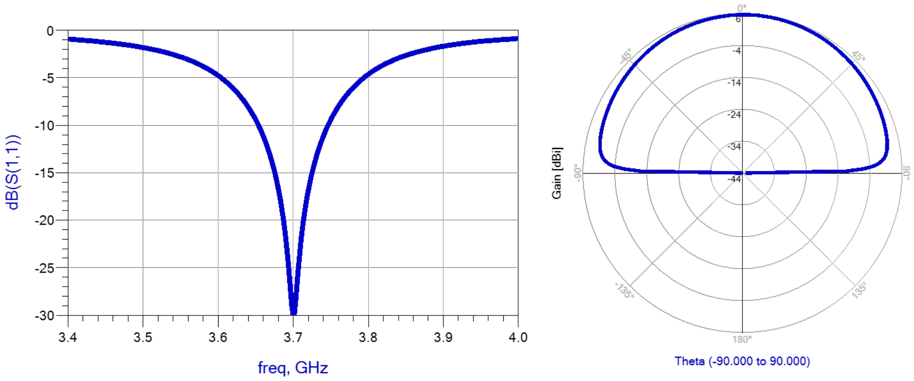
Figure 3.1 shows a basic rectangular microstrip patch antenna, characterized by a flat, planar copper patch mounted above a ground plane, separated by a dielectric substrate. Also, the patch is centrally fed by a microstrip line, indicating a common feeding technique designed to provide good impedance matching. The width of the rectangular patch is 35.1963 mm, and the length is 20.6179 mm. Meanwhile, the dimensions of the feeding line are 1.71033 mm by 10.2124mm. This type of antenna is widely used in wireless communication systems due to its low profile and ease of fabrication, but this one is specifically designed for this project.

Simulation of this single-element antenna exhibited a return loss achieved a value of nearly -30 dB, indicating excellent impedance matching. This result signifies minimal power reflection at the feed point, ensuring efficient energy transfer to the antenna structure. Figure 3.2 (a) illustrates the S_{11} plot. As for the radiation efficiency, it was measured at 0.716 (71.6%) of the input power was effectively radiated as electromagnetic waves, while the remainder was lost due to material and other inherent inefficiencies. The far-field gain pattern, as shown in 3.2 (b), highlights a directional radiation beam with a distinct main lobe directed at 0° and overall achieved a gain of 5.5 dBi, which is a decent reading for this design.

3.1.2 Series of Rectangular Patch Antennas

In the next step, the single-element antenna was upscaled to 4-element antennas in series, where the 2 single-elements are placed in the center and other two smaller patches are positioned to the sides. he track connecting the elements is 5.23443 mm in length and 1.15278 mm in width, while the input port length is 4.7216 mm, as

Figure 3.1: Rectangular patch antenna structure.



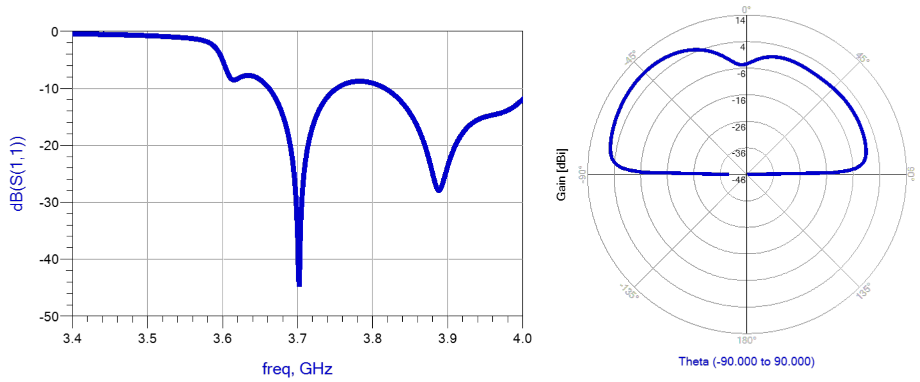
(a) (b)

Figure 3.2: (a) S_{11} of rectangular patch antenna, (b) Rectangular patch antenna far-field gain at 3.7 GHz.

shown in Figure 3.3 The small patches have dimensions of 19.1575 mm by 21.4548 mm.

Figure 3.3: Series antenna structure.

The simulation revealed that a patch antenna series has improved S_{11} of around -36 dB (Figure 3.4 (a)). However, the gain slightly deteriorated as it can be observed from Figure 3.4 (b), but it was compensated during further development into an array.



(a) (b)

Figure 3.4: (a) S_{11} of rectangular antenna series, (b) Antenna series far-field gain at 3.7 GHz.

3.1.3 Antenna Array

For the antenna array, 4 antenna series were placed in parallel to each other, like in Figure 3.5 The distance of 48.5 mm between the series was selected for the sake of optimal S-parameters and gain, as Figure 3.6 illustrates.

