



ESCOLA NAVAL

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GMAR EN-AEL Catarina Calvão Candeias

Design and Study of a Wearable Antenna for Aquatic Communication

A dissertation submitted in partial fulfillment of
the requirements for the degree of Marine Military
Sciences, specialisation of Naval Engineering in Weapons
and Electronics



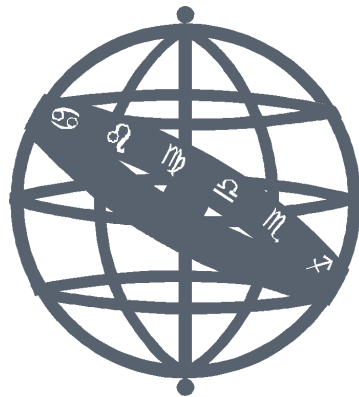
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Orientation of: João Monteiro Felício

Co-orientation of: Bruno D. Damas and Carlos A. Fernandes

The Master Student,

Assinado por: **Catarina Calvão Candeias**
Num. de Identificação: 15003492
Data: 2025.09.26 11:55:48+01'00'

Catarina Candeias

The Supervisor,

Assinado por: **João Manuel de Almeida Monteiro
Felício**
Num. de Identificação: 13726816
Data: 2025.09.25 21:54:16+01'00'

João Felício

Alfeite
2025

In loving memory of my dear grandfather, whose example continues to inspire me.

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The conclusion of this dissertation marks the end of my journey at the Naval Academy, a path that would not have reached a successful outcome without the support and help of those around me, to whom I am deeply grateful.

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Abstract

Efficient communication in aquatic environments remains a significant engineering challenge, due to the high permittivity and conductivity of water, which cause severe attenuation of electromagnetic waves. This dissertation explores a practical solution: the design and simulation of a wearable antenna integrated into a swimmer's suit, aiming to enable reliable short-range, of a few centimeters, communication between the user and an external receiver. Such a system is particularly relevant in scenarios where mobility, comfort and operational efficiency are essential, including aquatic sports, search-and-rescue missions and military operations. The antenna was designed to operate at 2.45 GHz, a frequency within the Industrial, Scientific and Medical (ISM) band, due to its compatibility with low-power wireless protocols such as Bluetooth. A theoretical analysis of electromagnetic wave propagation in water was conducted, including the impact of human tissue and water attenuation and material influence. Link budget calculations and analytical models were used to compare multiple operating frequencies and to define antenna positioning scenarios. Two antenna topologies were initially analyzed through numerical simulations using CST Studio Suite, the Inverted-F Antenna (IFA) and a Slotted Patch antenna. The latter antenna was selected and further optimized for integration into a flexible neoprene layer, simulating realistic wearable conditions near the human body. Further studies concluded that this antenna was sensitive to water layers changing its resonant frequency significantly. A search for an alternative antenna was needed. The study introduced a third antenna, the Wearable Parallel Patch Antenna (WPPA), simulations and experimental work were conducted and prevailed and the trials demonstrated good enough results for its fabrication. A homogeneous phantom was fabricated to replicate the dielectric properties of muscle tissue at 2.45 GHz, enabling realistic physical testing of the antenna in aquatic and non-aquatic environments. Experimental measurements were conducted using the fabricated antenna, and the final results showed a good agreement with the simulations. The WPPA exhibits a linear polarized antenna with a bandwidth of $|S_{11}| < 10dB$, achieving a gain of -5.11 dBi in the water environment and 6.36 dBi in the air environment. To enable data collection from the WPPA, an ESP32-CAM microcontroller with integrated Bluetooth was connected to it, while a second

ESP32-CAM was linked to the receiving antenna positioned outside the aquatic environment. This setup allowed the external antenna to capture both the distance between the two antennas and the Received Signal Strength Indicator (RSSI). Future research would be valuable to further investigate the practical application of this approach, particularly in using ESP32-CAM units with external antennas for wireless real world implementations.

Keywords: Wearable antenna; Aquatic communication; air-water interface; WPPA; Neoprene; Phantom model; 2.45 GHz frequency

Resumo

A comunicação eficiente em ambientes aquáticos continua a representar um desafio significativo para a engenharia, devido à elevada permitividade e condutividade da água, que causam uma forte atenuação das ondas eletromagnéticas. Esta dissertação propõe uma abordagem prática baseada no desenvolvimento e simulação de uma antena incorporada no vestuário do utilizador/nadador, concebida para permitir uma comunicação fiável, de curto alcance, com um recetor externo. A solução proposta assume particular relevância em contextos onde a mobilidade, o conforto e a eficiência operacional são determinantes, como nos desportos aquáticos, em missões de busca e salvamento e em operações militares.

A antena foi concebida para operar a 2.45 GHz, uma frequência pertencente à banda ISM (Industrial, Científica e Médica), pela sua compatibilidade com protocolos de comunicação sem fios de baixa potência, como o Bluetooth. A investigação incluiu uma análise teórica da propagação de ondas eletromagnéticas na água, considerando o impacto dos tecidos humanos, a atenuação induzida pela água e a influência dos materiais. Efetuaram-se cálculos para o *link budget* para verificar a validação da frequência de operação.

Duas topologias de antena foram inicialmente analisadas através de simulações numéricas com o software CST Studio Suite: a antena Inverted-F (IFA) e uma antena *Slotted Patch*. Esta última foi selecionada e posteriormente otimizada, em CST, para integração numa camada flexível de neoprene, simulando condições realistas *wearable* junto ao corpo humano. Estudos adicionais revelaram que a antena era sensível à presença de camadas de água, alterando significativamente a sua frequência de ressonância, o que motivou o desenvolvimento de uma nova configuração alternativa. Foi então introduzida, uma terceira antena, a designada *Wearable Parallel Patch Antenna*, WPPA, tendo esta sido submetida a simulações que justificaram a sua fabricação. Posteriormente a WPPA foi submetida a testes de validação experimental que demonstraram resultados positivos.

Para validação experimental, foi ainda desenvolvido um phantom homogêneo para replicar as propriedades dielétricas do corpo humano a 2.45 GHz, permitindo a realização de testes físicos realistas da antena em ambientes aquáticos e não-aquáticos. Foram realizados testes experimentais utilizando a antena fabricada, e os resultados finais apresentam uma boa concordância com as simulações. A WPPA apresenta polarização linear, com uma largura de banda definida por $|S_{11}| < 10dB$, obtendo um ganho de -5.11 dBi in no ambiente aquático e de 6.36 dBi no ambiente fora de água.

Para possibilitar a recolha de dados a partir do WPPA, este, foi ligado a um microcontrolador ESP32-CAM com *Bluetooth* integrado, enquanto um segundo ESP32-CAM foi ligado à antena recetora posicionada no exterior do ambiente aquático. Esta configuração permitiu à antena externa obter tanto a distância entre as duas antenas como o *Received Signal Strength Indicator* (RSSI). Para trabalho futuro, seria de grande interesse aprofundar a aplicação prática desta abordagem, nomeadamente na implementação de unidades ESP32-CAM com antenas externas em cenários reais de comunicação sem fios.

Palavras-chave: Antena *wearable*; Comunicação aquática; *Interface* ar-água; WPPA; Neoprene; Phantom; Frequência de operação 2.45 GHz

Statement

I declare that I have used generative artificial intelligence tools for spelling and semantic correction of the text

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Chapter 1

Introduction

1.1 Motivation and Objectives

Communication in aquatic environments plays an important role across various fields, including sports, military operations, maritime rescue and scientific studies. Often, it is necessary to communicate with people on the water's surface to ensure safety or to monitor real-time transmission of data, such as in the case of athletes, divers or rescue teams. However, for effective communication in such conditions, it is necessary to develop communication systems specific to this type of environment, as water and the human body present characteristics that hinder signal transmission.

Radiofrequency communication, despite facing challenges such as the attenuation of radio waves in water, the influence of the human body and the material coating the antenna, remains the most effective option for this study. This is because, in the context of this study, communication will be established between an antenna positioned on the water's surface and another located outside of it, therefore requiring the transition between two environments with significantly different physical properties.

Water has properties that directly affect the propagation of radio waves, causing significant losses in signal strength. This phenomenon is caused by the attenuation of radio waves as they propagate through water. Water absorbs and scatters electromagnetic waves, resulting in a rapid decrease in signal intensity with depth, which can considerably reduce the range and quality of communication.

Communication is facilitated through a wearable antenna, which directly impacts the swimmer's mobility. Wearable antennas are portable devices that can be integrated into the user's clothing, close to the human body. The use of these

antennas present additional challenges, as they must be designed to function effectively both in water and in the context of the human body. The human body consists of tissues that absorb and reflect electromagnetic signals, which can affect transmission quality and antenna performance. Therefore, the presence of both water and the human body requires selecting an antenna that can balance the characteristics of the aquatic environment with the limitations imposed by the body, additionally some type of wearable material is needed to support the antenna and the material itself may contribute for these limitations. In this context, the antenna should be lightweight and comfortable to avoid interfering with the swimmer's natural movements. It is essential to ensure that communication remains efficient without compromising the swimmer's performance or comfort during use. Therefore electromagnetic communication is particularly relevant, as it offers a solution that does not require wires or large devices, enabling efficient and unobstructed communication.

In addition to electromagnetic communication, there are other methods, such as optical and acoustic communication. However, both face significant challenges in the aquatic environment. Optical systems are heavily limited by light scattering and absorption, as well as visibility issues, particularly in turbid waters. Acoustic systems, on the other hand, are conditioned by the speed of sound propagation in water, which is approximately 1500 m/s and varies with factors such as temperature, salinity and pressure. Additionally, the medium has a high level of noise, which affects these systems and compromises communication quality.

The main objective of this study is to design, study and fabricate an efficient wearable antenna that is resistant to the human body, the material that coats the antenna and water. The antenna is designed to be integrated into the back of the swimmer's swimsuit. In a 50 meter swimming pool performance the antenna establishes communication with the receiver located outside of the water. In addition to this primary goal, several secondary objectives are pursued, starting off by designing and optimizing the antenna through the CST Studio Suite (Computer Simulation Technology), then fabricate a prototype, produce a phantom to replicate the dielectric properties of the human body and evaluate the antenna's performance both in and out of the water, comparing the experimental measurements with the numerical results. Then both antennas are each connected to a microcontroller with integrated Bluetooth capabilities, enabling wireless communication, in this case an ESP32-CAM. This enables the transmission of data from the wearable antenna that the swimmer is wearing to the external antenna.

In the following figure, a swimmer's physical parameters are being transmitted and monitored, in real time, by a coach located outside the pool water 1.1

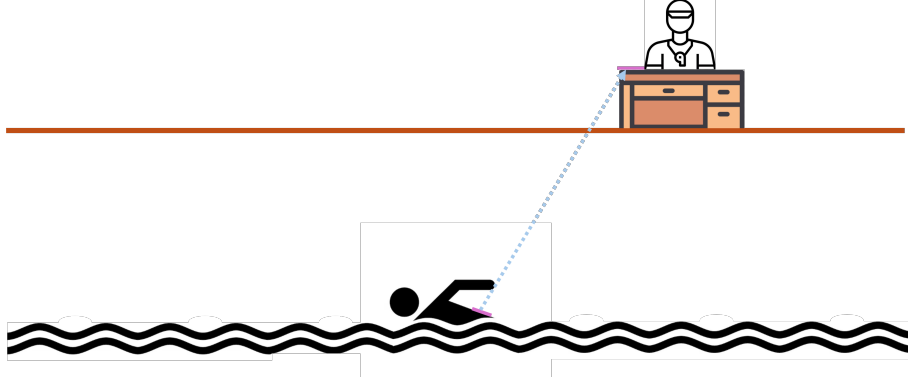


FIGURE 1.1: Water Surface to Air Antenna Transmission

In a future practical scenario, once the communication has been established, each of the antennas would be equipped with a microcontroller, like the ESP32-CAM allowing, for example, the biometric data to be stored. This data can be transmitted in real time to an external base station without interfering with the user's mobility, enabling data storage of the swimmer's vital signs, allowing continuous data transmission, while in movement.

The relevance of this study extends beyond sports applications and may also be applied to military cases. For instance, embedding an antenna into a marine's clothing could enable the ship to be promptly alerted in the event of a man-overboard situation.

1.2 State of the Art

The development of wearable aquatic communication systems is a complex and evolving field of study that intersects multiple areas of knowledge, ranging from wave propagation in high attenuation environment to the design of antennas adapted to the human body and technical fabrics. This section reviews the most relevant contributions from the scientific literature that support the present research, with particular emphasis on propagation mechanisms and the constraints imposed by the aquatic environment, as well as the evolution of compact and wearable antenna solutions.

It also addresses experimental validation methodologies using phantoms and emerging technologies for fabricating textile antennas, such as conductive embroidery and functional printing, which are increasingly relevant in merging electronics with flexible materials.

1.2.1 Challenges of Underwater Communication

The study of underwater communication, which has intensified since the 1960s, continues to pose a challenge due to the high attenuation of electromagnetic waves in water. Efficient transmission of submerged signals requires the mitigation of losses and optimization of signal propagation. Several approaches have been explored, including the use of specific frequencies, specialized antennas and alternative propagation paths.

In this context, studies show that in the near field region attenuation is dominated by conductive losses and can be very high, making broadband short range communication feasible. Leão et al. 2012 conducted an experimental and theoretical study on underwater radio communication using the $2.4GHz$ ISM band, focusing on its performance in freshwater environments. The work demonstrated that, although electromagnetic wave attenuation is considerable at these frequencies, it is still possible to achieve short-range communication. The study also highlighted the sensitivity of signal propagation to environmental parameters such as water salinity, antenna orientation and depth, reinforcing the potential of using high-frequency bands in specific, controlled scenarios.

To overcome the challenges imposed by the aquatic environment, Mena-Rodríguez et al. 2016 identified two alternative propagation mechanisms: up-over-down and lateral wave propagation, which allow part of the signal to travel through paths with lower attenuation. This study compared different types of antennas, highlighting that magnetic loop antennas outperformed dipole antennas, as they minimize electromagnetic wave absorption and extend the communication range. These results are particularly relevant for underwater wearable antennas, where mitigating losses is crucial to maintain efficient communication.

Another relevant approach was presented by Smolyaninov et al. 2018, who proposed an alternative underwater communication method based on the excitation of surface electromagnetic waves at the air–water boundary. Their work introduced a compact antenna system operating at 50 MHz, designed to propagate signals along the water’s surface. To enhance performance, the antenna, built as a helical monopole, was enclosed in a structure containing deionized water, which improved

impedance matching and reduced energy loss at the interface. Experimental trials carried out near Panama City, in saline water conditions, demonstrated communication over distances of up to 9 meters near the surface. Although environmental conditions such as wave turbulence affected performance, theoretical models suggested that, under ideal circumstances, surface wave propagation at this frequency could extend to 60 meters. These findings show that surface-bound signal transmission may serve as a viable solution for short-range underwater communication, especially in military, diver, or autonomous vehicle applications where near-surface operation is typical.

Although attenuation increases significantly with frequency, particularly above 1 GHz, certain specific contexts (such as short-range communication in freshwater or shallow zones) allow the use of higher frequency bands. This is the case with ISM bands such as 2.4 GHz, which have been tested in specific applications. Studies by Lloret et al. 2012 demonstrated the feasibility of establishing underwater electromagnetic links at 2.4 GHz over very short distances (typically under 0.5 meters), with stable data rates in freshwater scenarios. Similarly, Mohd Razali et al. 2021 analyzed patch antennas operating at 900 MHz in seawater, showing that although gain was significantly reduced compared to free-space operation, effective communication was still possible within a limited range. These studies confirm that, despite the high attenuation of electromagnetic waves in water, particularly at higher frequencies, short-range underwater communication is achievable, particularly in controlled environments such as swimming pools or test tanks, when antenna design is properly optimized.

1.2.2 Wearable Antennas

Wireless Body Area Networks (WBANs), explore wearable devices for communication between the human body and an exterior network, have gained prominence due to their applications in demanding environments such as the aquatic medium. In recent years, various studies have explored how to refine antenna structures and assess their behavior when exposed to conditions involving both water and human tissue, using full-wave electromagnetic simulation tools such as the CST Studio Suite in the early-stage design and optimization process.

Zhang et al. 2017 developed a dual-band, dual-mode button antenna for on-body and off-body communications, operating at 2.45 GHz and 5.8 GHz. The study highlighted the importance of controlling the Specific Absorption Rate (SAR) to ensure compliance with safety standards during close-proximity use.

As another relevant approach, Tak et al. 2015 introduced a compact dual-band antenna solution designed for WBAN, capable of supporting communication at 2.4 GHz and 5.8 GHz. The structure is based on a microstrip patch configuration, using a coplanar waveguide (CPW) and a combination of parasitic and circular patches. This arrangement enables two distinct radiation behaviors: one optimized for communication away from the body and another for signal propagation along the body surface. The proposed geometry contributes to improved impedance bandwidth and radiation efficiency, with potential for integration into wearable systems, particularly in medical and tactical environments. While not specifically developed for underwater use, the antenna's characteristics suggest adaptability to short-range biometric applications in controlled aquatic conditions.

