DEPARTMENT OF ELECTRICAL
AND COMPUTER ENGINEERING

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BSc in Electrical and Computer Engineering

DESIGN, SIMULATION AND OPTIMIZATION OF MICROSTRIP PATCH ANTENNAS FOR WI-FI 7

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NOVA University Lisbon
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Acronyms

AI Artificial Intelligence *(pp. 3, 17, 19, 20, 22)*

BCGA Binary-Coded Genetic Algorithm *(p. 17)*

CPW Coplanar Waveguide *(p. 11)*
CSRR Complementary Split-Ring Resonator *(pp. 14, 15)*

DGS Defected Ground Structure *(pp. 9, 14, 15)*

FDTD Finite-Difference Time-Domain *(p. 10)*
FSS Frequency Selective Surface *(p. 11)*

GA Genetic Algorithm *(p. 17)*

HPBW Half-Power BeamWidth *(p. 8)*

LAN Local Area Network *(p. 1)*

MIMO Multiple Input Multiple Output *(p. 15)*
MLO Multi-link Operation *(p. 1)*
MPA Microstrip Patch Antenna *(pp. 1–4, 8–10, 13, 19–22)*

PTFE polytetrafluorethylene *(p. 4)*

SVR Support Vector Regression *(p. 18)*

WLAN Wireless Local Area Network *(p. 1)*

1

Introduction

Wireless communication systems are technologies that transfer information through the air without any physical wires [35]. This way of communicating can be achieved through the use of a Wireless Local Area Network (WLAN) [29]. A Local Area Network (LAN) is a network of computers linked together in a limited geographic area whilst a WLAN is the equivalent without any wire constraints. A WLAN is built on a cellular architecture that divides a system into cells with each being administered by a base station [9]. The benefits of using a WLAN are the mobility, flexibility, ease of management, easy of maintenance and lowered cost [29]. There are multiple standards to a WLAN, also called Wi-Fi standards, some of them being 802.11n (Wi-Fi 4), 802.11ac (Wi-Fi 5), 802.11ax (Wi-Fi 6 and Wi-Fi 6E) and 802.11be (Wi-Fi 7), with these last two being the latest. 802.11ax offered greater throughput, better energy efficiency and enhanced performance in crowded environments [5], but with the increased demand for faster speeds and enhanced reliability in wireless communications [5], the Wi-Fi 7 is the most recent solution developed. The main improvements in Wi-Fi 7 that make it stand out from its predecessor are a channel bandwidth of up to 320 MHz that allows a more efficient and high-speed data transfer. The use of 4096-QAM modulation that lets the data that is transferred to be packed with more information in each radio wave and the introduction of the Multi-link Operation (MLO), that grants users the ability to connect to multiple frequency bands, like 2.4 GHz, 5 GHz, 6 GHz at the same time, giving the user a stable connection with reduced delay[22].

1.1 Problem Statement and Motivation

One of the most common antenna technologies for Wi-Fi 7 and the one this thesis will be focusing on is the Microstrip Patch Antenna (MPA), also called patch antennas. These are a type of antenna that consists of a metallic patch on a dielectric substrate with a ground plane on the other side. According to [24], the MPA was conceptualized in 1953 but only became practical by the 1970's, when low loss substrate materials became more available. At that time patch antennas were being mostly used in spaceborne applications [7], while in current times the MPAs are still used for aerospace applications and low-profile

communications [14].
MPAs are very versatile in their design and can be made to operate at multiple frequencies, as well as adapted to improve their shortcommings, such as their narrow bandwidth and low gain [24]. Therefore, motivation for this thesis is to answer the following question:

> *What are the best techniques to create/optimize an antenna of the type microstrip patch that efficiently operates in three different Wi-Fi 7 (802.11be) bands?*

This problem is relevant because in the current world, there is a growing need for high-speed wireless communication devices that can also handle the volume of data of today's applications [22], and MPAs allow for these objectives to be acheived in compact devices due to their advantages[24].

1.2 Objectives

To properly find an answer to the proposed question, we must first define some objectives:

- Design of a multiband MPA;
- Simulation of the designed antenna using MATLAB;
- Antenna optimization;
- Fabrication and measurement of the antenna's performance.

1.3 Document Structure

This document is devided into four chapters. Starting with this one, and is where the context, problem statement and objectives are presented. The second chapter is a literature review on MPAs, where its fundamentals are explained as well as the implementation techniques for multiband MPAs are shown. The next chapter presents this thesis' work plan, a breakdown of the tasks and respective timeline as well as work done and what is expected to be delivered. Finally, the last chapter presents some conclusions of the work done and some future work to be made.

2

State of the Art

2.1 Fundamentals of Microstrip Patch Antennas

The reason Microstrip Patch Antenna (MPA) are commonly used is due to its advantages, according to [14], some of them are the fact that the antennas' feed lines can be manufactured at the same time as the antenna structure, MPAs can also be integrated with the conventional antenna integrated circuits, they can easily be made with dual frequency and dual polarization, patch antennas are overall easy to mass produce as they have a low production cost and finally MPAs are low profile, meaning they are thin and light weight. Even with the advantages listed before, MPAs also have some drawbacks when juxtaposed to conventional microwave antennas [14] such as a smaller bandwidth, lower gain, poor efficiency, reduced radiated power due to the ohmic loss along the antenna components, difficulty maintaining low sidelobes because of surface wave excitation, cross-polarization problems due to asymmetry of the patch and feed line discontinuities, complex feed structures for high performance arrays and reduced flexibility for omnidirectional designs as it only radiates into half-space because the ground place blocks radiation. Nevertheless, the impact of some of these problems, such as bandwidth and surface wave losses, can be reduced in different ways like the ones mentioned in [8].