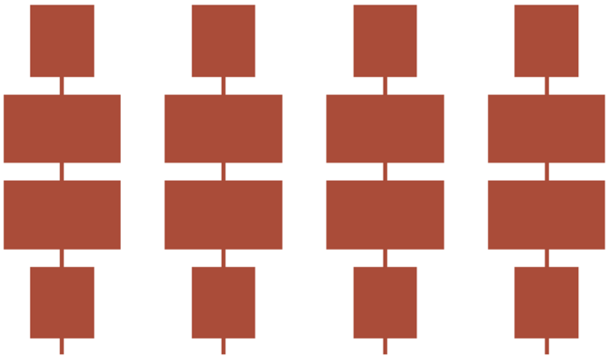
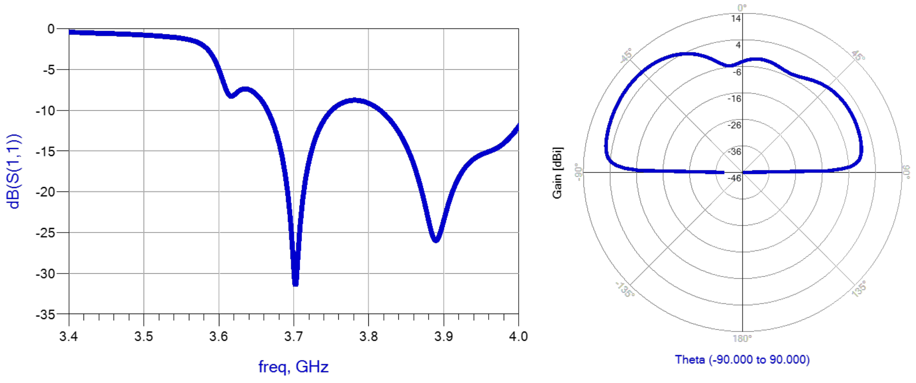


Figure 3.5: Antenna array layout.

3.1.4 Butler Matrix Components

3 main components are required to design the Butler matrix: hybrid couplers, crossovers and phase shifters. So, the Figure 3.5 shows a 3.7 GHz microstrip-based hybrid coupler with dimensions, featuring a symmetric square ring structure with



(a) (b)

Figure 3.6: (a) S_{11} of antenna array, (b) Antenna array far-field gain at 3.7 GHz.

four ports extending outward, allowing for equal power splitting and a 90° phase difference between output ports. Overall, a compact layout optimized for good isolation and impedance matching is suggested.

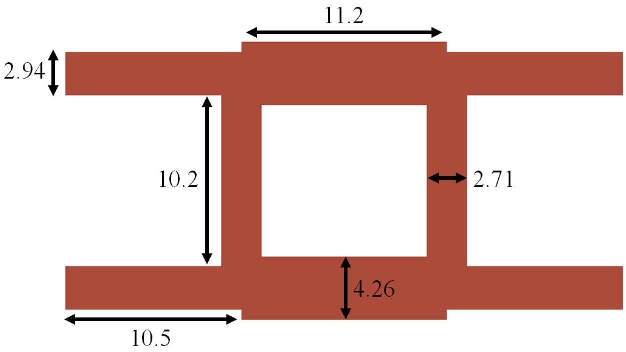
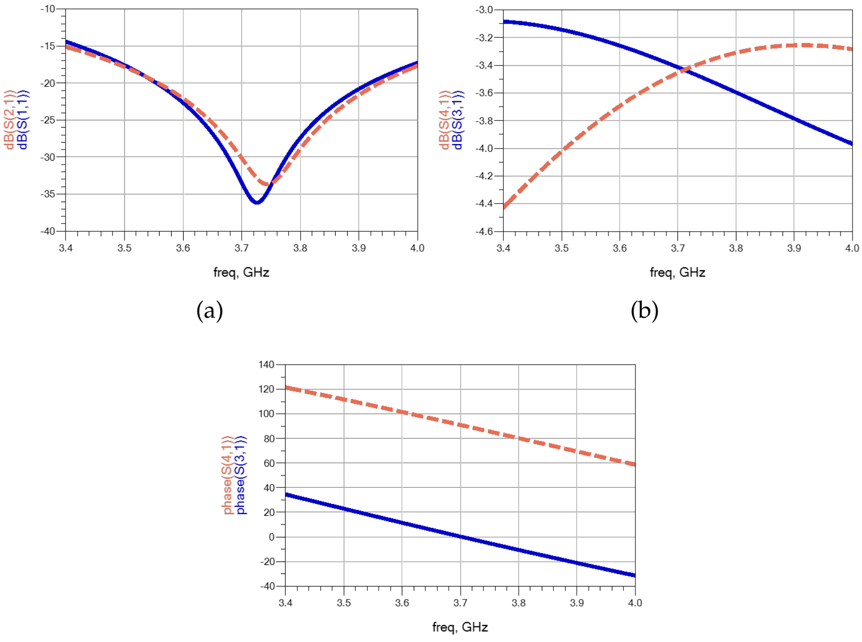


Figure 3.7: Quadrature hybrid coupler with dimensions in mm.

