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Controller Design for Varactor Based 2-bit Reconfigurable Intelligent Surface

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Resumo

A próxima geração de comunicações sem fios (6G) já está em desenvolvimento, prevendo-se a sua adoção durante a próxima década. Esta nova geração exigirá uma revolução na atual tecnologia de comunicações sem fios. Com isto, as superfícies inteligentes reconfiguráveis (RIS) têm vindo a ganhar importância ao longo dos anos, sendo vistas como uma das tecnologias revolucionárias para o futuro das comunicações sem fios. Com esta tecnologia, é possível construir antenas inteligentes com materiais de baixo custo e com baixo consumo energético. Estas antenas podem ser colocadas em posições estratégicas no interior de um edifício ou no exterior, permitindo uma melhor ligação entre os dispositivos emissores e receptores, graças à capacidade de controlar a direção dos sinais que elas refletem. Existem outras aplicações promissoras, como a deteção de objectos no interior de um edifício ou a monitorização de pessoas. Uma parte crucial das RISs é o circuito de controlo, responsável pela gestão do comportamento de cada elemento da RIS. O controlo preciso de cada elemento de uma RIS é essencial para ajustar a fase do sinal refletido, o que é conseguido através da ativação de um circuito de componentes elétricos como os díodos PIN ou os díodos varactor que, quando sujeitos a determinados níveis de tensão ou corrente, alteram as propriedades da superfície refletora do elemento da RIS. Para isto, o controlo pode ser calculado e transmitido à RIS por um microcontrolador dedicado ou por um sistema em circuito integrado (SoC), sendo os field-programmable gate array (FPGA) uma escolha comum para a implementação desta camada de controlo. Para controlar uma RIS com 2 bits (i.e., 4 níveis) de controlo por elemento, a conceção, o desenvolvimento e a avaliação do circuito de controlo têm de ter em conta fatores como o número de elementos, o consumo de energia, o custo de manutenção e produção e o tempo de resposta. Neste sentido, este trabalho tem como objetivo apresentar os componentes utilizados, explicar a sua funcionalidade e apresentar o sistema de controlo e a sua integração com uma RIS baseada em varactores. Será também abordada a metodologia de desenvolvimento do circuito de controlo, incluindo aspectos de hardware e software. Para além disso, foram realizados testes para avaliar a eficiência e o desempenho do circuito de controlo e foi feita uma caracterização do elemento da RIS. Com os resultados retirados a servirem para potenciais melhorias em iterações futuras.

Abstract

The development of the next generation of wireless communications (6G) is already underway, with an expected adoption throughout the next decade. This new generation will require a revolution in the current wireless communication technology. Reconfigurable Intelligent Surfaces (RISs) have grown in importance in recent years and are seen as one of the revolutionary technologies for future wireless communications. With this technology, it is possible to build intelligent antennas with low-cost materials and low power consumption. These antennas can be placed in strategic places inside a building or outside, allowing for a better connection between emitting and receiving devices by controlling the direction of the signals that they reflect. Other applications such as the detection of objects inside of a building or the monitoring of people are also promising options. A crucial part of RIS technology is the control circuit, which is responsible for managing the behaviour of each RIS element. The precise control of each RIS element is essential for adjusting the direction of the reflected signal, which is achieved through the activation of a circuit of electric components that, when subjected to certain voltage or current levels, change the properties of the reflective surface. This can be achieved by computing and feeding the control information to the RIS using a dedicated microcontroller or System-on-Chip (SoC) with field-programmable gate array (FPGA) SoC devices being a common choice for implementing this control layer. To regulate a RIS with 2 bits (i.e., 4 states) of control per element, the design, development and evaluation of the control circuit has to take into consideration factors such as the number of elements, the power consumption, maintenance and production cost and response time.

With this in mind, this work aims to present the components used, explain their functionality and present the control system and its integration with a varactor-based RIS. The methodology for developing the control circuit, including hardware and software aspects, will also be discussed. Furthermore, tests were conducted to evaluate the efficiency and performance of the control circuit and a characterisation of the RIS element was made. The retrieved experimental results serve for potential improvements in future iterations.

United Nation’s Sustainable Development Goals (SDGs)

The development of Reconfigurable Intelligent Surfaces for 6G wireless communications could contribute to several of the United Nation’s Sustainable Development Goals (SDGs). Table 1 identifies these contributions, detailing the specific ways in which this work contributes to them and presenting performance indicators that measure the impact of the work.



Figure 1: United Nation’s 17 Sustainable Development Goals

Table 1: SGDs covered by the work presented in this dissertation

SGD	Target	Contributions	Performance Indicators
SGD 7: Affordable and clean energy	Target 7.2: By 2030, increase substantially the share of renewable energy in the global energy mix.	More efficient communication technologies can be integrated with renewable energy sources.	As RISs have low power consumption, this technology would increase the renewable energy share in the total final energy consumption.
	Target 7.3: By 2030, double the global rate of improvement in energy efficiency.	Developing technologies that improve the energy efficiency of communications networks helps to double the global rate of improving energy efficiency.	Following the implementation of RIS in communication networks, it is possible to measure and deduce the reduction in energy consumption.
SGD 9: Industry, innovation and Infrastructure	Target 9.4: By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes.	The implementation of RIS has the potential to reduce energy consumption in both the infrastructure and retrofit industries, making them more sustainable and environmentally friendly.	By measuring the changes in energy efficiency resulting from the implementation of RISs, it is possible to determine the improvements in the energy consumption.
	Target 9.5: Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries.	The implementation of RIS can increase the quality of communication networks as well as provide access to them for more people.	Being a promising new technology for wireless communications, there is a high interest in its scientific research and the improvement of technological capabilities in various industrial sectors.
SGD 11: Sustainable cities and communities	Target 11.3: By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.	The implementation of RIS can increase the quality of communication networks as well as provide more ubiquitous network access to them for more people.	Following the implementation of RIS, it is possible to evaluate the improvements in the access to communication infrastructures.

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Acronyms

DAC	Digital-to-Analogue Converter
FET	Field-Effect Transistor
FPGA	Field-Programmable Gate Array
IC	Integrated Circuit
IRS	Intelligent Reflecting Surface
LASER	Light Amplification by Stimulated Emission of Radiation
LIS	Large Intelligent Surfaces
LOS	Line-of-Sight
MEMS	Micro-Electromechanical System
MIMO	Multiple-Input Multiple-Output
NLoS	Non-Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
OpAmp	Operational Amplifier
PIN	Positive-Intrinsic-Negative
PSO	Particle Swarm Optimization
PWM	Pulse-Width Modulation
RF	Radio Frequency
RFID	Radio Frequency Identification
RIS	Reconfigurable Intelligent Surface
SDG	Sustainable Development Goal
SNR	Signal-to-Noise Ratio
SoC	System-on-Chip
SPI	Serial Peripheral Interface
THz	Terahertz
VNA	Vector Network Analyzer

Chapter 1

Introduction

1.1 Context

From the conceptualization to the commercial application, there has been a consistent ten-year cycle between each generation of wireless communication, from 1G to the most recent 5G [10]. With this, it's predicted that the end of 5G and the beginning of 6G will happen at the end of this decade [1, 10]. The goals for this sixth-generation of wireless communication include the possi-

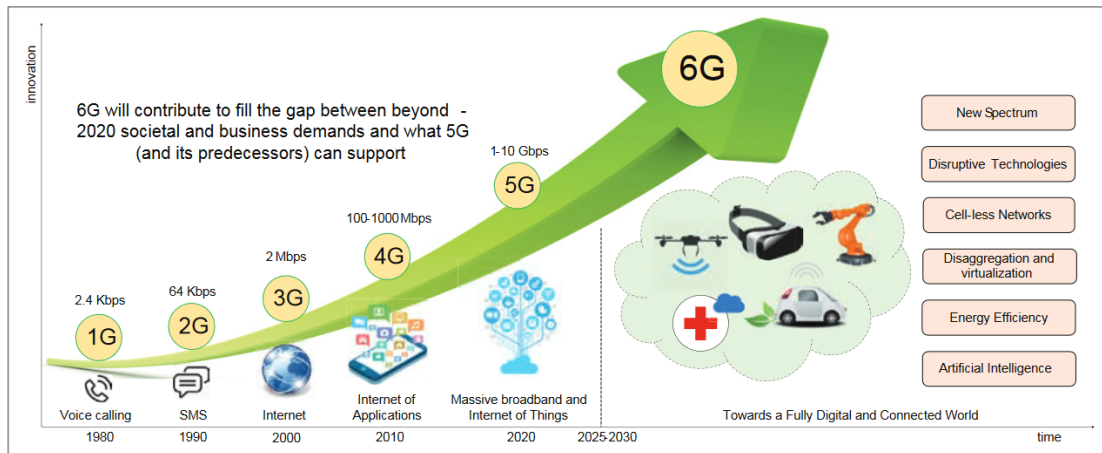


Figure 1.1: Evolution of wireless communications (adapted from [1])

bility of having instantaneous, data-driven wireless connection, as well as the ability to integrate intelligent connectivity, all of which is impossible to achieve with the current generation (5G) [11]. In order to fulfil the requirements of 6G, a new and innovative technology capable of supporting future generations of wireless communication is required. This need has motivated the development of intelligent antennas capable of redirecting a signal in a desired direction. This enables communication with reduced interference between different signals in the medium and therefore improves spectral efficiency. One type of device that fulfils the role of an intelligent antenna is the Reconfigurable Intelligent Surface (RIS). A RIS is a planar array of antenna elements, i.e. unit cells, arranged in a mesh. By controlling the phase delay of the reflections of an incident signal,

each emitted by one element, a focused beam can be produced, achieving a directional reflection [12].

1.2 Motivation

Currently, in 5G communication systems, there are already techniques that are capable of concentrating a signal in a desired direction through beamforming with the use of multiple-input multiple-output (MIMO) [12]. However, the use of high-frequency bands in the range of terahertz (THz) in 6G requires MIMO systems to have hundreds of antennas, which can lead to systems with up to 1024 antennas. This leads to high hardware costs, energy consumption and complexity due to the use of active elements as receivers and emitters [13]. To solve these problems, studies over the last decades have focused on developing a technology capable of generating a dynamic directional beam at a low cost and with low complexity. This technology can be called large intelligent surfaces (LIS), Reconfigurable Intelligent Surfaces or Intelligent Reflecting Surface (IRS) [12, 14].

RISs are a significant technological advancement for wireless communications due to their affordable hardware and low power consumption when compared to large MIMO without RIS [13, 14]. This technology is of great importance in the development of 6G wireless networks and is a cost-effective solution for implementing a smart antenna with spatial feeding, rather than using traditional feed networks. This technology has recently been the focus of considerable attention due to its promising applications in object detection within a room or remote monitoring of individuals [15]. Other applications of this technology include the strategic placement of RISs on interior walls as a solution to dealing with NLoS communication scenarios or integrated into windows and thin walls in urban settings to increase the reach of radio environments [16]. A RIS is composed of multiple elements, each with unique refraction phases that synthesize the required phase distribution over the antenna aperture to achieve the desired signal coverage within the environment where the RIS is deployed. These elements use electronically reconfigurable components that, when tuned, enable re-directing a received signal towards a specified point in a three-dimensional environment. Being composed of multiple elements, a system capable of controlling each of the elements individually is needed in order to control these antennas. This presents a challenge, as a microcontroller capable of controlling each of the elements is needed. Furthermore, the complexity of the element directly influences its performance, so a balance between these two needs to be achieved.

1.3 Objectives

This work aims to design and test a control circuit for a RIS element, i.e., a patch antenna, tuned for 6.5 GHz and with 4 states for the phase control per element, based on varactor diodes. A frequency of 6.5 GHz was chosen to align with the operation of Wi-Fi 6, which utilizes the 6 GHz band. Furthermore, this decision aligns with the preliminary nature of this research. At this stage,

the focus is not yet on addressing the specific frequency requirements necessary for 6G, but rather on establishing a stable and interference-free platform for further exploration. The use of varactor diodes requires the development of a prototype for a circuit to control the varactor diodes with a resolution of 2-bit, i.e., 4 states of control. Having this, another objective is to characterize the unit cell and the control system experimentally. This element with 2 control bits per element will then be integrated into an array of elements with, for example, the dimensions of 8x8 elements, resulting in a RIS. This will allow for a four-level control of the phase of the reflected wave, per element. The levels of control may be, for example, 0° , 90° , 180° , or 270° . The phase will be controlled by the varactor diodes working as discrete elements that will be integrated into the unit cell. The state of these discrete elements can be managed by a microcontroller or a control system based on an FPGA. With this said the main objectives of this dissertation are:

- Develop a control circuit capable of controlling one element of a 2-bit varactor-based RIS;
- Design the PCB for a control circuit for a 64-element RIS;
- Characterization of the varactor-based element
- Integrate the control circuit with the RIS element and evaluate its performance
- Compare the performance of the 2-bit unit cell using varactors with a PIN diode based unit cell and compare their functional characteristics

1.4 Document Structure

Including the Introduction, this document has six chapters. In Chapter 2, the concepts needed to understand the developed work that will be done are presented. These concepts include an explanation of what are Reconfigurable Intelligent Surfaces and the principles of how they work. Three different methods for reconfiguring each RIS element are also presented, as well as the different possible components that can make up an element with explanations of their advantages and disadvantages. Furthermore, in the state-of-the-art, relevant approaches of current literature related to RISs are presented. A table at the end of this section is used to summarize all of the pertinent information and to facilitate a more objective comparison between the approaches. Chapter 3 presets different approaches that were considered to fulfil the objective of developing a circuit capable of controlling a RIS with 64 elements at 6.5 GHz. Chapter 4 shows validation of the different approaches for the control circuit and also presents a PCB design for the control circuit compatible with a varactor-based RIS with 64 elements. Afterwards, an evaluation of the cost of the components for this circuit and its scalability is made. In Chapter 5 the experimental results for the control of the RIS will be presented and conclusions on its efficiency will be taken. Finally, Chapter 6 contains the conclusion for this dissertation as well as some perspectives for future work.

Chapter 2

Related Work

2.1 Background

2.1.1 Directional Communications

Traditional wireless networks primarily adapt transmission schemes at transceiver endpoints to optimize performance based on the dynamic multipath propagation environment [17]. With the shift from 5G to 6G, there is a need to move to higher frequency bands like millimetre waves and potentially into the terahertz band. However, these higher frequencies are more susceptible to environmental obstructions, which make the signal easily blocked in line-of-sight (LOS) transmission. Non-line-of-sight (NLOS) propagation leads to signal disruption through phenomena like reflection, refraction, diffraction, and scattering [13, 18]. These problems occur since wireless channel propagation remains an uncontrollable system that distorts the transmitted signals [13, 17, 19].

To tackle these challenges, smart communication systems have been proposed to achieve software-configurable radio environments [13]. These systems are expected to mitigate the destructive effect of multiple paths by directing the received signal towards a predefined target [18, 19]. This can give the ability to control the wireless environment rather than just adapt to it [13, 20].

By controlling the direction of the electromagnetic wave propagation, it is possible to create new degrees of freedom, thus improving the reliability and energy efficiency of wireless systems [17, 19]. Also, this ensures privacy and security for the communications, creating a protection, for example, for eavesdropping [13, 17].

2.1.2 Arrays of Antennas

In order to perform directional communications, technologies based on arrays of antennas, such as MIMO systems, for transmission and reception of wireless signals, have been proposed [19, 21]. These technologies allow the formation of beams in desired directions [21]. This is known as beamforming and consists of combining all the emitted signals from each of the antennas that constitute the array. Therefore, the signal emitted by the array results from the constructive and

destructive properties of the signals emitted by the antennas [14]. With this, the arrays are able to improve the signal-to-noise ratio (SNR), multiplex data signals in the spatial domain, and suppress interference by spatial filtering [21].

2.1.3 Reconfigurable Intelligent Surfaces and Reflectarrays

RISs are a type of antenna array made of nearly passive devices with low-power consumption components, for example, diodes, that are responsible for changing the electromagnetic properties of the reflective surfaces [11, 13]. These intelligent antennas are made essentially with dielectric substrates with a reflective surface on top. However, because they are passive, these surfaces are not capable of changing their electromagnetic properties. The reconfiguration of the reflective surfaces is achieved by enabling active elements introduced in the structure of the RIS element.

Being made mostly of passive components, the main RIS power consumption is due to the feeding circuit of the active components which can be in the order of μW (microwatt). This allows these antennas to have similar performance when compared to the more conventional MIMO antennas while having lower power consumption [13, 14].

These unique properties make RIS a promising technology to use in wireless communications. However, there are challenges in the process of developing the unit cells that need attention and will be discussed in further sections of this document.

RISs are generally based on planar metamaterial elements, which are called unit cells. Each two-dimensional unit cell is responsible for allowing the reconfigurability of the signal by changing its electromagnetic properties [22, 23].

The RIS itself cannot generate a signal, instead, each element creates a phase shift that will affect the reflection of a received signal. In the case of a fixed reflect-array, the phase shift depends on the size of each element. This means that each element has a different size that is related to the phase shift that it needs to generate [24]. On the other hand, reconfigurable reflect-array has active components, such as PIN diodes, varactor diodes or Micro-electromechanical Systems (MEMSs) that, when tuned, change the electromagnetic properties of the reflective surface of each element. As a result, each element phase shifts a signal according to its reflective properties. The different phase-shifted signals give the RIS the ability to produce constructive or destructive interference patterns. Constructive interference occurs when the phases of reflected signals are aligned, thereby improving signal strength in desired directions. Conversely, destructive interference may reduce or completely cancel signals emitted towards unintended areas [14]. The sum of all these shifted signals will create a beam resulting from the destructive interference in every direction except one, thus redirecting a received signal to a desired position in a 3D space. This means that the direction of the signal reflected by the RIS is given by the combination of every phase-shifted signal given by the RIS elements. By controlling the pattern we can control the direction of the reflected signal.

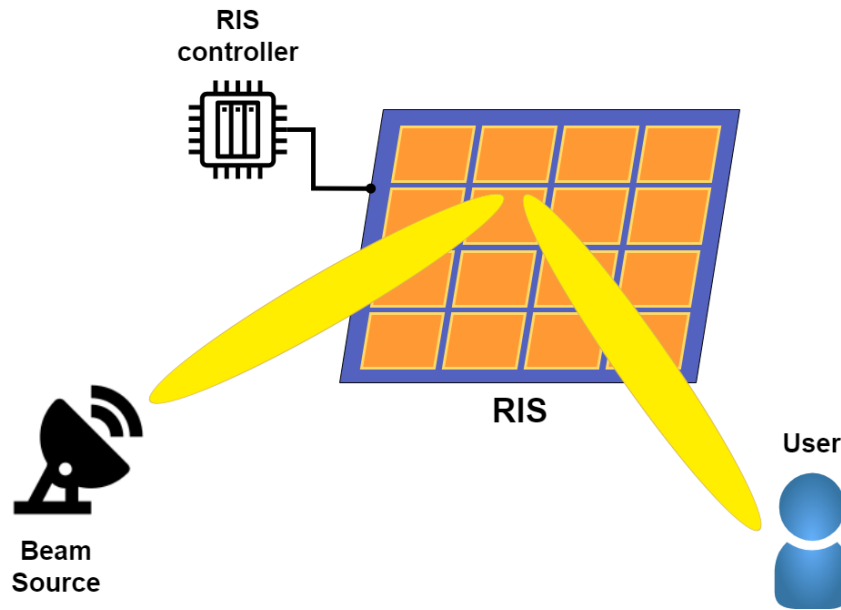


Figure 2.1: Illustration of the RIS control

2.2 State of the Art

2.2.1 Overview

Many studies have been conducted in order to improve and test the current technologies of intelligent antennas, in specific Reconfigurable Intelligent Surfaces. In this section, some of the exiting alternatives for implementing a RIS will be presented and compared. Firstly, the different approaches for controlling the electromagnetic properties of the element will be presented. In order to control the electromagnetic properties of the reflective surface of the unit cell it is crucial to know how to control the components responsible for its reconfiguration. Different methods to perform this control will be explored and compared. Finally, in order to validate the use of RISs in a practical environment, examples of prototypes introduced in the literature will also be presented.

2.2.2 Controlling techniques

To achieve total control of the beamsteering using a RIS, i.e., in any spatial direction, it is required that each element of the array be controlled independently [6]. For this, devices capable of controlling each element synchronously are needed [8]. As seen in Figure 2.1, the elements of the RIS are connected to a controller that feeds a bias voltage to each of the elements, controlling the direction of the beam reflected by the antenna. This section will look at some of the different approaches to controlling RIS elements.

Examples of FPGA-based control systems can be seen in [2, 6, 8, 25]. In [2] the authors present a way to simultaneously achieve various electromagnetic functions such as polarization control, scattering and focusing. Figure 2.2 shows a representation of these functions. To achieve the various functionalities, a genetic algorithm, a binary coding matrix, and an inverse fast Fourier

transform technique were combined and applied to the metasurface. In order to reduce the complexity of the wiring and the control system, an approach is used in [2] where an FPGA is used to control 1600 elements by sending data in parallel to 200 shift registers. Each shift register is responsible for the control of 8 PIN diodes. Simulations were conducted to verify the beamforming performance of the respective RIS. These simulations were then used to compare with the measured results, demonstrating the potential use of the proposed RIS for practical scenarios.

In [8], the authors experimentally show a method to individually control 64 2-bit elements using an FPGA. Their approach divides the software of the FPGA into four sub-modules. Afterwards, the FPGA produces the serial data needed to individually control the elements through demultiplexing. In [6] the authors use FPGA-based control systems to realize complex signal processing, including channel coding, constellation mapping and Orthogonal Frequency Division Multiplexing (OFDM) demodulation. Finally, [25] presents a way to individually control the phase of active RIS elements. Besides FPGA-based control systems, methods to control the elements using DC sources are also presented in [5, 26]. In these articles, the state of the tunable element is changed by varying the DC source output voltage. In [9] the elements are controlled with bias network methods. The bias voltage used to control the tunable elements is applied to them through vias that connect to the bias network, which is arranged on the back of the RIS element.