This chapter will start by first analyzing a standard rectangular MPA, then an explanation of some of the main performance parameters of an antenna. After these two topics, we will follow with an overview of different geometries, sizing methods, bandwidth enhancement methods, dual and tri-band methods with some use cases, feed methods and in the end some Artificial Intelligence (AI) optimization techniques.

2.1.1 Standard Rectangular Microstrip Patch Antenna

To give context to this thesis, we should better understand MPAs. For this we should start with a brief explanation and analysis of the rectangular MPA using [31] for reference. As stated before, the MPA consists of a metallic patch on a dielectric substrate with a ground plane on the bottom of the substrate. The patch has length L and width W, and the substrate has thickness h and relative permittivity ϵ_r. For this analysis we will assume a coordinate system where the MPA is parallel to the xy-plane.

The next important topic of discussion in this analysis is the substrate's choice as it can affect the performance, accuracy and manufacturability of the MPA. [10] lists some common materials such as polytetrafluorethylene (PTFE), which has low loss and is used in high-performance antennas, FR-4 which is cheap but has high loss and is not ideal for precision antennas and Ceramics which are used for very small patches but can have a very high ϵ_r.

The dominant mode of an MPA is TM_{10} meaning the rectangular patch resonates when its $L \approx 0.49 \cdot \lambda_d$, with λ_d being the wavelength inside the dielectric. This antenna is called half-wave patch and its electric field distribution exhibits fringing fields, which happens when the electric field spills into the air at the edges, making the patch longer than its physical length, this explains why the L of the patch is less than half its wavelength. However, this is just a starting point, where the input impedance is calculated based on the frequency and after finding the resonant frequency the patch is scaled and adjusted to match it. The L of the patch is chosen according to the desired resonance, and the W is chosen according to the input impedance, as a wider patch signifies lower input resistance and a narrower patch the opposite.

The problem with the starting resonant L formula is that it doesn't consider the fringing fields, meaning that the actual L of the antenna is longer than what was calculated. To account for this, the resonant L should be below a half wavelength to still achieve resonance. So, the new formula is $L = \frac{0.5 \cdot \lambda_d}{\epsilon_r} - 2\Delta L$, where $2\Delta L$ is the L of the fringing field on both sides of the patch. To calculate the fringing length ΔL we use

$$\Delta L = 0.412t \frac{(\epsilon_{re} + 0.3)(\frac{W}{t} + 0.264)}{(\epsilon_{re} - 0.258)(\frac{W}{t} + 0.8)}$$

where the effective dielectric constant ϵ_{re} is given by

$$\epsilon_{re} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}(1 + \frac{10t}{W})^{-\frac{1}{2}}$$

which takes into account that some fields are in the dielectric and other in the air.

The radiation pattern of the MPA will have a beam peak in the z-direction, perpendicular to the patch surface. To get the pattern expressions, we first need to understand why the patch radiates broadside and why the feed line doesn't radiate. The first one happens because of the fringing fields at the edges of the antenna that act as two slot antennas separated by L. They are 180° out of phase, but the physical separation introduces another 180° phase shift in the far field, canceling these shifts allowing for the two slots to radiate in phase, making the beam radiate normal to the patch. The feed line doesn't radiate because it is very narrow compared to a wavelength, meaning that the electric fields on its two sides are equal in opposite directions and the radiation of each fringing field cancels in the far field as its phases have a 180° difference. Therefore, the far field pattern is the combination of a sin function from the aperture W and a cos function from the two-slot array separated by L.

The general far-field components, according to [31] and assuming the z-axis is perpendicular to the patch are $E_\theta = E_0 \cos\phi f(\theta,\phi)$ and $E_\phi = E_0 \cos\theta \sin\phi f(\theta,\phi)$. The pattern function, also according to [31], with β being the free-space phase constant, is as follows:

$$f(\theta,\phi) = \frac{\sin(\frac{\beta W}{2}\sin\theta\sin\phi)}{\frac{\beta W}{2}\sin\theta\sin\phi} \cdot \cos(\frac{\beta L}{2}\sin\theta\cos\phi)$$

θ is the elevation angle and is measured from the $+z$ axis down and ϕ is the azimuth angle and is measured in the xy-plane.

This pattern function can be evaluated in two planes: the E-plane and the H-plane. The E-plane, where $\phi = 0°$ is the plane that contains the feed

$$F_E(\theta) = \cos(\frac{\beta L}{2}\sin\theta)$$

and the H-plane, where $\phi = 90°$ is the plane perpendicular to the feed

$$F_H(\theta) = \cos\theta \frac{\sin(\frac{\beta W}{2}\sin\theta)}{\frac{\beta W}{2}\sin\theta}$$

The E-plane can be controlled by L and the H-plane can be controlled by W.

2.1.2 Main Figures of Merit

The performance of an antenna, can be characterized by numerous figures of merit although it isn't required to analyse them all to get a thorough description of the antenna as the importance of each parameter depends on the application of the antenna. It is important to note that some physical characteristics of the antennas can also influence these metrics such as the size of the antenna. According to [7] increasing the height of the antenna's substrate improves both the bandwidth and efficiency, however there is an inherent trade-off with these changes as a taller antenna produces more surface waves which in turn degrade both the radiation pattern and polarization. The metrics that will be considered in this thesis will be described next in this chapter.