The optimized hybrid coupler demonstrated excellent performance metrics during simulation. It achieved a very low reflection coefficient of approximately -35 dB at the design frequency, indicating minimal power is reflected back to the input port. This confirms good impedance matching. In addition, the power division between the two output ports was nearly ideal, with insertion losses just under -3.4 dB at each port, which means that the input power is almost evenly split. The coupler's functionality as a quadrature hybrid is validated, since the phase difference between the two output ports was exactly 90°. Refer to Figure 3.8

After the coupler, the crossover was designed. Refer to Figure 3.9 for its dimensions and structure. This component plays the role of the bridge, routing the signal between the transmission lines with minimum coupling.



(a) (b)

(c)

Figure 3.8: (a) S_{11} of the coupler, (b) power division at output ports of the coupler, (c) phase difference between output ports of the coupler.

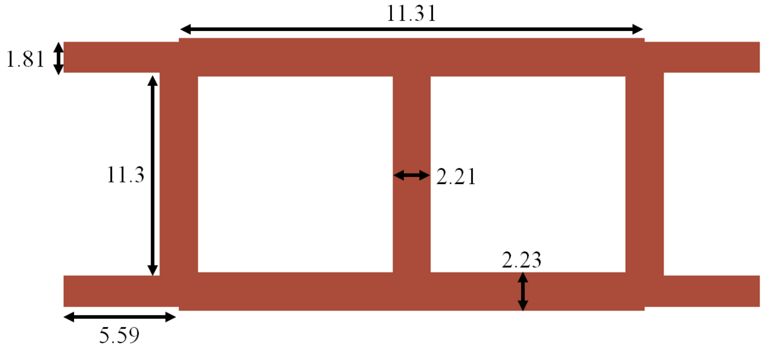
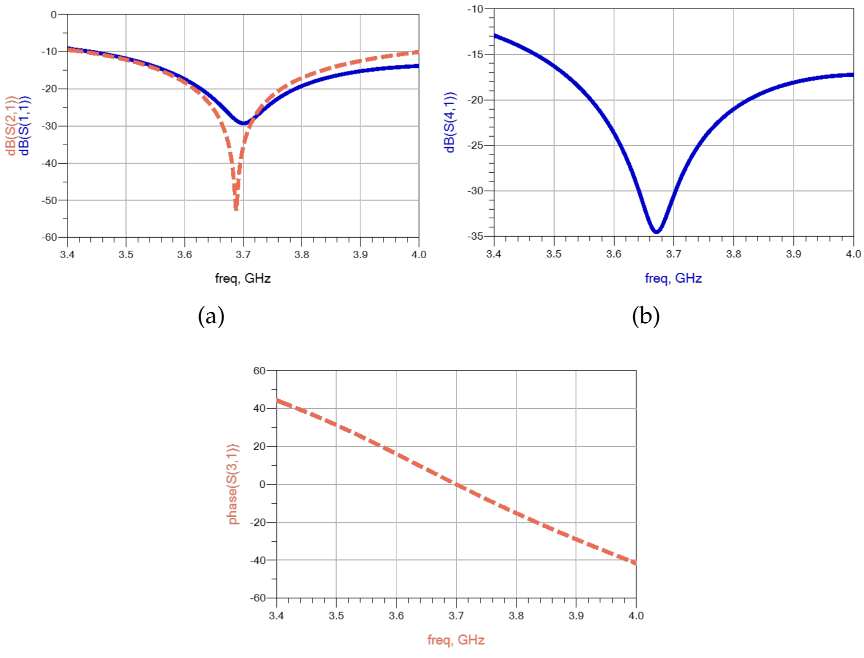


Figure 3.9: Crossover design with dimensions in mm.

In this case, the crossover demonstrated a relatively low reflection coefficient, indicating that only a small portion of the incident signal is reflected. So, the desirable characteristic is that it ensures efficient signal transmission is achieved. Furthermore, the majority of the input signal is successfully transmitted across the structure to the opposite port, which is proved by low S_{41} (-30 dB) - a sign of strong isolation between non-adjacent ports. For crossover to work properly, it has to have 0 phase difference, which is the case according to Figure 3.10 (c).



(a) (b)

(c)

Figure 3.10: (a) S_{11} of the crossover, (b) S_{41} of the crossover, (c) phase difference between output ports of the crossover.

For the Butler matrix, the phase shifter was the final crucial component to create. So, a distinctive, hoof-shaped transmission line was optimized to provide an exact 45° phase shift at the output port. The variant used for this project is depicted in Figure 3.11; all dimensions are in mm.