In the field of compact antennas for aquatic environments, Abbosh et al. 2010 developed a 433 MHz Ultra High Frequency (UHF) antenna optimized for water. The introduction of dual wedge-shaped slots minimized resonant frequency variations, reducing propagation losses and improving transmission efficiency.

In addition to enabling data communication, flexible wearable antennas have also supported the creation of body-worn systems for physiological monitoring. These solutions collect bio-signals in real time and transmit them wirelessly, extending the role of antenna design into biomedical and human performance domains. Such systems are also used in aquatic settings, applied to track vital parameters and movement, relying on miniaturized antenna structures and reliable transmission techniques.

In parallel with studies dedicated to data transmission in water, the use of wearable systems for biomedical monitoring in aquatic environments has also gained relevance in recent years. These systems aim to collect physiological data in real time without compromising user mobility and present several challenges due to water interference and antenna-body interaction. A particularly relevant contribution is the system proposed by Santos et al. 2021, which integrates, into a single wearable device, inertial sensors, biomedical sensors (heart rate and oxygen saturation) and a low-power radio transmitter. Communication between modules is performed via LoRa at 433 MHz, allowing stable real-time data transmission up to 1.4 meters deep. The system consists of a transmitter (Tx), a base station (Rx) and a computational application for data visualization and analysis. This setup enabled the collection of metrics such as acceleration, orientation, cadence and swimming style, using machine learning algorithms for classification and interpretation.

The study showed that communication performance is affected by body

position during swimming, with the backstroke style posing the greatest difficulty due to the obstruction of the line of sight between the transmitter and the receiver. Nonetheless, the system demonstrated robustness and reliability, operating continuously during real competitive swim training. This example highlights the potential of wearable antennas optimized for aquatic environments, while also exposing current limitations in underwater biomedical communication. It reinforces the need for wearable solutions that combine robustness, comfort and discreet integration with the human body. In this context, the development of antennas embedded in conductive textile materials (supported by flexible and precise manufacturing techniques) has gained relevance in addressing the ergonomic and functional demands of such systems.

Another particularly relevant contribution to the advancement of WBAN communications was presented by Felício et al. 2016b, who developed a broadband implantable antenna designed to operate with impulse radio ultrawideband (IR-UWB) technology between 1.4 and 4.2 GHz. The XETS-type antenna (crossed exponentially tapered slots) was optimized to function embedded in human muscle at a depth of 3 mm and demonstrated data rates of up to 750 Mbps over short distances (up to 50 mm), even under realistic in-body propagation conditions. The system was designed to operate battery-free, using energy scavenging from external 2.4 GHz signals. Experimental tests and simulations on a multilayer human tissue model demonstrated good electromagnetic performance, with low pulse distortion (fidelity above 95 %) and reflection coefficients below -10 dBi. The integration of an electronic chip and a bio compatible layer did not compromise antenna performance, validating the concept for real-world applications in high-data-rate implantable devices.

All these functional demands have driven antenna research toward textile integration, where precision manufacturing techniques play an important role. So, alongside traditional electronic developments, research on wearable antennas has evolved toward the integration of antennas into conductive and flexible fabrics. Kiourti et al. 2015 introduced a new embroidery process using Electrisola threads composed of seven filaments (0.12 mm in diameter), achieving a geometric precision of 0.1 mm (comparable to that of printed circuit boards). This technique allows for a 24-fold reduction in production costs and a 50% reduction in manufacturing time, while maintaining solid radio frequency performance. The antenna was fabricated using a programmable sewing machine, effectively “printing” the antenna directly onto the fabric with high precision. Validation was carried out using a textile spiral antenna operating between 1 GHz and 5 GHz, showing good agreement between

experimental measurements and simulations up to 3 GHz. The performance deterioration above this frequency was attributed to the roughness of the textile substrate and imperfections in the metallization, specifically, the physical structure of the embroidered conductive threads, whose discontinuous geometry and irregular surface compromise antenna performance at higher frequencies.

This method opens the door to the integration of discreet antennas into clothing items such as vests or wetsuits, offering comfort and adaptability, particularly when adapted to flexible materials such as polyester or neoprene. Despite their potential, these textile-integrated antennas must still be carefully assessed in realistic aquatic scenarios and account for the specific challenges of wearable operation near or in contact with biological tissue.

1.2.3 Phantoms for Experimental Validation

Beyond antenna development, experimental validation under conditions that faithfully simulate the human body is crucial for ensuring the realistic performance of wearable communication systems. In this context, electromagnetic phantoms (physical models that replicate the dielectric properties of human tissues) play a fundamental role in the calibration and testing of antennas in contact with or in proximity to the body. While phantoms are well established in biomedical antenna research, their use in aquatic and amphibious communication remains limited.

Bonds and Weller 2017 proposed a highly reliable physical phantom, the Human Core Model (HCM), composed of multiple solid and liquid layers designed to replicate the dielectric properties of major human tissues (skin, muscle, fat and blood) within the 1 to 2 GHz frequency range. This band is especially relevant for wearable and biomedical communication systems due to its favorable propagation characteristics. The outer layer of the phantom includes a solid hybrid structure replicating skin and muscle with nonuniform thicknesses, whose electrical properties were modeled based on the dielectric data compiled by C. Gabriel and S. Gabriel 1996. The inner core, consisting of a liquid solution, mimics abdominal tissues rich in blood and fat. Measurements of complex permittivity and impedance closely matched those of established reference models, validating the HCM as a reliable and realistic platform for evaluating antenna performance in body-centric wireless applications.

Subsequent developments extended phantom models to cover broader frequency ranges, including those directly relevant to ISM-band communication. Costanzo

et al. 2021 presented a simple yet effective gelatin-based fabrication method for multilayer phantoms emulating skin, muscle, fat and blood. Their dielectric characterization, performed between 500 MHz and 5 GHz, confirmed close agreement with the classical Gabriel database, ensuring that the phantom accurately reproduces the behavior of human tissues at 2.45 GHz. This contribution is particularly valuable for wearable antenna research, since it offers a reproducible, low-cost solution for validating antenna performance in the same frequency band adopted by short-range wireless technologies such as Bluetooth.

The progressive refinement of phantom models, from multilayer constructs emulating the main biological tissues to advanced muscle-specific variants that incorporate physiological variability, highlights the importance of accurate experimental validation in wearable antenna research. These models ensure reproducibility in controlled laboratory environments and enable the assessment of antennas under realistic and heterogeneous body conditions. As such, they provide an indispensable bridge between numerical simulations and practical implementation, creating the conditions for identifying open research challenges and future opportunities in the development of reliable aquatic communication systems.

In this study, Mendes and Peixeiro 2018 developed and experimentally validated a dual-mode, on-body and off-body, wearable antenna that operates at 2.45 GHz. The evaluation was carried out using a homogeneous phantom, known as a two-third phantom, which replicates the human body torso. This phantom was designed to assess its impact on the antenna performance. The results showed a slight frequency detuning and a minor degradation of the S-Parameters. However, the values remained below -10 dB across the ISM band. The results confirmed that the two-third phantom provides a reliable representation of the human body, while being simpler and more practical than inhomogeneous models.

1.2.4 Synthesis and Research Opportunities

The analysis of the significant studies in this field reveals notable progress in overcoming the challenges of underwater communication, particularly those related to electromagnetic signal attenuation, compact antenna design and integration with the human body. The reviewed solutions demonstrate the feasibility of several approaches, ranging from magnetic and microstrip antennas adapted to different bands, to fully functional real-time biomedical monitoring systems. However, substantial limitations persist when trying to combine electromagnetic performance, user comfort, water resistance and manufacturability.

In this context, wearable antennas emerge as a promising solution, especially when designed to ensure both physical and electrical integration with common clothing materials such as neoprene or polyester. The use of emerging technologies, such as precision embroidery with conductive threads, enables the development of compact geometries with good performance in terms of impedance matching and resonance stability, even in the presence of the human body.

Despite these advances, current studies have not yet sufficiently explored the behavior of these antennas in lossy environments such as water, nor the adaptation of antenna structures to varying material thicknesses between the antenna and the skin (a common condition in swimwear or diving suits). Similarly, there remains a need to understand which geometric parameters are most influential on antenna performance when operating in environments with high dielectric permittivity or electrical conductivity.

Therefore, this study proposes to explore and optimize wearable antenna configurations for underwater communication, focusing on parametric performance analysis under various operating conditions using simulation tools such as CST Studio Suite. The goal is to contribute sustainable and adapted solutions for wearable systems in aquatic environments, reinforcing the role of WBANs in sports, biomedical and military contexts.

1.3 Thesis Structure

To provide a clearer overview of the organization of this study, a diagram representing a schematic representation of this thesis structure is shown in Figure 1.2. The development process was designed to be progressive, beginning with analytical calculations and the simulation of various antenna topologies, followed by their optimization and culminating in an experimental validation phase.

This structure enabled an iterative approach in which each stage was informed by the outcomes of the previous one, ensuring a coherent and well-founded progression from theoretical conception to practical implementation. The diagram, shown in Figure 1.2, outlines the three main components of the study, numerical calculations, CST Studio Suite simulations and experimental testing.

The structure of this thesis is organized into four main chapters. Chapter 1 introduces the motivation and objectives of this study followed by an overview of the state of the art. Chapter 2 presents the fundamental concepts required for the development of this wearable antenna along with the link budget calculations. In

Chapter 3 the analytical and numerical design of the antennas under study were detailed. This study includes the Inverted F Antenna (IFA), the Slotted Patch Antenna and the proposed Wearable Parallel Patch Antenna (WPPA), evaluating their performance across various environments, under the influence of the human body, with neoprene coating and in the presence of water. This chapter also introduces the integration of an adapted WPPA in a military application. Chapter 4 describes the experimental setup and methodology, covering phantom fabrication and dielectric measurements along with neoprene. It also covers the experimental validation of the WPPA, with a comparison between measured and simulated results.

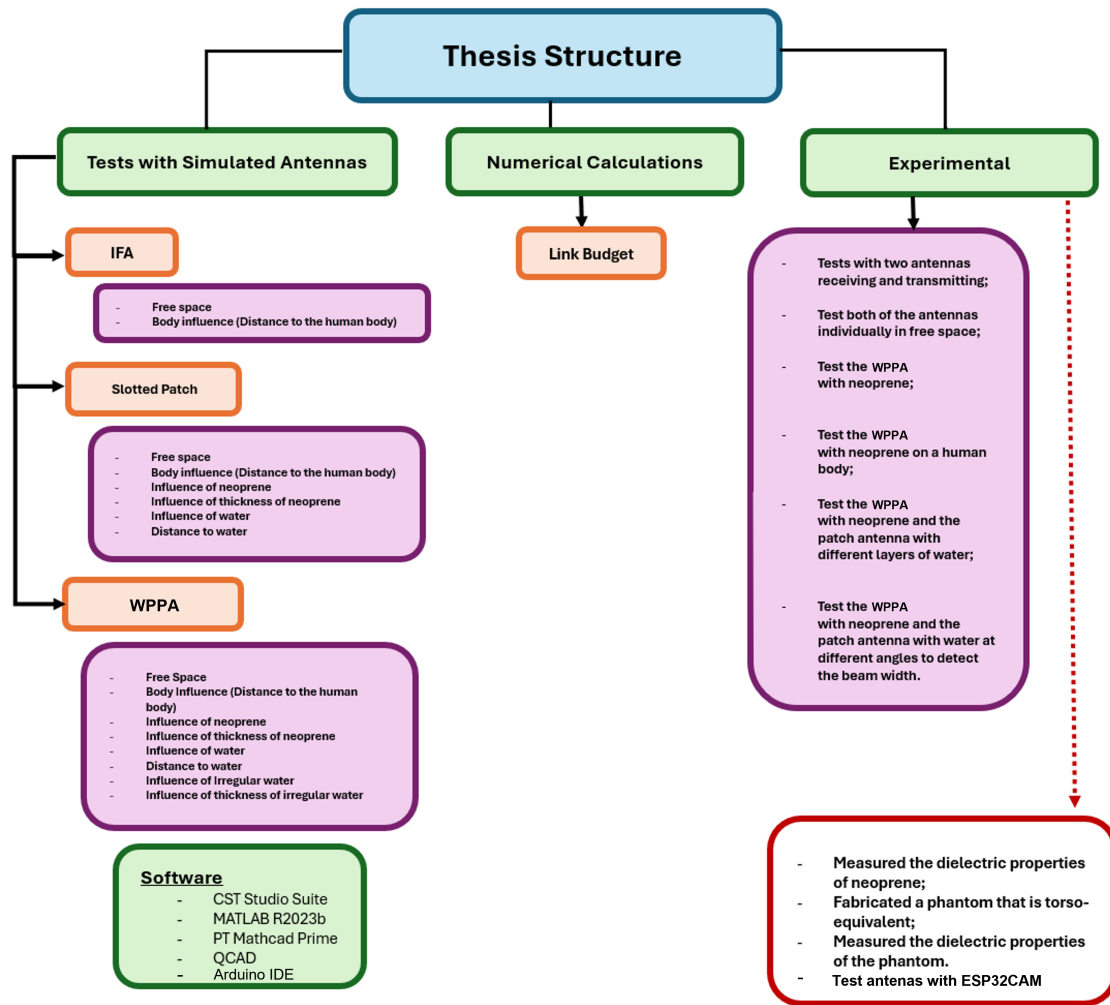


FIGURE 1.2: Thesis Structure

The analysis presented in the diagram highlights the level of complexity and detail involved in the development of the wearable antenna in these environments, the evaluation of multiple antenna designs, the modeling of human body and water interactions.

This study validated the feasibility of the proposed solution while also advancing the understanding of the key parameters influencing antenna performance in aquatic environments. By combining simulations with practical experimentation, a strong consistency was established between theoretical expectations and real-world behavior. This alignment reinforces both the credibility of the results and the potential applicability of the developed antenna in operational contexts.

Chapter 2

Basic Concepts

2.1 Water Propagation

2.1.1 Principles of Electromagnetic Communication

Electromagnetic waves, which are generated when electric charges are accelerated, are fundamental for wireless communication. This motion creates a varying electric field, which generates an associated magnetic field. These two fields oscillate perpendicular to each other and in the direction of the wave propagation, thereby forming the electromagnetic wave. Unlike sound waves, electromagnetic waves do not require a physical material to propagate and can travel through vacuum.

The main characteristics of electromagnetic waves are frequency, wavelength and their propagation speed and the latter depends on the propagation medium. The behavior of these waves is described by Maxwell's equations, which explain how the electric and magnetic fields interact during propagation (Guru and Hiziroglu 2009).

Maxwell's equations are a set of four fundamental equations in electromagnetism that describe how electric and magnetic fields interact with each other and with charges and currents. They are essential for understanding electromagnetic wave propagation, which is central to study air-to-water surface communication near the human body, involving a medium like water and human tissues.

Maxwell's equations in the differential form are:

Gauss's Law for Electric Fields

$$\nabla \cdot E = \frac{\sigma}{\varepsilon} \quad (2.1)$$

where E is the electric field $[V/m]$, σ the free charge density $[C/m^3]$ and $\varepsilon = \varepsilon_r \varepsilon_o$ the permittivity, with $\varepsilon_o = 8,854 \times 10^{-12} [F/m]$. This law describes how electric fields arise from charges. In source-free regions such as water surface or human tissue, $\sigma = 0$ and in this case

$$\nabla \cdot \mathbf{E} = 0$$

Gauss's Law for Magnetic Fields

$$\nabla \cdot \mathbf{B} = 0 \quad (2.2)$$

where $\mathbf{B} = \mu \mathbf{H}$ is the magnetic field $[T]$, $\mathbf{H}$ is the magnetic intensity $[A/m]$ and $\mu = \mu_0 \mu_r$ the permeability, $\mu_r \approx 1$ for non-magnetic medium like air, water, neoprene and human body as they are non-magnetic, therefore $\mu = \mu_0$. This implies no magnetic poles.

Faraday Law of Induction

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (2.3)$$

It explains that a time varying magnetic field induces an electric field. It is critical for electromagnetic wave propagation as it couples the electric and magnetic fields in the wave.

Ampere's Law with Maxwell Correction

$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \quad (2.4)$$

It relates the magnetic field intensity to the conduction currents $\mathbf{J} = \sigma \mathbf{E}$ and displacement currents $\varepsilon \frac{\partial \mathbf{E}}{\partial t}$. In conductive medium like water and the human body, $\mathbf{J}$ is significant due to non-zero conductivity σ .

It explains a time varying electric field and current inducing a magnetic field.