2.1.2.1 Bandwidth

The bandwidth, according to [7], is the range of frequencies where the antenna characteristics still have an acceptable value within the center frequency. There are two general ways we can classify an antenna based on its bandwidth: broadband and narrowband. Broadband antennas have a greater range of frequencies acceptable to the center frequency. Narrowband antennas have a smaller range of frequencies allowed on the bounds of the center frequency. A distinction is also made between the reasoning behind these frequencies limits as the antenna characteristics vary for different reasons, one of them being impedance and the other pattern. An impedance antenna is related to input impedance and the radiation efficiency, while a pattern antenna is linked to the gain and the radiation pattern. Small antennas encounter problems related to their impedance bandwidth while larger antennas face difficulties with their pattern bandwidth. If the antenna is neither large nor small, it can be influenced by either problem depending on its application.

2.1.2.2 Gain

The gain of the antenna, according to [7], is the ratio of the intensity of the antenna in one direction by the intensity of the antenna if it was a perfect isotropic antenna. It combines both the antenna's efficiency and its directional capabilities. Usually, the relative gain is what is used. The relative gain has the same definition as the gain, but the values of the isotropic antenna are changed for the ones of a reference antenna whose gain is already known, keeping in mind that both antennas must have the same power input. In [7] two gains are defined: the gain and the realized gain. These can have the same value if the antenna is matched to the transmission line as the realized gain considers mismatch loses.

2.1.2.3 RF Efficiency and Reflection Coefficient

The RF efficiency, or total efficiency, is defined in [7] as the antenna efficiency and is calculated by $e_0 = e_r \cdot e_c \cdot e_d$, where e_r is the reflection efficiency, e_c is the conduction efficiency and e_d is the dielectric efficiency. [7] states that e_c and e_d are usually combined and become the radiation efficiency, which will be explained next. The reflection efficiency, also called mismatch efficiency, is calculated using the voltage reflection coefficient, Γ or S_{11} (if the reference impedance is equal to the system impedance): $e_r = 1 - |\Gamma|^2$. The reflection coefficient, according to [7], is obtained by $\Gamma = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0}$. The voltage standing wave radio, shown in [7], can also be obtained in function of Γ: $VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$. In [31] it is explained that impedance mismatch decreases the power delivered to/from an antenna and that there are numerous ways to quantify this, some of them can be reflection coefficient, VSWR or return loss. Also shown in [31] is the return loss in function of Γ: $RL = -20 \log_{10} |\Gamma|$. Typically, we want a high RL, meaning a low Γ to have a good match. The usual values of these parameters are also shown in [31]: $VSWR \leq 2$, $|\Gamma| \approx \frac{1}{3}$ and $RL \approx 9.5\, dB$.

2.1.2.4 Radiation Eficiency

The radiation efficiency, or just efficiency, is defined by [17] as the ratio of the radiated power by the power received by the antenna. In [7], the radiation efficiency is called e_{cd} and it considers the conduction and dielectric losses a single measurement called loss resistance, and the ratio is of the power sent to radiation resistance by the power sent to both the radiation resistance and the loss resistance:

$$e_{cd} = \frac{R_r}{R_r + R_l}$$

2.1.2.5 Radiation Pattern

The radiation pattern is defined by [7] as a graphical representation in space coordinates of different radiation properties such as directivity, intensity and polarization. It is usually determined in the far-field region in directional coordinates. [7] mentions there are three ways to visualize the signal: field pattern (linear scale), power pattern (linear scale) and power pattern (dB). The field pattern represents the strength of the electric or magnetic field in relation to the angular space. The power pattern in linear scale characterizes the square of the electric or magnetic field also in relation to the angular space. The power pattern in dBs depicts the electric or magnetic field in dBs in relation to the angular space.

The radiation pattern is represented by lobes that are separated by regions of low radiation intensity. As stated in [7] these lobes can be subclassified in major/main lobe, minor lobe, side lobe and back lobe. The main lobe is the one that contains the maximum signal strength. It is possible to have more than one major lobe, [7] mentions split-beam antennas as an example of this. The minor lobe is all the other lobes not considered major and represents the radiation in any other direction as the intended one. The side lobes are a subcategory of these, but they are right next to the main ones. The back lobe is the minor lobe that is exactly 180° away from the main lobe. All minor lobes should be minimized.

To properly analyze the radiation pattern, we must define planes to view it. These planes are the E-plane, that is parallel to the electric-field vector and the H-plane, that is parallel to the magnetic-field vector. [7] explains that with most antennas, it is common to align one of the principal plane patterns with one of the geometrical principal planes. An example mentioned in [7] is of the omnidirectional pattern that has an infinite number of principal E-planes and only one principal H-plane.

According to [7], there are three regions around the antenna: the reactive near-field, the radiating near-field and the far-field. The reactive near-field is the region immediately touching the antenna where the reactive field predominates and the angular field distribution is evenly spread with minor variations. The radiating near-field is the region in between where the reactive field still predominates and depending on the distance from the antenna the pattern may begin to form. For antennas that are roughly the same size as the wavelength and antennas that are very small in size compared to the wavelength this region may not be present. The far-field, where we observe the radiation pattern graph, is where the angular distribution is stable and we are able to see the different lobes.

To measure the radiation patterns size we need to determine its angles, both in the plane field and in the solid field. The radian lets us calculate the width of a beam in the plane field and the steradian lets us calculate the beam's solid angle.