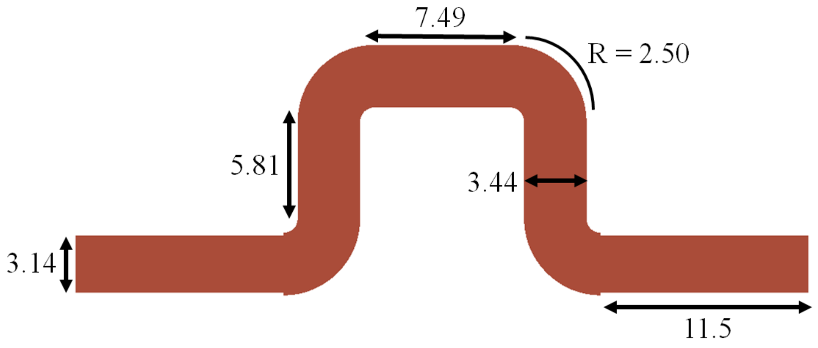
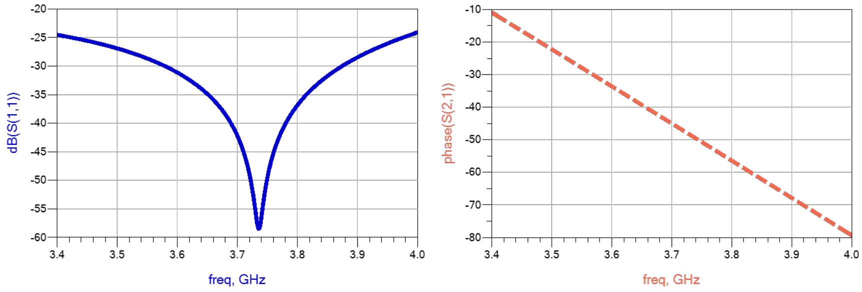


Figure 3.11: Phase shifter design with dimensions in mm.

The design was validated by ADS simulations. With a return loss (S_{11}) of -40 dB, which indicates effective impedance matching and minimal signal reflection, as well as a constant 45° phase shift at the output across the operational bandwidth. Overall, the project's requirements are satisfied. The S-parameter magnitude response and phase characteristics over the frequency range of interest are included in Figure 3.12



(a) (b)

Figure 3.12: (a) S_{11} of the phase shifter, (b) phase difference of the phase shifter.

3.1.5 Butler Matrix Performance

In the next stage of the project, the Butler matrix was assembled using the previously designed components. The layout was carefully planned to ensure optimal signal integrity with the positioning of each component being introduced in Figure 3.13 Thus, the consistent phase relationships across the matrix's output ports were maintained.

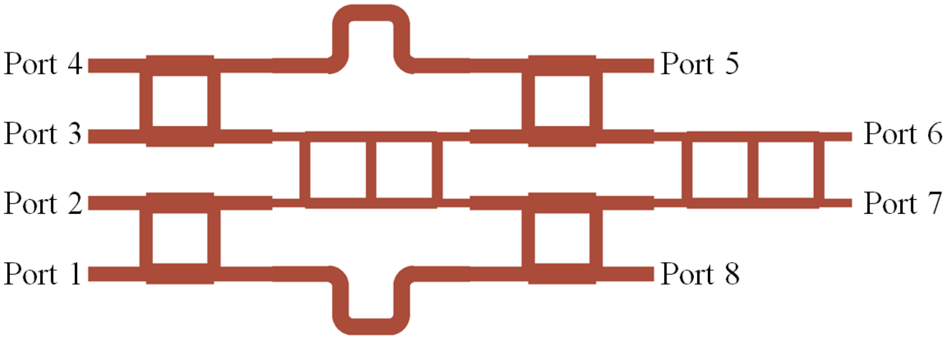


Figure 3.13: Initial Butler matrix layout.

The assembled Butler matrix confirms the correct functioning of its component parts by supplying the necessary -45° phase difference between its output ports, as shown in Figure 3.14 However, extra transmission tracks must be put in place to link the Butler matrix outputs to the appropriate antenna array elements in order to create a full beamforming system.

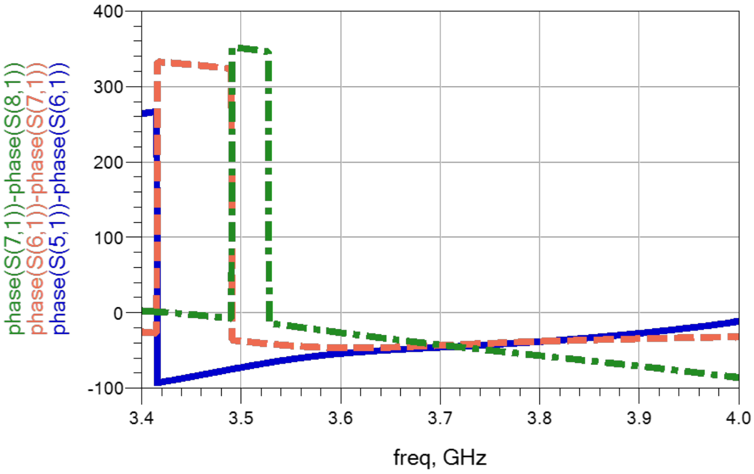


Figure 3.14: Initial phase differences between outputs.

When implementing additional transmission lines, the challenge of acquiring the original phase difference emerges. After multiple simulation iterations and design changes,the efficient linking structure was developed. It is illustrated in Figure 3.15 with the corresponding dimensions in mm.