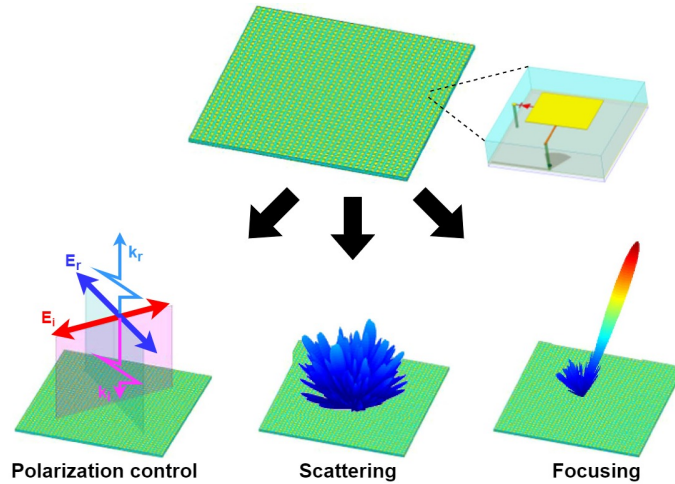


Figure 2.2: Schematic view of multiple functions (adapted from [2])

In order to reconfigure the RIS elements, the electromagnetic properties of the reflective components of the antenna need to be changed. This is achieved by inducing an external stimulus to these components. There are multiple approaches proposed to perform the reconfiguration of the RIS elements, with the common element being the change of the area/geometry of the antenna or by changing the properties of the reflective surface. The three main approaches used to reconfigure the elements of the antenna are made with mechanical actuation, photoconductive materials and electronic devices [18, 27].

Physical/Mechanical Reconfiguration

This reconfiguration uses mechanical rotation and translation to provide different characteristics to the main radiator of the antenna [3, 27]. A servo motor can be used, for example, to rotate the reflective surface of the antenna, which will result in different radiation patterns depending on the rotation applied (this can be seen in Figure 2.3). This type of reconfiguration has the

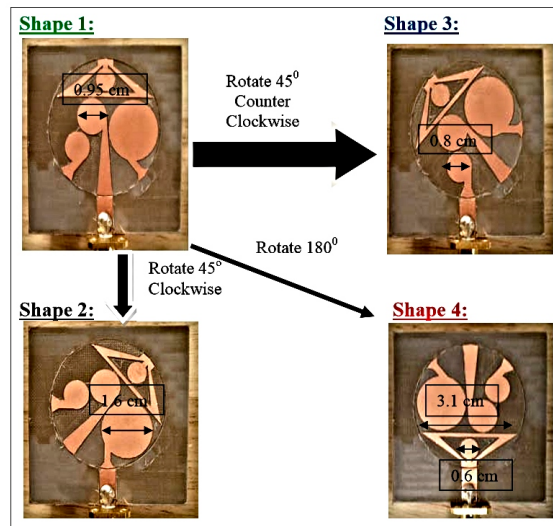


Figure 2.3: Different configurations for the antenna element using mechanical reconfiguration (adapted from [3])

advantage of not needing active elements or biasing systems. However, this type of technique has a slow response, which means that the change of the electromagnetic properties of the reflective component of the antenna will need a large amount of time to happen. Another disadvantage of this method is the need for a power source to feed, for example, the servo motors used [3, 5].

Optical Reconfiguration

This reconfiguration uses photoconductive switches, which have the advantage of not needing the use of bias lines. The reason why this is an advantage is because the bias lines cause interference on the electromagnetic properties of the antenna, which can affect the reflected signal's pattern. Another advantage of this approach is the speed of the response, which can be in the range of nanoseconds. However, this type of reconfiguration needs Light Amplification by Stimulated Emission of Radiation (LASER) diodes for the activation /deactivation mechanism, which increases the complexity of the control [3, 5]. For this method, n-type silicon material can be used as a switching element to tune the properties of the reflective surface of the antenna [5].

Electric Reconfiguration

Finally, the electric reconfiguration uses electronic devices such as PIN diodes, varactor diodes, Field-Effect Transistors (FETs), or Micro-electromechanical System (MEMS) switches to per-

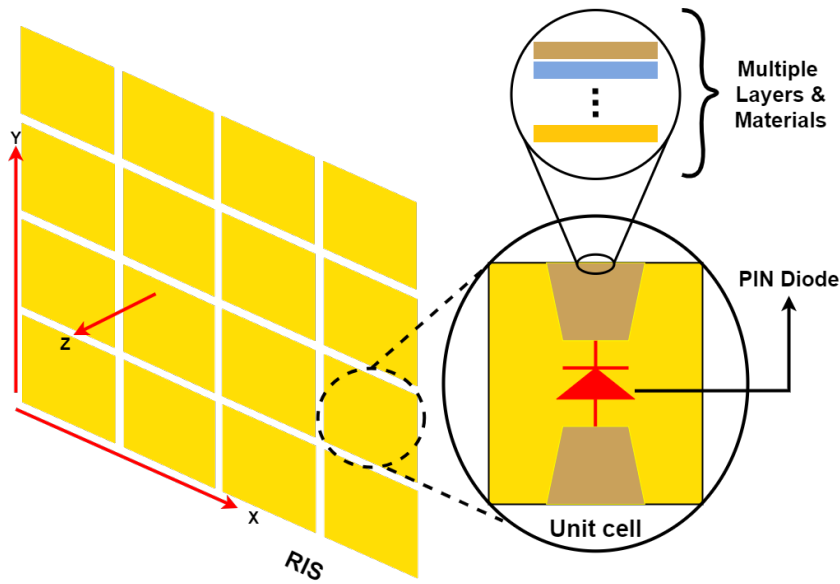


Figure 2.4: Representation of RIS and unit cell (adapted from [4])

form the required tunability in the antenna. [3, 5, 27]. This approach has been widely used due to its fast response time, low reflection loss, low energy consumption and ease of implementation [3, 27]. This method uses these electronic devices, activated by applying a bias voltage to them, to change the electromagnetic properties of the reflective surfaces of the antenna. One negative implication of this approach is the interference caused by the biasing lines (needed for the activation/deactivation of the switching elements) in the radiating plane of the antenna. Also, this type of reconfiguration can create complex unit cell structures [3, 5]. This approach will be used in this work in order to reconfigure the RIS elements.

2.2.3 Components

Commonly, RIS unit cells have a sandwich structure composed of different layers. These are typically metallic layers (for example patches and ground planes) and layers of dielectric substrate. Using electric reconfiguration methods, the electronic devices responsible for changing the reflective properties of the unit cell can be placed on top of the layers, integrated on the reflecting patch [2, 4, 13, 28, 29]. PIN diodes are the preferred device used to tune the electromagnetic properties of the RIS element [4, 14]. However, other tuning elements, such as varactor diodes, are used in the literature with good results in terms of phase and magnitude response of the reflected signal. These unit cells are then arranged in an array of these elements that can be controlled either by a single controller or a set of controllers. This structure, and control scheme, comprises the RIS itself, which is exemplified in Figure 2.4.

Patch

Patches are metallic surfaces (usually copper) that can vary in shape and size, for example, they can be square, circular or have other shapes [28]. The size of the patch needs to be optimized in order to maximize the phase resolution while minimizing the average reflection loss [30]. For this, some proposed methods that employ the Particle Swarm Optimization (PSO) algorithm can be used [30, 31].

Patches are used in the RIS element to receive electromagnetic waves emitted by a source and to radiate a phase-shifted signal [29]. By integrating switches, for example, PIN diodes, with the patches, it is possible to phase shift a received signal by altering the state of the diode. This will induce a variation in the current distribution and thus a phase shift will occur [16, 28].

Dielectric Substrate

As previously stated, the dielectric substrate is where all the unit cell's components will be placed. This substrate has a very important role in achieving desirable electrical and physical characteristics [32]. With this, the choice of a suitable dielectric substrate for the RIS is fundamental. It is important to know what are the materials that have the desired electromagnetic behaviour for the intended signal frequencies.

As with patches, proposed methods that employ PSO can be used in order to calculate the optimal thickness of the dielectric substrate, having into consideration the material's dielectric constant and permeability [30, 31].

Varactor Diodes

As said before, varactor diodes are semiconductor devices that can be used to electronically re-configure the properties of the reflective surfaces. By altering the bias voltage applied to the diode it is possible to alter its capacitance, which will alter the effective electrical length of the reflective surface, thereby altering the reflection phase shift over a continuous range [3, 6, 33]. The equation for calculating this capacitance is given by:

$$C_j = \frac{C_d}{(V_b - V)^m} \quad (2.1)$$

where C_d is the diode capacitance at 0V, V_b is the barrier voltage, V is the reverse bias voltage and m is a material dependent constant. From this equation, it's possible to see that the diode capacitance (C_j) is inversely proportional to the applied bias voltage (V), i.e. that increasing the applied voltage will reduce the capacitance and vice versa. This allows the reflective characteristics of the surface to be dynamically adjusted by varying the voltage, which varies the capacitance.

A single varactor diode can be used to achieve multi-level phase shifts [27] and only requires a control current in the order of the μA or less [4]. However, it needs a wide range of biasing voltages that, when used in RIS with a large number of elements, lead to complex bias circuits

[14]. Another disadvantage of using varactor diodes as tuning elements is the fact that they are nonlinear and have low dynamic range [3].

An example of a RIS using this type of element to control the reflection phase given by its unit cells can be seen in [5]. Here, a varactor diode is used to achieve a varactor-based reconfigurable filter. This filter is integrated with the feeding line of a printed antenna, achieving with this integration, frequency tuning without causing distortion in the antenna's radiation characteristics. To change the operating frequency of the filter, this approach uses the varactor diode to change the capacitance of the structure by supplying different voltage levels to the varactor.

PIN Diodes

PIN diodes are semiconductor devices that can act as a variable resistor when a voltage is applied. When a forward bias voltage is applied to the PIN diode, the resistance decreases, allowing the diode to conduct; conversely, when a reverse bias voltage is applied, the resistance increases, stopping conduction. Compared to varactor diodes, PIN diodes are more straightforward, they are switch-type devices that produce discrete phase shifts. This means that there is a trade-off between phase resolution and the complexity of the RIS element when using PIN instead of varactor diodes [6, 29].

These diodes also have lower biasing voltage than varactors (0.7V-0.8V) but a current in the order of mA. With this, the power consumption with PIN diodes is generally higher than with varactor diodes. Even so, PIN diodes are preferred because of their control simplicity and because it is more cost-effective to implement, in a RIS with a large number of elements, discrete phase shifts with a small number of control bits for each element [4, 14].

A PIN diode state (ON or OFF) can be controlled by the biasing voltage applied to its terminals [14, 27]. The number of control bits can vary depending on the number of diodes used in the unit cell. Each PIN diode corresponds to a control bit, which means that in each cell we have 2^N states with N being the number of diodes.

Using only 1-bit elements results in a low aperture efficiency and higher sidelobe levels, sometimes causing unwanted grating lobes. Increasing the number of bits can solve the sidelobe problems [30]. Higher bit resolution also allows for finer control of the phase shift applied to the reflected signals, enabling more precise beamforming with an increase in its aperture efficiency and lower reflection losses [34, 22]. With this, designs with 2-bits are a well-balanced choice between performance and complexity giving four possible choices of phase shifts. However, this increases the complexity of the unit cell design because more transition structures and electronic devices are needed [6].

In [6] a 2-bit RIS is proposed where two PIN diodes are used to create a $0^\circ/90^\circ$ digital phase shifter. The realization of the phase shift is done by tuning both PIN diodes to work at ON-ON or OFF-OFF states. A 1-bit vertical current reversible dipole is then used to achieve the 2 bits, i.e., the four desired state configurations. These state configurations will modify the RIS reflective surface parameters, thus changing the phase of the reflected waves [17]. In order to maintain a stable desired phase shift, two tuning stubs are also included. Another approach with PIN diodes

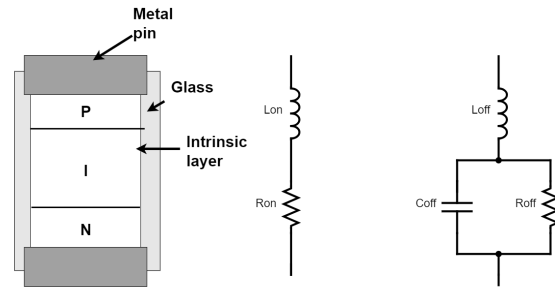


Figure 2.5: PIN diode and its equivalent circuit

is presented in [8]. Here the authors use two PIN diodes connected between three strip lines. This approach is interesting as it manages to obtain a high-accuracy RIS by controlling each diode individually. In [9], the PIN diodes are used to switch the RIS element between the states of absorption or reflection. These states can be achieved by varying the bias voltage applied to the diodes, which will increase or decrease the reflection of the unit cell. With the diodes in the OFF state, the article shows that the element has nearly perfect absorption, while when it is in the state ON, the reflection changes to almost unity [9]. For these diodes to change the properties of the reflective surfaces they need to have one end connected to a bias voltage and the other connected to the ground. By changing the bias voltage, the diodes can change between states [2]. When in the ON state, the PIN diodes can be represented as an inductor in series with a resistor, while in the OFF state, a capacitor in parallel with the resistor is introduced [28]. A representation of the internal circuit of a PIN diode can be seen in Figure 2.5

An approach that combines both PIN diode and varactor diode methods can be seen in [26]. In this article, these diodes are used together to dynamically control a RIS element's surface impedance.

Micro-electromechanical System

MEMS are similar to PIN diodes in the sense that they also work as switches. The main difference is that MEMS use mechanical movement to achieve open or closed circuits and with this the ON and OFF states. They are better than varactors and PIN diodes in some ways, having high isolation and linearity. However, they need high voltage to be controlled and are slower to switch between states [3]. MEMS methods like radio frequency (RF) switches can be found in the literature, for example in [25].

In Table 2.1 we can see a summary of the advantages and disadvantages of each electronic device responsible for the reconfiguration of the RIS element.

2.2.4 Noteworthy Contributions

Many prototypes for RISs have been developed in order to validate different approaches for these intelligent antennas. In the previous section, some examples of elements that can be used to

Table 2.1: Comparison of different tunable elements for electric reconfiguration

Control	Advantages	Disadvantages
PIN-Diodes	• Simple control	• Higher power consumption
	• Extremely low-cost	• Discrete phase
	• Common choice for reconfiguration	• Can become complex
Varactors	• Small current flow	• Nonlinear
	• Continuous tuning	• Low dynamic range
	• Ease of integration	• Complex bias circuitry
MEMS	• High isolation and linearity	• High-control voltage
	• Wide impedance bandwidth	• Slow switching speed
	• Low power losses and low noise figure	• Limited life span

implement the electrical reconfiguration of the RIS were presented. This section will provide some examples of different approaches to making an element for a RIS.

There are many applications for RIS antennas, and so, there are many possibilities when developing a RIS element. In [5], the authors proposed a RIS element that is frequency-reconfigurable. This was achieved by introducing a bandpass filter that can be controlled with the supplying voltage. In Figure 2.6 a representation of the unit cell model can be seen. Practical tests show that this element is capable of tuning its operating frequency with good results for frequencies between 6.17 GHz and 6.47 GHz.

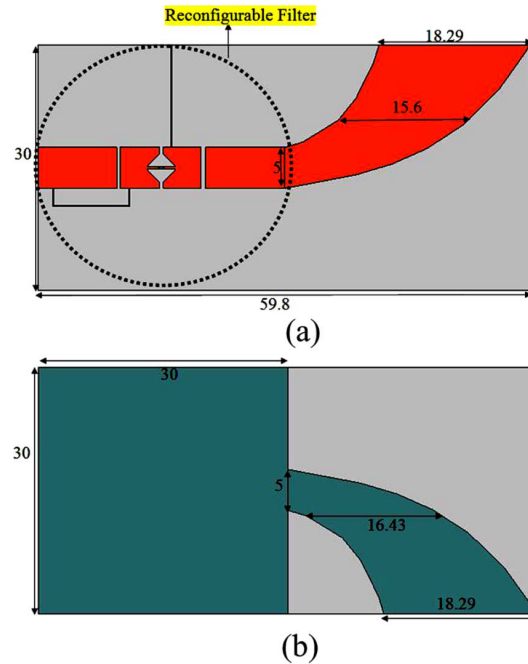


Figure 2.6: (a) Top layer and (b) bottom layer of the filter antenna (from [5])

A novel 2-bit transmissive RIS with a 90° digital phase shifter is proposed in [6]. In this article, the authors present a prototype for beyond 5G communications. Each of the RIS's elements consists of a number of one-dimensional subarrays aligned in parallel (a representation can be

seen in Figure 2.7). This model has the ability to receive and transmit a signal which, in the tests performed by the authors, resulted in a peak gain of 20.0 dBi at 27.0 GHz with 16 x 16 elements.

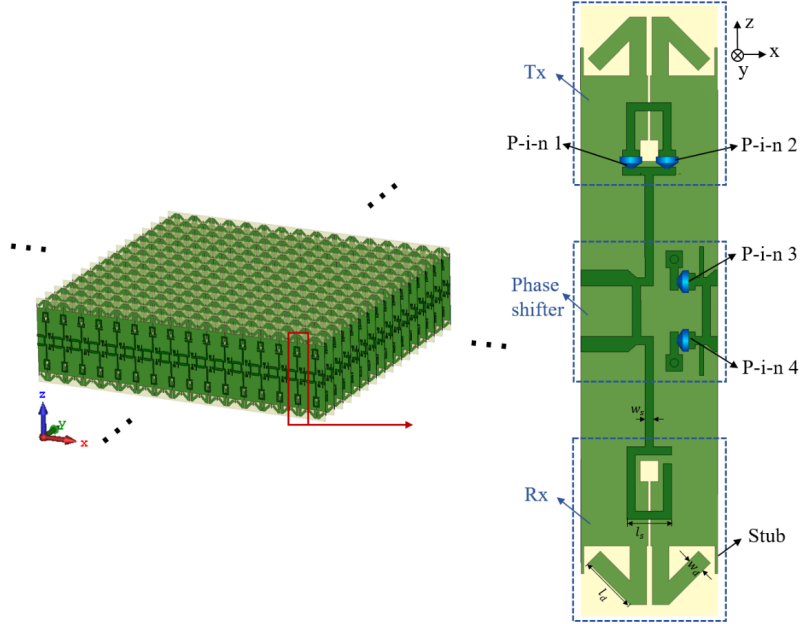


Figure 2.7: Structure of the transmissive RIS proposed in [6]

Another RIS capable of amplifying a received signal is proposed in [25]. This approach has a RIS that is formed by 4 x 4 identical and independently reconfigurable elements, each of which is an antenna with a phase-reconfigurable reflection amplifier. The simulations performed by the authors and the experimental results validate the RIS beam-scanning and amplification capabilities in real world applications.

In [7], a 2-bit unit cell capable of covering a 360° for three different frequencies (3 GHz, 5.2 GHz, and 6.2 GHz). This element can be seen in Figure 2.8. For this approach, twelve different voltages were divided into groups of four, each corresponding to one of the frequency bands. Each group covers phase shifts from 0° to 270° in steps of 90° , achieving the 2-bit characteristic. Simulations showed that this approach can maintain absorption losses below 3dB through all the stages. Moreover, the element is insensitive to polarization, thanks to its symmetry.

A design of a varactor-based unit cell aiming for high phase tuning capabilities and reduced reflection losses while keeping the element compact can be seen in [35]. In simulations, it was verified that the unit cell (with 3 bits of phase quantization) has a maximum phase tuning of 330.7° between 26.37 and 29.61 GHz and reflection losses below 0.7 dB.

The capability to change the direction of a signal towards a desired location is one of the reasons why RIS technology has been getting so much attention in recent years. In [8], a method for individually controlling 8 x 8 elements of a 2-bit RIS is presented. In Figure 2.9 a representation of the approach used to control the 64 elements can be seen. In this approach, one pin of the FPGA is used to control 16 elements of 2-bits. The image shows a serial parallel conversion where the four chips are divided into two groups, each one responsible for controlling 32 elements. For example,

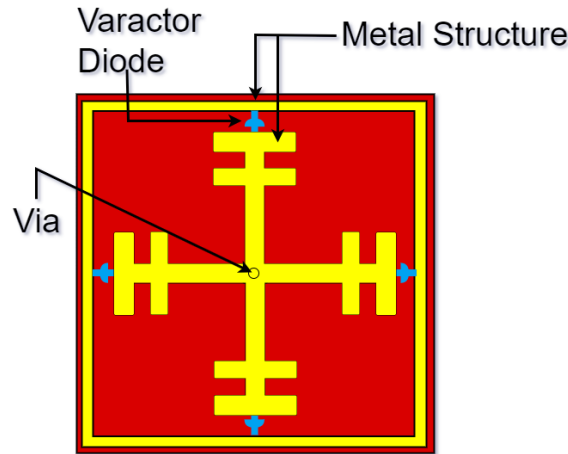


Figure 2.8: RIS unit cell for 3 frequency bands (from [7])

the authors grouped U2 and U3, with U4 and U5 making part of the other group. The experiments conducted by the authors show that the proposed RIS can achieve deflection within 30° with an error inferior to 1° .