An antenna can have different classifications based on its radiation pattern, [7] describes three. The first one being an isotropic antenna, that emits radiation equally in every direction with no losses. It is only a theoretical concept, but it is used as a reference for real antennas to see how directive they are. The next is a directional antenna, that has one direction where its directivity is much greater than in any other direction, the reference point for these antennas are the half-wave dipole antennas. The last antenna is the omnidirectional antenna whose pattern on the azimuth plane (H-plane) is nondirectional and on the elevation plane (E-plane) is directional, its shape is commonly known as a donut.

2.1.2.6 Directivity

The directivity is defined as the ratio between the radiation intensity in a specific direction and the radiation intensity averaged in all directions, according to [7]. If there is no direction specified, the directivity refers to the direction where the radiation intensity is maximum. The directivity is relative as it compares the directional properties of the antenna to an isotropic one whose directivity is one. [7] mentions that the total directivity for antennas with orthogonal polarization components is the sum of partial directivities of any two orthogonal polarizations. These partial directivities are the radiation intensity in the specific polarization divided by the total average radiation over all directions. Different antennas can have different patterns, and each pattern has a way to approximate its directivity. For directional antennas, who have a single major lobe and insignificant minor lobes, the directivity is based on the Half-Power BeamWidth (HPBW) in two perpendicular planes. For omnidirectional antennas there are two different ways to approximate the directivity: the McDonald function and the Pozar function. The McDonald function is usually more accurate for patterns with minor lobes. The Pozar function is more accurate for patterns with little to none minor lobes. However, these approximations won't work well if there is more than one major lobe or if there are any significant minor lobes.

2.2 Implementation State of the Art

2.2.1 Geometry

An important factor in the design of a patch antenna is its geometry. As said before, MPAs are composed by a metallic patch and a dielectric substrate, for the substrates choice, as stated in [7], what is sought is a thick one with a dielectric constrain in the lower end of the usual range ($2.2 \leq \varepsilon_r \leq 12$), as for the patch there are a variety of different shapes to pick: from the most basic shapes such as rectangular, circular and triangular to some other unique shapes like flowers, trees or butterflies, as seen in [23]. The rectangular patch is considered by [14] as the most basic because it is easy to fabricate, simple to analyze and can be used for a wide range of applications. The circular patch can be seen, also by [14], as an alternative to the basic rectangular shape in certain applications, namely arrays, as it is slightly smaller than it. The triangular shape is stated by [28] to be an alternative to both the rectangular and circular geometries, when the priority is miniaturization as it occupies less metalized area on the substrate than the previous. However, at the present time, especially in Wi-Fi 7, these simpler designs don't satisfy the need for multi-band operation to accommodate multiple services [7], to get this we need modified antenna shapes. Some methods with modified shapes that let multiple frequencies resonate are slotted patches, that allow for dual-band when a U-slot is cut in one of the patches and for triple-band when another U-slot is cut into either patch, as described in [24]. Stacked MPAs which, as mentioned in [23], consist of different layers of dielectric material and patches that allow for a broader bandwidth and gain, however as mentioned before the increase in height causes degradation of the radiation pattern. Defected Ground Structure (DGS), as it is explained in [23], is used on the ground plane changing its paths length, as well as its impedance and capacity values resulting in a larger bandwidth. Fractal geometry, described in [7], as a recursively generated geometry that uses an iterative process which leads to structures that are self-similar and self-affine that provide multiple current paths of different lengths leading to multiple resonant frequencies.

2.2.2 Sizing Methods

Sizing methods according to [7], [14] and [31] are analytical models used as a first step in simulations to determine the physical parameters of the antenna such as the length, width, size of the patch and substrate parameters by evaluating input impedance, pattern, and bandwidth. The most popular sizing methods are the transmission line model, the cavity model and the full wave model.

2.2.2.1 Transmission Line Model

The transmission line model, as stated by [7], is the easiest one and it gives good physical insight, but it is le. It determines the characteristic impedance and the propagation constrain by the patch size and substrate parameters. [14] defines the rectangular patch by four edges where the variation of the field defines if the edge is a radiating type or not. It also uses the mode TM_{10} as an example, explaining that the edges at $x = 0$ and L are radiating types because along them the electric field is uniform and the walls at $y = 0$ and W are non-radiating types because along them there is half-wave variation. For this reason, [14] states that the patch antenna's radiation patterns are treated as an array of two narrow slots separated by the path length. The input admittance is obtained by transforming these edges admittances to the feed point.

2.2.2.2 Cavity Model

The cavity model, as opposed to the transmission line model, is not restricted to rectangular patches and one-dimensional variations. In this model, according to [7], the region between the patch and the ground plane is treated as a cavity, bounded by electric conductors above and below with magnetic walls around. [14] tells us that this model relies on the assumption that, because the substrates is very thin, the fields in the interior region do not vary with z. To accurately determine these fields [14] tells us a good assumption to make is that the wall all around the periphery of the patch is magnetic. For a thin low dielectric constant this wall is placed at a distance approximately equal to its thickness. The problem with this model is that even though the interior fields are easy to determine, this is only correct for the first order because the effect of the exterior fields has been excluded from the interior field determination. Despite this, it is still easy to determine the interior electric field distribution in terms of the cavity's eigenfunctions.

2.2.2.3 Full Wave Model

The full wave model is stated by [14] to be able to overcome the limitations of the other two models. This model includes the effects of dielectric loss, conductor loss, space wave radiation, surface waves and external coupling and removes the simplifying assumptions made by the other models. It maintains accuracy by enforcing the boundary conditions at the air-dielectric interface using Green's functions or differential forms of Maxwell's equations. This method is very versatile as it provides the most accurate solution for the impedance and radiation characteristics, it can size arbitrary shapes, arrays and stacked elements. However, as it is numerically intensive and complex it requires a big computational cost and provides less immediate results. Common popular full-wave techniques, according to [14] are spectral-domain full-wave solution, mixed-potential electric field integral equation approach and Finite-Difference Time-Domain (FDTD).