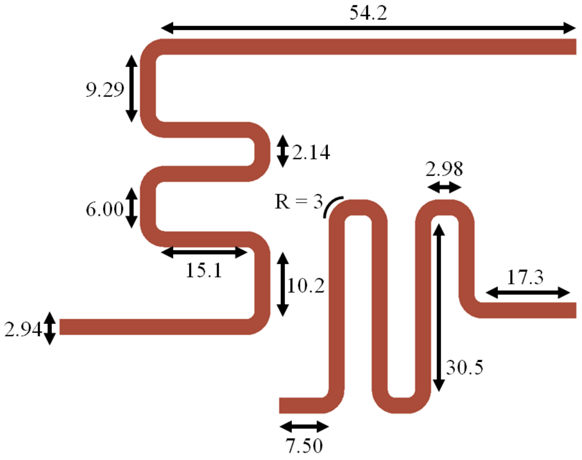


Figure 3.15: Linking structure between Butler matrix and antenna array with dimensions in mm.

Thus, the final Butler matrix design with linking system is presented in Figure 3.16 below. As it is apparent from Figure 3.17 the phase difference between output ports was preserved at around -45°, and S-parameters indicated that the power from each input port is being evenly split among the four output ports (all around -8 dB). Specifically, the phase difference between ports 5 and 6 is -43.089°, between

6 and 7 is -42.244°, and between 7 and 8 is -44.474°.

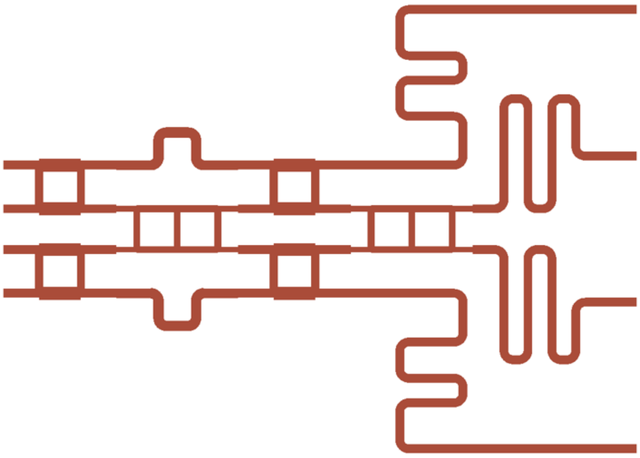
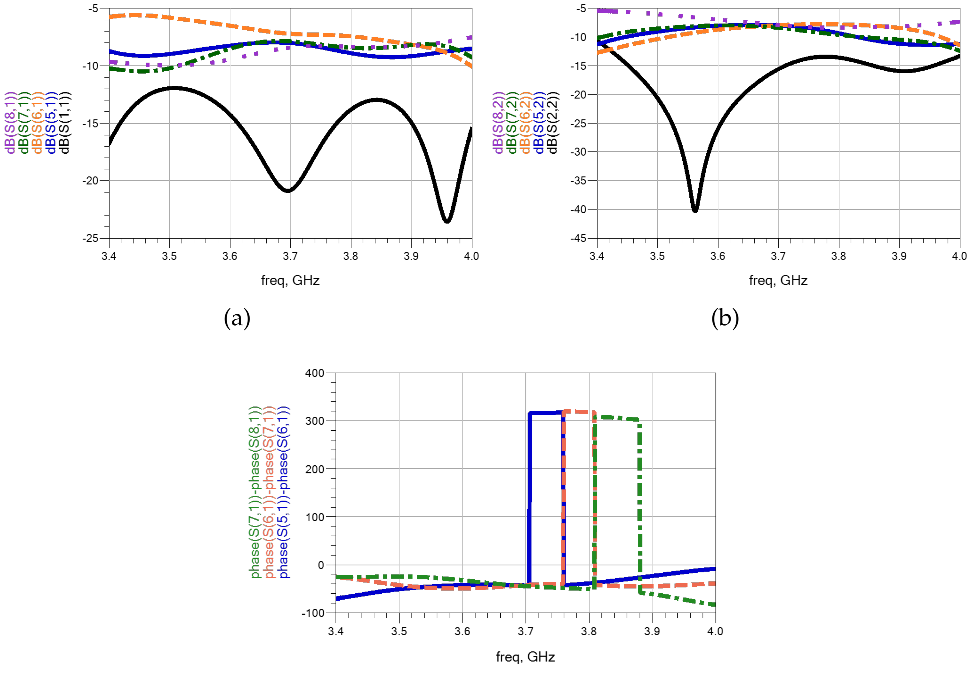


Figure 3.16: Butler matrix layout with linking structure.



(a)

(b)

(c)

Figure 3.17: (a) Port 1 excitation simulation, (b) port 2 excitation simulation, (c) phase differences between outputs with linking structure.

The designed Butler matrix was fabricated and the prototype is shown in Figure

3.18 Also, as shown in Figure 3.19, the manufactured prototype was linked to a Vector Network Analyzer (VNA) in order to experimentally verify the matrix's operation. Phase differences on the outputs across the target frequency range were measured using the VNA. So, the Butler matrix's s-parameters were presented in Figure 3.20.