2.1.2 Wave Propagation in Free Space and in Lossy Environments

In the case of free-space propagation, the electromagnetic wave travels without significant interference, as there are no losses, thus maintaining the amplitude of the electric field along the path. This phenomenon is described by Helmholtz's equation for the electric field (Bayliss et al. 1985), which is derived from Maxwell's equations and describes the propagation of electromagnetic waves in a given medium. The spatial variation of the electric field is related to the wavenumber, k [$rad.m^{-1}$], which depends on the frequency of the wave and the properties of the medium $k = \frac{\omega}{c} \sqrt{\epsilon_r \mu_r}$ where ϵ_r and μ_r are relative permittivity and permeability, respectively and c represents the speed of light in vacuum, approximately $c \approx 3 \times 10^8$ m/s:

$$\nabla^2 \vec{E} + k^2 \vec{E} = 0, \quad \text{for } k = \frac{\omega}{v} = \beta \quad (2.5)$$

However, when wave propagation occurs in a lossy medium, such as water, it is significantly altered due to interaction with the medium. This phenomenon is described by the propagation constant (γ), which consists of two terms: the attenuation constant (α [Np/m]), which quantifies the loss of wave intensity over distance and the phase constant (β).

The propagation constant is expressed in terms of permittivity (ϵ), permeability (μ) and conductivity (σ), by the equation (Al-Shamma'a et al. 2004).

$$\gamma = j\omega \sqrt{\epsilon\mu - j\frac{\sigma\mu}{\omega}} = \alpha + j\beta \quad (2.6)$$

Therefore, the propagation of the electric field, as part of an electromagnetic wave in a lossy medium, can be described by the following expression,

$$\mathbf{E}(z) = \mathbf{E}_0 e^{-\alpha z} e^{-j\beta z} \quad (2.7)$$

where:

- $e^{-\alpha z}$, represents the decrease in the electric field amplitude due to attenuation.
- $e^{-j\beta z}$, represents the phase variation along the propagation.

Among these two parameters, the term $e^{-\alpha z}$ is particularly relevant, as it represents the decrease in the electric field amplitude. On the other hand, the term

$e^{-j\beta z}$, represents the phase variation of the wave and it has a smaller impact in mediums with significant losses, such as water, where attenuation dominates the propagation behavior.

2.1.3 Electromagnetic Wave Propagation and Challenges

Water represents a complex medium for electromagnetic wave propagation once significant signal losses occur, through attenuation, due to its high conductivity. In fact, conductivity has a direct impact on signal attenuation (Hayt Jr and Buck 2013). However, it is possible to reduce these limitations and enable effective communication with the proper choice of antenna and frequency optimization (Leão et al. 2012).

The human body also presents a significant challenge when developing effective communication systems. It is composed of different layers of tissue such as of skin, fat, muscle or bone. Each have varied dielectric properties forming a body where distortions occur by attenuation and absorption of electromagnetic signals.

To integrate a wearable antenna, it must be designed to maintain communication with another antenna even in the presence of the human body. The human body, therefore, presents characteristics that directly affect antenna performance due to its high electrical permittivity ($\epsilon_r = 36$ and $\tan\delta = 0.16$) (Mendes and Peixeiro 2017). The relative permittivity characterizes the material's ability to store electrical energy in an electric field, while the loss tangent quantifies the dielectric losses within the material. This high permittivity can cause impedance mismatches in the antenna, consequently compromising its radiation efficiency and causing signal degradation (Su et al. 2020). In other words, direct contact between the body and the antenna may lead to significant absorption by the body tissues, resulting in substantial signal degradation.

To simulate and test transmissions in the presence of the human body, advanced software programs are available that, among other features, simulate human tissues. These programs allow for detailed analysis of the interaction between the antenna and the human body, enabling the identification and mitigation of problems and the optimization of antennas before manufacturing. After this stage, the antenna can be physically manufactured and tested either on a human body or using phantoms (Mendes and Peixeiro 2018). Phantoms are physical models that simulate the properties of human tissue and they are also used to avoid the use of real human tissues, providing a controlled way to represent these properties. These phantoms can be composed of layers, such as skin, fat and muscle, commonly known as the

Multilayer Model, or they can be homogeneous, like liquid phantoms (Felício et al. 2016c).

For this study, the use of a homogeneous liquid phantom is a viable option to represent the properties of the human body and accurately simulate the environment in which the antenna operates, specifically in contact with the human body (Felício et al. 2016a)

2.1.4 Types of Swim Suit and their Thickness

To integrate antennas into a flexible fabrics, such as neoprene, commonly used in swimsuits and scuba diving suits, it is important to evaluate and determine the optimal coating thickness to minimize signal attenuation in water. There are many types of swim suites for various purposes. Most of them use neoprene as the material of election. The wetsuit's thickness is measured in millimeters and indicate the neoprene's insulation level. The thickness is normally represented in combinations torso/limbs but in this case the only relevant number is the first one because the antenna will be introduced on the back of the individual. There are several factors that determine the appropriate wetsuit thickness, including water temperature, depth and the duration of the swimmer's immersion.

Generally different water activities require different swimsuits. A scuba diver will wear a 3 to 7 mm thickness full suit while an open water swimmer will wear a 1 to 5 mm thickness suit, as shown in Swimming 2025

For the scuba diving purpose, the suit is very similar to the surfing wetsuit, which keep the divers warm and shield them from marine hazards. To apply this study to a military field these would be the measurements considered for the study. Open water swimming is better suited for scenarios involving competitive athletes, where the goal is to monitor their performance in real time during training.

Water Temperature	Wetsuit Thickness	Wetsuit Type	Booties	Gloves	Hood
Below 18°C (64°F)	3-5 mm	Fullsuit	Optional	Optional	Optional
18-24°C (64-75°F)	2-3 mm	Springsuit/Shorty	Not required	Not required	Not required
Above 24°C (75°F)	1-2 mm or less	Rashguard	Not required	Not required	Not required

FIGURE 2.1: Open Water Swimming Wetsuit Thickness Guide, taken from Swimming 2025

Water Temperature	Wetsuit Thickness	Wetsuit Type	Booties	Gloves	Hood
Below 10°C (50°F)	7 mm or thicker	Fullsuit	5 mm Required	5 mm Required	5 mm Required
10–16°C (50–61°F)	7 mm or 5 mm	Fullsuit	5 mm Recommended	3 mm Recommended	3 mm Recommended
16–21°C (61–70°F)	5 mm	Fullsuit	3 mm Optional	3 mm Optional	3 mm Optional
21–24°C (70–75°F)	3–5 mm	Fullsuit/Springsuit	Optional	Optional	Optional
Above 24°C (75°F)	3 mm or less	Springsuit/Shorty	Not required	Not required	Not required

FIGURE 2.2: Scuba Diving Wetsuit Thickness Guide, taken from Swimming 2025

For this study, the optimal neoprene thickness ranges from 3 to 5 mm, as it is suitable for both scenarios.

2.2 Link Budget

The development of reliable air-to-water surface electromagnetic communication systems is critical for applications such as water surface wireless networks, swimmer communication and wearable biomedical devices. However, the presence of water and the human body introduces significant challenges due to their high permittivity and conductivity, which cause substantial signal attenuation and impedance mismatches. This study does research on the performance of antennas operating at ISM frequencies, 400 MHz, 900 MHz and 2.4 GHz, in aquatic environments, with a focus on optimizing antenna design and link budget analysis to ensure robust communication. This study provides insights into overcoming the physical and environmental constraints of air-to-water surface communication near the human body by evaluating the effects of water propagation, human tissue interactions and key link budget parameters such as antenna gains, transmitted power and propagation losses.

This study started off by conducting some tests for three distinct frequencies: 400 MHz (Abbosh et al. 2010), 900 MHz (Razali et al. 2021) and 2.4 GHz (Mendes and Peixeiro 2018), selected for their potential to operate in aquatic environments and in scenarios involving the human body, aligning with the intended objectives. Additionally, these frequencies can be used freely, without authorization from the Autoridade Nacional de Comunicações, ANACOM, which is the entity responsible for regulating postal and electronic communications in Portugal and by the International Communication Union, ITU, worldwide.

In the first approach, the influence of water on signal propagation was analyzed. For this, two antennas were considered in the numerical calculations: one positioned above the water and the other submerged, initially at the surface.

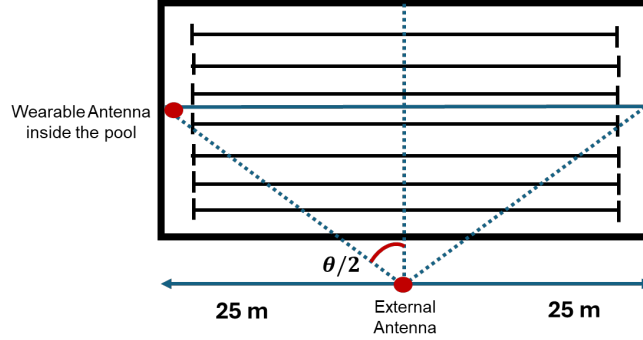


FIGURE 2.3: Communication Between the Two Antennas to Determine the Received Power

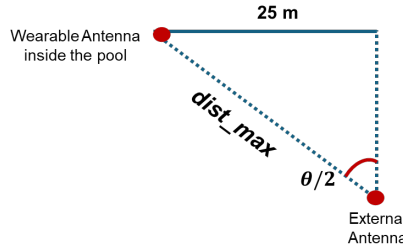


FIGURE 2.4: Maximum Distance Between Antennas

A swimming pool with a length of 50 meters was considered for this study, with the far ends being the most distant points from the external antenna. It was assumed that when the swimmer is positioned directly in front of the external antenna. For preliminary calculations, the external antenna was considered to have a directivity of 6 dBi. To estimate the beam width under this condition, the following equation was used:

$$\theta = \sqrt{\frac{4\pi}{D}} \quad (2.8)$$

Considering the external antenna to have a directivity of 6 dBi, the corresponding beamwidth was calculated to be 1.78 radians. Based on this beamwidth, the objective was to determine the maximum distance at which the swimmer could remain from the external antenna. This analysis led to the conclusion that the maximum allowable distance is approximately 32.2 meters (Figure 2.4).

$$\sin\left(\frac{\theta}{2}\right) = \frac{25}{dist_{\max}} \Rightarrow dist_{\max} = 32.2 \text{ m}$$

The following scenario was initially considered to determine the best operating frequency in the absence of the human body, for a transmission involving the transition between environments. Assuming that there is a receiving antenna above water and a transmitting antenna, the wearable antenna, located at the transition between the two environments. A defined distance between the two antennas is considered and according to the Friis equation, represented in 2.9. For the values in free space, it is known that the gain of the transmitting antenna, considering for the time being a dipole antenna, is $\approx 2.15 \text{ dBi}$, a value that can be verified in CST Studio Suite, enabling the analysis of antenna performance in free space and identifying those that provide the most efficient signal transmission in this ideal environment, after simulating a dipole antenna in free space.

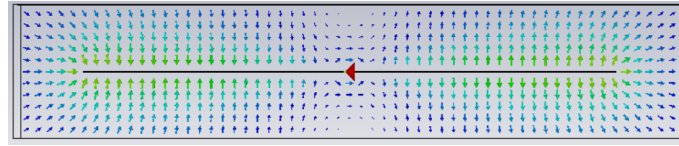


FIGURE 2.5: Dipole Antenna in Free Space

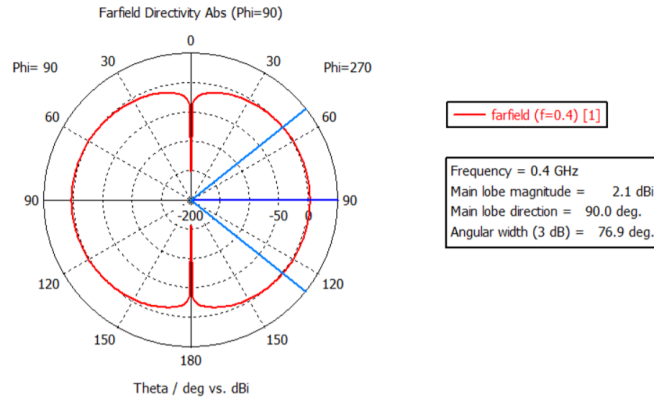


FIGURE 2.6: Farfield of a Dipole Antenna in Free Space

However, considering that the dipole is influenced by water, it was assumed for the transmission gain of the wearable antenna was $G_t = -15 \text{ dBi}$ instead of 2.15 dBi . As for the gain of the receiver, it was considered a patch antenna with the gain of $G_r = 6 \text{ dBi}$. The value of λ depends on the operating frequency. Since $\lambda = \frac{c}{f}$ it is possible to determine the wavelength for different frequencies and, consequently, the received power for each operating frequency at a given distance. The distance

is calculated assuming that the minimum received power will be above -123 dB, the receiver's sensitivity, $P_{min_r} > -123\text{dBW}$ and $P_t = -26\text{dBW}$, for the three operating frequencies under study, these two values were based on the WT51822-S4AT (Technology n.d.).

The analysis began by calculating the received power at water surface for each frequency using the Friis transmission equation, without accounting for water attenuation.

The *Friis* equation describes the power received by an antenna as a function of the transmitted power and, in this case, the distances between the antenna at the water surface and the external base station (Leão et al. 2012). The formula is given by:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \quad (2.9)$$

Where P_r is the received power, P_t is the transmitted power, G_t and G_r are the gains of the transmitting and receiving antennas, λ is the wavelength and d is the distance between the two antennas. All these parameters play a crucial role in determining the efficiency of communication. In the aquatic environment, these parameters are influenced by the physical properties of water, such as its dielectric constant and conductivity. Designing an ideal antenna considering these characteristics is a big challenge.

The resulting received power values for the different frequencies were the following,

Frequency	Received Power
2.4 GHz	-105.21 dBW
900 MHz	-96.69 dBW
400 MHz	-89.647 dBW

TABLE 2.1. Received Power the Surface of the Water at Different Frequencies Without Accounting for Water Attenuation

However, we are not dealing with an ideal situation, since the transmission will occur in a lossy environment, making it necessary to also account for the attenuation caused by water in the received power. To do this, it is necessary to include the water attenuation, A_w , in the Friis equation 2.10.

$$P_r = P_t G_t G_r \frac{\lambda^2}{(4\pi)^2 d^2} A_w \quad (2.10)$$

With the aim of analyzing and understanding the influence of this attenuation, calculations were carried out for the different frequencies in order to identify which one experiences the greatest attenuation.

The attenuation of electromagnetic waves in water can be expressed in terms of the electric field intensity. The relation between attenuation and the squared magnitude of the electric field can be expressed by $|e^{-\alpha z}|^2$, as this term is predominant compared to the phase constant in a lossy environment, as stated in (Al-Shamma'a et al. 2004).

$$A_w \propto |E|^2 = |e^{-\alpha z}|^2 \quad (2.11)$$

Based on these results, additional assumptions were defined in order to assess the influence of water attenuation for each of the frequencies. The following assumptions were made,

- $\varepsilon = \varepsilon' - j\varepsilon'' = 78 - j34$: Represents the complex permittivity of the medium;
- $E_0 = 1$: Amplitude of the electric field;
- z : Represents Depth in meters

Frequency	400 MHz	900 MHz	2.4 GHz
Wavelength [m]	0.750	0.33(3)	0.125
Angular Frequency [rad/s]	2.516×10^9	5.655×10^9	1.508×10^{10}
Propagation Constant	$15.779 + 75.682i$	$35.502 + 170.292i$	$94.672 + 454.113i$
Attenuation Constant (α) [Np/m]	15.779	35.502	94.672
Electric Field	$e^{-15.779 \cdot z}$	$e^{-35.502 \cdot z}$	$e^{-94.672 \cdot z}$

TABLE 2.2. Wavelength, Angular Frequency, Propagation Constant, Attenuation Constant and Electric Field of: 400 MHz, 900 MHz and 2.4 GHz

Thus, it was possible to verify the behavior of the signal by relating the distance with the attenuation of water.

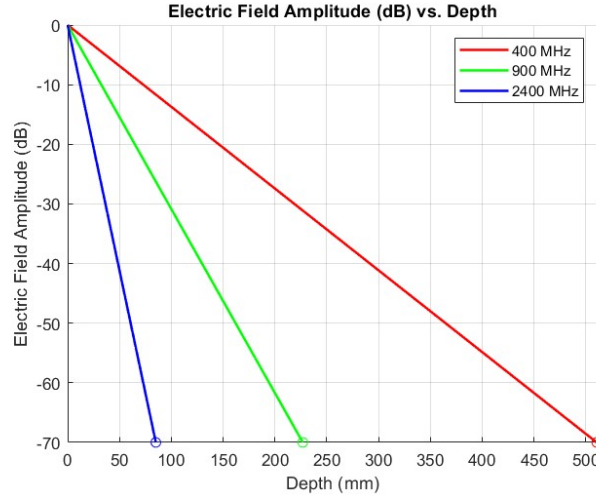


FIGURE 2.7: Depth of the Reach of each Signal at the Three Different Frequencies with the Attenuation of Water

Through the presented graph, it is possible to observe the attenuation behavior for the three different frequencies and how it influences the transmission distance. Each frequency exhibits distinct characteristics and behaviors that affect efficiency in different scenarios.