2.2.3 Bandwidth Enhancement Techniques

The MPA, though widely used, still has the major disadvantages of a narrow bandwidth and low gain. A lot of research has been done to improve these problems while keeping their compact structure, such as in [18]. In this section we will discuss some of these techniques.

2.2.3.1 Slot loading

In the slot technique, slots of various shapes such as U or L [2] or of irregular shapes [20], are implanted on the antenna's patch and strategically alter the current path length and impedance, improving its matching and allowing for a wider bandwidth without increasing the antenna's size. Adding more slots adds new resonate frequencies and therefore the bandwidth is enhanced [20]. The slot method however, can introduce structural instability, surface wave loss [2] and decreased the radiation efficiency [30]. This method can show a decrease, [30], or an increase, [4], in gain depending on the implementation.

2.2.3.2 Defected Ground Structure

In the defective ground structure technique, a defect is engraved on the ground plane beneath the patch, this engraving disrupts the surface wave propagation across the substrate layer. The defects can be simple or more complex depending on the desired performance [20] [4]. This method improves the bandwidth and enhances the radiation efficiency [2] and it can be used in transmission lines, power amplifiers, oscillators and more mentioned in [20] and [4]. The trade-off of this technique, as stated in [2], is the weakening of the ground plane's robustness and it adds complexity to the fabrication process.

2.2.3.3 Advanced Material Integrations

Another bandwidth enhancement method is advanced material integrations [2], that with its integration improves gain and enhances bandwidth. [2] provides us with two examples, the first one being the Frequency Selective Surface (FSS) layers that introduce bandwidth filtering and the other, which is also mentioned in [4], is metamaterials that improve antenna radiation performance as it minimizes the side lobe ratio and improves directivity. However, according to [2] this method increases the antenna's thickness and fabrication complexity as well as the cost.

2.2.3.4 Feeding Techniques

The next method for improving the bandwidth is the feeding technique. This technique has multiple implementations, which are Coplanar Waveguide (CPW)-fed, multiple feeding technique and dual feed technique. The CPW-fed uses a center conductor between two ground planes to feed the antenna. Its advantages and disadvantages are mentioned in [2]: it makes fabrication simple and keeps the antenna compact, but without a design optimization it can have radiation losses and lack of impedance match. The multiple feeding technique is, as stated in the name, the use of multiple feed lines to feed the antenna in multiple points. According to [30] this causes an increase in the radiation efficiency and impedance match. It enhances the bandwidth because it creates multiple resonance frequencies close to one another. The dual feed structure is mentioned in both [20] and [4], it works by having two feed points in one or two patches and is used to control the vertical mode and prevent other modes from being excited. It prevents polarization degradation, helps with impedance matching and improves gain. Some feeding methods not included in this category that also increase bandwidth will be explained further in the feeding methods part of this thesis.

2.2.3.5 Parasitic Patch

The parasitic patch method is a technique that works by adding extra radiating patches that are not being fed near the main radiating patch, allowing them to couple with the main patch causing multiple frequencies to resonate close to each other enhancing the bandwidth [30]. It is used to improve gain according to [20] and [4] and it has better impedance matching and radiation efficiency according to [30]. This technique can have two configurations that are mentioned in both [20] and [4]: the coplanar technique and the stacked technique. In the coplanar technique, multiple patches are coupled on a single plane above the dielectric substrate and one of them is given radiation, becoming the main patch. In the stacked technique, the patches are stacked vertically with a dielectric layer in between, which allows the patches to share common aperture area. In this last configuration the parasitic patches with lower dielectric constant are added on top of the radiating patch, which gives us the advantages mentioned before while maintaining its physical size.

2.2.3.6 Air Gap

The air gap method is a method that utilizes air as the substrate in between the ground and the radiating patch. According to [30], it is used to overcome the limitations of high dielectric materials such as lower radiation efficiency, gain and narrower bandwidth. The use of air as a dielectric substrate, stated by [20] and [4], allows for an effective radiation pattern and low return loss. This happens because air has lower permittivity. According to [20] this technique creates more directive antennas. It is also explained in [20] that using this technique in a single patch and in an aperture-coupled antenna, allows for two frequencies to resonate in the structure. Both [20] and [4] state that increasing the height of the air gap causes the distance between the two frequencies to decrease, which is useful for bandwidth enhancement and gain improvement.

2.2.3.7 Shorting Pin

The shorting pin technique, according to [20] and [4], works by adding a pin to the patch antenna, which leads to a decrease in the resonating frequency while maintaining the antenna's size. Both references state that to increase high impedance matching, the pin must be placed close to the antenna's feed point. [20] states that the shorting pin model allows for lower resonance frequency, which in turn allows for a bigger degree of miniaturization for a fixed frequency. In addition to improving both bandwidth and gain this method helps decrease cross-polarization levels.

2.2.3.8 Dielectric Substrate

According to [20] and [4] the primary function of the substrate is to provide strength to the antenna's structure. The choice of material is essential as it directly impacts some critical parameters such as bandwidth, efficiency and radiation pattern. [4] states that low dielectric constants usually provide excellent performance in terms of higher bandwidth, in comparison to high substrate constants. [20] and [4] mention that the propagation of surface waves' state can be reduced by choosing the correct dielectric substrate. Furthermore, [4] states that the bandwidth can be improved by using multilayer dielectrics.