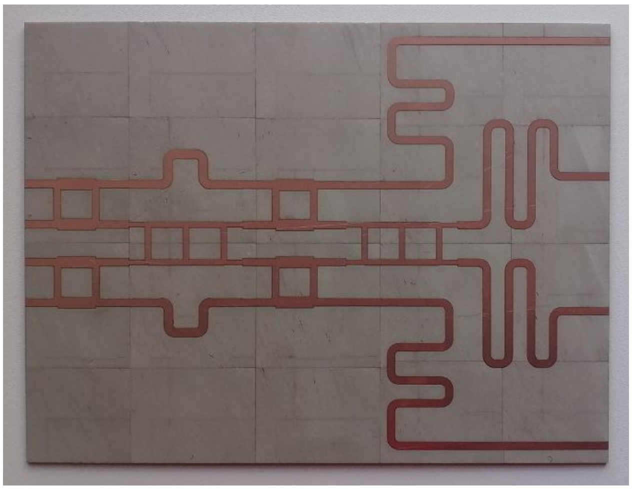


Figure 3.18: Real-life Butler matrix model.

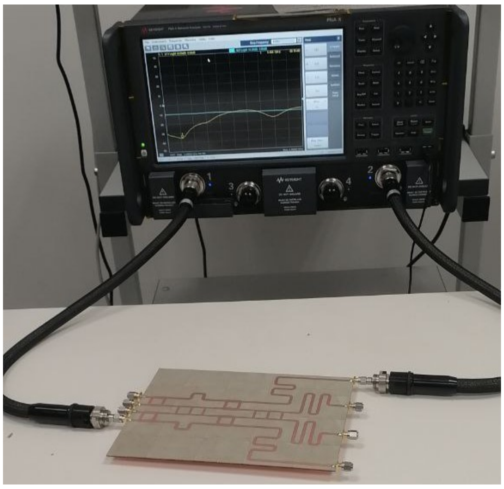
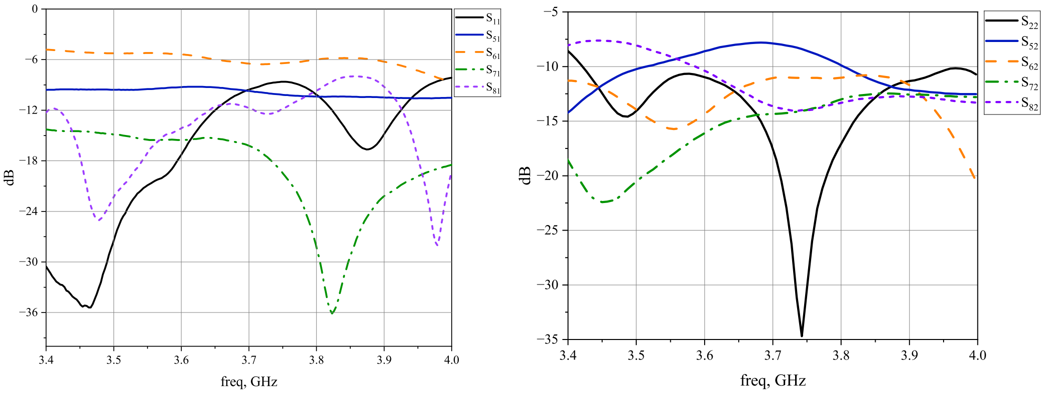


Figure 3.19: Setup of Butler matrix connected to VNA.

As it is evident form comparing the theoretical and practical parts, the soldering flaws, connector mismatches, and realistic fabrication tolerances could have been the causes of mismatches between the measured and simulated results; Though, the practical S-parameters had greater results range (from -6 dB to -17 dB for port 1, and from -8 dB to -15 dB for port 2) the overall pattern of theoretical results is repeated. The only drastic outliers are S_{11} (-35.9 dB) that drifted to around 3.46 GHz, and S_{22} (-34.9 dB) that is now around 3.74 GHz. Nonetheless, the acquired results are still within the range of 5G frequencies, which confirms the design's suitability for beamforming applications.



(a) (b)

Figure 3.20: (a) VNA readings when port 1 is excited, (b) VNA readings when port 2 is excited.

There are also mismatches in phase differences between output ports. Compared with theoretical values, the needed phase difference between ports 5 and 6 occurs at 3.44 GHz, 6 and 7 at 3.82 GHz, and 7 and 8 at 3.72 GHz.