For the 400 MHz frequency, attenuation is relatively low at greater distances, allowing efficient transmission over long ranges. Regarding the 900 MHz frequency, there is more attenuation when compared to the 400 MHz frequency. This frequency offers a balance between range and performance; however, at longer distances, attenuation has a greater impact, unlike at 400 MHz, which may limit its use in long-distance applications. Finally, for 2.4 GHz, attenuation is quite pronounced from the start. At this frequency, transmission is more efficient over short distances compared to the other frequencies; however, it is not suitable for longer distances, as signal degradation occurs more rapidly.

To further quantify the effect of attenuation, a comparative analysis was carried out using a fixed depth at 20 mm. This made it possible to calculate the received power for each frequency by first determining the corresponding attenuation based on their respective attenuation constants and then calculating the received power with the influence of attenuation 2.13.

$$A_w = |e^{-\alpha z}|^2 \quad (2.12)$$

$$P_{r_{attenuation}} = P_{r_{frequency}} \cdot A_{w_{frequency}} \quad (2.13)$$

Frequency	P_r	A_w	P_r (Attenuation)	Max Depth
2.4 GHz	-105.21 dBW	0.02266	-121.657 dBW	21.6 mm
900 MHz	-96.69 dBW	0.24169	-102.857 dBW	85.32 mm
400 MHz	-89.647 dBW	0.53144	-92.392 dBW	243.4 mm

TABLE 2.3. Influence of Attenuation in the Received Power

These results show that, for the same propagation depth, attenuation affects each frequency differently. Specifically, higher frequencies experience greater attenuation. This is evident when comparing the results with and without attenuation: at 400 MHz, the received power is barely impacted, on the other hand at 2.4 GHz, there is a significant loss due to attenuation.

To better understand the influence of attenuation across different frequencies, an analysis was conducted on the maximum penetration depth, shown in Table 2.3 and how this depth varies with frequency, as shown in Table 2.8.

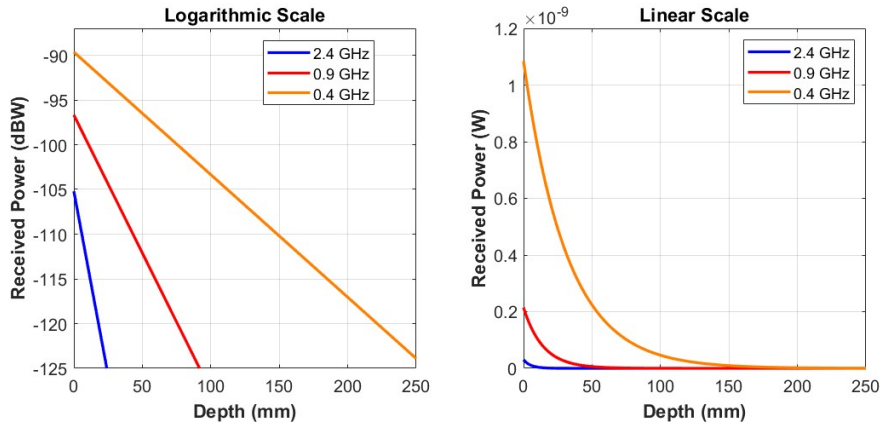


FIGURE 2.8: Received Power with the Influence of Attenuation

In addition to these characteristics, it should be taken into account that variations in frequency also affect the size of the antenna. At lower frequencies, the antenna will be larger, while at higher frequencies, it will be smaller. This factor is extremely important, especially because the antenna is in contact with water and it will be integrated into the swimmer's clothing, so it must not interfere with their movement (Su et al. 2020).

It was observed that, although the 2.4 GHz frequency is not as efficient as the others, as shown in Table 2.8 it still provides satisfactory performance since the received power remains above the receiver's sensitivity, $P_{min_r} > -123dBW$, when considering that the antenna doesn't go to depths further then 20 mm. Moreover, given that the optimal operating frequency for this study is the Bluetooth band, the most suitable choice is the 2.4 GHz frequency.

2.3 Propagation in Transmission Lines (theory)

A transmission line is a structure designed to guide electromagnetic waves that carries electrical energy from a source to a load, as illustrated in Figure 2.10. When a signal is applied at the source, $S1$, it does not reach the load instantaneously. This delay occurs due to the distributed inductors and capacitors present along the transmission line, which affect how the signal propagates.



FIGURE 2.9: Representation of a Transmission Line

There is a wave traveling on the line and that wave can be described by the wave equation that is a differential equation:

$$\frac{d^2V(z)}{dz^2} = \gamma^2V(z) \quad (2.14)$$

2.3.1 Propagation Constant

First, γ is known as the propagation constant, a complex constant composed of a real part α and imaginary part β . The real part, α , is the attenuation constant, which indicates how the signal's amplitude decreases along the transmission line, the bigger the value of α the greater the attenuation along the line [Np/m]. The imaginary part, β is the phase constant, which describes how the phase of the signal changes as it propagates along the line [rad/m].

2.3.2 Voltage and Currents in the Line

When the differential equation is solved this is the general solution:

$$\begin{aligned} V(z) &= V_0^+ e^{-\gamma z} + V_0^- e^{\gamma z} \\ I(z) &= \underbrace{I_0^+ e^{-\gamma z}}_{\text{forward wave}} + \underbrace{I_0^- e^{\gamma z}}_{\text{backward wave}} \end{aligned} \quad (2.15)$$

In this solution V_0^+ , V_0^- , I_0^+ and I_0^- are constants that represent the amplitudes of the forward and backward traveling voltage and current waves, respectively. The parameter γ may vary depending on the characteristics of the transmission line while z represents the position along the line.

2.3.3 Wavelength Reduction Factor

The propagation velocity on the line can be given by the following equation,

$$v = \frac{\lambda}{T} = \lambda \cdot f = \frac{\omega}{\beta} \quad (2.16)$$

This velocity can also be derived from basic physics, where it depends on the material filling the transmission line. The filling is characterized by its relative permittivity ε_r and relative permeability μ_r . In the absence of filling, that is, when the transmission line is in vacuum, the permittivity and permeability reduce to their free-space values ε_0 and μ_0 and the propagation velocity becomes $v = c$, the speed of light in vacuum, just like its represented in 2.17 and the T represents the wave period, also defined as the inverse of the frequency. Following this and admitting that there is a free space wavelength, λ_0 , then we can express it as $\lambda_0 = \frac{c}{f}$

$$v = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} = c = 3 \cdot 10^8 \text{ [m/s]} \quad (2.17)$$

The transmission line model presented here is intended to analyze the propagation of electromagnetic waves in microstrip lines. So when the transmission line is filled with a dielectric material instead of a vacuum, it is typically assumed that the material is non-magnetic, meaning $\mu_r = 1$. However, the dielectric always exhibits a effective relative permittivity ε_e , which leads to the modified expression given in 2.18.

$$v = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_e \mu_0}} = \frac{1}{\sqrt{\varepsilon_e}} c \quad (2.18)$$

This also defines the guided wavelength, indicating that in a transmission line filled with dielectric material, the wave always propagates slower than in free space. This reduction speed is reflected by the wavelength reduction factor $\frac{1}{\sqrt{\epsilon_e}}$.

$$\lambda_g = \frac{v}{f} = \frac{1}{\sqrt{\epsilon_e}} \lambda_0 \quad (2.19)$$

2.3.4 Line Impedance

By relating I_0^+ and I_0^- to the corresponding voltage V_0^+ and V_0^- , it is possible to obtain the expression for the characteristic impedance shown in 2.20. The negative sign in the fraction arises from the direction of the current associated with the backward-traveling wave.

$$Z_0 = -\frac{V_0^-}{I_0^-} = \frac{V_0^+}{I_0^+} \quad (2.20)$$

The characteristic impedance can also be derived by the following parameters of the transmission line R' , the resistance per unit length, L' , the inductance per unit length, G' , the conductance of the dielectric per unit length and C' , the capacitance per unit length 2.21

$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \quad (2.21)$$

Although, if the losses are neglected L' and C' are fixed parameters of the line and R' and G' are not considered just as shown in 2.22. Under these conditions, the characteristic impedance Z_0 becomes a constant that depends on the physical dimensions and dielectric properties of the transmission line.

$$Z_0 = \sqrt{\frac{L'}{C'}} \quad (2.22)$$

A terminated transmission line is one that is connected to a load at its end. When a forward-propagating wave travels along the line, part of the signal is reflected back. The presence of this reflected wave is a direct result to how the load impedance compares to the line's characteristic impedance.

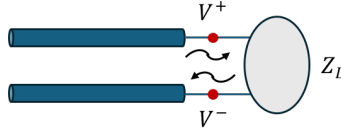


FIGURE 2.10: Forward and Backward Propagation Wave Reflected on the Matched Load

The reflected wave is represented by the reflection coefficient represented the following way,

$$\Gamma = \frac{V^-}{V^+} \quad (2.23)$$

The reflection coefficient can be determined by considering $V = V^+ + V^-$, $I = I^+ + I^-$ and $Z_L = \frac{V}{I}$. By substituting these equations and doing the necessary algebraic calculations the following can be deduced 2.24, while considering that $Z_L \neq Z_0$. This equation is fundamental in transmission line theory because it quantifies the portion of incident signal that is reflected back due to the impedance mismatch at the load.

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (2.24)$$

There are some special cases to consider, such as:

- Open line end with $Z_L = \infty$ where the incident and reflected wave have the same amplitude: $\Gamma = 1$;
- Shorted line with $Z_L = 0 \Omega$ where the incident and reflected have the same amplitude and a 180 phase difference: $\Gamma = -1$;
- Matched Load where the load impedance is equal to the line impedance $Z_L = Z_0$ and there are no reflections: $\Gamma = 0$.

2.3.5 Input Impedance of a Transmission Line

The input impedance of the transmission line is the impedance at the source. It depends on the characteristic impedance, the load impedance and the electrical length of the line. Considering a lossless case scenario, where $\gamma = j\beta$ it is possible to obtain the expression 2.25.



FIGURE 2.11: Input Impedance of the Transmission Line

$$Z_{\text{in}} = Z_0 \frac{Z_L + jZ_0 \tan(\beta l)}{Z_0 + jZ_L \tan(\beta l)} \quad (2.25)$$

When open-circuit and short-circuit transmission lines are considered, the following equation 2.25 simplifies to equations 2.26, respectively.

$$Z_{\text{in}} = -jZ_0 \cot(\beta l) \quad \wedge \quad Z_{\text{in}} = jZ_0 \tan(\beta l) \quad (2.26)$$

Chapter 3

Analytical and Numerical Design

This chapter presents the antennas analyzed throughout the study. It begins with two dual-band antennas that were taken as reference from literature, the Inverted-F Antenna and the Slotted Patch Antenna, whose feasibility for the intended application was assessed. Based on the limitations identified in these designs, a new antenna, the Wearable Parallel Patch Antenna (WPPA) was developed. This design was then selected for fabrication and experimental testing.

3.1 Inverted F Antenna (IFA)

The Inverted-F Antenna, IFA, is a planar antenna widely used in wearable and IoT applications (Bengloan et al. 2021) due to its simple geometry and impedance characteristics. The Internet of Things, IoT, refers to a network of physical devices embedded with sensors and software enabling them to exchange data with very little human intervention (Kommina et al. 2021). This antenna's planar structure supports integration with flexible substrates, making it well suited for wearable systems.

3.1.1 Antenna in Free Space and in the Presence of the Human Body

In this thesis, several simulations were carried out in CST, starting off by a dual-band IFA featuring an 'F'-shaped element on each side of the antenna to enable operation at two different frequencies, at 915 MHz and 820 MHz, proposed by Bengloan et al. 2021 for applications near the human body more specifically Wireless Body Area Networks, WBAN. The antenna maintains a stable impedance regardless of the distance to the human body, which contributes to a consistent performance.

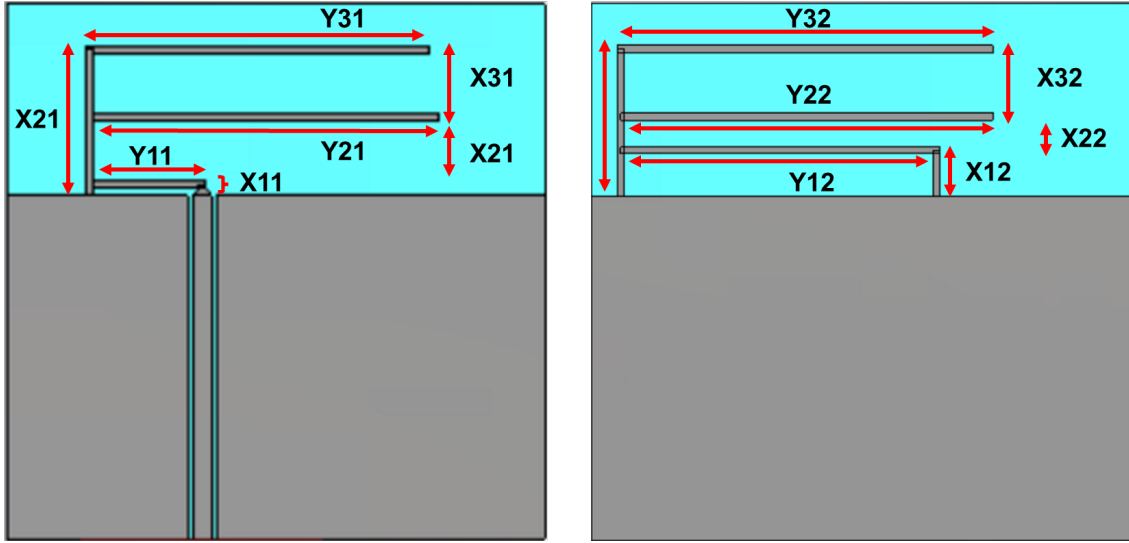


FIGURE 3.1: Representation of the 'F' shaped design as viewed from both sides of the antenna

To understand how each parameter influences the communication, more specifically how it affects each of the resonant frequencies, as shown in Table ??, a parametric study was carried out with the antenna in free space. The analysis began with the S_{11} parameter, which represents the reflection coefficient of the signal that goes back to the antenna. A lower magnitude of S_{11} indicates a better performance, as it means less signal is reflected back to the antenna. Ideally, maximum transmission occurs when the reflection is minimal, and in practice, good performance is considered when the S_{11} is below -10 dB at a given frequency. This analysis helps identify which parameters have the greatest impact on variations in the resonant frequencies. In this case, a polyester substrate was also included to simulate an antenna which is not placed directly on human skin. The substrate has a relative permittivity of 2.8 and an electrical conductivity of 0.01 S/m.

820 MHz	915 MHz
Y11, Y12, Y21, Y31, X12, Y32, X11, Y22, X22	X31, X21, X12

TABLE 3.1. Parameters Influencing the 820 MHz and 915 MHz Frequencies

After analyzing all the parameters, the objective was to optimize the antenna to operate at the desired frequencies. The gain obtained for the antenna in free space was -17.3 dBi at 920 MHz and -15.4 dBi at 820 MHz. These results are not satisfactory, as the target gain considered during the Link Budget was approximately -15 dBi, in a worst case scenario. Furthermore, these values were obtained

without considering the presence of the human body or water in the simulations, which are expected to further degrade the antenna's gain and performance.

Afterwards, a block was added to the simulation and the antenna was placed above the body-mimicking block, with a relative permittivity of 32.7 and a loss tangent of 0.05, used by Bengloan et al. 2021, simulating a homogeneous two-thirds muscle model, which is a model accepted by the scientific community as a good representation of the human body. The block had the following dimensions: 150 mm x 150 mm x 50 mm (X, Y, Z) and was positioned at a 10 mm distance from the antenna to evaluate its performance in the presence of the human body, as shown in Figure 3.2. With the inclusion of the block that simulates the human body the obtained gain was -14.7 dBi at 810 MHz and -18.1 dBi at 920 MHz. These results were negative, as the antenna already exhibits significant efficiency loss merely in the presence of the human body, before even accounting for the additional impact of integrating it into a lossy environment, such as water. These frequencies correspond to the original frequencies of the antenna. Based on these results, no optimization was carried out towards 2.4 GHz, since the tendency would be to further degrade the antenna's performance.