2.2.4 Dual and Triple Band Methods

The need for multiband MPAs was already mentioned in the geometry section. Continuing that idea is [33], that also mentions its need in compact communication devices and systems to allow for multiple wireless communication standards in a single antenna system. Different methods to achieve dual and tri-band antennas are: through the geometry of the antenna, through feeding techniques, by adding multiple resonant elements, through loading and traps, through metamaterials or through hybrid techniques.

2.2.4.1 Geometry

The geometry techniques are slots, such as U, E and H, which work by having secondary resonant paths allowing for dual-band if there is only one slot, and tri-band if another one is added, this fact is stated in [24]. In [3], in addition to an U-shaped slot we can see I-shaped and T-shaped slots. The next geometry method is fractal geometry, whose patterns allow for multiple paths of different sizes. In [38], they mention that the most common fractal geometries are: Hilbert curve, Sierpinski gasket, and Koch snowflake and in addition to those, the paper focuses on an H-fractal antenna. In [27], Sierpinski gasket is the topic of study, and it also states that fractal antennas are inherently multiband. The last geometry method is the meandered fork-shapes, which works as a combination of the action of meandering, meaning the arms of the fork are folded to achieve miniaturization, and a fork shaped antenna. The benefit of meandering, stated in [25], is that it increases the electrical length of the antenna without increasing its size. Each arm of the fork-shaped antenna corresponds to a different resonance, and each stub corresponds to a specific frequency band, this is explained by [39]. The benefit of this fork shape is that each stub can be individually adjusted, allowing to shift a frequency without compromising the rest.

2.2.4.2 Feed

The feeding techniques are three, two of them will be further explained in the feed methods chapter of this thesis and the third was already explained about in the bandwidth enhancement methods. These are aperture coupling, proximity coupling and dual feed techniques. For the aperture coupling, [36] explains that it is a non-contacting feeding method where the feed line and the patch aren't directly connected. In the same paper, it is stated that with this feeding method an antenna can operate at dual frequency just by modifying. Finally on that same paper, it is said that dual frequency aperture coupled antennas can substitute large bandwidth planar antennas, as having two distinct bands allows for separation of transmit-receive functions. For the proximity coupling, also a non-contacting feeding method, where two substrates are used: one as the feeding line and the other the radiating patch. In [21], proximity coupling is used in an antenna with two spiral strips of different lengths, which generate different frequencies based on its dimensions allowing for a tri-band antenna with omnidirectional radiation patterns. For the last method, the dual feed, as it was explained in a previous chapter, works by having two feed lines connected to the same patch in different points. In [16], this method is obtained by using a planar feed and a coupled feed to excite different frequencies, these frequencies don't interfere with each other as they are electrically different and physically separated.

2.2.4.3 Multiple Resonant Elements

For multiple resonant elements, we will only explain stacked patches and coplanar parasitic elements. Stacked patches work by stacking extra radiating patches that are not fed but get energy by coupling with the main patch. They were already mentioned in the bandwidth enhancement methods chapter as they work for both broad banding and multi banding, more specifically for dual band, as stated in [13], by having the two stacked patches have different relative dimensions. Coplanar parasitic elements work by placing other elements on the same layer as the patch which is the only one being fed. This works as the parasitic elements stated before in the bandwidth enhancement chapter. An example of this is in [6], where two U-shaped parasitic elements are placed around the patch. In this paper the two elements are responsible for the second and third frequency bands, as they have different sizes, they vibrate at different frequencies.

2.2.4.4 Loading/Traps

Loading techniques work by adding structures that "load" the antenna. This can be done through reactive loading, shorting pins or DGS, the last one was also mentioned in the bandwidth enhancement methods. With reactive loading we can achieve a dual-band antenna like in [10], and it works by loading the patch with a rectangular slot in a specific position and size. This creates a new path of different electrical length allowing for a second frequency to resonate. With shorting pins, we can achieve a dual-band antenna like in [26] by placing physical metallic pins connecting the radiating patch and the ground plane. These pins are inserted in a specific location to tune the input impedance of the TM_{01} mode and the feed is placed to provide the desired input impedance of the TM_{03} mode, making the antenna support two different resonant modes.

2.2.4.5 Metamaterials

For metamaterials, which are layers placed above the antenna radiator used to redirect, focus or create new electromagnetic resonances, we have complementary split ring resonators and superstrates. Complementary Split-Ring Resonator (CSRR), exhibit negative permittivity and permeability. In [1] the CSRR are embedded on the ground plane and act like an artificial resonator, which allows for multiband design as the new resonances are created by the excitation of the CSRR. In the same paper we can see the multiband designs, as it is shown that adding one CSRR introduces a new lower frequency to the patch making it dual band, while adding two CSRR of different sizes introduces two new unique frequencies making it tri-band. Superstrates such as the superstrate metal ring used in [11], work by "splitting" a single band into two bands, a resonating lower band because of the radius of the metal ring and a higher band due to the induced electrical fields between the patch and the superstrate.

2.2.4.6 Hybrid

The final method to achieve dual and triband antennas is a hybrid method. Hybrid methods are a combination of two or more of the methods stated, such as in paper [16], dual feed is used to get two different resonant modes and to achieve high isolation in a small antenna, a T-shaped slot is cut into the radiating patch and a L-shaped slot is cut into the ground patch. The combination of these two techniques allows for a good isolation from signal leaks onto each port, resulting in high radiation efficiency of the dual band antenna. [31] can also be considered a hybrid method as it combines both parasitic elements and U-slots. DGS which were mentioned in the bandwidth enhancement chapter, could also work for multi bands as it can introduce new resonant frequencies, however as in [19] it usually doesn't work alone making it a hybrid method. In [37], aperture coupling is used in combination with air gap stacked patches, which work for dual-band and possibly tri-band with the aperture coupled patch creating the lower band and the stacked patch creating the second, the air gap can tune the resonant frequencies.