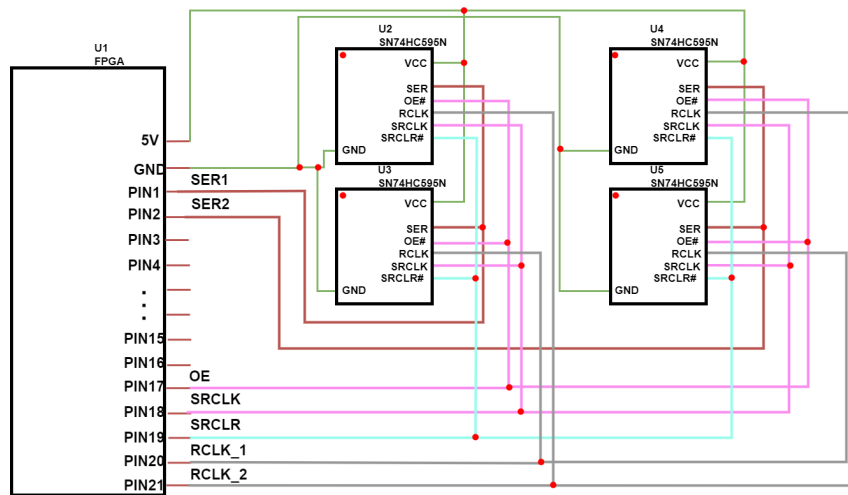


Figure 2.9: Serial parallel conversion (adapted from [8])

In [36, 37], a method to control the RIS using Radio Frequency Identification (RFID) is proposed. The aim is then to create a wireless, low-power RIS to offer a more efficient and cost-effective solution when compared to traditional reprogramming hardware, eliminating the use of physical wiring. This approach uses RFID antennas to wirelessly change the state of PIN-based RIS. More recent RFIDs Integrated Circuits (ICs) can be programmed and used as a DC power supply. With this, this approach proposes a method where the IC is programmed to execute a predetermined command when a certain RF field is present, changing the state of the PIN diode to HIGH or LOW. A schematic of how this works can be seen in Figure 2.10.

Besides changing the phase of a reflected signal, there are other interesting approaches for RIS elements. In [2, 26] reconfigurable metasurfaces capable of performing multiple electromagnetic

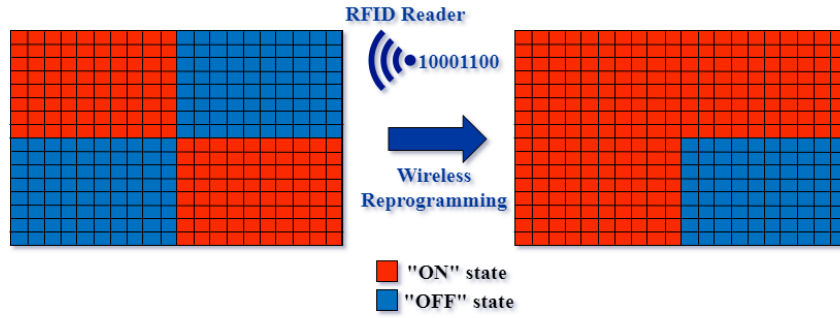


Figure 2.10: Concept of a RFID controlled RIS

functionalities (such as polarization control, scattering and focusing) are proposed. As can be seen in Figure 2.2, the element proposed can work in polarization control mode, scattering mode, or focusing mode.

In [2], polarization control can be obtained when the elements of the RIS are all in the state ON or OFF. This results in a uniform coding matrix with ones or zeros that allow for the element of the RIS to perform reconfigurable polarization. The polarization then gives the possibility to also perform versatile scattering and to generate a focused beam.

In [26], the polarization is achieved by continuously tuning the reflection phase along the y-axis. The authors perform beam-splitting by generating two symmetric phases (i.e. with a difference of 180°). Finally, this approach achieves beam steering by tuning the varactor diodes. Both approaches have good experimental results that validate the RIS element prototype in each functionality.

A controllable electromagnetic wave absorber or reflector is proposed in [9]. To alternate between states, this approach uses PIN diodes as a switch that can alternate between absorption and reflection modes. In Figure 2.11, a representation of the metasurface maximum absorption is shown. This approach shows promising results when using varactor diodes to switch the structure between nearly total reflection and total absorption for 3.74 GHz.

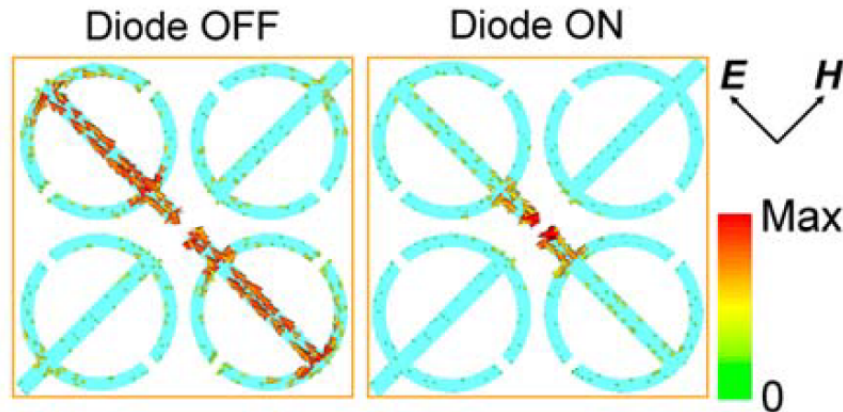


Figure 2.11: Peak absorption frequency under normal incidence (from [9])

Other approaches present in the literature include, for example, a 2.75-bit unit cell [30], a unit cell with multi-bit azimuthal control [33] and a 2-bit tunable unit cell for 6G [22].

2.2.5 Closing Remarks

Table 2.2: Summary of the reviewed works

Ref.	Controller	Phase Control	Year of Publication	Functions
[2]	FPGA	PIN diodes	9-12 GHz	Wave manipulation
[25]	FPGA	RF switches	2.4 GHz	Beam-scanning and amplification
[8]	FPGA	PIN diodes	—	Beam steering
[6]	FPGA	PIN diodes	27 GHz	22 dBi gain at 27 GHz
[5]	DC source	Varactor diodes	6.2-6.5 GHz	Reconfigurable Frequency
[26]	DC source	PIN and varactor diodes	11-13 GHz	Multifunctional wave control
[9]	Bias network	PIN diodes	3.34 GHz	Switch between reflection / absorption
[7]	Bias network	Varactor diodes	3 GHz, 5.2 GHz and 6.2 GHz	RIS tunable for multi-frequency bands
[35]	Bias network	Varactor diodes	26.37-29.61 GHz	High-precision beamforming of 5G/6G mm-waves
[36, 37]	RFID	PIN diodes	860-960 MHz	Wireless beam steering

This chapter presented some of the approaches used when making a RIS element. Through the presented approaches, it is possible to see the extent of RISs applications. Going from wave manipulation to a reconfigurable surface capable of reflecting or absorbing a signal. The multiple phase control methods using electric reconfiguration can also be seen, with examples of RISs elements with PIN diodes, varactor diodes, or MEMS as tunable elements. Furthermore, different methods to control the elements of the RIS were also presented with examples of control via FPGA SoC, DC sources, or bias networks. Table 2.2 presents a summary of these different approaches present in the literature.

Chapter 3

Proposed Approach

The main objective of this work was to develop and test a circuit capable of controlling a RIS with 2-bit resolution per element using varactor diodes as the element responsible for the reconfiguration of the unit cell's surface. As can be seen in Figure 3.1, a microcontroller will be used to communicate with the control circuit. Each element has 2 bits, so to control the 64 elements a 128-bit stream has to be sent to the control circuit. With this, the control code running on the microcontroller sets the 2 bits of the intended element to be controlled to HIGH or LOW depending on the intended configuration or reflection angle. The control circuit will then translate this information in the form of a 2-bit code to select the desired state for the element applying, with this, the required voltage for the varactor diode to perform the intended reconfiguration of the surface of the unit cell. By doing this to all the elements, it will be possible to beam steer the reflection of the received signal. An external power source will power both the microcontroller and the control circuit.

This chapter presents the approach employed in this work to develop a circuit capable of controlling a 2-bit RIS array with varactor diodes at a frequency of 6.5 GHz.

As mentioned previously (Section 2.2) varactor diodes are semiconductor devices that can be continuously tuned by changing the bias voltage applied to them. To obtain the 2-bits of control for the elements of the RIS, the control of the varactor needs to be discretized into four voltage values that, when biased to the diode allow for a reflection of, for example, 0°, 90°, 180° and 270°.

The first step was the development of a unit cell with a varactor diode as the reconfigurable element. A unit cell designed to operate at 6.5 GHz, incorporating varactor diodes, was developed separately from the work done for this dissertation. This unit cell was used as the target for the experimental control circuit and for the characterization experiments.

The second step was the design of the control circuit for the 2-bit element using varactor diodes. A prototype circuit in a breadboard was made to test the control of a single unit cell and a PCB was designed to control a RIS with 64 elements.

The final step was to test the control circuit and the performance of the RIS. This process involved both experimental measurements and simulations to assess the reflective properties of a single RIS element. The element's performance was then tested using a waveguide and a VNA.

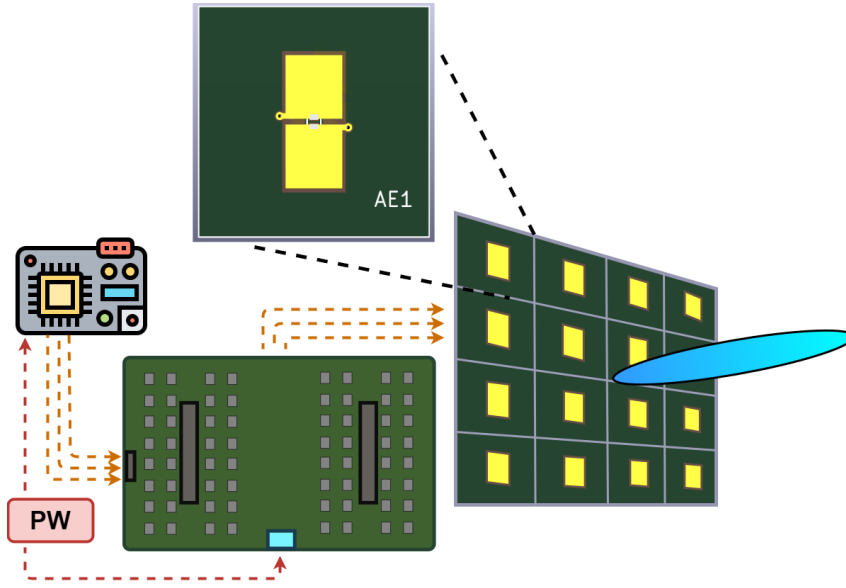


Figure 3.1: Complete diagram of the RIS system, the designed control board would support up to 64 RIS elements with 4 settings for the phase control of each element

Finally, a simulation of a full RIS was made to evaluate if the used element was a viable option. This was done by measuring the overall performance of the RIS when scaled up to a 64-element or higher configuration.

This chapter will present the approach for developing the control circuit for the 2-bit RIS. In Section 3.1 the unit cell used is presented and its design is described. In Section 3.2, different approaches that were considered for the control circuit are presented and a comparison between them is made.

3.1 Unit cell

As previously stated, this project aims to develop a 2-bit RIS with varactors as tunable elements, focusing on developing a controlling circuit for it. Although the development of the RIS element is not part of this work, the unit cell is still crucial. Therefore, this document will present the element that was used. The unit cell used for this work is the one that can be seen in Figure 3.2. This element is 20.19x20.19 mm and has four layers: the patch, two dielectric substrate layers and the ground plane.

The patch layer consists of two rectangular surfaces made of copper, which are connected with a varactor diode. One of the patches is connected to the voltage source (VCLR) and the other is connected to the ground. As discussed in Section 2.2, the patch is responsible for receiving an incident signal and radiating the phase-shifted signal. The patches were dimensioned to ensure that the element would operate at the target frequency of 6.5 GHz resulting in patches of 5x5.6 mm each with a spacing of 0.5 mm between them.

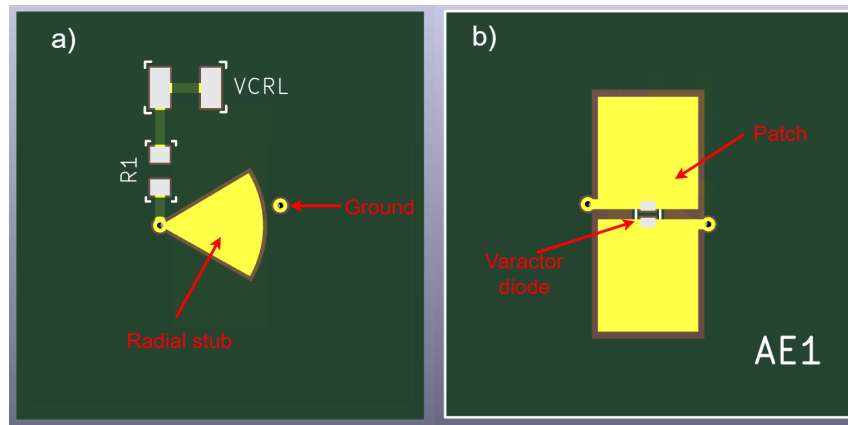


Figure 3.2: Representation of the unit cell a) rear view and b) front view

The dielectric substrates used are the F4B and the FR-4. The F4B is a high-frequency material with a dielectric constant that can go from 2.2 to 3. For this material, a 4 mm layer was used. For the FR-4 material, a layer of 0.5 mm was used. FR-4 is a composite material consisting of woven fibreglass cloth with an epoxy resin binder.

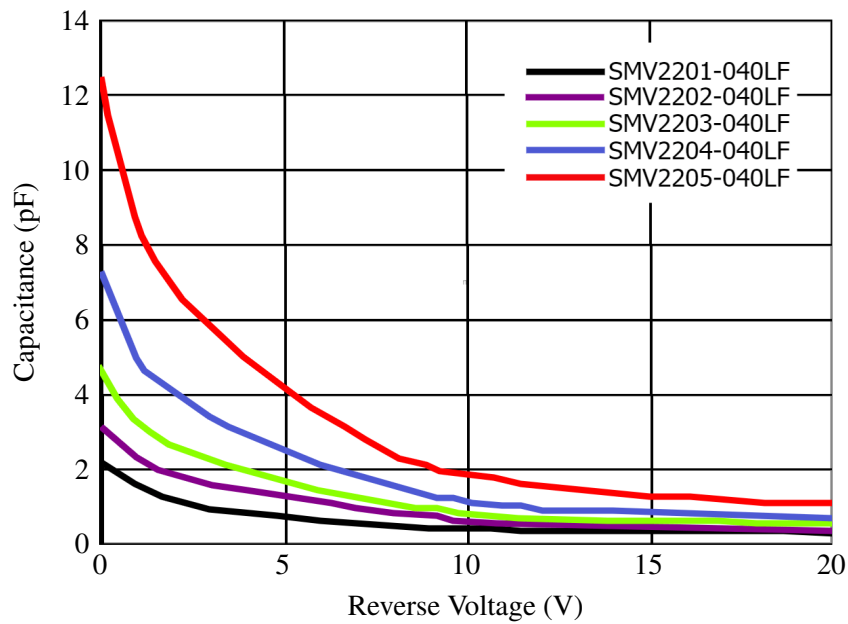
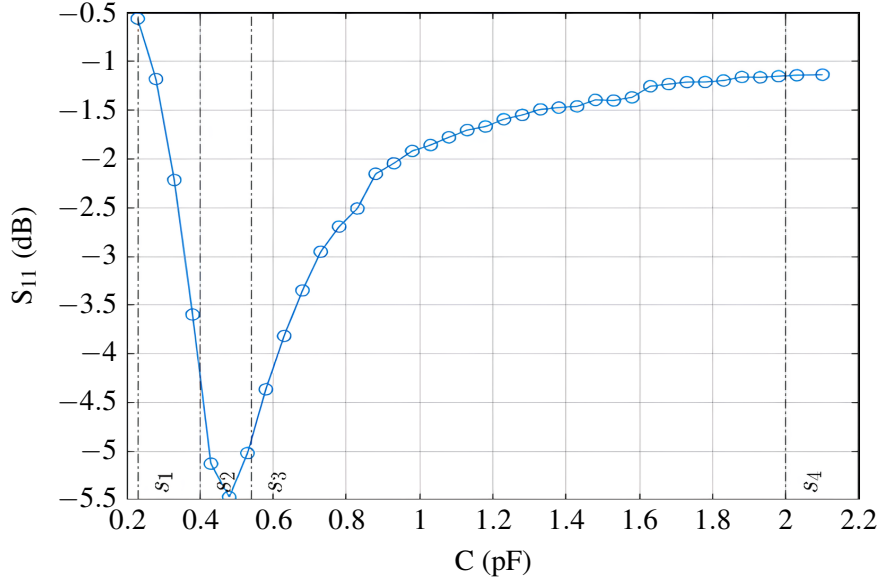


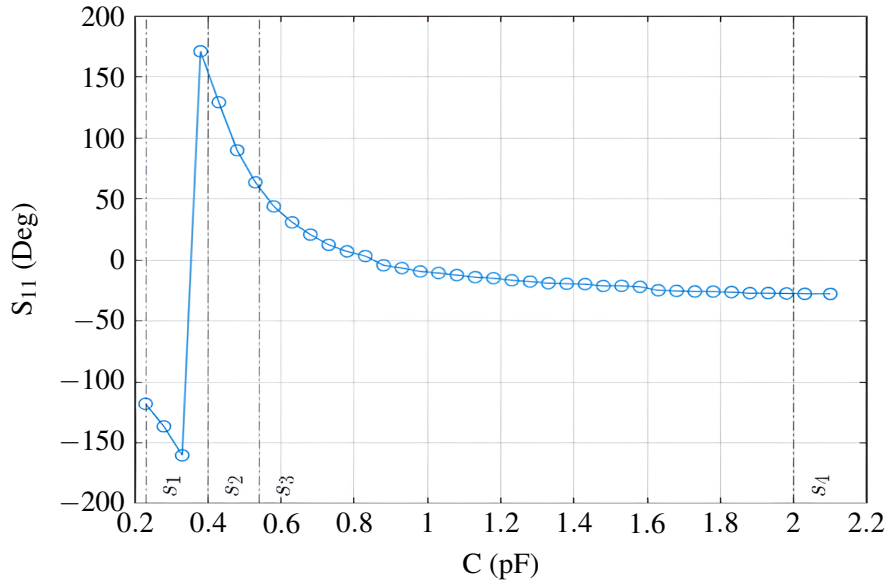
Figure 3.3: Capacitance vs reverse voltage for the selected varactor diode (SMV2201-040LF: black colored curve)

For this element, the model SMV2201-040LF was chosen as the varactor diode. As shown in Figure 3.3 from the datasheet, this model allows for capacities ranging from 0.23 pF to 2.10 pF for a reverse voltage between 0 V and 20 V. To obtain the desired phases, simulations were made where the magnitude and phase of the element were obtained. In Figure 3.4 it is possible to see simulated values. From here, the four states of control s_1 , s_2 , s_3 and s_4 were selected for -118° , 155° , 59° and -27° respectively with the values for the capacitances being the ones shown

in Table 3.1. The respective reverse voltages were obtained by analyzing the characteristic curve of the selected varactor diode and selecting the corresponding voltage for the needed capacitance.



(a)



(b)

Figure 3.4: CST simulations for (a) magnitude and (b) phase of the varactor-based element

To prevent RF signals from being affected by the biasing components and vice versa, a radial stub is used to isolate the DC biasing network from the RF path.

Table 3.1: Voltage values for the different phases

Phase	Capacitance (pF)	Reverse Voltage (V)
s1	0.23	20
s2	0.48	6.6
s3	0.58	5.4
s4	1.95	0.2

3.2 Unit cell control

In order to develop the control circuit for a RIS with 64 elements some approaches were considered. This section aims to present these approaches, explain how they work and then compare their advantages and disadvantages, justifying the chosen approach.

3.2.1 Control through low-pass filter

To control the unit cell, a circuit capable of selecting the four voltage values on command is needed. The response time of this circuit needs to be as fast as possible while keeping low power consumption values and the capability to control an array of 64 RIS elements. With this, a low-pass filter was considered to select the voltage values [38, 39].

The low-pass filter controlling circuit uses a Pulse-Width Modulation (PWM) signal to generate the required voltage levels. By adjusting the duty cycle of the PWM signal, different average voltages can be produced. The low-pass filter then smooths out the PWM signal to provide a stable DC voltage.

Due to its simplicity, cost of components, the ability to have continuous control over the varactor diode and fast response, the low-pass filter appeared to be a promising solution. However, by performing some tests that will be presented in Section 4.1 it was possible to conclude that the needed maximum voltage of 20 volts posed a challenge for this approach. Also, it was possible to conclude that the control of multiple elements would need as many connections to a microcontroller as the number of intended elements, which is not viable given the number of GPIO pins typically available.

3.2.2 Control through DAC

The use of digital-to-analogue converters (DACs) as the device responsible for outputting the four different voltages was also considered. With this, we could control each element of the RIS with an assigned DAC and control all the DACs with a microcontroller. The use of DACs allows for precise and stable biasing voltages, which is essential for accurately controlling the varactor diodes in the unit cells. Because DACs capable of outputting up to 20V are expensive, a version of the same circuit with Operational Amplifiers (OpAmps) was also considered [40, 41].

Figure 3.5 shows a representation of this circuit for one element. This approach only needs one DAC per element which results in a simple control circuit for the full RIS with 64 elements.

The use of DACs also provides precise control of the biasing voltage that is being sourced to the varactor diode and has low power consumption. However, once again this method poses challenges when trying to expand it to the full array of 64 RIS elements because of the complexity of the resulting circuit and the amount of I/O ports needed from the microcontroller to control all the DACs independently. These problems could be solved by using the DACs to generate the four voltages that would then be selected using switches or multiplexers (MUXs) [42]. DACs are also expensive components, which is not ideal when the objective is to control 64 elements which would lead to the necessity of multiple of these components. Moreover, this approach requires the implementation of additional control software for the DAC, which introduces an increased level of complexity (as seen in tests presented in Section 4.2).