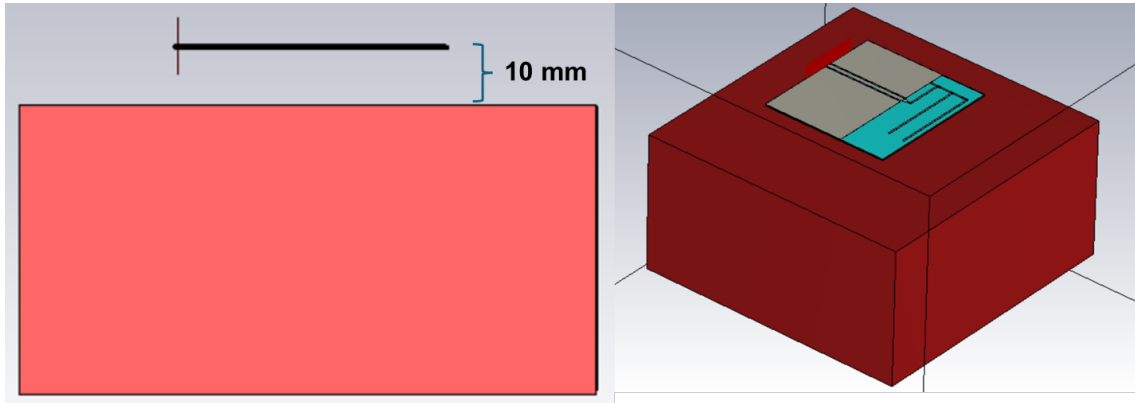


FIGURE 3.2: Inverted-F Antenna 10 mm from the Human Body Model

3.2 Slotted Patch Antenna

After analyzing the IFA antenna, it was concluded that it would not be the most suitable option for this study. Although the presence of the human body did not significantly alter the antenna's gain, its performance was already so low that it fell below -15 dBi threshold, which had been established as a reference based on prior numerical math. As an alternative, a slotted patch antenna was considered. According to Musa et al. 2023, the slots in the patch and ground alter the current

distribution, enabling the possibility to have a antenna that can operate in more than one frequency (multiband operation) and in this case at 2.4 GHz, ISM band, and 5.8 GHz which are critical for wearable antennas in WBAN applications being a dual-band antenna. In the present work, the objective is to re-purpose this antenna as a dual-mode system, so instead of operating at two different frequencies the main objective would be to operate at just 2.4 GHz, the Bluetooth frequency, in two different environments, at the surface of the water, shallow waters and air environments.

As a starting point the antenna on CST done by Musa et al. 2023 was replicated and had the following structure; an inverted *U*-shaped slot to add a resonant frequency at 2.4 GHz, two slots and a partial ground at the patch's bottom edge to increase the antenna's bandwidth and gain Musa et al. 2023. The objective was to analyze the variation of the simulated reflection coefficient, S_{11} in free space for specific parameter values. 3.3 shows the slotted patch antenna used by Musa et al. 2023 with all the parameters identified on both front and back side and 3.4 shows the slotted patch antenna constructed in CST for this study at this stage.

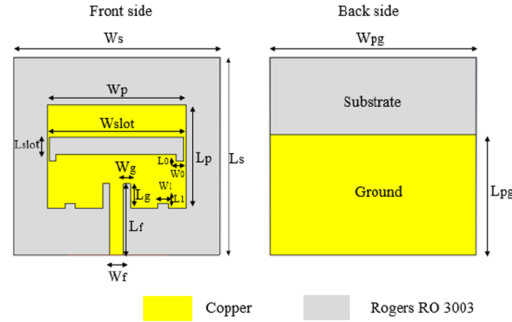


FIGURE 3.3: Structure of the Slotted Patch Antenna taken from Musa et al. 2023

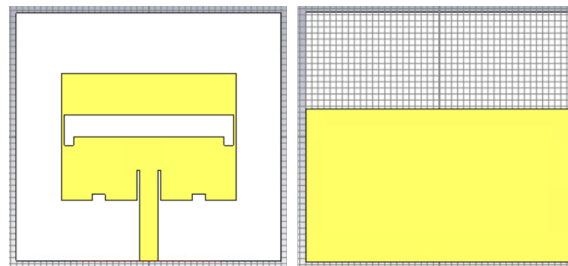


FIGURE 3.4: Slotted Patch Antenna Constructed on CST

The following graph 3.5 represents the S_{11} , confirming that the antenna developed by Musa et al. 2023 operates at the given frequencies of 2.4 and 5.8 GHz.

3.2. Slotted Patch Antenna

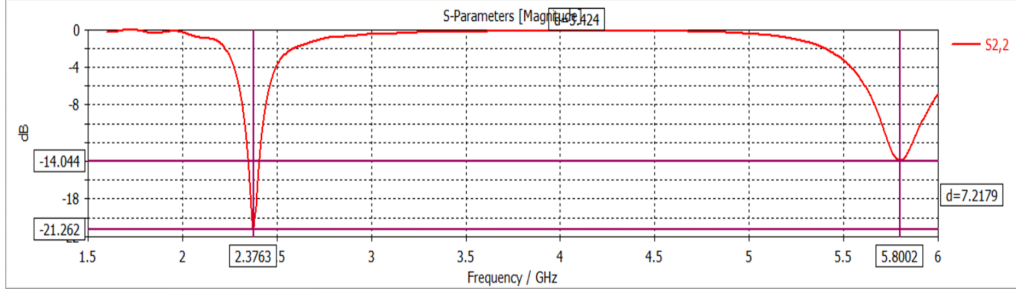


FIGURE 3.5: S_{11} of the Slotted Patch Antenna in Free Space

The study of this antenna began with an analysis of its behavior in free space, through a parametric study aimed at understanding the influence of specific parameters on the operating frequency, following a similar methodology to that used for the IFA antenna. The initial step involved varying the parameters L_g , L_{slot} , W_g , W_{slot} , L_{pg} , W_p and L_p to identify which ones had the greatest impact on frequency performance. This analysis was based on the observation of the S_{11} response curves. The graphs shown in 3.6 through to 3.12 show the variation of the S_{11} for all the parameters mentioned before.

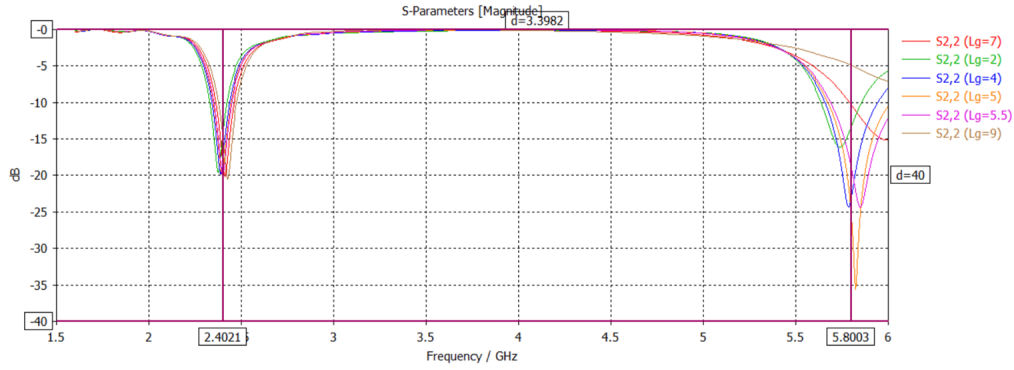


FIGURE 3.6: Parameter Sweep to Understand the Antenna's Behavior - L_g [2; 4; 5; 5.5; 7; 9]

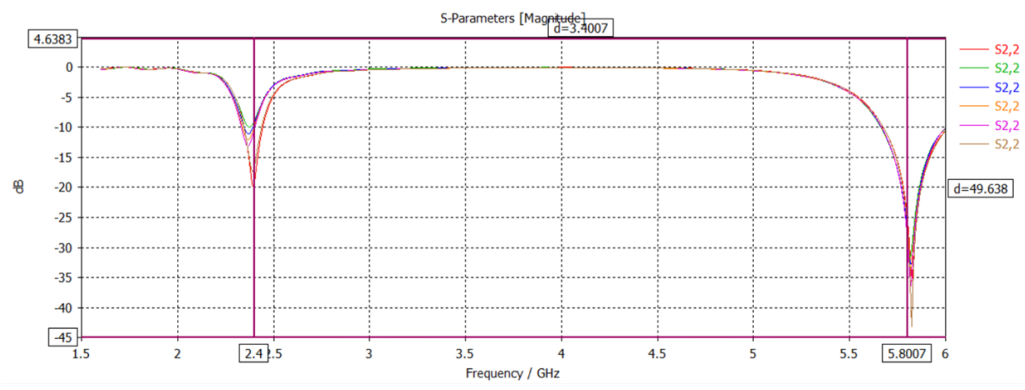


FIGURE 3.7: Parameter Sweep to Understand the Antenna's Behavior - *Lslot* [2.5; 2.8; 3; 3.2; 3.5; 3.7]

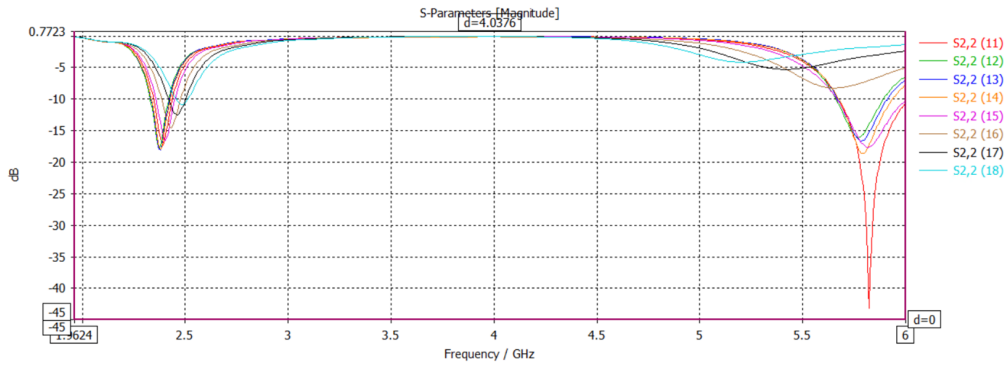


FIGURE 3.8: Parameter Sweep to Understand the Antenna's Behavior - *Wg* [0.5; 0.75; 1; 2; 3; 5; 7; 9]

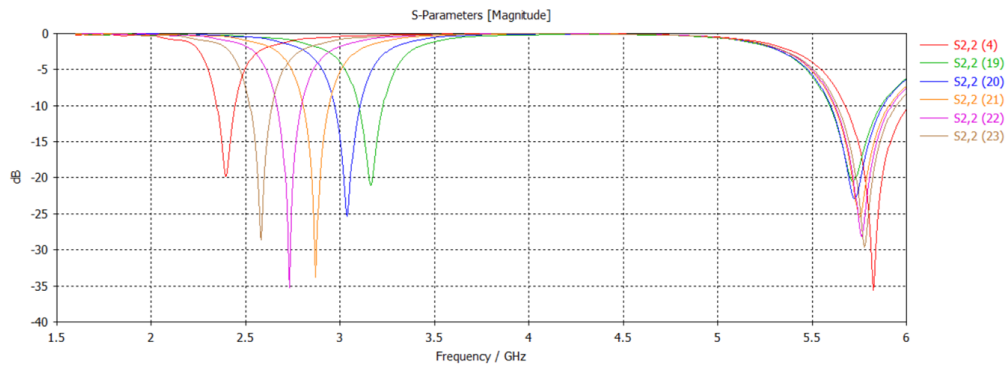


FIGURE 3.9: Parameter Sweep to Understand the Antenna's Behavior - *Wslot* [23; 24; 25; 26; 27; 28]

3.2. Slotted Patch Antenna

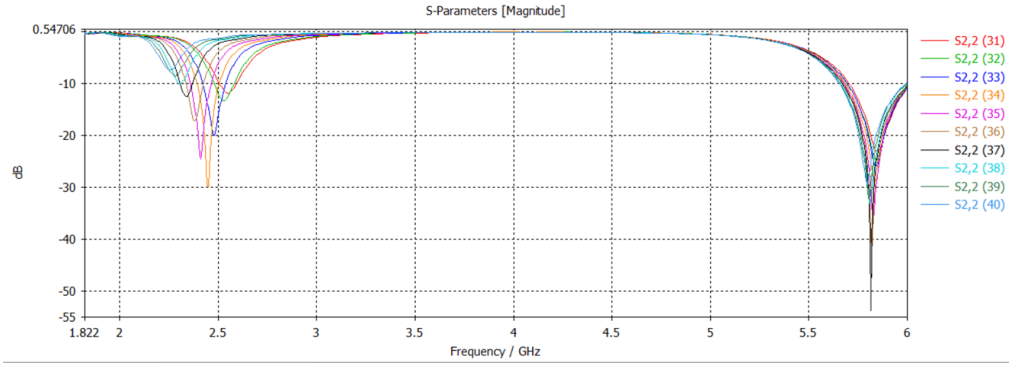


FIGURE 3.10: Parameter Sweep to Understand the Antenna's Behavior - L_{pg} [24; 24.22; 24.44; 24.66; 24.88; 25.1; 25.33; 25.55; 25.77; 26]

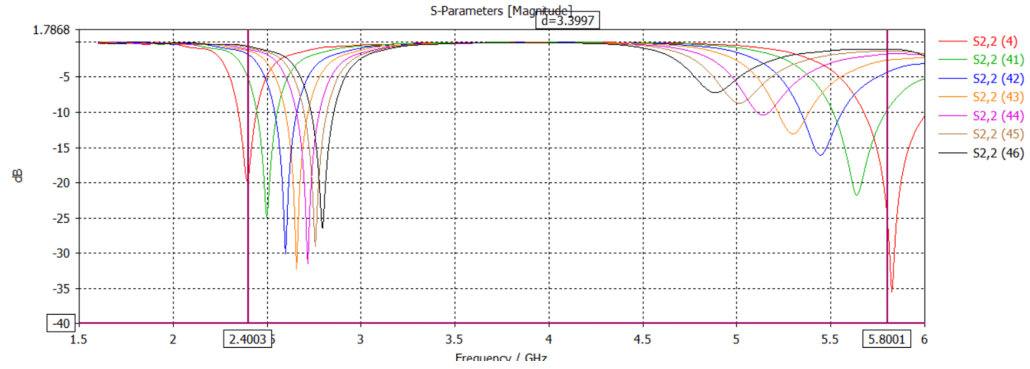


FIGURE 3.11: Parameter Sweep to Understand the Antenna's Behavior - W_p [29; 30; 31; 32; 33; 34; 35]

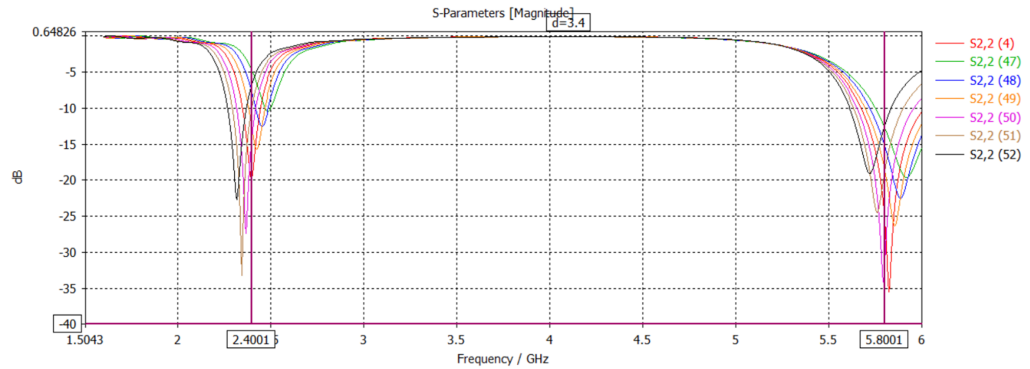


FIGURE 3.12: Parameter Sweep to Understand the Antenna's Behavior - L_p [18; 19; 20; 21; 22; 23; 24]

The figures above illustrate the influence of each parameter on the antenna's performance. By identifying which parameters have the greatest impact on each resonant frequency and its corresponding magnitude, it becomes easier to understand and guide the antenna optimization process. The table below summarizes the results presented previously.

Parameters	Freq. 2.4 GHz	Freq. 5.8 GHz	Mag. 2.4 GHz	Mag. 5.8 GHz
Lg	No	Yes++	No	Yes+++
Lslot	No	No	Yes	Yes
Wg	Yes	Yes++	Yes	Yes+++
Wslot	Yes+++	Yes	Yes++	Yes++
Lpg	Yes+	No	Yes++	Yes++
Wp	Yes++	Yes+++	Yes++	Yes+++
Lp	Yes	Yes	Yes++	Yes+++

TABLE 3.2. Influence of Parameters on Resonant Frequency and Magnitude

After analyzing the summarized results, it becomes evident that the parameters $Wslot$ and Wp have the greatest influence on both the resonant frequency and magnitude at 2.4 GHz. For the 5.8 GHz resonant frequency, the most influential parameters are $Wslot$, Lg , Wg and Wp , while the magnitude at this frequency is mainly affected by $Wslot$, Wg and Wp . Overall, $Wslot$ and Wp consistently demonstrate the strongest influence across both frequencies and their corresponding magnitudes, making them critical parameters to focus on during the optimization process.

3.2.1 Antenna in the Presence of a Simulated Human Body

After identifying the parameters with the greatest influence, the antenna optimization process was initiated. The first step consisted in reproducing the antenna with the inclusion of a block representing the human body, similarly to what had been previously done with the Inverted-F Antenna. This block was modeled the same way as of the previous antenna, Inverted-F Antenna, with a relative permittivity of 32 and a loss tangent of 0.05, with the objective of assessing the impact of the human body on the antenna's performance. The Figure 3.13 shows the behavior of the antenna in the presence of the human body through the S_{11} .