2.2.4.7 Use Cases

Referring back to the beginning of this section, where the need for multiband antennas is mentioned, we will now see two examples of this. The first one being [34], which proposes a tri-band antenna for Wi-Fi 7, suitable for Multiple Input Multiple Output (MIMO) applications and mobile access points. The paper proposes an antenna with high antenna efficiency and stable radiation patterns. The second one being [32], which presents a multiband antenna design for smartwatch devices. This last antenna was projected with a large amount of resonant frequencies and it even includes extended band for future generation compatibility.

2.2.5 Feed Methods

For the feeding of the microstrip antenna there are many configurations that can be used, the four most popular ones according to [7] are the microstrip line, the coaxial probe, the aperture coupling and the proximity coupling. To choose the appropriate feeding technique we have to take into consideration some factors. [14] considers the efficiency of power transfer between the feed line and the antenna one of those factors, because if there is no impedance matching there will be surface wave loss and some unintended radiation leaking from the feed leading to bigger side lobes. A good choice of feeding method is one that minimizes this unintended radiation according to [14].

2.2.5.1 Microstrip Line Feed

The microstrip feed line, also known as inset feed, is a narrow strip of metal, much thinner than the patch itself that connects directly to its edge. The inset feed advantages, mentioned in [7], are the ease of fabrication, simplicity to match (just adjust the inset position) and model. The disadvantages are also mentioned in [7] where it is explained that with the thickness increase of the substrate there will be an increase in unintended radiation and surface waves, these factors will limit the usable bandwidth to a very narrow range.

2.2.5.2 Coaxial Probe Feed

The coaxial probe feed is also easy to fabricate and match. A description of the feed is presented in [14], where it is said that the center coaxial conductor passes through the substrate and is soldered onto the antenna patch where the best impedance match is achieved, and because of this it has low unintended radiation. Its disadvantages are mentioned in [7], with them being, much like the previous one, having a narrow bandwidth and being difficult to model. [7] mentions another problem shared by both the microstrip feed line and the coaxial probe feed: they possess inherent asymmetries, because they connect to the patch at a single point or edge. This problem generates higher order modes which in turn produce cross-polarized radiation.

2.2.5.3 Aperture Coupled Feed

To solve the problems of narrow bandwidth, unintended radiation and cross polarization presented by both the microstrip feed line and the coaxial probe feed, the aperture coupling microstrip feed was introduced. The aperture coupling feed is a non-contacting technique that, according to [7], consists of two substrates separated by a ground plane. A microstrip feed line is located on the bottom side of the lower substrate and the radiation patch is on the top side of the upper substrate. The feed line couples its energy to the patch through the slot between the substrates. The advantages of this feed can be taken from [7] and [14] and they are improved bandwidth, independent optimization of the feed mechanism and of the radiation element, prevents united radiation and improves polarization purity, because the ground plane creates a shielding effect. The disadvantages of this feed line can be found in [7] and they are the increased difficulty of fabrication and the added complexity to match.

2.2.5.4 Proximity Coupled Feed

The last feeding method mentioned was the proximity coupled microstrip feed, which [14] also mentions as electromagnetically coupled microstrip feed. This is also a non-contacting feed technique that uses two substrate layers where the lower layer has the feeding line, and the top layer has the radiating patch. In this case the energy is capacitively transferred through the substrate layers. The advantages of this method, stated in [7] and [14], are larger bandwidth than the rest, reduced unintended radiation, as there is no soldering, cross polarization and pattern degradation problems are reduced and it has flexibility in the design. The disadvantages are also stated in both books, and they are the difficulty in fabrication and the lack of the shielding effect created by the slot in the aperture coupling feed method.

2.2.6 AI Optimization

Usually, to find the right antenna dimensions for dual and tri-band antennas engineers can use mathematical formulas or even trial and error. The problem with these methods is the many variables an antenna has, making it hard and time consuming to find the perfect antenna combination. A solution to this problem is the use of AI and Machine Learning to help us find the best design for our needs.

2.2.6.1 Genetic Algorithm

An AI method used for optimization is Binary-Coded Genetic Algorithm (BCGA), an example of this is [12] where it is used to improve a tri-band antenna. The Genetic Algorithm (GA) works by making iterations including selection, reproduction and variation. It starts with random antenna designs and after testing each design, selects the ones with the best tri-band response and combines them to get a new generation of antennas, it also adds random changes to maintain diversity. The BCGA in [12] works by adding or removing radiating cells from the patch allowing for non-intuitive shapes. This method reduces complexity and residual radiation and improves the impedance bandwidth, directivity and gain. However, this method needs significant computation resources and several interactions making the design cycles longer.

2.2.6.2 Support Vector Regression

The method to solve this, stated in [15], is the Support Vector Regression (SVR), a supervised machine learning technique, that predicts performance and optimizes the design parameters of the antenna more efficiently. It is best suited for complex and nonlinear relations between the antenna's physical dimensions and its performance parameters. SVR works by first running many simulations to create a dataset, after this training is done the model can instantly calculate the best dimensions to achieve any specific dual or tri-band antenna. The advantages of this method, according to [15], are the speeding of the optimization process and minimizes the necessity for lengthy simulations.