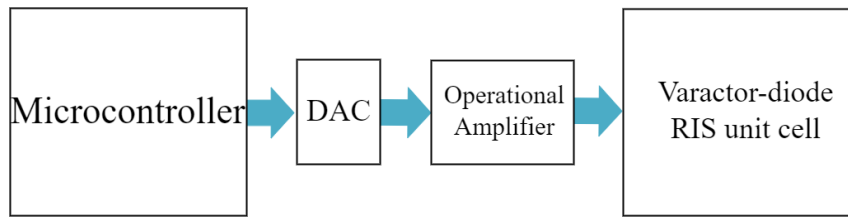


Figure 3.5: Control circuit diagram using DAC

3.2.3 Control through MUX

Another method to generate the four voltages would be by using potentiometers along with multiplexers instead of DACs since this approach would be simpler. A representation of the circuit for one unit cell can be seen in Figure 3.6.

The circuit depicted in the figure operates on a 20V power supply. This voltage is directly supplied to the multiplexer, serving as one of the necessary voltages for controlling the varactor. The other three required voltages (6.6V, 5.4V, and 0.2V) are generated using potentiometers. These potentiometers possess a resistance of 100k Ω to keep the power consumption low by limiting the current. To control multiple elements, shift registers were used. For this approach, the chosen MUX was the TMUX4051, a multiplexer with an output range of 24V.

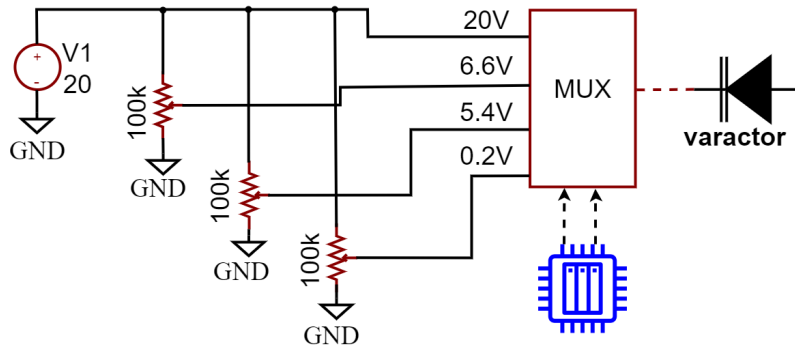


Figure 3.6: Control circuit for one unit cell using MUX

The components used in this approach are low-cost and as later tested (Chapter 4), have low power consumption. Moreover, due to the use of potentiometers, the voltages can be manually adjusted, which means that this circuit can be reused for other 2-bit RIS applications that might need different voltage values for the control. As better presented in Section 4.3, the downside of this approach is that the use of potentiometers is prone to imprecision. The PCB for the control of the 64 elements also proved to be complex.

3.2.4 Summary

In this section, three approaches for controlling the RIS were presented, one using a low-pass filter, one using a DAC as the outputting device and finally, the approach that will be used in this project where the four values of voltage are generated with the help of potentiometers and with MUXs being used to select the voltage intended for each element of the array. In Table 3.2, a comparison between the different controlling approaches is presented.

Table 3.2: Comparison of different controlling circuits

Control circuit	Advantages	Disadvantages
Controlling through low-pass filter	• Simple circuit • Cheap components • Continuous control • Fast response	• Ripple • Multiple elements might need more than one microcontroller • Higher voltages require other approaches
Controlling through DAC	• A DAC per element means it is a simple circuit • Precise output • Low power consumption	• Expensive • Can require complex algorithms to be controlled • Multiple elements might need more than one microcontroller
Controlling through MUX	• Cheap components • Control voltages can be manually adjusted • Low power consumption	• Imprecisions by the potentiometers • Multiple elements require a complex control circuit

Chapter 4

Testing and validation of the control circuit approaches

4.1 Control circuit with low-pass filter

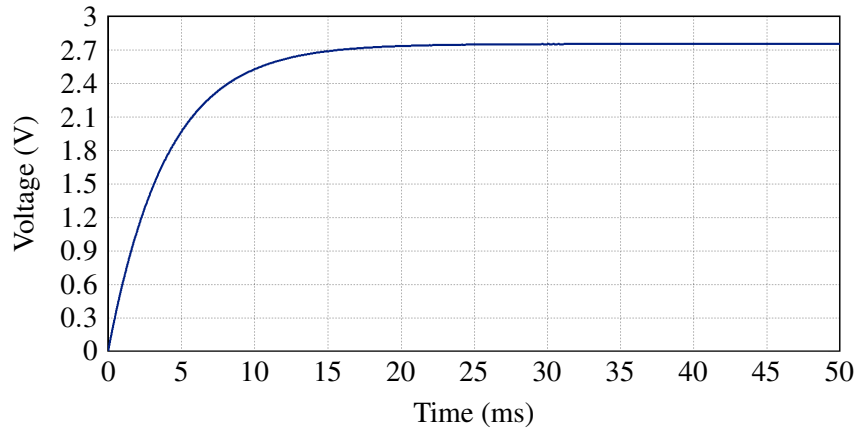
Considering a frequency of 490kHz for the PWM signal, an RC filter was designed with a cutoff frequency (F_c) of 40kHz. This filter was tested in LTspice resulting in an outputted signal with a high amount of ripple (about 600mV peak to peak). It is possible to mitigate this by decreasing the cutoff frequency, however, a tradeoff for this is the increase in the response time. These results can be seen in Figure 4.1.

To reduce the amount of ripple, another pole was introduced to the low-pass filter making it an RLC filter [43]. As seen in Figure 4.2, using a cutoff frequency of 40kHz, the ripple was decreased to about 40mV while keeping a response time in the range of microseconds.

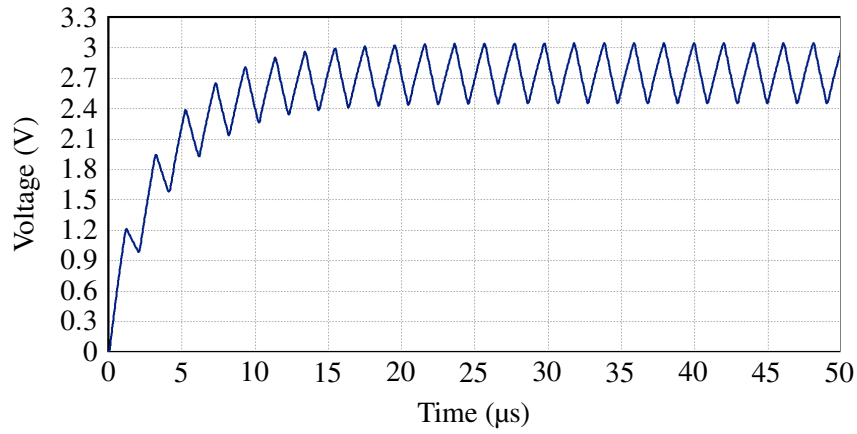
Due to its good response time and low ripple characteristics, the RLC low-pass filter appeared to be a promising solution. However, the need for a PWM signal with a maximum output voltage of 20 V while keeping a low power consumption posed a significant challenge since standard microcontrollers and digital signal generators typically operate at lower voltage levels (e.g., 3.3 V or 5 V). Moreover, in order to control the 64 elements of the RIS, a microcontroller capable of providing at least 64 different PWM signals was needed. This requirement exceeds the capabilities of most microcontrollers and creates the need for more advanced or specialized hardware.

4.2 Control circuit with DAC

To test the control circuit using the approach with DACs, a DAC61401 was used. This is a 12-bit DAC capable of outputting 0 V to 40 V unipolar voltages or bipolar voltages of ± 20 V. This DAC uses a Serial Peripheral Interface (SPI) for communication which needs four wires to communicate with the microcontroller (MISO, MOSI, CS, and SCLK). Due to this, the control of multiple elements would require the number of connections to the microcontroller to be four times the number of elements in the RIS.



(a)



(b)

Figure 4.1: RC filter response for a cutoff frequency of (a) 40Hz and (b) 40kHz

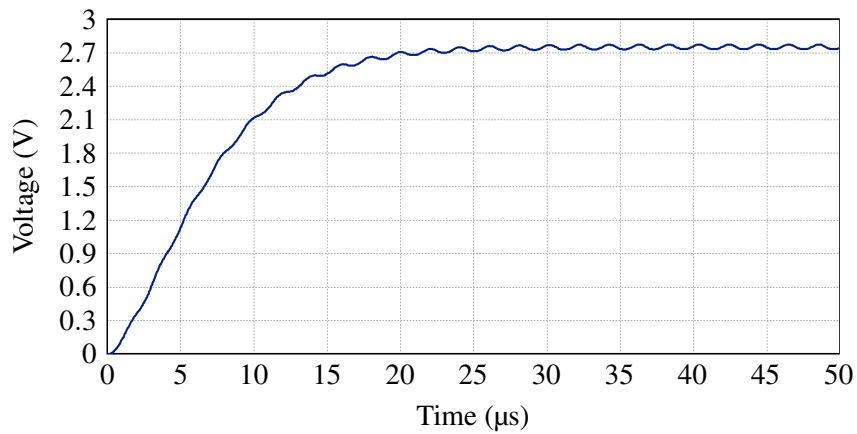


Figure 4.2: RLC filter response for a cutoff frequency of 40kHz

An attempt to write a code to control this DAC using an Arduino UNO was made, however, some issues were encountered. Although communication with the DAC was possible, we were not able to change the voltage output values. Initially thought as a hardware malfunction, this was

then discovered to be a problem in the code that, although correctly implemented to some extent (sending and receiving data through SPI), didn't have the specific commands or sequence required to adjust the DAC output.

Given the complexity of the problem, the cost of the components and the limited time available, the validation of this approach was eventually abandoned.

As a reference for future works, the code used in this attempt to control the DAC is the following:

```

1  #include <SPI.h>
2  #include <Arduino.h>
3  #define CS 10
4  #define RREG 0xC0
5
6  SPISettings spi_set = SPISettings(16000000, MSBFIRST, SPI_MODE2);
7
8  inline void CSON()
9  {
10     digitalWrite(CS, LOW);
11 }
12 inline void CSOFF()
13 {
14     digitalWrite(CS, HIGH);
15 }
16
17 void write_reg(uint8_t reg, uint16_t wdata) {
18     uint8_t lsb = ((uint16_t)wdata >> 0) & 0xFF;
19     uint8_t msb = ((uint16_t)wdata >> 8) & 0xFF;
20     SPI.beginTransaction(spi_set);
21     CSON();
22     SPI.transfer(reg);
23     SPI.transfer(msb);
24     SPI.transfer(lsb);
25     CSOFF();
26     SPI.endTransaction();
27 }
28
29 void read_reg(uint8_t reg) {
30     uint8_t buf[3]; //15-0
31     SPI.beginTransaction(spi_set);
32     CSON();
33     SPI.transfer( (RREG | reg) );
34     SPI.transfer(0x00);
35     SPI.transfer(0x00);
36     CSOFF();
37     CSON();
38     buf[0] = SPI.transfer(0x00);
39     buf[1] = SPI.transfer(0x00);
40     buf[2] = SPI.transfer(0x00);
41     SPI.endTransaction();
42     uint16_t res = ((buf[1] << 8) | buf[2]);
43 }
44
45 void setup() {
46     pinMode(CS, OUTPUT); // set the CS pin as an output
47     SPI.begin();         // initialize the SPI library
48     Serial.begin(9600);
49     write_reg(0x00, 0x0000);
50     write_reg(0x10, 0x0000);
51     write_reg(0x04, 0x0000); //power up the internal reference
52     write_reg(0x03, 0x0A06); //power up the device
53     write_reg(0x09, 0xFFFE); //power up the DAC output
54 }

```

Listing 4.1: DAC Control Code

4.3 Control circuit with MUX

A simplified circuit was made on a breadboard to test the control of the MUX. Figure 4.3 shows a representation of this circuit. As can be seen, the four voltage values used to be selected by the MUX are 22V given by an external power source and 5V, 3.3V and 0V given by an Arduino UNO. These voltages are connected to the MUX through the pins S3, S0, S1 and S2 respectively. The 22V input is also connected to the VDD pin of the MUX, with a decoupling capacitor of $0.1\mu\text{F}$ to ensure a reliable operation. Since only positive voltages are inputted into the MUX, the VSS pin is connected to the ground. The $\overline{EN}$ pin is also connected to the ground as its logical value needs to be zero for the MUX to work. The model TMUX4051 is an 8-to-1 multiplexer but since only four source pins are used in this application, the remaining pins (S4 to S7) are left floating. The same happens to the digital input pin A2 as it is not needed in this configuration.

To change the voltage values outputted by the circuit, a simple code was developed for the Arduino UNO where the pins 4 and 7 were defined as outputs to control A0 and A1 respectively and then their value was set to HIGH or LOW according to the voltage value intended at the output. The code used is the following:

```

1  #define A0 4
2  #define A1 7
3
4  void setup() {
5      // put your setup code here, to run once:
6      pinMode(A0, OUTPUT);
7      pinMode(A1, OUTPUT);
8  }
9
10 void loop() {
11     // put your main code here, to run repeatedly:
12     digitalWrite(A1, LOW);
13     digitalWrite(A0, LOW);
14     delay(100);
15 }
```

Listing 4.2: Mux Test Code

In Section 5.1 the results of the power consumption and response time analysis of the MUX using this code are shown.

4.3.1 PCB design for control of 64 2-bit elements using MUX

As previously stated, the control circuit for the RIS array will utilize shift registers to manage multiple elements. The model chosen for this is the 74HC595PW. Each of these shift registers is capable of controlling four MUXs. These shift registers can also be connected in a daisy-chain configuration, which means that they can be connected in series such that the serial data output of one shift register is connected to the serial data input of the next shift register. This way, the data can be shifted through all the registers sequentially. As a MUX per unit cell is needed, the control circuit for the array would need 16 shift registers.

Figure 4.4 shows a zoomed version of the KiCad schematic for the 64-element control circuit. This figure shows that each shift register controls with QA and QB the inputs A0 and A1 of one of the MUXs, with QC and QD, the inputs A0 and A1 of another MUX and so on. The QH output

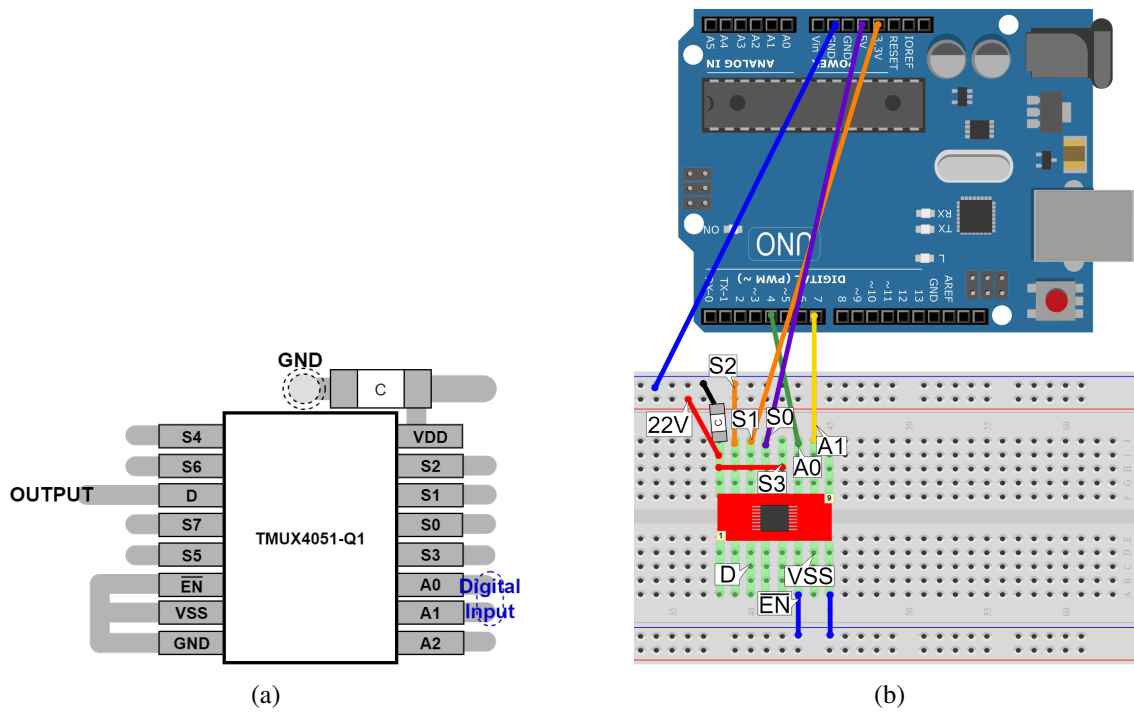


Figure 4.3: (a) TMUX4051 pinout (b) Breadboard testing circuit

is used not only to control one of the MUXs but also to send the data to the next shift register in the chain as previously explained. The outputted signal of half the MUXs is connected to a 2x20 male pin header and the other half is connected to another 2x20 male pin header. Each of these pin headers has 8 pins that are connected to the ground as these aren't required for the circuit operation.

The PCB design was made to connect the control circuit to the back of the RIS. With this, one of the requirements for the PCB design was that each pin header was separated by 92 mm. Another thing that was considered during the design of the PCB was that it should be as compact as possible. With this said, the 3D model for the PCB can be seen in Figure 4.5.

This PCB is approximately 83x163 mm. On the left side (front view) it has a 1x6 male pin header that will be used to connect the shift registers to the microcontroller. In the middle of the PCB, a terminal block (used to connect the 20 V power supply) and the three potentiometers (used to obtain the voltages of 6.6 V, 5.4 V and 0.2 V) were placed. The MUXs are positioned around the 2x20 pin headers, with 32 MUXs allocated for each header. The same thing happens for the shift registers, with 8 shift registers for each of the pin headers. These are placed in the back of the PCB.

4.3.2 Cost of components and scalability

This section evaluates the scalability of the control circuit by analysing its cost and how it varies for RISs with different numbers of control bits.

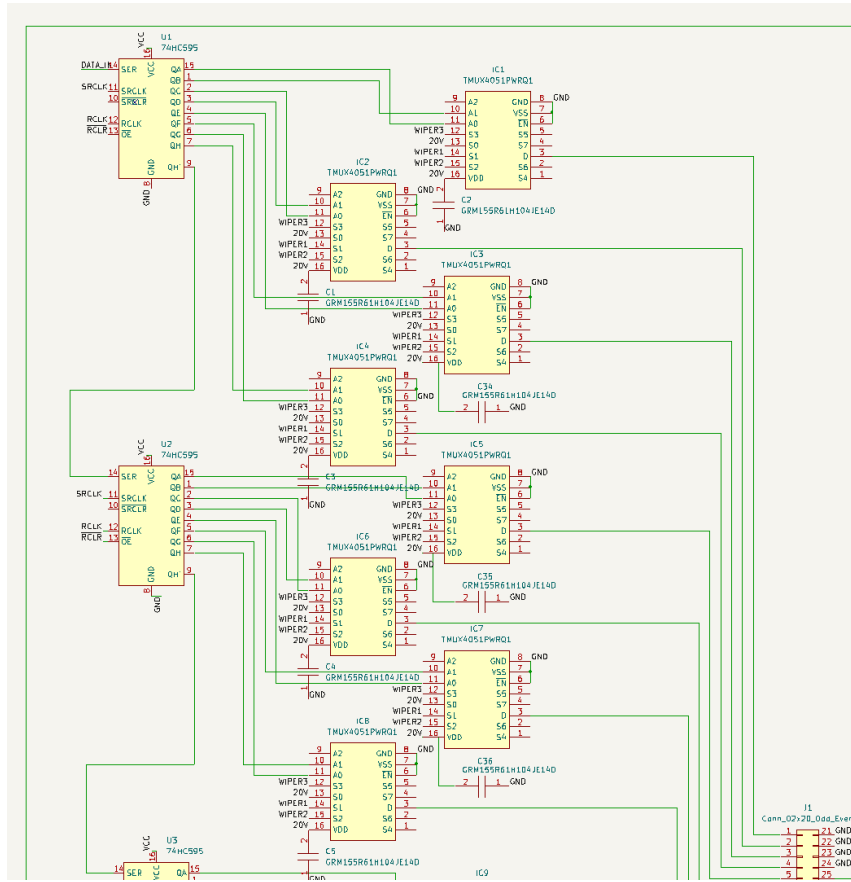


Figure 4.4: Zoomed-in version of the schematic for the control circuit

The cost of the needed components for the control circuit for a 64-element RIS is estimated to be the one seen in Table 4.1. From this table, it is possible to see that the components needed for the control circuit of the 64-element RIS have a total cost of 41.67 €.

To analyze the scalability of the control circuit for a RIS with different numbers of elements, we have calculated the total cost of the components needed for a control circuit designed to control from 1 to 1000 elements. These calculations were made for 1-bit, 2-bit and 3-bit varactor-based RISs. For comparison, the cost of production for a 1-bit PIN-based RIS was also included. It is important to notice that the control circuit for the PIN-based RIS is different than the one for the varactor-based one. For this comparison, a control circuit developed separately from this work was used. The cost of the microcontroller and the cost of production for the PCB are not included in the costs. Figure 4.6 shows how the number of elements relates to the total cost.