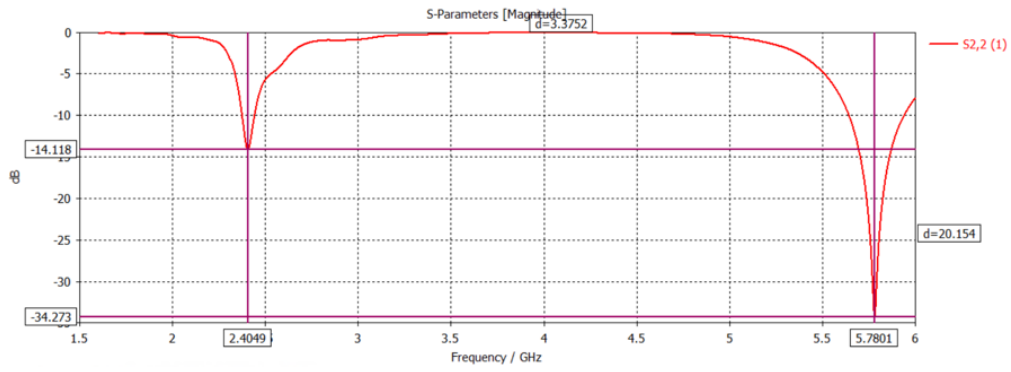


FIGURE 3.13: S_{11} of the Slotted Patch Antenna with the Human Body

The results indicated that the human body had a more significant effect on the magnitude at the lower operating frequency of 2.4 GHz, causing a variation of approximately 4 dB. In contrast, at 5.8 GHz, the influence was minimal, with a difference of only 1 dB. Therefore, it was concluded that the presence of the human body does not substantially affect the transmission performance of this antenna, except slightly at the lower frequency band.

3.2.2 Antenna's Realized Gain and Directivity as a Function of the Distance to the Human Body

To better understand the influence of the simulated human body on the antenna's performance, a test was conducted to analyze the effect of distance between the antenna and the body on the transmission, gain and directivity of the antenna. In this test, the antenna was positioned at various distances ranging from 0.4 to 10 mm from the body in order to evaluate how proximity affects its behavior, as shown in Table 3.3

Distance to the body (mm)	Directivity 2.4 GHz(dBi)	Directivity 5.8 GHz(dBi)	Gain 2.4 GHz(dBi)	Gain 5.8 GHz(dBi)
0.4	6.58	5.31	-11.60	-0.39
0.9	6.84	6.01	-7.06	1.56
1.6	7.33	6.35	-3.95	2.74
2.0	7.71	6.36	-1.73	3.36
2.5	7.85	6.38	-0.52	3.69
3.0	7.97	6.33	0.41	3.96
3.5	8.05	6.27	1.14	4.08
4.0	8.12	6.16	1.81	4.16
6.0	8.34	5.94	3.66	4.56
10.0	8.56	6.14	5.79	5.21

TABLE 3.3. Antenna Distance from Body

This helped understand that the human body has a greater impact on the first frequency, as previously mentioned. The 2.4 GHz frequency, with its higher wavelength compared to the 5.8 GHz frequency, is better able to penetrate the human body. Consequently, more energy is absorbed by the body leading to a greater degradation in gain when compared to a 5.8 GHz frequency, especially as the antenna gets closer to the body.

3.2.3 Neoprene Coating over the Slotted Patch

The slotted patch antenna cannot be exposed directly to water without a protective coating, because water contains impurities, such as dissolved minerals, that are electrically conductive. This conductivity can create unintended current paths between isolated sections of the metalized microstrip, potentially leading to a short circuit (Light et al. 2004).

Neoprene was chosen as the preferred coating material, as it is commonly used in athletes swimsuits and diving suits due to its flexibility and water resistance. The coating design consists of 2 mm layer of neoprene placed between the antenna and the simulated human body, followed by an additional 2 mm layer covering the antenna itself. This configuration is illustrated in the figure below.

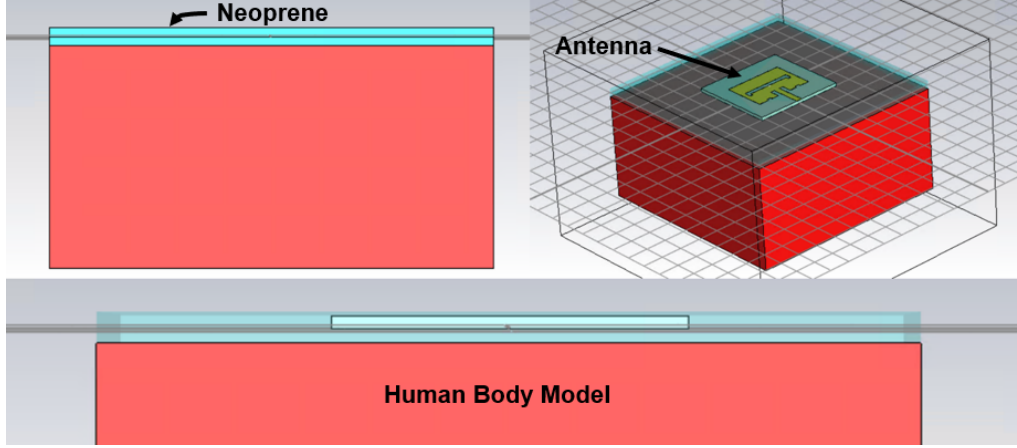


FIGURE 3.14: Design of the antenna in the presence of a human body model and a layer coating of neoprene

After embedding the antenna in neoprene, the S_{11} parameter was analyzed to assess whether it still operated effectively at 2.4 GHz and 5.8 GHz. The results in the figure below showed that the antenna no longer resonates at 2.4 GHz after the application of the 4 mm neoprene coating, resulting in a significant performance loss. This degradation limits the antenna's intended communication capabilities as the 2.4 GHz is the most critical frequency for this application, being the standard frequency for Bluetooth communication.

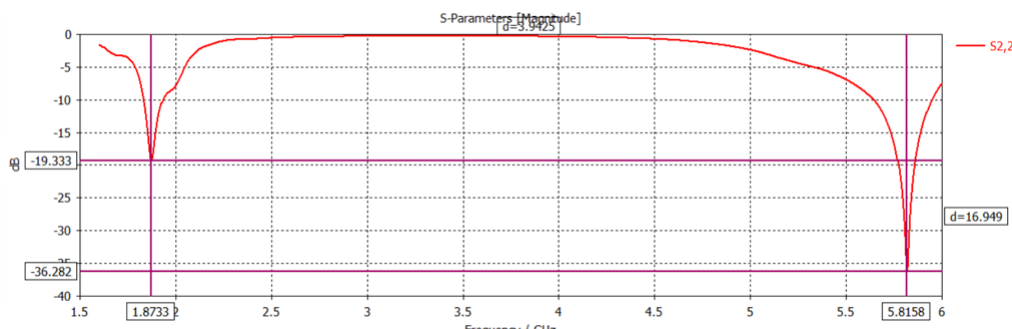


FIGURE 3.15: S_{11} graph of antenna embedded in neoprene

In addition to the mismatch in operating frequency, the antenna also exhibits very low gain at 2.4 GHz, because it hasn't been optimized yet. The realized gain at this frequency was -14.3 dBi, which is nearly equivalent to the value observed in preliminary numerical math where water was not yet included and the directivity at 2.4 GHz was 6.39 dBi. At 5.8 GHz, the antenna performs better, with a realized gain of 3.76 dBi and directivity of 7.71 dBi, so the optimization of the antenna embedded in the neoprene became necessary.

After analyzing the influence of each one of the parameters of the embedded antenna in the neoprene and in proximity to the human body, following the same procedure used for the free-space configuration, the resulting S_{11} after optimization is shown in the following figure.

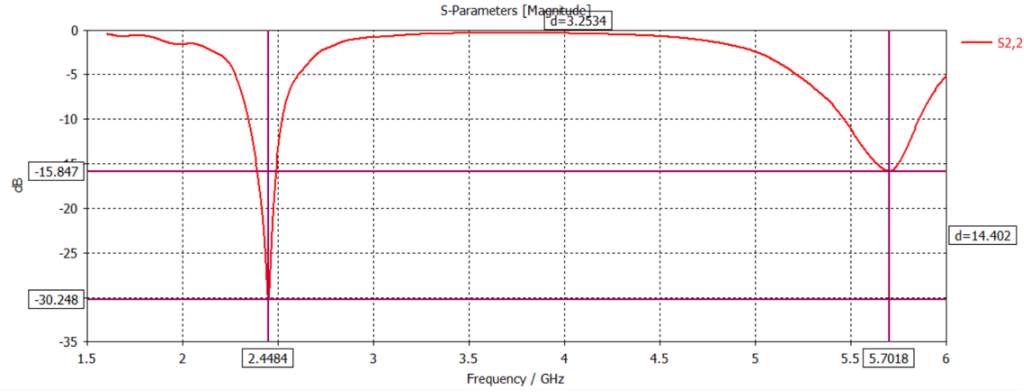


FIGURE 3.16: S_{11} graph of antenna embedded in neoprene optimized

The realized gain at 2.4 GHz improved significantly, reaching -1.41 dBi, with a corresponding directivity of 8.91 dBi. At 5.8 GHz, the performance slightly decreased, with a realized gain of 3.07 dBi and a directivity of 7.36 dBi.

3.2.4 Thickness of the Neoprene

After optimizing the antenna in the presence of neoprene and the human body, the next step was to analyze whether the thickness of the neoprene influenced the antenna's performance, which it did. The study began by varying the neoprene thickness from 2.2 mm to 5 mm, considering that 2 mm were already placed between the body and the antenna ground. This means that the total neoprene thickness between the body and the surrounding water ranged from 4.2 mm to 7 mm.

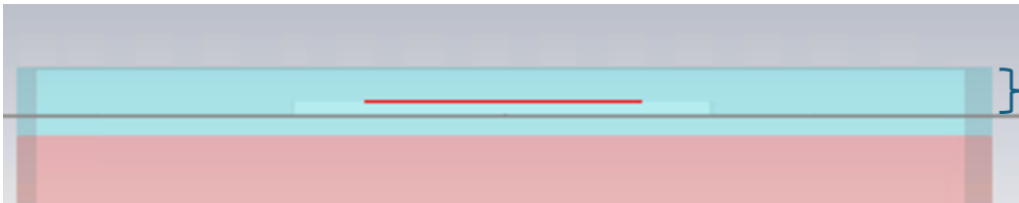


FIGURE 3.17: Studying Neoprene's Thickness

The results indicate that as the neoprene layer becomes thicker, the quality factor of the resonant frequencies degrades. Increasing the thickness of the neoprene

leads to a downward shift in both the 2.4 GHz and 5.8 GHz resonant frequencies. In terms of magnitude, the impact is particularly significant at 2.4 GHz, while the 5.8 GHz frequency is comparatively less affected.

Height (mm)	Freq.2.4 GHz	Freq.5.8 GHz	Mag.2.4 GHz	Mag.5.8 GHz
2.2	2.405	5.610	-26.582 dB	-17.235 dB
2.3	2.387	5.576	-27.092 dB	-18.064 dB
2.5	2.365	5.516	-29.368 dB	-19.442 dB
3.0	2.326	5.401	-34.157 dB	-19.966 dB
4.0	2.264	5.291	-46.879 dB	-15.876 dB
5.0	2.224	5.213	-41.399 dB	-12.318 dB

TABLE 3.4. Influence of neoprene’s thickness on the resonant frequencies and the magnitude

After analyzing the results from the simulation of the thickness of the neoprene it was visible that it is critical to vary the neoprene’s thickness because it changes the efficiency of the antenna. The resonant frequencies suffer changes and the magnitude for the 2.4 GHz resonant frequency change significantly.

3.2.5 Slotted Patch Antenna in the Presence of Water

After analyzing the results, it was observed that the mimicked human body had minimal impact on the antenna’s performance. Consequently, the 5.8 GHz frequency, originally intended to mitigate potential interference caused by the human body, was concluded to be non-essential for the antenna’s operation. Instead of implementing a dual-band antenna operating at both frequencies, the antenna was optimized to operate solely at 2.4 GHz, the Bluetooth frequency, functioning as a dual-mode antenna.

After optimizing the antenna to operate at 2.4 GHz for both environments, a water layer was introduced into the simulation to evaluate its impact on signal transmission. The water was modeled with a relative permittivity of 77.2 42 and a loss tangent of approximately 0.12 43 (calculated as $9.43/77.2$). These parameters were based on the predefined “debye” water material available in the CST material library.

To better understand the influence of water on the transmission of the antenna, several water layers with varying thicknesses were added to the simulation, starting at 5 mm and increasing incrementally 5 by 5 up to 25 mm as shown in

Fig. 3.18. The results showed that the antenna is highly sensitive to the presence of water, indicating that it may not be the most suitable choice for this type of application.

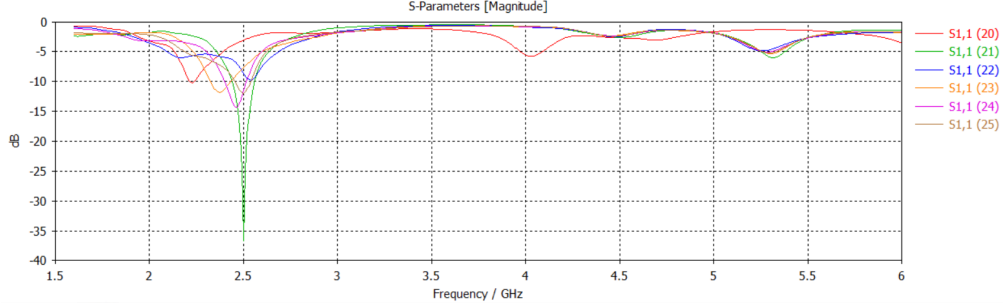


FIGURE 3.18: Variation of Thickness of Layers of Water

At this point, there was a need to develop a new wearable antenna with slightly different characteristics such that it could operate in approximately optimal conditions with all the environments included. Further analysis gave rise to a new antenna which was named the Wearable Parallel Patch Antenna (WPPA).

3.3 Analytical Design of the Wearable Parallel Patch Antenna

After evaluating previous antenna designs and determining their unsuitability for this application, a new wearable antenna was developed, the WPPA. This antenna was specifically optimized to operate in both air and aquatic environments at a frequency of 2.45 GHz.

The WPPA consists of two parallel patch antennas, chosen for their robustness and suitability for integration with the human body. One antenna is optimized for operation in air, while the other is specifically designed for use in water. Each antenna is individually matched to its respective environment to ensure the best performance (Figure 3.19).

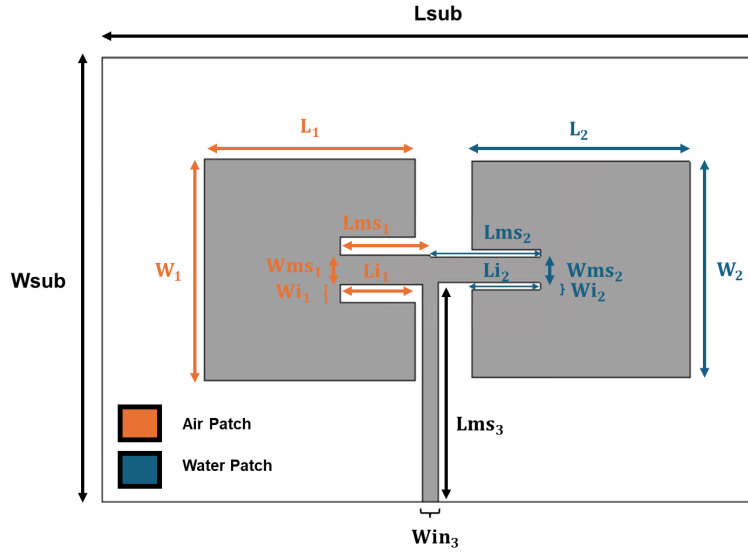


FIGURE 3.19: Parameters of the WPPA

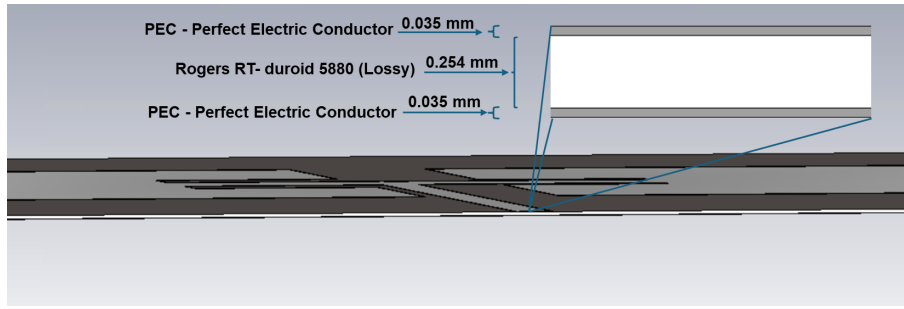


FIGURE 3.20: Parameters of the WPPA

For the WPPA to function properly, all the impedances must be matched to 50 ohm. When the WPPA is in air, the antenna optimized to that specific environment should present a 50 ohm load, while the antenna optimized for the aquatic environment remains disconnected, representing an open circuit with infinite impedance.