3

Work Plan

As it was proposed in the first chapter and the title, the main purpose of this thesis is the design, simulation and optimization of MPAs for Wi-Fi 7. The development approach includes theorectical research, preliminary designs, simulation in MATLAB and fabrication of the designed antenna for validation of the results. An initial analysis was needed to better understand the standards, techniques and multiband approaches for MPA. Only after that, the design, simulation and optimization part of this thesis actually start. In the following section a task breakdown of the development approach is presented. A timeline of the tasks will also be presented as well as the preliminary work and the expected deliverables.

3.1 Tasks

Following that explanation, the tasks proposed for the development of this thesis are as follows:

Task 1 - Background Analysis and State-of-the-art: In this first task, research is made to better understand Wi-Fi 7 and MPAs. Different MPA methods were studied, and a literature review is conducted including some multiband methods for the MPA.

Task 2 - Specifications Definition and Preliminary MPA Designs: In the second task, the antenna's specification will be defined based on Wi-Fi 7 standards and an analysis of the optimal geometry/substrate/feeding methods will be conducted. An antenna will be designed using MATLAB scripting.

Task 3 - Simulation and Optimization: In the third task, the main figures of merit, including radiation patterns, S-parameters and radiation efficiency will be simulated. Then a multi-objective optimization that includes area, bandwidths, antenna gain and performance stability will be conducted using MATLAB. In this phase some AI optimization techniques will also be cosidered.

Task 4 - Fabrication and Measurements: In the fourth task, final considerations and insights will be thought off. The project files will be generated using MATLAB (Gerber) and the antenna PBC will be manufactured. After that, the performance metrics will be measured and a final discussion and comparison between theory, simulation and experimental data will be made.

Task 5 - Thesis writting: The fifth task, will run in parallel with the other tasks, as it is important to do it continuously so that no detail from other tasks is forgotten.

3.2 Timeline

The time allocated for each task will be as follows:

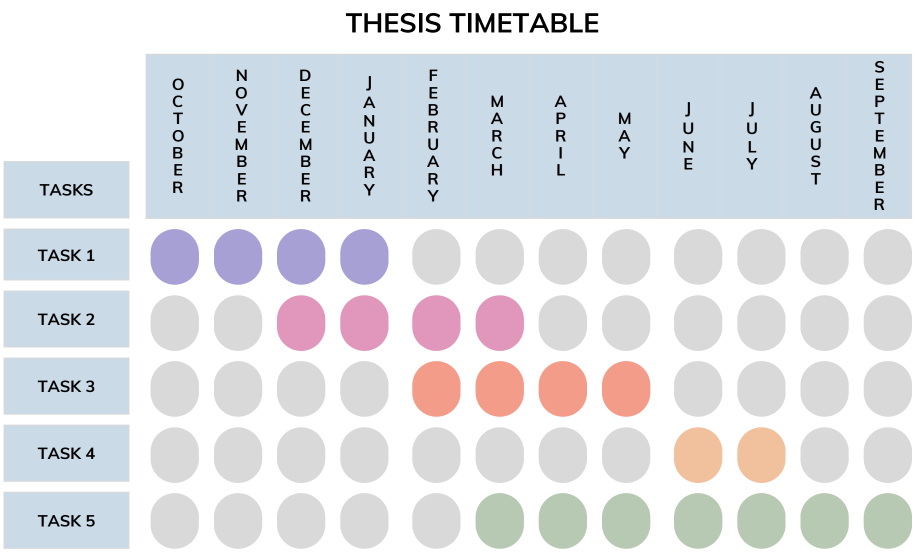

Figure 3.1: Timeline for the tasks in a Gantt chart (October 2025 - September 2026)

3.3 Preliminary Work and Expected Deliverables

The preliminary work that was done for this thesis was only theorectical, as it was essencial to learn about an antenna's main performance metrics, some of its geometries, different feeding, sizing and bandwidth enhancement methods. It was also important to learn the basics of a rectangular MPA analysis and on the other side of the spectrum, it was essencial to learn different techniques for multiband MPAs and some AI optimization methods. For the simulation part of this thesis, MATLAB was the chosen tool, as it has a vast library for antenna design and simulation including some pre-made examples.

The expected deliverables for this thesis are:

- the final design parameters of the optimized MPA for Wi-Fi 7;
- the final MATLAB script;
- the Gerber files generated from MATLAB;
- the manufactured MPA;
- the performance metrics measurements of the final MPA;
- the comparision results between theory, simulation and experimental data.

4

Conclusions

In this final chapter, some conclusions and future work will be presented. This preparatory report focuses mostly on the theorectical part of the work, where first we understand MPAs and their characteristics, and then present possible techniques to answer the proposed question. In the first part of chapter two, we saw the advantages and limitations of MPAs, as well as, their main performance parameters and the analysis of a basic rectangular MPA. Then, in the second part of the same chapter, we saw multiple geometries and techniques for sizing, bandwidth enhancement, feed and methods to acheive dual and tri-band operation, as well as, some use cases of multiband MPAs. Finally in the end of that chapter, we looked at some AI optimization techniques for the design of MPAs. In the third chapter of this work, a timeline and work plan was presented, with tasks, which include the objectives defined in chapter one, to find the solution to the problem.

The future work is the major step to answer the proposed question. Starting with the definition of the specifications for the MPA and its preliminary design. After this, the chosen design will be simulated to find the antenna's performance metrics and then optimized. Once the final design is acheived, the fabrication of the antenna will proceed and real world measurements will be made. These measurements will then be compared with those obtained in the simulation to validate the design.

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