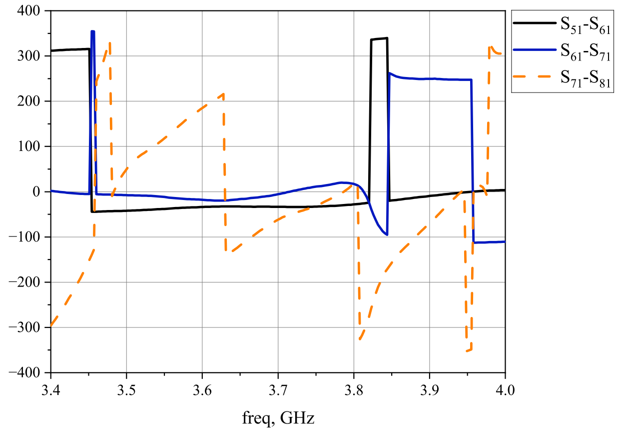


Figure 3.21: VNA phase difference readings.

3.1.6 Phased Antenna Array Simulation

After the separate Butler matrix was successfully validated, the next step was to simulate its integration with an antenna array in order to test the system's overall beamforming/beam-steering capability. Only ADS simulation results are shown in this subsection due to equipment limitations, specifically the lack of appropriate measurement tools for low-frequency antenna arrays.

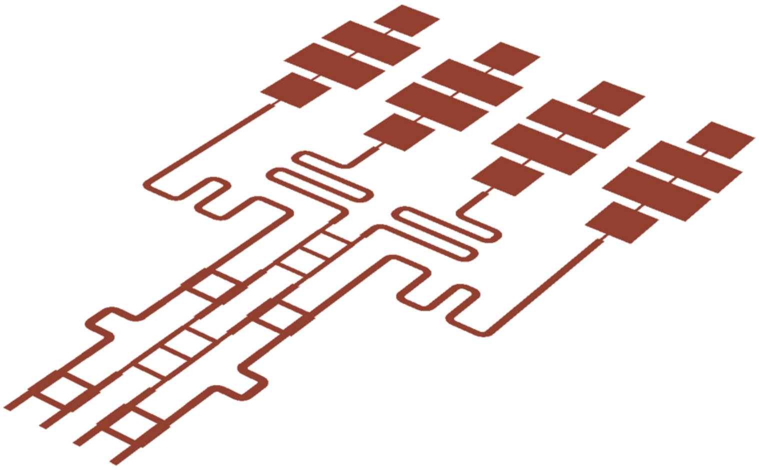


Figure 3.22: Assembled beam-steerable antenna array with integrated Butler matrix.

The general layout of the integrated system is laid out in Figure 3.22, where a four-element microstrip patch antenna array is connected to the outputs of the Butler matrix. Realistic substrate parameters were taken into consideration when simulating the system. Meanwhile, Figure 3.23 presents the surface current distribution at one of the excitation ports, where power routes through the matrix and into the antenna elements were highlighted.

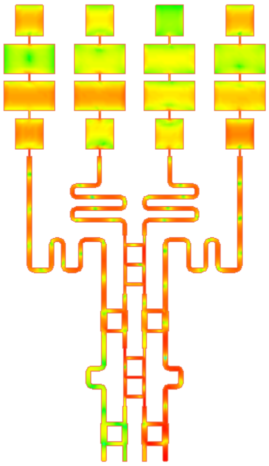
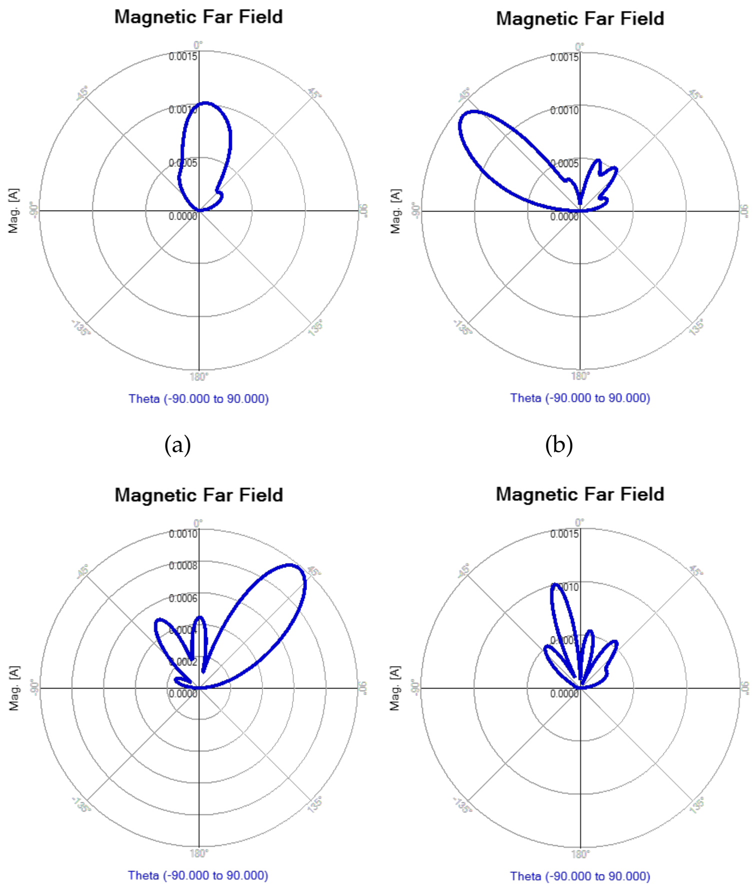


Figure 3.23: Surface current distribution of the phased array.