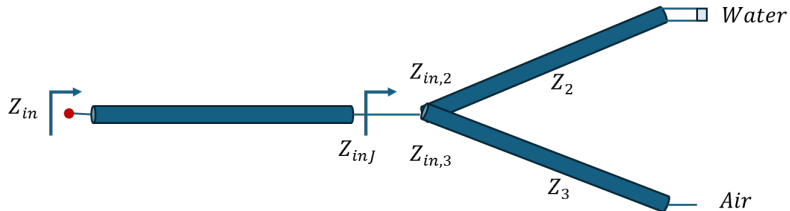


FIGURE 3.21: Representation of the antenna operating in an aquatic environment

On the other hand, when operating in water, the antenna optimised to operate in aquatic environments, should present 50 ohm load and the air antenna should act like an open circuit. This ensures that, in either environments, the input impedance is always 50 ohm, minimizing reflections and maximizing the efficiency of the antenna in each environment.

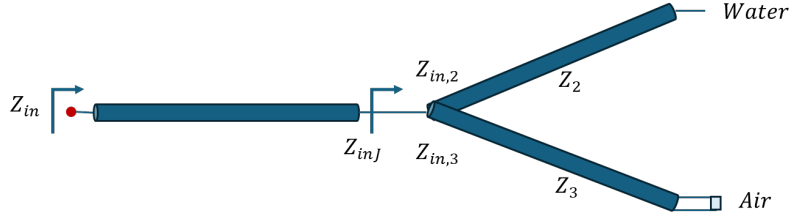


FIGURE 3.22: Representation of the antenna operating in air

To better justify this approach, the input impedance at the antenna junction can be analyzed using the transmission line theory represented in Equation 2.25. The total input impedance at the junction can be modeled as two different impedances, shown in

$$Z_{inJ} = \left(\frac{1}{Z_{in,3}} + \frac{1}{Z_{in,2}} \right)^{-1} \quad (3.1)$$

On the other hand, if one branch is matched (50Ω) and the other is open circuit, the resulting impedance seen at the feed point is shown in the equation below

$$Z_{in,J} = \left(\frac{1}{50} + \frac{1}{\infty} \right)^{-1} = 50 \Omega$$

To determine $Z_{in,2}$ and $Z_{in,3}$, the transmission line theory Equation 2.25 was applied by substituting the appropriate load values for each branch. For example, when the water environment antenna is active, $Z_{in,2}$ is calculated with $Z_{L,2} = 50 \Omega$ and $Z_{in,3}$ with $Z_{L,3} \rightarrow \infty$ (open circuit):

$$Z_{in,2} = Z_0 \frac{50 + jZ_0 \tan(\beta l)}{Z_0 + j50 \tan(\beta l)} = Z_0$$

$$Z_{in,3} = Z_0 \frac{\infty + jZ_0 \tan(\beta l)}{Z_0 + j\infty \tan(\beta l)} \approx \infty$$

The same happens, when the air antenna is active, the calculations are inverted: $Z_{in,3}$ uses $Z_{L,3} = 50 \Omega$ and $Z_{in,2}$ uses $Z_{L,2} \rightarrow \infty$:

$$Z_{in,3} = Z_0 \frac{50 + jZ_0 \tan(\beta l)}{Z_0 + j50 \tan(\beta l)} = Z_0$$

$$Z_{in,2} = Z_0 \frac{\infty + jZ_0 \tan(\beta l)}{Z_0 + j\infty \tan(\beta l)} \approx \infty$$

This parallel configuration guarantees that, regardless of which patch is active, the antenna always presents a 50Ω input impedance, ensuring an efficient operation and minimal signal reflection in each environment.

To model this concept the CST Studio Suite was used to simulate this antenna as done before with the previous antennas.

3.4 Numerical Design of the Wearable Parallel Patch Antenna

The objective of this section is to simulate the previously developed concept and to design the antenna in a manner that enables its subsequent fabrication.

The process begins with the optimization of each patch in free space to ensure operation at the intended frequency. After this, one patch is analyzed and optimized for operation in the aquatic environment, while the other is optimized to operate in air. The influence of the human body and a neoprene coating on the performance of each patch is then assessed. Afterwards, both patches are integrated and the antenna is further tuned to function efficiently in both environments. Finally, the resulting design is considered to be attached to fabric and used in swimmer's swimwear or for potential military applications once it is a wearable antenna.

3.4.1 Evaluation of Each Patch's Response in Air and Water

CST Studio Suite was used to simulate the WPPA by analyzing each patch individually. Each patch was then optimized to operate at 2.4 GHz (3.23a and 3.23b), ensuring efficient operation at the target frequency prior to the further analysis in the aquatic environment.

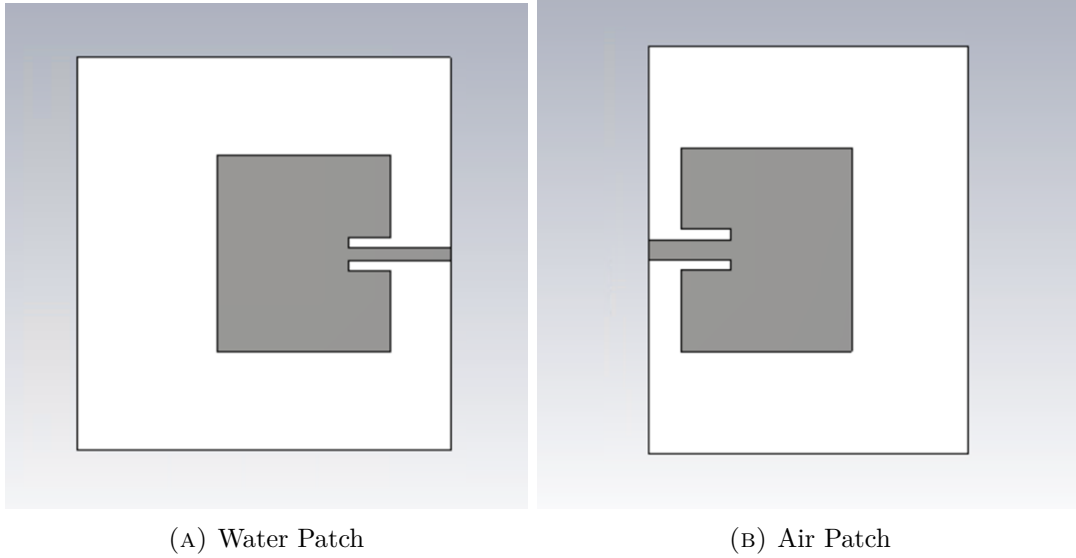


FIGURE 3.23: Simulation design of both patches

To ensure that each patch operated at the correct frequency, the same procedure used for the previous antennas was applied. Initially, the resonance frequency was adjusted to 2.4 GHz by analyzing the S_{11} parameter and confirming that it remained below -10 dBi.

Understanding which parameters were more influential on the resonant frequency, when altered, was the start off for the optimization process (Figure 3.24).

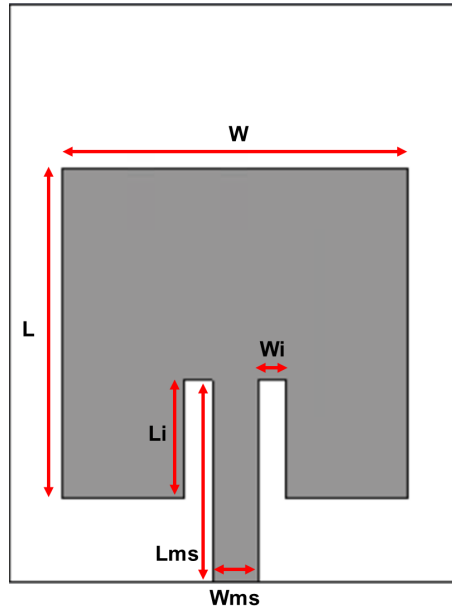


FIGURE 3.24: Parameters of the patch

It was observed that, for both patches, the most critical parameters influencing the S_{11} magnitude were the length (L) and width (W), as these define the essential dimensions of the patch. In order to fine-tune the resonant frequency, the Li parameter plays a significant role, not only to achieve the correct frequency but also to adjust the input impedance approximating it to an open circuit when the patch is operating outside its intended environment. The parameters Lms and Wms also play an important role in the adjustment of the input impedance.

The water patch was simulated with a 10 mm layer of water. It was positioned, 5 mm above the antenna and optimized in that environment, as shown in Figure 3.25.



FIGURE 3.25: Water Patch distanced by 5 mm from a 10 mm layer of water

On the other hand, the patch that operates in the air was optimized in free space.

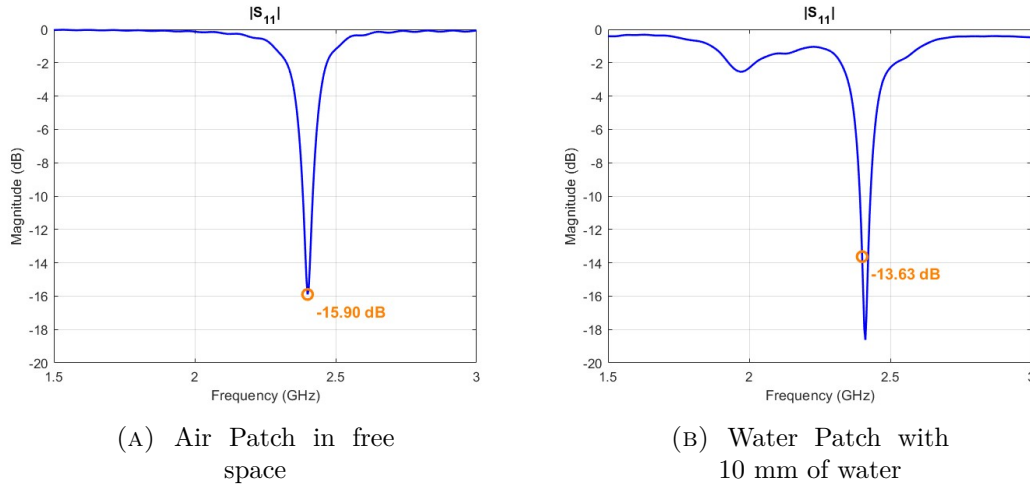


FIGURE 3.26: Simulation of both patches in their own environment

As shown in Figure 3.26, the magnitude at the intended frequency is indicated by an orange circle. It is evident that both patches were successfully optimized and are operational within their respective environments at a preliminary phase.

It is essential to ensure that the optimization process does not affect the input impedance. While optimizing each patch to operate at the correct frequency

in its respective environment, it is necessary to maintain an input impedance as close as possible to 50Ω .

The input impedance consists on both real and imaginary components and for optimal matching, the imaginary part should be minimized to zero, ensuring that the input impedance remains a real impedance at 50Ω . The values of the input impedance for each patch were 36Ω and 52Ω . Although these values do not exactly match the ideal impedance, they are within an acceptable range to proceed with further analysis of the antenna.

3.4.2 Impact of the Human Body and Neoprene Coating on each Patch

After analyzing each patch within its respective environment, namely the water patch with a surrounding layer of water and the air patch in free space, without any external interference, the next step involved introducing a block to simulate the presence of the human body, as shown in 3.27. This block was modeled with the same characteristics as those used in the previous antenna simulations. The red area represents the body, the thin white layer the antenna and the blue area the water.

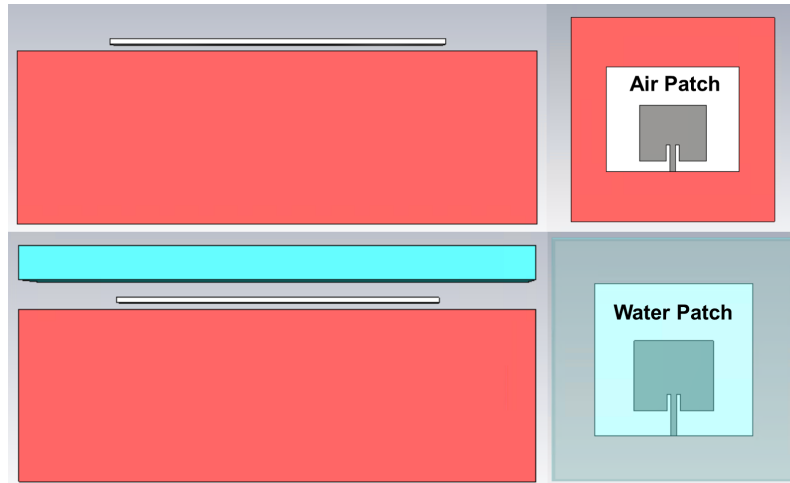


FIGURE 3.27: Each Patch Interacting With the Human Body in Their Environment

After introducing the human body simulation block, the reflection results were obtained, as shown in Figure 3.28. There was some improvement in the S_{11} magnitude. The antenna went from -15.90 dB to -26.25 dB in magnitude representing an improvement of 10 dB. This can be observed in Figure 3.28 which represents the S_{11} parameter of the Air Patch. Additionally, the resonant frequency shifted

closer to 2.4 GHz. On the other hand, the water patch experienced a decline in performance, with the S_{11} magnitude changing from -13.63 dBi to -9.5 dBi (Figure 3.29), which does not meet the -10 dBi threshold.

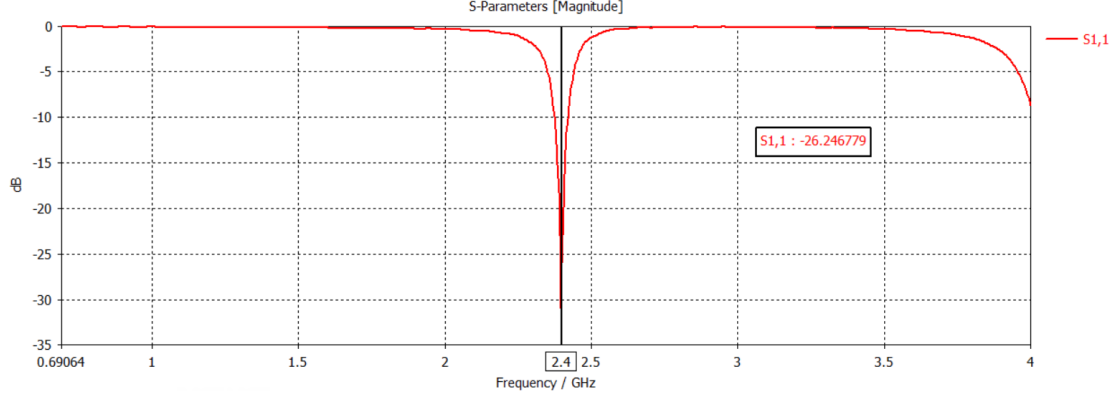


FIGURE 3.28: Air Patch With the Human Body

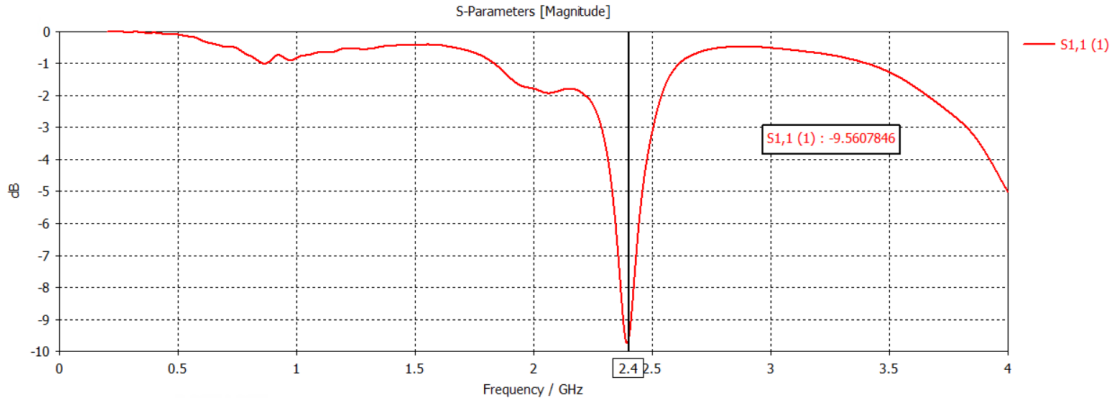


FIGURE 3.29: Water Patch With the Human Body

A neoprene coating was introduced, with $\epsilon_r = 1.7$ and a loss tangent of $\delta = 0.0168$ as shown in Figure 4.12. The optimization process was then repeated for both patches, simulations were conducted by analyzing each patch individually. First, the air patch was optimized with both the human body and neoprene, ensuring that its S_{11} parameter and input impedance in the air environment met the expected values, specifically an input impedance of 50Ω . The same patch was then evaluated in the presence of a water layer, with the goal of minimizing the imaginary part of the input impedance and maximizing the real part to approximate an open circuit as closely as possible. Subsequently, the water patch was optimized following the same methodology, but within its respective environment and its behavior was also analyzed in air to confirm that it approximated an open circuit in that scenario.