As can be seen, there are falls in the total cost of components, this is because the unit price of each component gets cheaper depending on the number of components that are bought. For example, the unit cost of the MUX is 0.577 euros if only one unit is purchased and 0.385 euros if 100 units are purchased. Also, it is possible to see that, as should be expected, the number of controllable bits influences the cost of the components for the control circuit. This happens because, while components like the MUXs and the capacitors are only influenced by the number

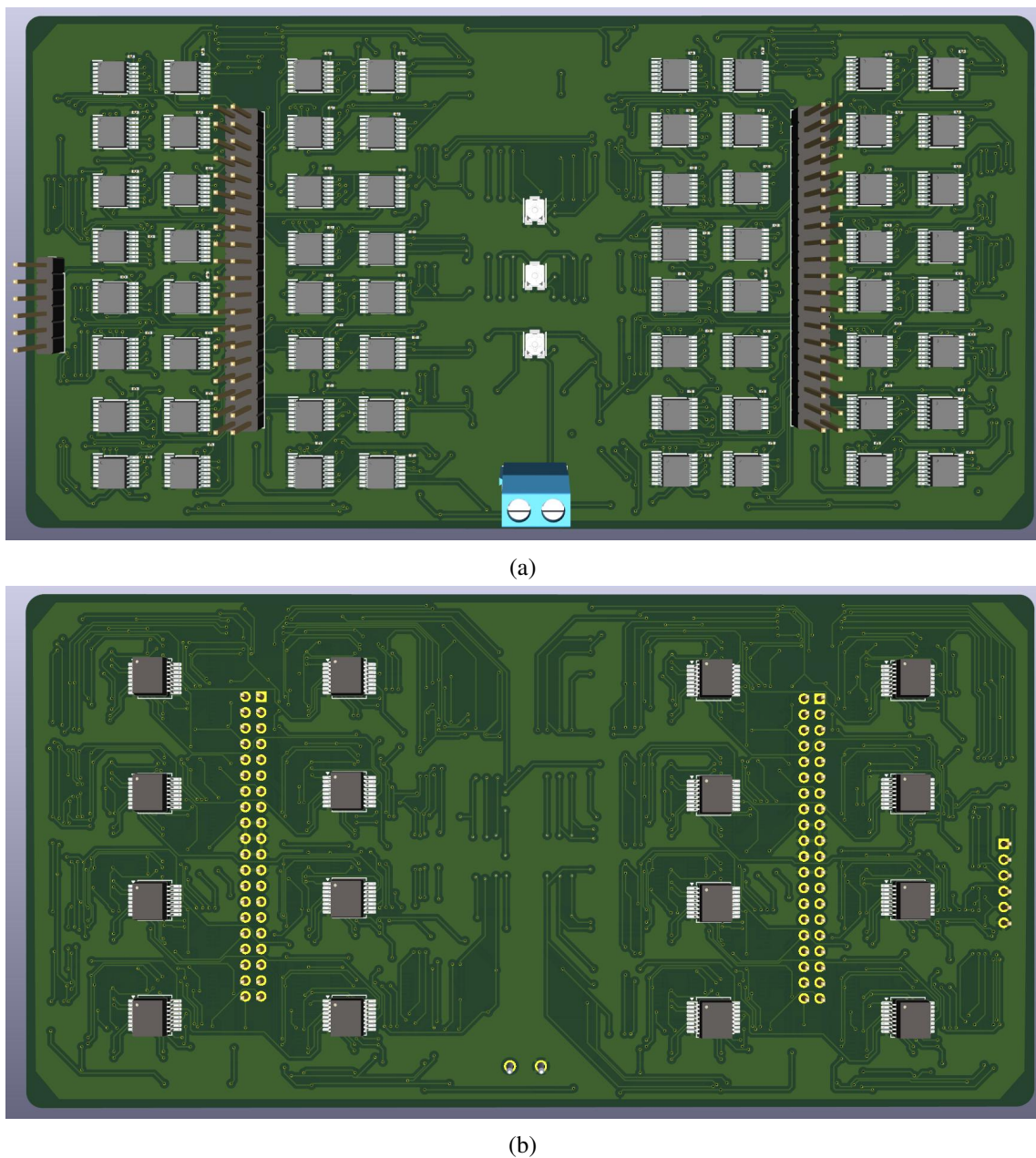


Figure 4.5: 3D model of the control circuit (a) front view and (b) back view

of controllable elements, a higher number of bits will need more potentiometers and more shift registers per controllable element, thus increasing the cost. By comparing the cost of production of the control circuit for the RIS with varactor diodes with the control circuit for the RIS with PIN diodes, it is possible to see that the control circuit for the PIN-based RIS is much cheaper than the one for the varactor-based RIS. Once again, this is due to the fact that the control circuit for the PIN-based RIS has different components with different costs from the one developed for the varactor-based RIS. We can conclude with this that if the objective is to control a control circuit for a RIS with fewer bits, the most logical solution is to use a PIN-based RIS. However, since

Table 4.1: Control circuit component costs in euros for a 64-element varactor diode RIS

Component	Qty	Price/unit	Total price	Description
C1005X5R1H104K050BB	64	0.04€	2.56€	0.1 μ F capacitor
06TR4DA104CP	3	0.437€	1.31€	100k Ω potentiometer
TMUX4051PWRQ1	64	0.502€	32.13€	8:1 Multiplexer
74HC595PW-Q100	16	0.24€	3.84€	8 bit shift register
10129381-940001BLF	2	0.865€	1.73€	2x20 male header
PH1-06-UA	1	0.102€	0.10€	1x6 male header

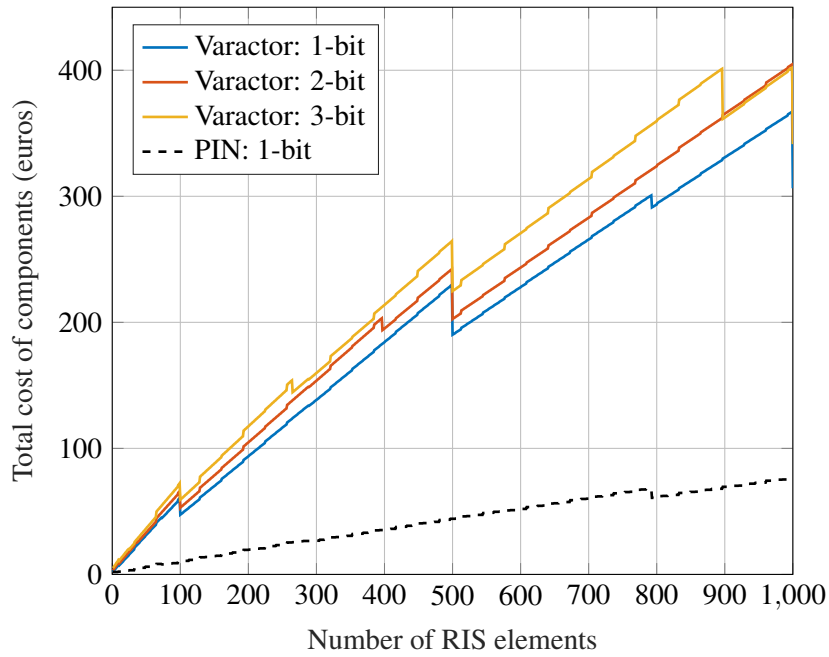


Figure 4.6: Total cost of control circuit components vs. Number of RIS elements

PIN diodes can only give 2 different controllable states to the RIS, for a higher number of bits, the increase of bits in the RIS would increase the required PIN diodes, resulting in an increase in complexity both in the unit cells and the control circuit. For that, the varactor-based RIS becomes a much more plausible solution, since it is possible to use only one diode for N states thanks to its ability to be continuously tuned.

It is also interesting to note that from 897 to 1000 elements, the cost of components for a control circuit for a 2-bit RIS is slightly higher than for a 3-bit RIS. This implies that it is possible to have a RIS with higher resolution and, consequently, enhanced performance without an increase in the cost of the components.

Chapter 5

Experimental Results

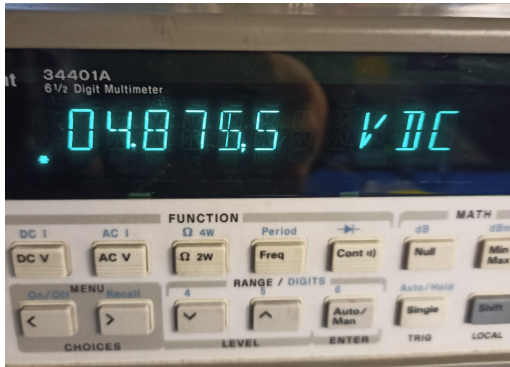
5.1 Characterization of the control circuit with MUXs

5.1.1 Measurement of the output voltages

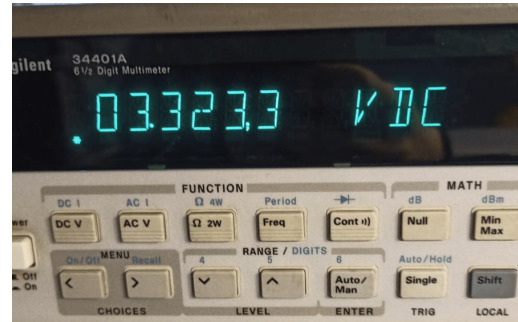
Measurements were taken to ensure that the voltages outputted by the MUX were the same as those at the source pins (S0, S1, S2, S3). For these measurements, the breadboard testing circuit seen in Figure 4.3 is used. These measured values can be seen in Figure 5.1. The measured values matched the input voltages, confirming that the MUX accurately transfers the source voltages to the output without significant loss or distortion. This validation step was made to ensure that there was no need to compensate the sourced voltages for accurate control of the unit cell. To change the outputted voltage values from the circuit, the code presented in Section 4.3 was used.

5.1.2 Response time

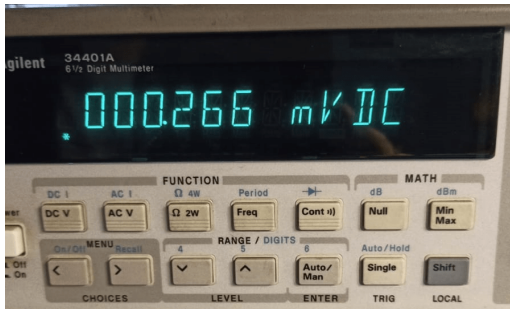
The fast response time of the RIS and its circuit is a crucial aspect of the effective operation of the system. In practical applications, it is often required to rapidly adapt to changing environmental conditions, such as varying signal paths or interference. A quick response time ensures that the system can easily adjust its configuration to optimize signal reflection. To test the response time, a voltage of 2 V was applied at S1 and 0 V at S0. The Arduino was then programmed to switch between the two source pins with a period of 2 ms. Using an oscilloscope to see the outputted signal we obtained the waveform that can be seen in Figure 5.2. As can be seen, the response time is 300 μ s as this is the time it takes to reach a steady-state voltage after switching. Other measurements were made to determine the time interval between the activation of the Arduino or microcontroller and the beginning of voltage alteration at the output by the multiplexer. Once again, the oscilloscope was used to determine the temporal difference between the two signals. The results showed that the time required for an action to be initiated by the MUX following the transmission of a command by the Arduino is approximately 0.1 μ s which is a negligible amount of time in comparison to the response time of the multiplexer. Therefore, given that an Arduino UNO operates at 16 MHz and is executing relatively simple code, it is reasonable to conclude



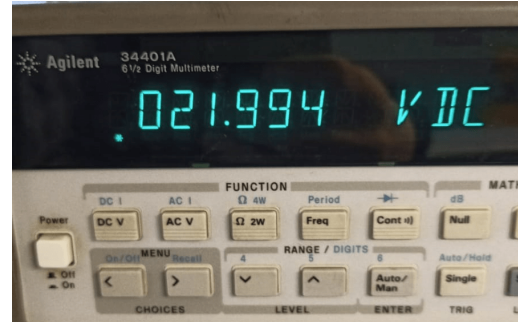
(a)



(b)



(c)



(d)

Figure 5.1: Voltage measurements with A1 and A0 equal to (a) 00, (b) 01, (c) 10 and (d) 11

that the time taken to send each instruction to the multiplexer will also be considerably less than the MUX's response time. With this, the circuit's overall response time can be estimated to be approximately 300 μ s.

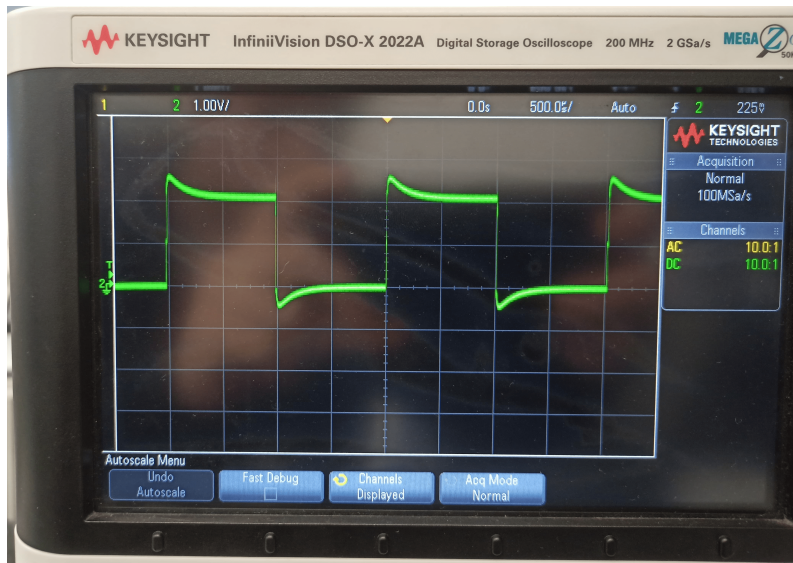


Figure 5.2: Response time of the control circuit with MUX

5.1.3 Control circuit power consumption

Another important aspect to know was the power consumption of the control circuit. For this, a prototype of the control circuit for one element of the RIS was built on a breadboard. The varactor diode in the RIS element is controlled by a reverse voltage, which means that the current going through it is practically zero. With this in mind, the output pin of the MUX was left floating to simulate the diode.

From the previous test where we confirmed that there were no voltage losses between the source and the output pins, the current entering the MUX through these pins was expected to be zero. Furthermore, by measuring the current entering the address line pins (A0, A1, A2) of the multiplexer, it was possible to verify that it was also zero. This means that all the current consumed by the MUX goes through the VDD pin. The current of the whole circuit was measured giving a total of $597 \mu\text{A}$. By measuring the current entering the MUX it was possible to verify that the current going through the potentiometers was $575 \mu\text{A}$ and through the MUX was $22 \mu\text{A}$. The value of the current entering the multiplexer corresponded with what was expected from the datasheet, however, the current going through the potentiometers was slightly lower than anticipated. Each potentiometer had a resistance value of $100 \text{ k}\Omega$ and experienced a voltage drop of 20V across its terminals, giving an expected current of approximately $200 \mu\text{A}$ per potentiometer (giving a total of $600 \mu\text{A}$ for three potentiometers). The currents measured in each potentiometer correspond to resistances of approximately $107.5 \text{ k}\Omega$ ($186 \mu\text{A}$), $105.3 \text{ k}\Omega$ ($190 \mu\text{A}$), and $100.5 \text{ k}\Omega$ ($199 \mu\text{A}$). A possible explanation for this difference is the tolerance of the potentiometers (the ones used had a tolerance of 20%). These values are within the expected range considering the tolerance. With this said, for calculations, an approximation of $200 \mu\text{A}$ per potentiometer will be used.

The current consumption of the shift register (74HC595PW) was also measured, showing a current output with the value of $20 \mu\text{A}$ when powered at 3.3V . With this, considering the variables V_{MUX} and I_{MUX} for the voltage applied to the multiplexers and the current consumption per MUX, V_{POT} and I_{POT} for the voltage applied to the potentiometers and the current consumption per potentiometer and V_{SR} and I_{SR} for the voltage applied to the shift registers and the current consumption per shift register, it is possible to estimate the power consumption of a control circuit for N elements (P_{total}). The power consumption per multiplexer (P_{MUX}) is given by $V_{MUX} \times I_{MUX}$, the power consumption per potentiometer (P_{POT}) is given by $V_{POT} \times I_{POT}$ and the power consumption per shift register (P_{SR}) is given by $V_{SR} \times I_{SR}$. Since a multiplexer is needed per element, the number of multiplexers in the control circuit is equal to N . For the potentiometers, only 3 are needed per control circuit, which means that the number of potentiometers is equal to 3 times the ceiling of the division $\frac{N}{64}$. The number of shift registers is equal to the ceiling of the division $\frac{N}{4}$ as a shift register can control up to 4 multiplexers. With this, the equation for the total power consumption is given by:

$$\begin{aligned}
P_{total} &= N \times P_{MUX} + 3 \times \left\lceil \frac{N}{64} \right\rceil \times P_{POT} + \left\lceil \frac{N}{4} \right\rceil \times P_{SR} \\
&= N \times V_{MUX} \times I_{MUX} + 3 \times \left\lceil \frac{N}{64} \right\rceil \times V_{POT} \times I_{POT} + \left\lceil \frac{N}{4} \right\rceil \times V_{SR} \times I_{SR} \quad (5.1)
\end{aligned}$$

Since the number of elements intended to control is equal to 64, the power consumption of the control circuit is given by:

$$\begin{aligned}
P_{total} &= 64 \times 20V \times 22\mu A + 3 \times \left\lceil \frac{64}{64} \right\rceil \times 20V \times 200\mu A + \left\lceil \frac{64}{4} \right\rceil \times 3.3V \times 20\mu A \\
&= 28.2mW + 12mW + 1.1mW \\
&= 41.3mW
\end{aligned}$$

These calculations do not include the power consumption of the microcontroller since this will vary depending on the one chosen, however, if we consider that an Arduino Uno will be used to control the circuit, an estimation of the resulting power consumption can be made. Using the application USBDeview it was possible to see the current coming out of a computer's USB ports. By connecting the Arduino Uno to the computer, it was possible to see that the current it draws is 98 mA. Since the voltage outputted by a USB port is equal to 5V, the power consumption of the Arduino is 490 mW. With this, the power consumption of the Arduino and the control circuit for the 64 elements RIS is 531.3 mW.

5.2 Phase control performance for waveguide

In order to analyse the functionality of the control circuit when regulating the RIS, an approach will be used where a single element of the RIS is controlled using the prototype of the control circuit, mounted in a breadboard, with its performance being evaluated and then simulated for the complete 64-element RIS. This evaluation was initially made for the frequency of 6.5 GHz, with other frequencies tested later, using a waveguide to guide the test signal and a Vector Network Analyzer (VNA). The VNA will be used in the characterization process to measure the scattering parameters or s-parameters. These parameters describe the relationship between input and output ports in an electrical system. With this, for a two-port network, the s-parameters are S11 for the input port voltage reflection coefficient, S12 for the reverse voltage gain, S21 for the forward voltage gain and S22 for the output voltage reflection coefficient. For the conducted tests only one port of the VNA will be used to measure the forward reflection coefficient (S11) of the RIS element. By analyzing these parameters, we can determine the RIS element's efficiency, phase shift, and other critical performance metrics.

5.2.1 Testing of a single RIS element on waveguide

This section will present the results obtained when measuring the parameter S11 of a 2-bit varactor-based RIS element. These measurements will also be made for a configuration with 1-bit. The results will then be compared with those obtained for a 1-bit RIS using PIN diodes in order to draw conclusions regarding the differences in signal phase accuracy and amplitude and the element's power consumption. The waveguides used for the tests are the ones that can be seen in Figure 5.3.

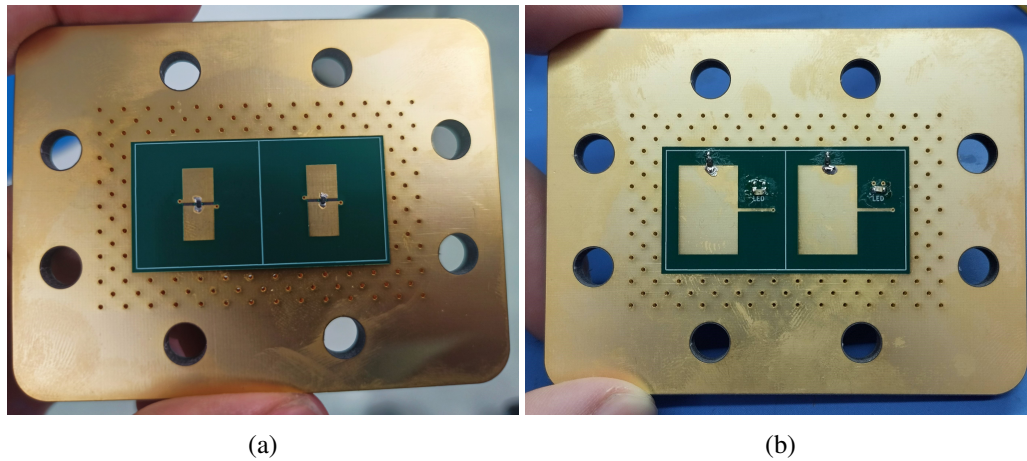


Figure 5.3: PCB for the waveguide tests with a) varactor diodes and b) PIN diodes

As stated in Section 3.1 the element using varactor diodes was developed in parallel with this work by a separate group, the same goes for the element using PIN diodes. For both versions of the waveguides, two elements were used rather than a single one. This allows for the simulation of the periodic environmental effects observed on a RIS array.

Using CST Studio Suite, simulations were made to obtain the predicted curves for the magnitude and phase response of the varactor-based element to a 6.5 GHz signal. These simulations were first made considering an angle of incidence of 0° , however, this is not the case for the waveguide, which imposes a different angle due to its dimensions. With this taken into account, the incident angle was calculated using the equation $\sin \theta = \frac{\lambda_0}{\lambda_g}$, where λ_0 is the free-space wavelength and λ_g is the cut-off guided wavelength. With this, considering $\lambda_g = 2a$ (where a is the waveguide's larger side) an incident angle of 34.85° was obtained for the frequency of 6.5 GHz. Simulations were then made considering the incident angle of 0° and 34.85° resulting in the graphs that can be seen in Figure 5.4.