In Figure 3.24, the far-field radiation patterns for four distinct Butler matrix input ports are displayed. The array shows beam steering when each input port is excited separately. The results confirm that the structure allows for angular diversity for antenna applications and closely match theoretical expectations for a 4x4 Butler matrix. Other simulation outcomes include gain of 11.7 dBi, and around 60% efficiency.



(a)

(b)

(c)

(d)

Figure 3.24: (a) Port 1 is excited, (b) Port 2 is excited, (c) Port 3 is excited, (d) Port 4 is excited

3.2 Discussions

Overall, the development of a 4×4 Butler matrix driven microstrip patch antenna array at 3.7 GHz offers interesting insights into passive beamforming for 5G mid-band applications. Below, the project's outcomes are contextualized within existing research. Also, implementation challenges and wider implications for future 5G systems were addressed.

First off, the single-element patch antenna performed satisfactorily meeting theoretical predictions for microstrip designs at 3.7 GHz with a radiation efficiency of 71.6% and a return loss of -30 dB. Scaling to a 4-element series configuration, however, came with a trade-off: the gain somewhat dropped while the return loss improved to -36 dB as a result of improved impedance matching. Though, the final 4x4 parallel array's gain compensation (11.7 dBi) emphasizes how crucial it is to maximize layout symmetry and inter-element spacing (48.5 mm). This draws attention to a crucial design principle: array performance is not solely dependent on individual element quality but also on strategic positioning to balance coupling and gain.

Secondly, the accuracy of the Butler matrix's phase shifters, crossovers, and hybrid couplers determines how well it operates. In addition, electromagnetic simulations (ADS) were used for estimating coupling, and the crossover's isolation (-30 dB) and nearly zero phase error further confirmed its design and ensured low signal deterioration. Notably, the hoof-shaped phase shifter achieved a precise 45° shift with a return loss of -40 dB. Minor differences between the simulated and measured phase differences (-43.089° vs. -45°) nevertheless point out how susceptible passive systems are to manufacturing tolerances. Although these variations are controllable in fixed-beam applications, they may restrict performance in systems that need sub-degree phase accuracy.

The comparison of experimental and theoretical results reveals considerable discrepancies, which can be attributed to soldering imperfections, connector mismatches, and the natural fabrication tolerances. Despite these real-world limitations, the measured S-parameters still tend to exhibit the overall pattern observed in simulations. For instance, the signal distribution behavior, as anticipated, was preserved. The highest deviations were experienced in the return losses. These movements are suggestive of potential mismatch or detuning effects. Furthermore, the phase differences between consecutive output ports weren't precisely equal to theoretical expectations, indicating the dispersive nature of the matrix. Nonetheless, all critical parameters fall within the defined 5G frequency band, verifying design practicability for beamforming applications despite minor practical deviations.

This design operated at 3.7 GHz, placing it in the 5G mid-band spectrum, which sets a balance between bandwidth and coverage. In addition, the spatial multiplexing is boosted by the demonstrated beam-steering capability. Although the project demonstrated the possibility of low-cost 5G infrastructure using off-the-shelf substrates and prototyping techniques. In general, this work fills a practical gap in the industry by concentrating on mid-band frequencies since the deployment of high-frequency mmWave systems is still harder due to coverage restrictions and increased costs.

Chapter 4

Conclusion

In general, the feasibility of passive beamforming for 5G mid-band applications was effectively illustrated by the introduced design, simulation, and deployment of a 4x4 Butler matrix coupled with a microstrip patch antenna array operating at 3.7 GHz. This work demonstrated how low-cost, low-complexity technologies might be used to meet the increasing need for high-capacity wireless communication systems in suburban and urban areas.

Despite thorough simulations, certain challenges were imposed during real-world implementation. Phase imbalances were caused by substrate inconsistency, connector mismatches, and soldering irregularities. Yet, the project used additional transmission lines to lessen these problems. Furthermore, uncertainty is introduced by the integrated antenna-matrix system's reliance on simulations. Even though ADS beam-steering results were encouraging (11.7 dBi gain, 60% efficiency), experimental validation is still necessary to verify performance in real-world settings, especially in urban.

Regarding the possible future works in the scope of this research, scaling the design to larger arrays presents both opportunities and challenges. Though greater angular coverage and finer beam resolution would be possible with larger matrices, there is a chance that layout complexity and transmission line coupling will increase. Furthermore, alternative approaches, such as metamaterials or tunable dielectrics, could allow for limited reconfigurability without active components.

In other words, this project demonstrates that passive beamforming with microstrip patch antenna arrays and a Butler matrix is feasible for 5G mid-band systems. The attained performance metrics—60% efficiency, 11.7 dBi gain, and dependable beam-steering—showcase the applicability of this strategy in real-life environments. This work contributed to a fundamental framework for creating effective, affordable beamforming solutions by fusing theoretical research with prototyping.

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