From the figure, it is possible to see that a phase range of 270° is expected in both cases. This means that the 2 bits of control (0° , 90° , 180° , 270°) should be possible for the varactor-based element. In terms of magnitude, it is possible to see that the lowest value occurs approximately at the same capacitance, between 0.4 and 0.6 pF. This means that the expected results for the element with the selected varactor would have the lowest magnitude values for voltages of approximately 7 or 8 volts.

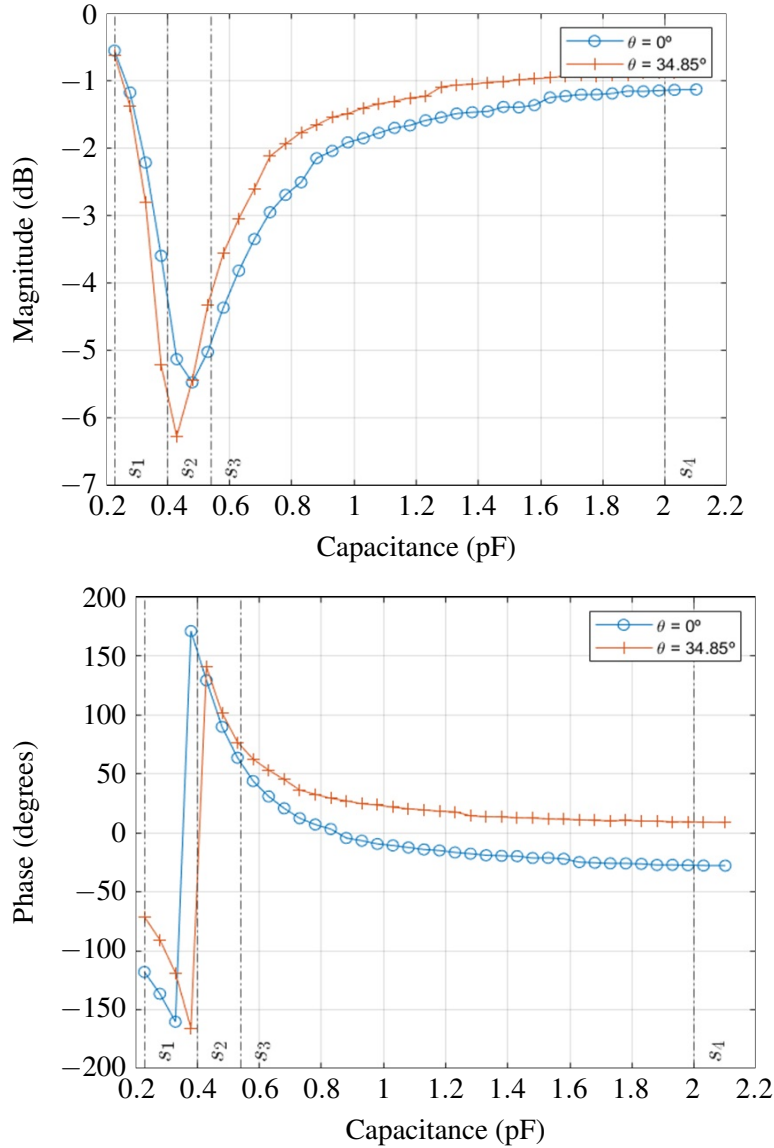


Figure 5.4: Simulated reflection magnitude and phase at 6.5 GHz

Tests were made to verify if the performance of the RIS elements (with PIN and varactor diodes), when subjected to a signal at a frequency of 6.5 GHz, was in accordance with what was expected. The N5224B PNA Microwave Network Analyzer was used for these tests. This is a microwave network analyzer manufactured by Keysight Technologies capable of operating in frequencies ranging from 10MHz to 43.5 GHz. Consequently, it is suitable for use in this experimental evaluation, as it can easily cover the required frequencies. As previously stated, a single port will be utilised for the measurement of the s-parameters. To connect the waveguide and the VNA, a right angle rectangular waveguide to coaxial adapter was used. Since the adapter had a limitation of 7.05 GHz and the intended frequency for the unit cell to operate was 6.5 GHz, the measurements were made across a range of frequencies, from 5.75 GHz to 7 GHz. For the varactor-based element, the reverse voltages applied were the ones previously determined (Ta-

ble 3.1) with the S11 parameters being measured for the magnitude and phase across the previously mentioned range of frequencies. For the PIN-based element, these measurements were taken for the ON and OFF states. These results are represented in Figure 5.5.

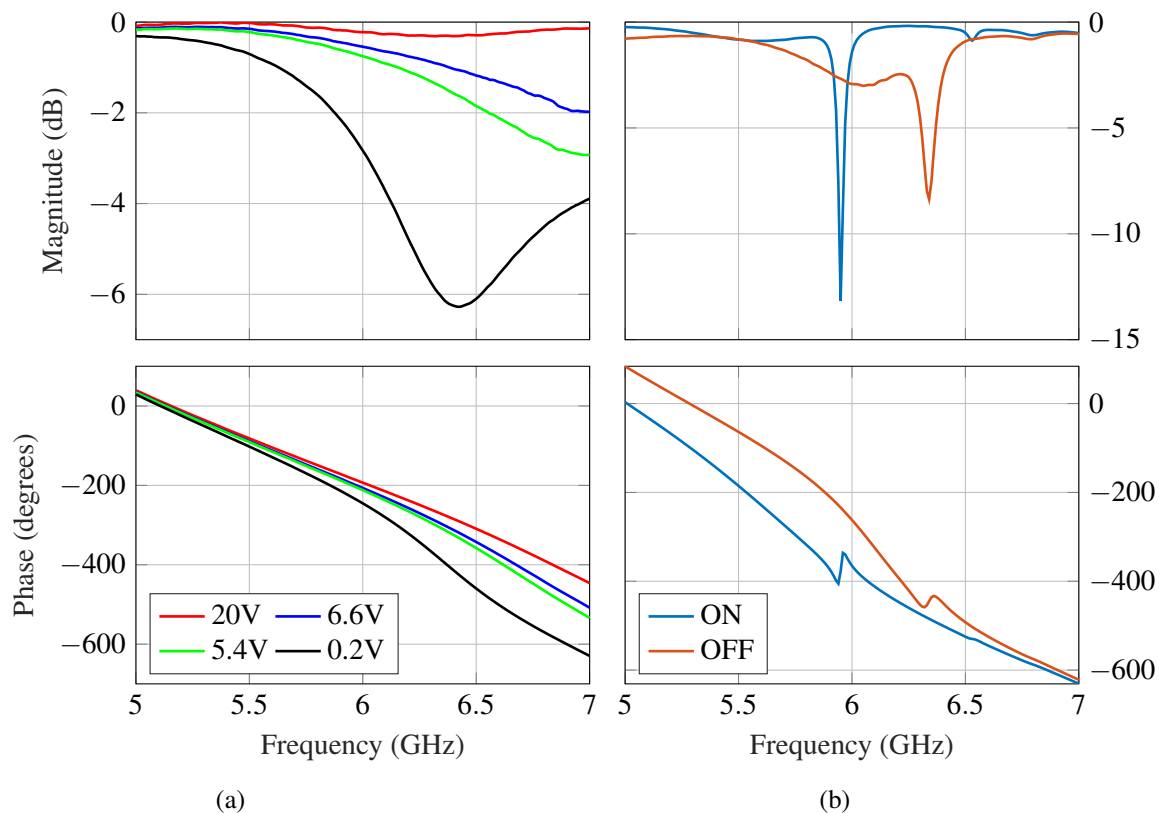


Figure 5.5: Measured reflection phase and magnitude for (a) varactor-based element with different voltages and (b) PIN-based element in both states

As can be seen in Figure 5.5a, with the varactor-based element, the phases do not differ by the expected 90° . The initial hypothesis regarding the discrepancy in results was that the voltages selected for the varactors were not optimal. This meant that the values had to be fine-tuned in order to obtain better control over the element. It is also possible to see that for the frequency of 6.5 GHz, while the magnitude minimum value is within what is expected, reaching a value of approximately -6 dB, it happened at 0.2 V instead of the before mentioned 7 V or 8 V obtained from the simulations.

The results of the tests conducted with the PIN diode element, shown in Figure 5.5b, showed that at 6.5 GHz, the magnitude has low attenuation. However, the phase difference between the ON and OFF states was relatively low, with a value of approximately 20° . At 5.9 GHz, this difference is greater, reaching approximately 180° . Even so, at this frequency, the magnitude shows a considerable attenuation in the ON state, reaching -13 dB. Therefore, in order to achieve optimal performance from the PIN-based element, it is necessary to operate it at frequencies around 5.9 GHz, while taking measures to ensure that the signal is not excessively attenuated.

By comparing the two elements it is possible to conclude that, despite not having the desired range, the varactor diode approach shows a greater phase range and allows for a more continuous control. Furthermore, this element demonstrated superior magnitude results compared to the implementation with PIN diodes when operating at the frequency that provides the greatest phase range. With respect to frequency, it can also be observed that the varactor-based element can operate at higher frequencies.

Their power consumption was also evaluated and compared, for this, the PIN-based element has higher values than the varactor-based element. This can be explained by the fact that, although the PIN diode draws current, the varactor, when reversely biased, acts as an open circuit, avoiding any current consumption for its respective element.

As previously stated in Section 3.2 one of the advantages of the control circuit is that it is possible to adjust the voltages freely. In order to determine the phase range of the varactor-based unit cell, a sweep was conducted across the full range of voltages that can be applied to the diode. In this sweep, measurements were taken every 0.2V for both phase and magnitude. Subsequently, a Matlab algorithm was employed to scroll through all the files containing the measured values, with the resulting data plotted on a graph as a function of voltage on the x-axis and magnitude and phase values on the y-axis, at a selected frequency.

From the obtained results, it was possible to see that, at a frequency of 6.5 GHz, the element was not able to achieve the intended range of at least 270° for the 2-bit configuration. Instead, a range of about 158° was achieved limiting the range to something closer to a 1-bit configuration for the previously mentioned frequency. To verify whether the issue was due to the frequency at which the S11 parameters were being measured, the same experiment was conducted at multiple frequencies. To better visualize the phase range for each frequency, each phase was shifted to start at 0° . Figure 5.6, illustrates the results obtained for phase and magnitude in the various scenarios. Additionally, a dashed line has been included for the value of 180° .

As illustrated in the figure, despite the objective being to achieve a phase range of 2 bits, the element was unable to reach a phase range exceeding 200° at any of the frequencies tested. Nevertheless, at a frequency of 6.6 GHz, the range gets very close to the 180° value while at 6.7 GHz and 6.8 GHz, the range exceeds this value. These frequencies also show less magnitude attenuation. Although higher frequencies are not shown in the figure, it is interesting to notice that, while the phase range remains relatively consistent from 6.7 GHz onwards, the magnitude shown at the lower voltages is still improving.

To determine the causes of this deviation from the simulated behaviour, measurements were conducted with the objective of evaluating the potential for parasitic capacities within the element's PCB. For this, a completely passive element was used, that is to say, an element without diodes and with no power applied to it. These measurements were then compared to the expected results obtained in CST Studio Suite (as seen in Figure 5.7)

As can be seen, the measured values are in accordance with what was expected, with this, we can conclude that the problem could reside in the active component of the element. This could be happening due to unexpected behaviour in the selected varactor diode, i.e., the aforementioned

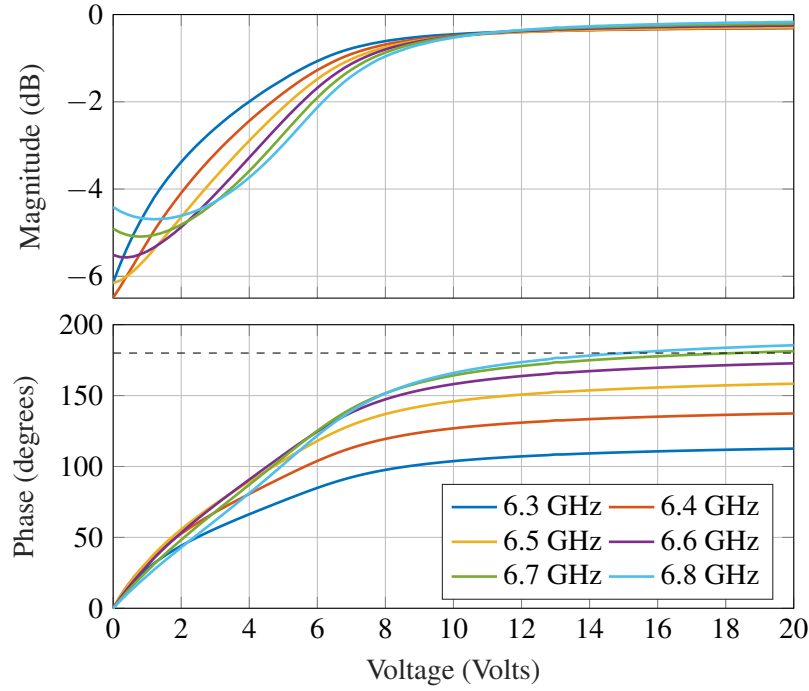


Figure 5.6: Measured reflection phase and magnitude for 6.3 GHz, 6.4 GHz, 6.5 GHz, 6.6 GHz, 6.7 GHz and 6.8 GHz

parasitic capacitance preventing even high control voltages from lowering the varactor capacitance to 0.23pF. This may be attributed to unanticipated behaviour shown by the selected varactor diode resulting in the degradation of its performance. Upon soldering the element, a change in the capacitance characteristics of the diode may occur, resulting in the previously observed alterations in the phase and frequency response. Another potential cause for the problem could be the design of the element itself. As seen previously, the measured magnitude reached a minimum of -6 dB which could indicate that the element might be absorbing the signal rather than reflecting it. This could reduce the efficiency of the reflection and further degrade overall performance.

Due to the phase range limitations, one potential approach for this element would then be to control the element similarly to a PIN diode, applying two voltages to achieve the desired two states. For instance, this could be achieved by applying 0 and 20 volts, or any other suitable combination. Another approach would be to keep the 2 bits of control within a 180° range, although this is not the intended application for the 2 bits of control, it should still allow for more precise beamforming patterns when compared to a 1-bit RIS which leads to better spatial resolution and higher signal quality at the receiver, improving overall communication performance.

5.2.2 Integration of the control circuit with the varactor-based element

As previously mentioned, due to the limitations of the phase range, two possible applications for the varactor-based element would be to apply only 1 bit of control or 2 bits of control for a range of 180° . Since the element was found to perform best at frequencies above 6.6 GHz, with no changes

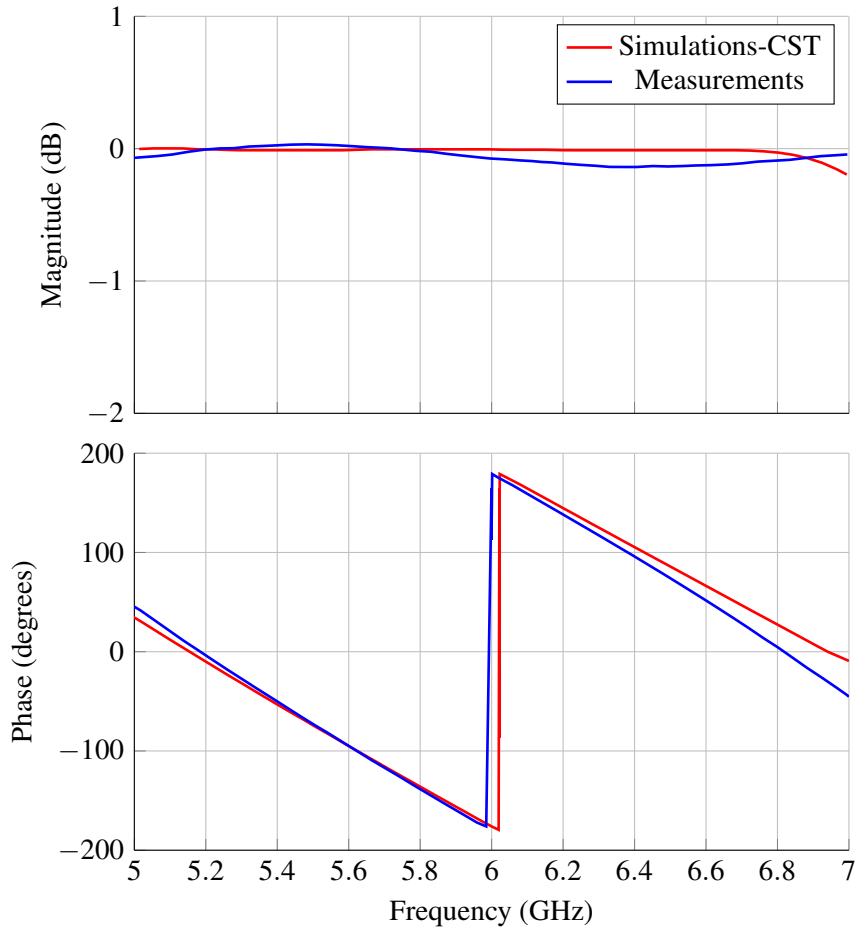


Figure 5.7: Comparisson of the measured and expected magnitude and phase for a passive element

in the phase range for these frequencies, the frequency of 6.8 GHz was chosen to determine which voltages would guarantee a phase difference of 60° between them for 2-bit control. By analyzing the results obtained for this frequency the values expected when the element is integrated with the circuit were determined to be 20, 6.4, 3.4 and 0.4 volts for a control of 2 bits. These voltages were applied to the S3, S2, S1 and S0 pins of the MUX respectively. Figure 5.8 shows the setup used to validate the control circuit performance over the varactor-based element.

Since the varactors have to be reversely biased, their negative electrodes are connected to the output of the MUX and the positives are connected to the ground. As explained previously, the different voltages applied to the MUX are adjusted using potentiometers that work as voltage dividers for an external power source that outputs 20 V. The output of the MUX is controlled by the MC (in this case an Arduino UNO) through a binary code (2 bits). In this case, the MC is being powered through a USB connection with a computer, however, this could also be done by applying a voltage divider to the external power source and powering the MC with the resulting 5 V.

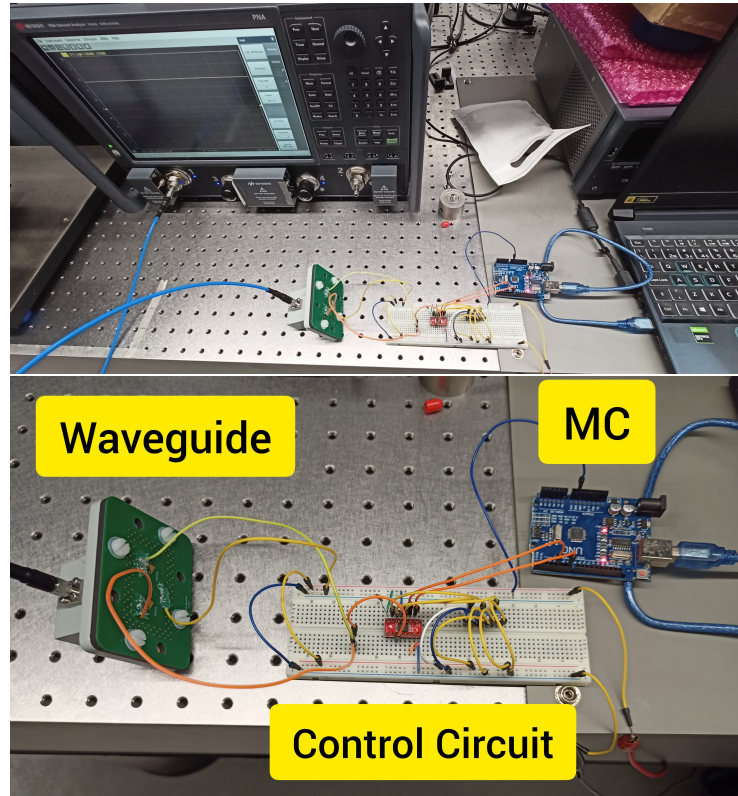


Figure 5.8: Testing setup for the phase shift applied by the circuit to the element

These results where the control of the waveguide is performed by our control circuit composed of the configurable potentiometers and MUX, driven by an Arduino UNO, are shown in Figure 5.9.

As can be seen, by applying the previously determined voltages, the circuit performed as expected. A phase difference of 60° can be seen between the different applied voltages for frequencies starting at 6.7 GHz. Regarding the magnitude, for the same frequencies, it is possible to see that at 20 V it remains static. At 6.4 V there is a decrease of magnitude going from -1.7 dB to -2.2 dB. At 3.4 V the magnitude stays almost static increasing slightly for frequencies over 6.9 GHz, going from -3.9 dB to -3.8 dB. The most noticeable changes in magnitude occur at 0.4 V where the magnitude increases from -4.6 dB to -3.6 dB.

Since for frequencies starting at 6.8 GHz the lowest value for magnitude is always approximately -4 dB, it is possible to conclude that any of these frequencies can achieve the 2 bits of resolution for a phase range of 180° with similar performance.

5.2.3 Simulated RIS array

64-element RIS

In order to understand the impact and utility of a phase range limited to 180° and discretised into four different states (0° , 60° , 120° , 180°), a study was conducted to compare the behaviour of a RIS comprising these elements with the behaviour of a RIS with one-bit resolution and a RIS with

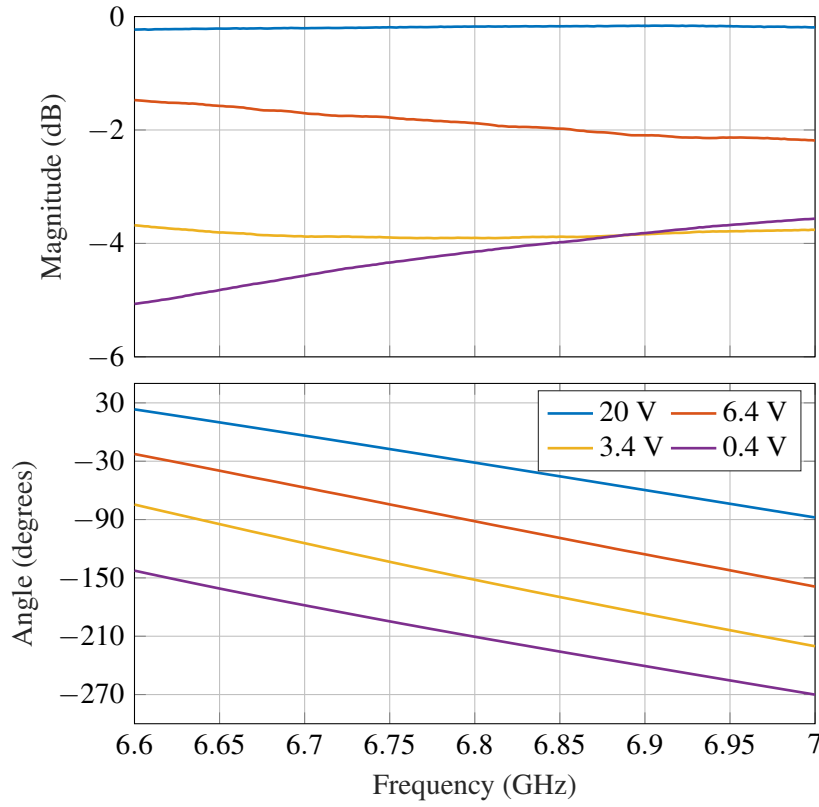


Figure 5.9: Resulting magnitude and phase from the element control

two-bits. Firstly, the radiation pattern and discrete phase of each unit cell were simulated for a 64-element RIS with two control states (1-bit), with four control states limited to 180° (2-bit phase-limited) and with four control states (2-bit). These results were obtained with the transmitting antenna in a near-field configuration and for a desired beam direction of $\theta = 60^\circ$ and $\phi = 0^\circ$. The simulations were initially made for ideal elements, i.e., the measured amplitude was not considered for these initial simulations and instead a unit response was considered for the unit cell for all phase control settings. The ideal results are presented in Figure 5.10.

It can be observed, by comparing Figure 5.10e and Figure 5.10d, that the 2-bit phase-limited RIS exhibits a performance that is comparable to that of the 1-bit RIS, with the presence of a very intense sidelobe which is not seen for the 2-bit RIS. This phenomenon can be attributed to the observation that most of the elements of the 8×8 RIS with the limited phase are in the phases of 180° or 0° with only the 2 elements of the top corners having a different phase which can be regarded as a 1-bit behaviour since these 2 elements are not enough to make significant changes in the beam formation.

The simulations were then repeated with the transmitting antenna in a far-field configuration, which enabled the verification of the impact of additional control levels (although limited to 180°). Figure 5.11 illustrates the resulting graphs from the simulations for a desired beam direction of $\theta = 60^\circ$ and $\phi = 0^\circ$. This test demonstrated better performance of the 2-bit phase-limited RIS when compared to the 1-bit RIS, showing a better beam control. Comparing the phase-limited 2-

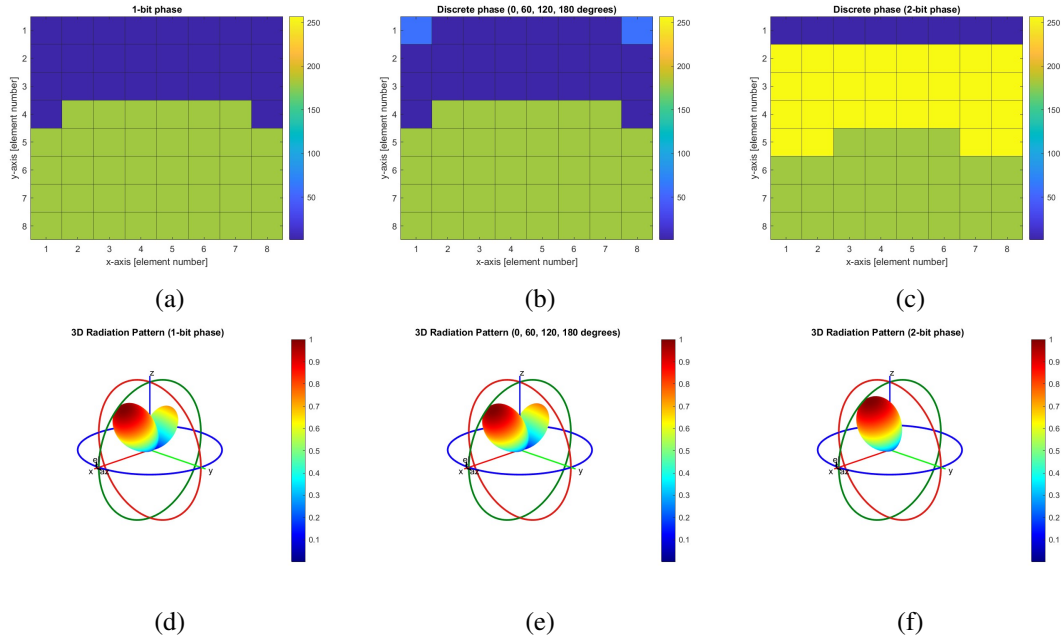


Figure 5.10: Near-field simulation with 64 elements of the discrete phase for (a) 1-bit, (b) 2-bit phase-limited and (c) 2-bit RIS and 3D radiation pattern for (d) 1-bit, (e) 2-bit phase-limited and (f) 2-bit RIS

bit RIS (Figure 5.11e) with the ideal 2-bit RIS (Figure 5.11f) shows that, while the beam generated was not as concentrated in the former case, there is a notable reduction in the sidelobe relative to the later case.

The analysis of the 2D radiation patterns for multiple phases ranging from -60° to 60° for the different RISs (1-bit, 2-bit phase-limited, 2-bit) assisted in the comprehension of why this was happening for the far-field setting. The 2D radiation patterns, which represent a slice of the 3D radiation pattern for $\phi = 0^\circ$, can be seen in Figure 5.12.

These simulations were repeated now considering the measured magnitude response of the unit cells and again compared to observe how a RIS made of elements with the measured S11 parameters for the magnitude would perform in comparison to a RIS with ideal performance when its phase is limited. Figure 5.13 shows the simulation results.

As can be seen, in a near-field setting, the non-ideal 2-bit phase-limited RIS (Figure 5.13c) demonstrates a performance that is consistent with expectations, showing a main beam that is less focused than the one obtained in the ideal RIS (Figure 5.13a) and that has a slight merging with the secondary lobe. However, the results showed matching performances between both RISs in a far-field setting (Figure 5.13d and Figure 5.13b). By analysing the 2D radiation pattern for different phases (seen in Figure 5.14) it is possible to see that for a near-field setting, with 64 elements, a RIS composed of 2-bit elements limited to a phase range of 180° is incapable of accurately steering the beam, presenting a wide lobe for every phase tested when using the measured magnitude response. When in far-field, as stated before, the performance of the RIS with the real measured parameters is similar to what was obtained for the ideal 2-bit phase-limited RIS.

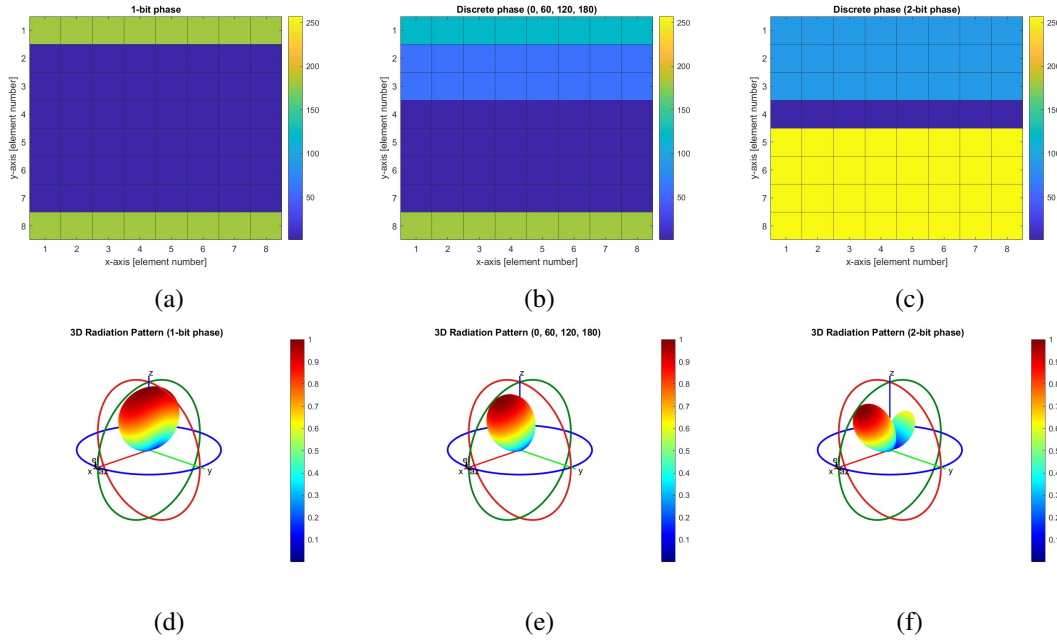


Figure 5.11: Far-field simulation with 64 elements of the discrete phase for (a) 1-bit, (b) 2-bit phase-limited and (c) 2-bit RIS and 3D radiation pattern for (d) 1-bit, (e) 2-bit phase-limited and (f) 2-bit RIS

From the presented results, it is possible to conclude that in a far-field setting, the non-ideal 2-bit phase-limited RIS performs better than the 1-bit RIS. It is also possible to see that, although not creating sidelobes (which can be seen in the appearance of valleys in the different graphs), the radiation is not precise, with the beam reaching multiple directions for each simulated phase both when using ideal parameters and the measured ones in the simulations. From these simulations, it was also possible to see that the 1-bit RIS encountered difficulties in maintaining precise control of the beam in the far field. This can be attributed to the discrete phase of the 1-bit RIS, which has only two states of control and therefore lacks the necessary complexity to achieve the required precision. The 64 unit cells are insufficient for the combinations needed to achieve more precise control of the beam. With this, new simulations were made for near-field and far-field but this time, for RISs with 256 elements.

256-element RIS

For the 256 elements, the process was the same one that was explained for the 64-element RIS. Firstly, simulations were made for a near-field setting using ideal parameters, with the results being the ones that can be seen in Figure 5.15

As can be seen in this figure, with more elements, the differences between the 1-bit RIS (Figure 5.15d) and the ideal 2-bit phase-limited RIS (Figure 5.15e) are now clearer with the phase-limited RIS having now a clear presence of elements in the four available states. By analysing the radiation pattern, it is also possible to see that the phase-limited RIS shows a behaviour closer to that of the 2-bit RIS (Figure 5.15f), with a main lobe that is now well evidenced.

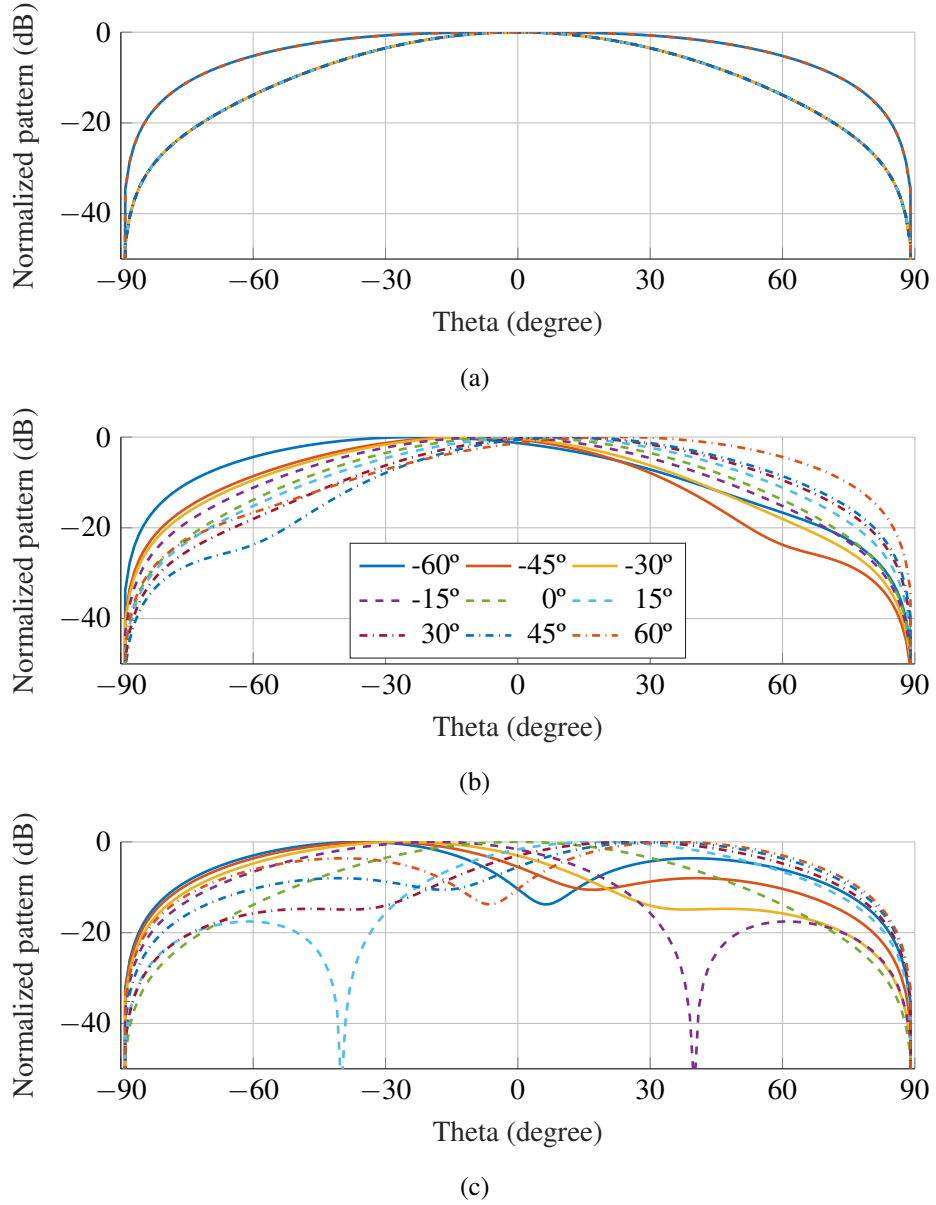


Figure 5.12: 2D radiation patterns for 64-element RIS in a far-field setting with ideal RISs of (a) 1-bit, (b) 2-bit phase-limited and (c) 2-bit

From what was seen previously in simulations with 64 elements, the 2-bit phase-limited RIS showed better performance when in a far-field setting with the same being expected for the simulations with 256 elements. Given that previous simulations with this number of elements had already demonstrated that the phase-limited RIS showed performance characteristics identical to those of the 2-bit RIS, this time, the far-field tests were conducted to compare its performance with that of a continuous-phase RIS, i.e., a RIS in which each element can be tuned to an "infinite" number of states. The results can be seen in Figure 5.16

Here it is clear to see the presence of a sidelobe in the 1-bit RIS, while the phase-limited and the RIS with the elements with continuous phase control, show a clear main lobe.

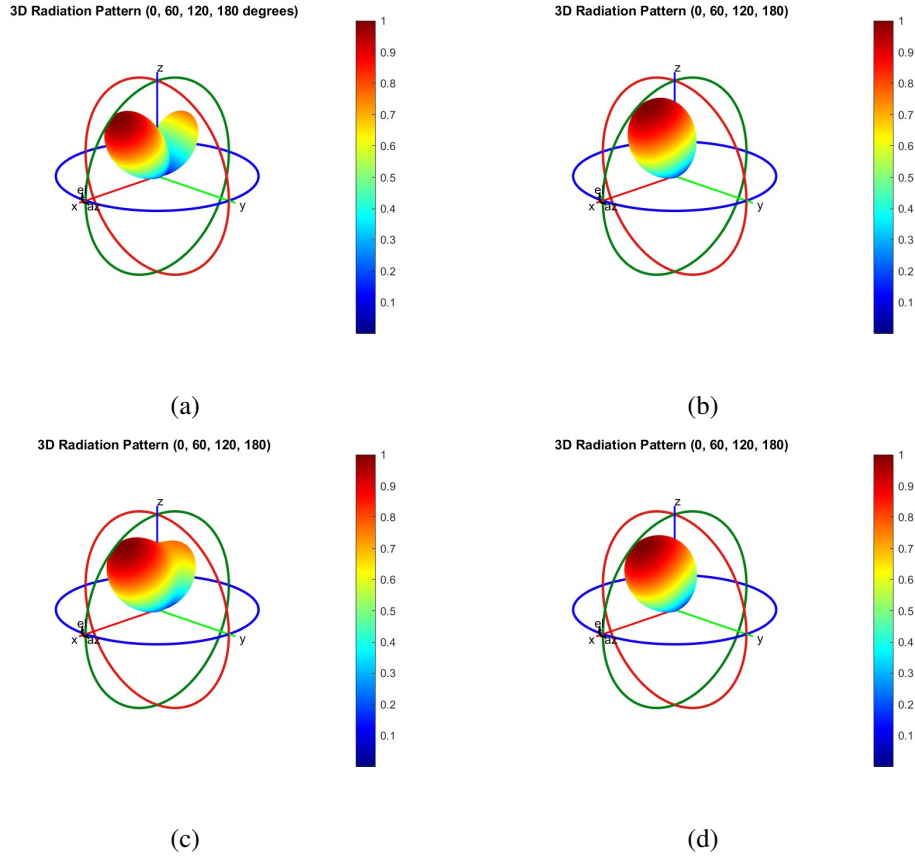


Figure 5.13: Radiation pattern comparison for 2-bit phase limited RIS with 64 elements (a) in near-field with ideal magnitude response, (b) in far-field with ideal magnitude response, (c) in near-field with the measured magnitude response and (d) in far-field with the measured magnitude response

Simulations were conducted for the 256-element RIS to observe how a RIS composed of elements with the measured S11 parameters for the magnitude (non-ideal elements) would perform in comparison to a RIS with ideal performance when its phase is limited. These results can be seen in Figure 5.17

By observing these results, it is possible to see that, when in near-field, the simulations showed that a non-ideal 2-bit phase-limited RIS with 256 elements (Figure 5.17c) would have a performance comparable to the RIS with the ideal parameters (Figure 5.17a). However, when in far-field, the radiation pattern shows that the RIS with the non-ideal parameters (Figure 5.17d) has a significantly bigger lobe in the centre than the ideal one (Figure 5.17b), being almost as intense as the main lobe.

From the analysis of the simulated 2D radiation patterns (see Figure 5.18), it is also possible to see that the phase-limited RIS can beamsteer the signal to the desired direction, both in near-field and far-field, with the main lobe of the radiation pattern successfully reaches the desired direction, demonstrating the RIS's ability to control the phase of the reflected signals accurately. By comparing the simulated results for a RIS with ideal parameters and a RIS with the measured

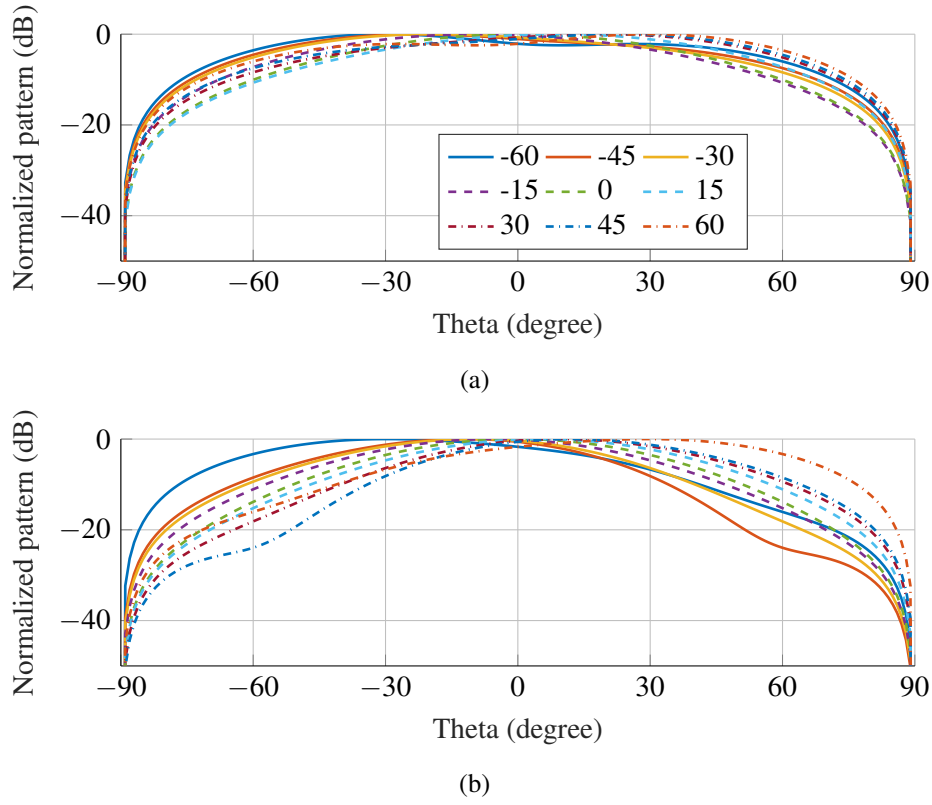


Figure 5.14: 2D radiation patterns for 64-element RIS with non-ideal 2-bit phase-limited elements for (a) near-field and (b) far-field settings

parameters, it is also possible to see that they have similar results in terms of accuracy, however, the non-ideal RIS shows higher intensity in secondary lobes. Nevertheless, the radiation patterns when using non-ideal parameters are sufficiently similar to the ideal RIS performance to justify the acceptance of its performance.

5.3 Summary

In this chapter, an approach to control a 2-bit varactor-based RIS was presented. To test the control circuit, a prototype was developed to control one element and measure its performance through waveguide measurements. However, the element did not perform as intended, showing a maximum range of 180° rather than the 270° required for the 2-bit resolution of control (i.e., four states of control). A possible explanation for this would be some unforeseen parasitic capacity that prevented the varactor diode from reaching the lower levels of 0.23 pF. To verify if a RIS comprising 64 of these elements could still outperform a 1-bit RIS, simulations were made. The simulations demonstrated that, in a near-field setting, a RIS comprising 64 of these elements exhibited performance characteristics comparable to those of a 1-bit RIS when using a RIS composed of ideal elements. When using the measured parameters for the simulations, it is shown that the RIS can barely direct the beam when under a near-field illumination (Figure 5.14a). However,

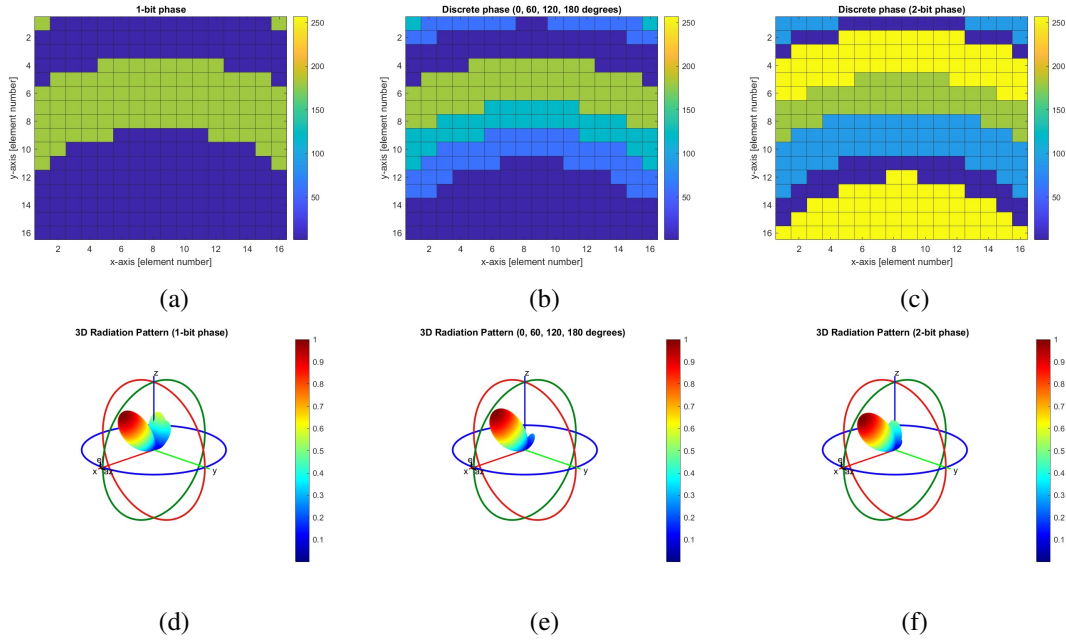


Figure 5.15: Near-field simulation with 256 elements of the discrete phase for (a) 1-bit, (b) 2-bit phase-limited and (c) 2-bit RIS and 3D radiation pattern for (d) 1-bit, (e) 2-bit phase-limited and (f) 2-bit RIS

by increasing the number of elements or by transitioning to a far-field setting, the RIS began to take advantage of the four control states. This demonstrated that the element could perform in a manner similar to that of a 2-bit RIS, indicating that it could be a viable option for use in a RIS operating as a 2-bit controlled by the developed control circuit.

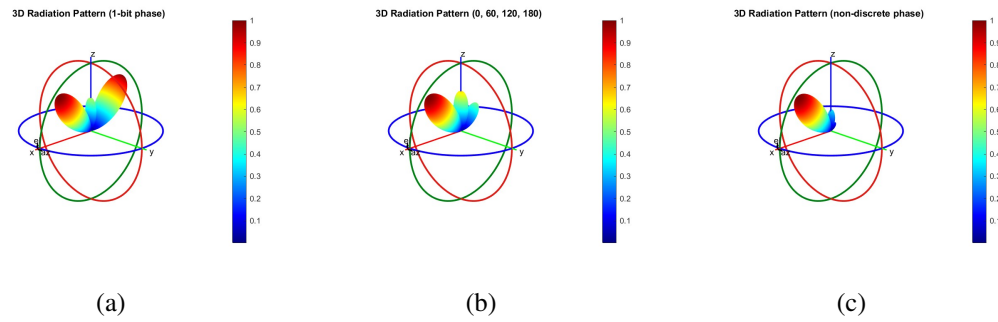


Figure 5.16: Far-field simulation with 256 elements of the discrete phase for (a) 1-bit, (b) 2-bit phase-limited and (c) continuous-phased elements RIS

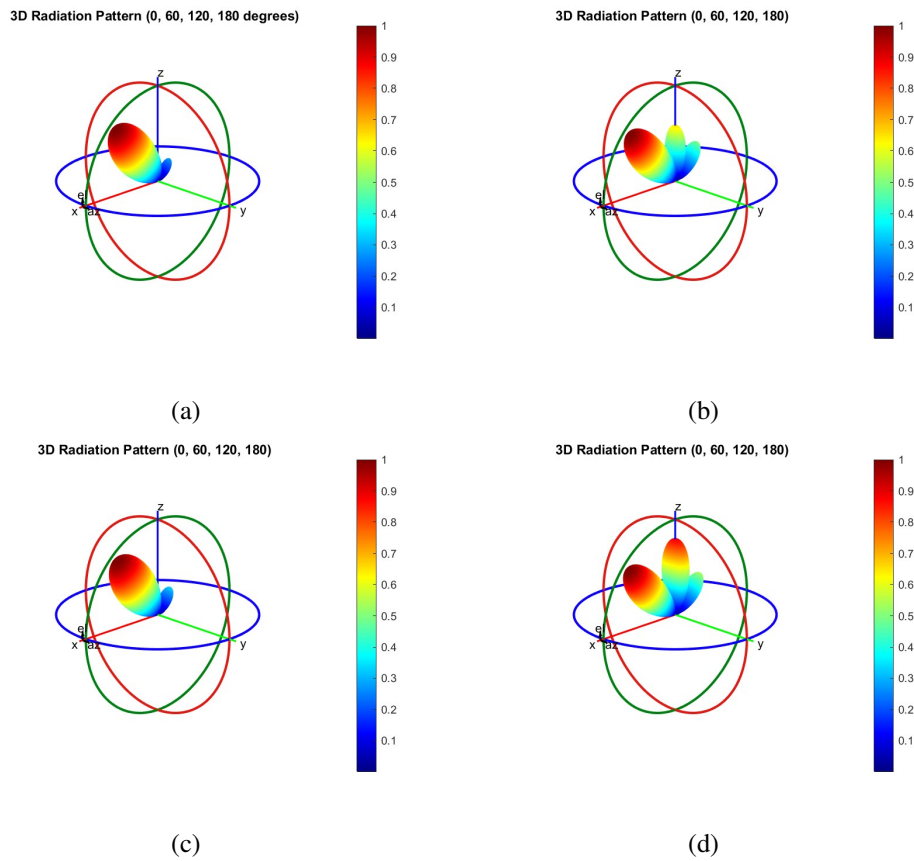


Figure 5.17: Radiation pattern comparison for 2-bit phase limited RIS with 256 elements (a) in near-field with ideal magnitude response, (b) in far-field with ideal magnitude response, (c) in near-field with non-ideal magnitude response and (d) in far-field with non-ideal magnitude response

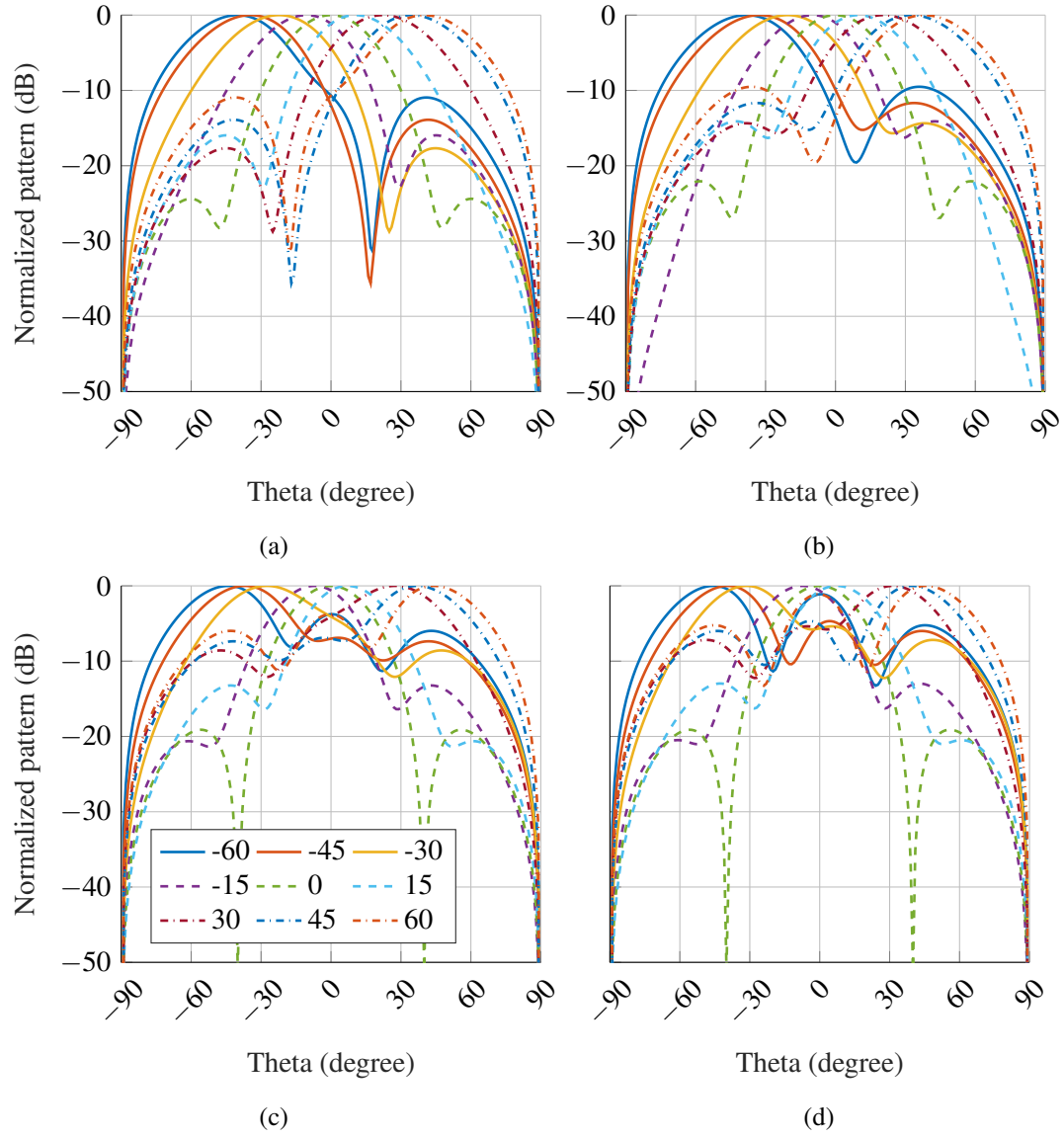


Figure 5.18: 2D radiation patterns for 256-element RIS with 2-bit phase-limited in (a) near-field with ideal parameters, (b) near-field with measured parameters, (c) far-field with ideal parameters, and (d) far-field with measured parameters

Chapter 6

Conclusion

In order to develop the technologies required for the next generation of wireless communications, known as 6G, a revolution in current communications technology will be necessary. RIS has emerged as a promising technology for the wireless communications future, enabling the construction of low-cost smart antennas. These antennas make it possible to redirect a received signal and thus solve the problems caused by obstacles in high-frequency signals. In order to direct the signal effectively, various forms of control can be applied to the RIS, therefore, it is important to characterise and understand the most efficient way of implementing these devices.

The creation of a control circuit requires the consideration of multiple factors, including the type of reconfiguration to be employed. This may be physical/mechanical, optical, or electrical. Consequently, a range of reconfigurable elements may be utilised, including PIN diodes, varactor diodes, and MEMS. Additionally, the number of RIS control bits must be taken into account, as this affects beam factors such as accuracy, sidelobe levels, and complexity.

Given this context, the aim of this dissertation was to develop a control circuit capable of controlling a 64-element RIS with varactor diodes as the reconfigurable element of the unit cells. The research presented in the dissertation introduces different ways of controlling the RIS, analysing their performance, their advantages and disadvantages and their application in the 64-element RIS.

In order to understand the impact that different reconfigurable elements have on the RIS element, a varactor-based element and a PIN-based element were characterised. In addition, a study was also made on the impact of the number of control bits in the varactor diode element on the performance of the complete RIS.

6.1 Satisfaction of Objectives and Future Work

Throughout the development of this project, several objectives were taken into account. However, it was not possible to finalise all of them in the way that had been hoped.

Regarding the control circuit, a prototype was developed which demonstrated the capacity to control an element of the RIS efficiently. However, the complete RIS comprising 64 elements was not produced in time for submission of this dissertation. The same situation occurred with the

control circuit although a PCB schematic was designed for it and so, it was only possible to test the control in one element.

The characterization of the RIS elements (both varactor-based and PIN-based) showed that the elements did not perform the intended way, with the PIN-based element showing its best performance at a frequency lower than the intended and with the varactor-based element being incapable of obtaining the desired phase reach. With this, due to the limitations, instead of comparing the performance of a varactor-based and a PIN-based RIS, a study was conducted through simulations in order to understand the effects of more controllable bits in a RIS with elements that only reach 180° .

With this said, for future work, it would be interesting to try different approaches for controlling the varactor-based element. For example, with more time, it would be worthwhile to finalise the implementation of the control circuit with DAC presented in this thesis and compare it in terms of performance with the implementation used with MUXs.

It would also be interesting to carry out tests using a full varactor 2-bit RIS with the designed control circuit for the 64 elements. Ideally, these tests would be carried out with different elements for both the varactor and PIN models, as the ones tested in this thesis did not work as intended. This should allow more accurate conclusions to be drawn about the effect of the number of control bits.

Finally, for this work, the focus was the implementation of a control circuit for a 2-bit RIS for the frequency of 6.5 GHz, in the future this could also be done for RISs with a higher number of elements and with higher frequencies. Additionally, it would also be interesting to increase the operating frequency and the number of RIS resolution bits to 3 or even higher, possibly even an "infinite" number of bits i.e. a continuous control of 360° over each element.

Appendix A

KiCad schematics

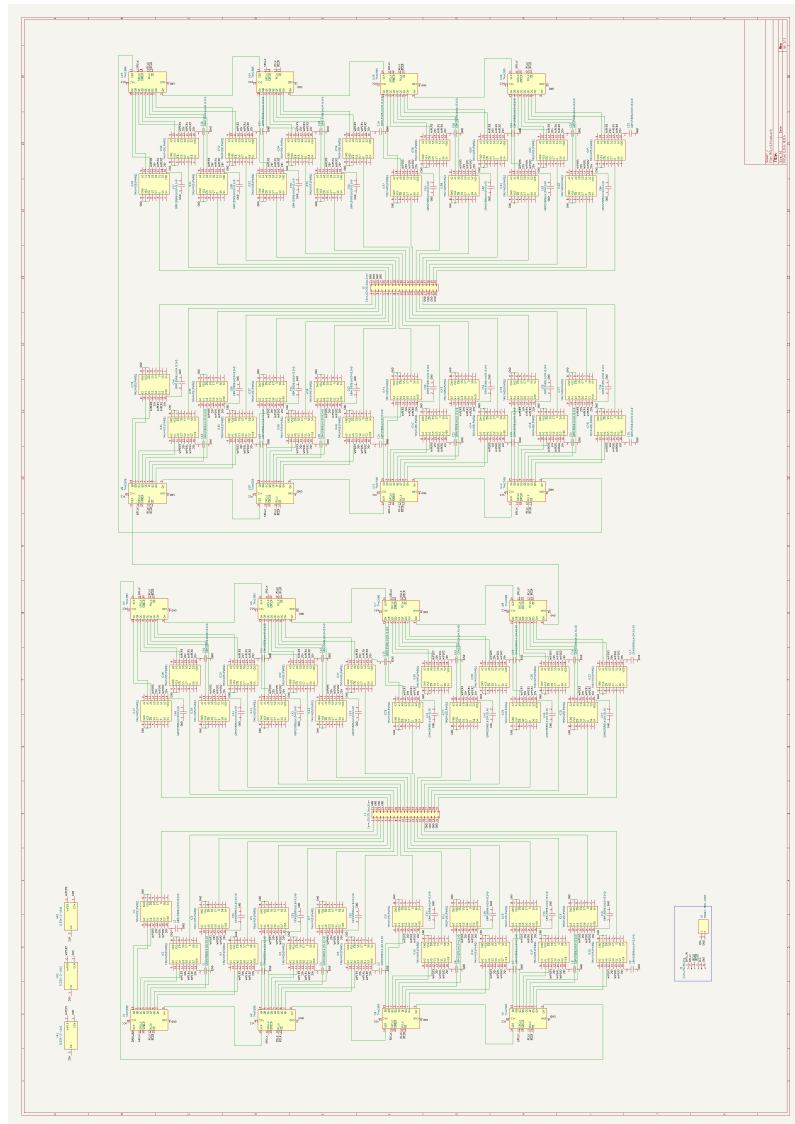


Figure A.1: Schematic of the control circuit for 64 elements

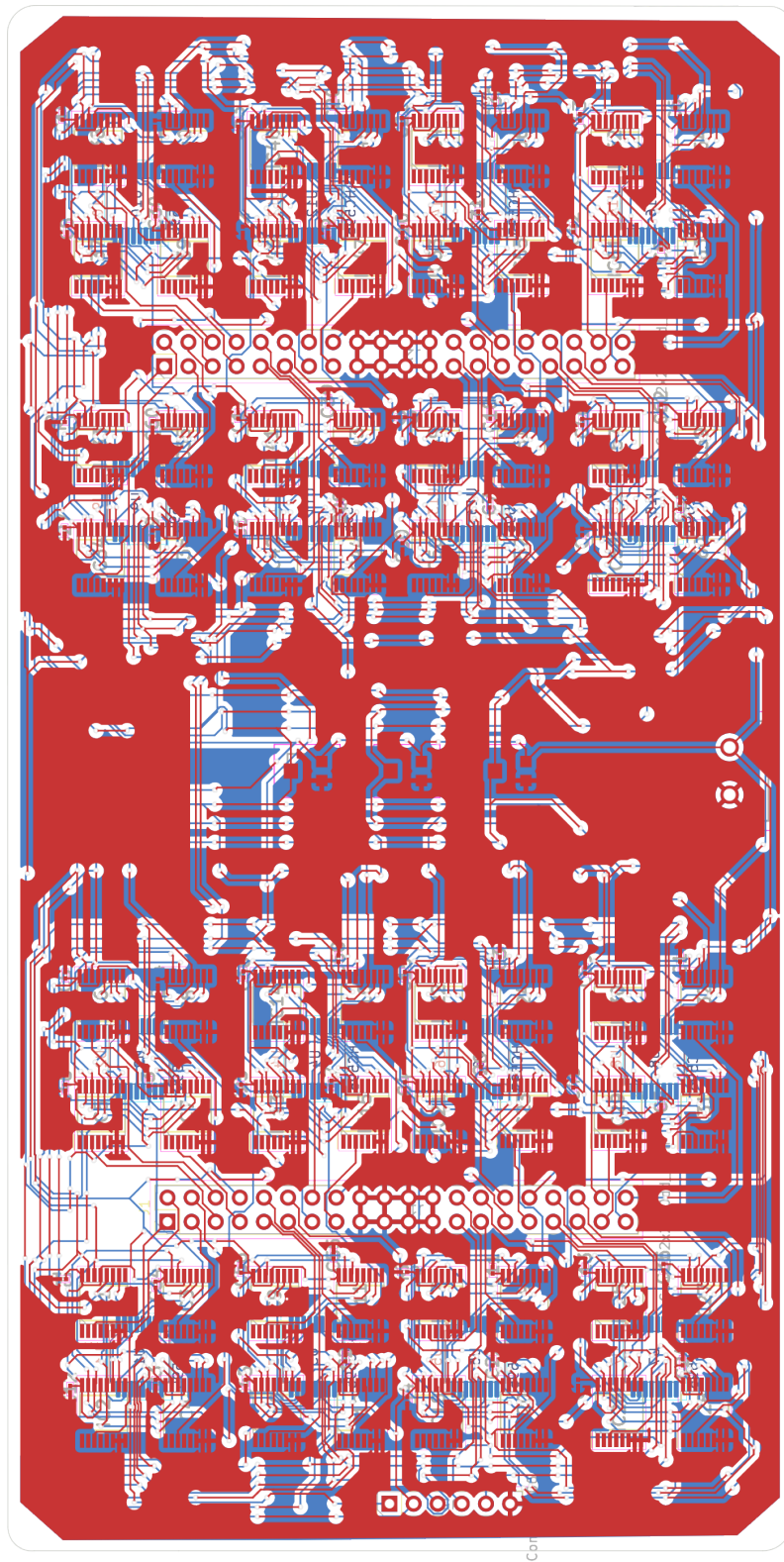


Figure A.2: PCB layout of the control circuit for 64 elements

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