After analyzing the influence of the human body on signal transmission, it became evident that its presence negatively impacted the performance of the water patch. On the other hand, the human body introduced significantly less interference for the air patch when compared to the effects on the water patch.

Given the high conductivity of water, the antenna design should incorporate a smaller separation between the antenna and the human body compared to the thickness of the neoprene layer between the antenna and the water. This design approach was applied to each patch individually, allowing for independent testing and optimization.



FIGURE 3.30: Water Patch With the Human Body and Neoprene

To achieve this, the configuration illustrated in Figure 3.30 was adopted. A neoprene thickness of 1 mm was placed between the body and the patch, while a 3.5 mm layer separated the patch from the water. This design maximizes the antenna's protection against interference from the aquatic environment. The neoprene coating over the antenna was designed to closely replicate the actual shape and fit used in practical experiments, ensuring optimal ergonomics and minimizing any impact on the individual's movement.

The analysis began by evaluating the S_{11} magnitude for each patch in its respective environment, as shown in Figure 3.31 for the water patch and Figure 3.32 for the air patch. Additionally, the input impedance for each patch was examined, and the results are presented in Figure 3.33 for the water patch and Figure 3.34 for the air patch.

3.4. Numerical Design of the Wearable Parallel Patch Antenna

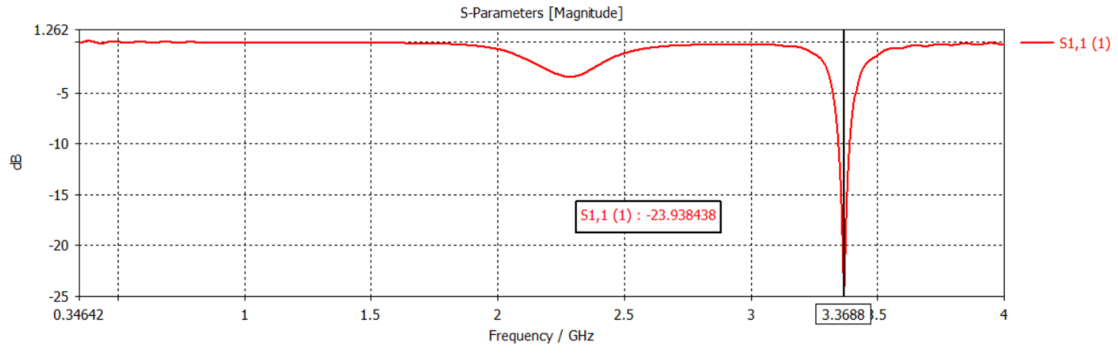


FIGURE 3.31: S_{11} before Optimization of the Water Patch in the Presence of the Human Body and Neoprene

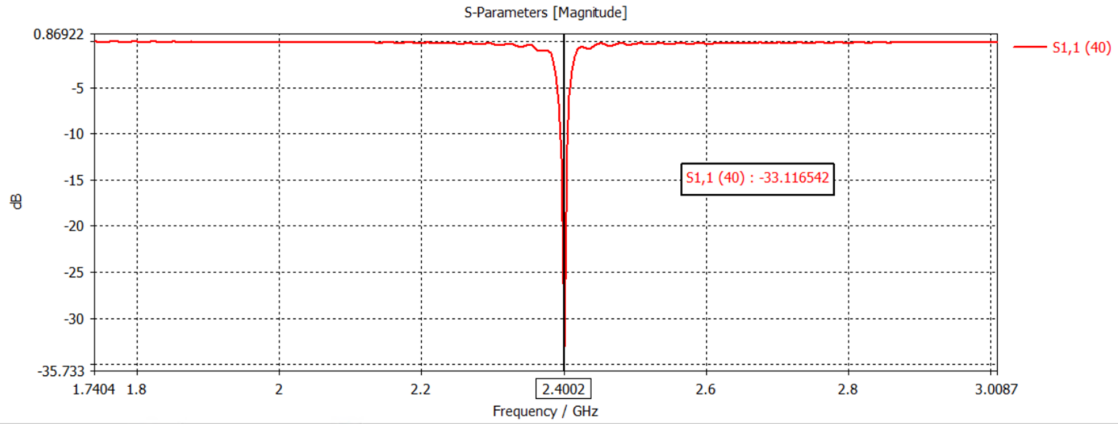


FIGURE 3.32: S_{11} before Optimization of the Air Patch in the Presence of the Human Body and Neoprene

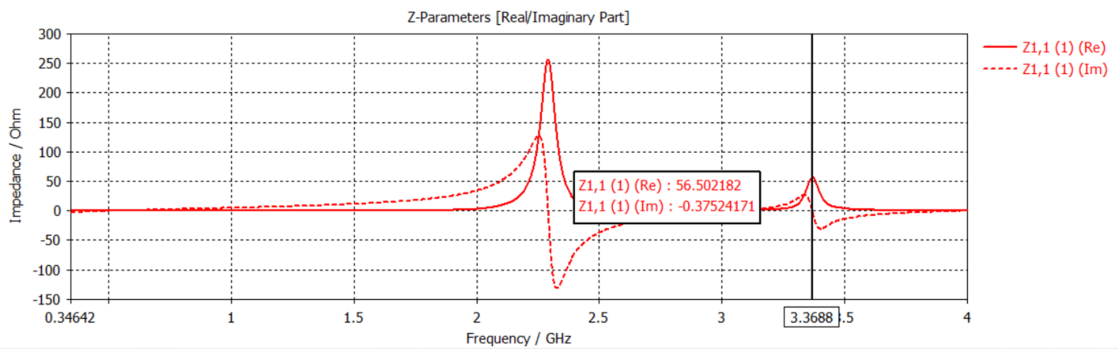


FIGURE 3.33: Input Impedance - Water Patch With the Human Body and Neoprene

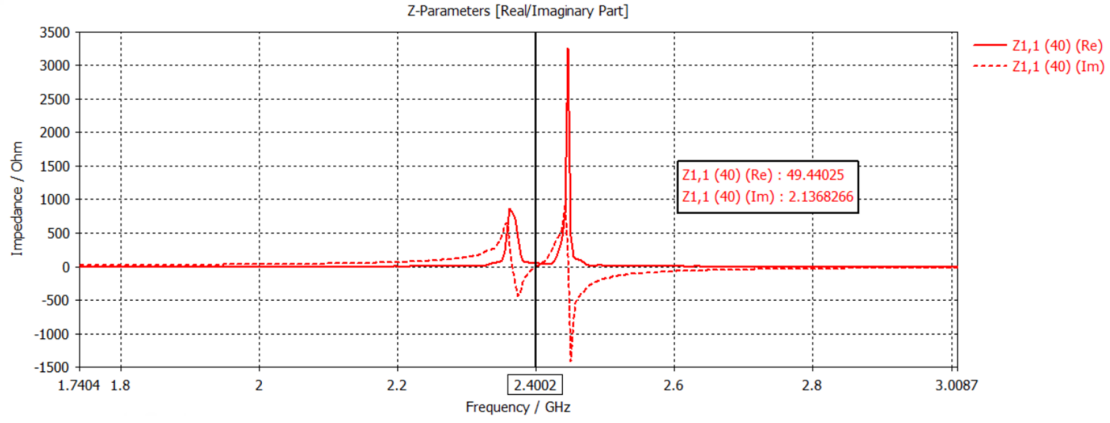


FIGURE 3.34: Input Impedance - Air Patch With the Human Body and Neoprene

Several significant changes were observed, particularly for the water patch when analyzing the results prior to separate optimization of the patches. The resonant frequency for the water patch shifted considerably away from the target frequency of 2.4 GHz, as illustrated in Figure 3.31. On the other hand, the performance of the air patch improved significantly with the inclusion of both the neoprene layers and the human body model, the S_{11} magnitude changed from -15.90 dBi to -33.11 dBi, with the resonance precisely aligned at the desired frequency.

Regarding the input impedance, both patches showed values close to the desired 50Ω , as shown in Figure 3.33 and Figure 3.34.

The next step was to optimize each patch to operate at the Bluetooth frequency. Specifically, the target frequency was 2.45 GHz rather than 2.4 GHz, as 2.45 GHz is commonly used and is centrally located within the 2.4 GHz ISM band (Balanis 2005)

After an extensive optimization process, the final results for each patch in its respective environment were obtained and are shown in, 3.35, 3.36, 3.37 and 3.38. These figures demonstrate that each patch operates as intended within its designated environment.

3.4. Numerical Design of the Wearable Parallel Patch Antenna

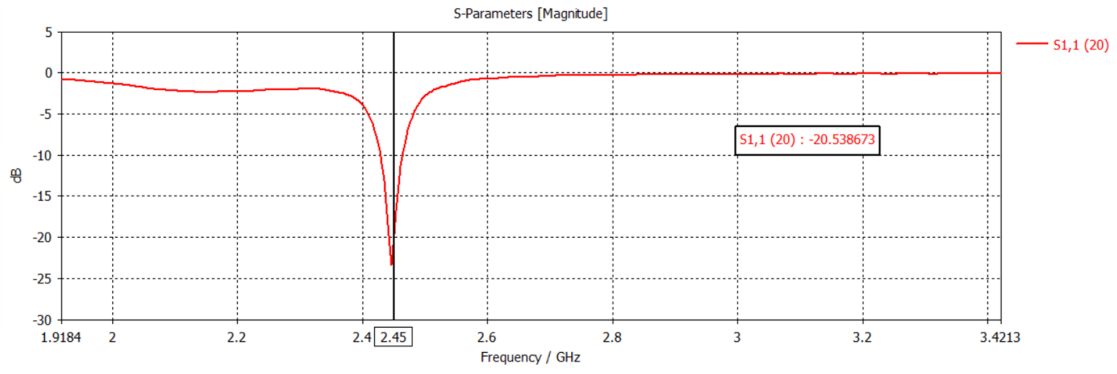


FIGURE 3.35: S_{11} - Optimized Water Patch

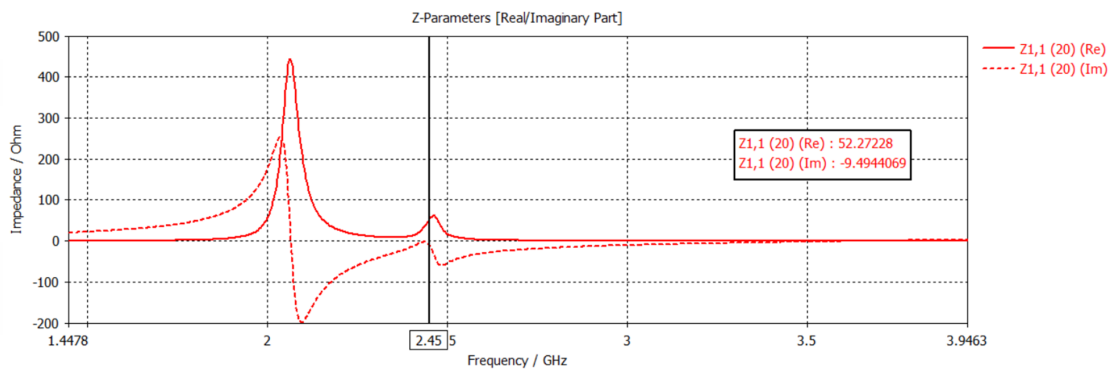


FIGURE 3.36: Input Impedance - Optimized Water Patch

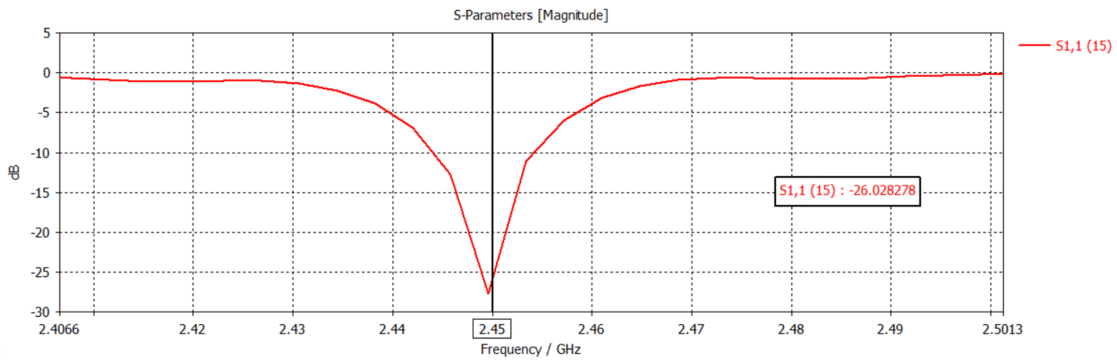


FIGURE 3.37: S_{11} - Optimized Air Patch

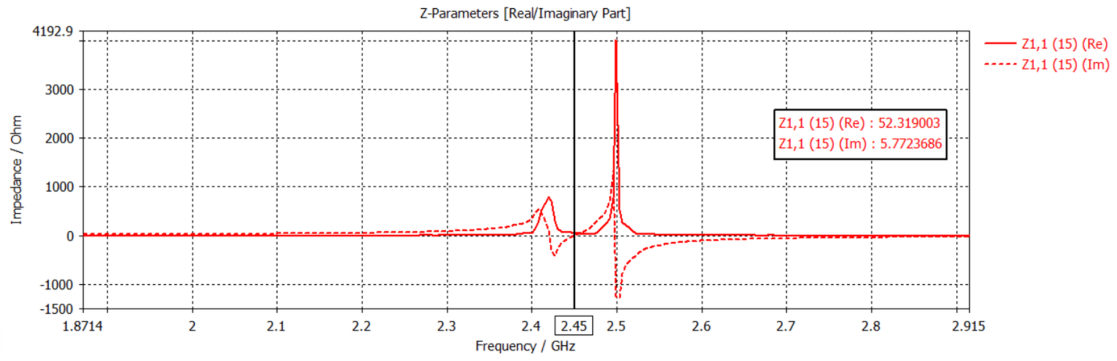


FIGURE 3.38: Input Impedance - Optimized Water Patch

Regarding the input impedance in the open circuit condition for each antenna, both patches were also optimized to operate under these conditions, as illustrated in Figure 3.39 and Figure 3.40

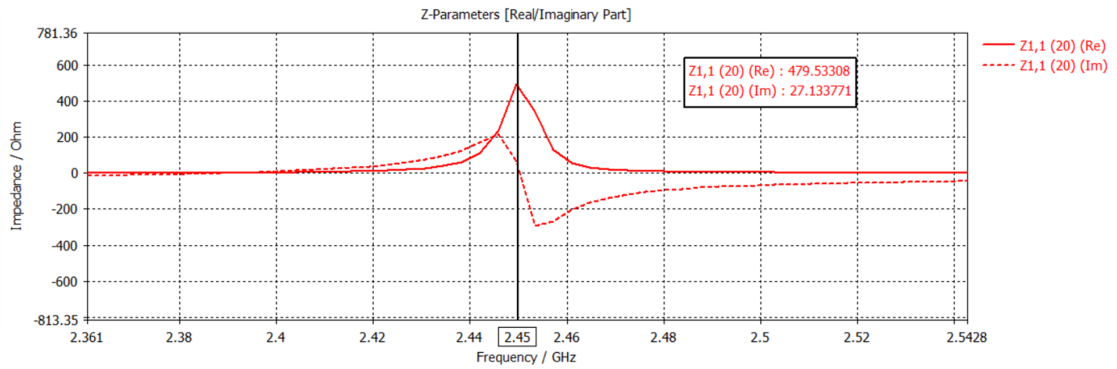


FIGURE 3.39: Open Circuit - Water Patch

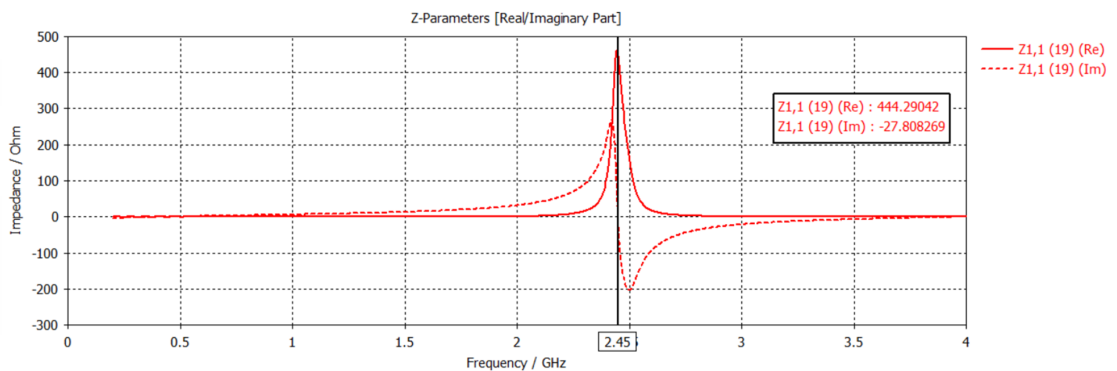


FIGURE 3.40: Open Circuit - Air Patch

The realized gain and directivity obtained from each patch were the following shown in Table 3.5 with the corresponding farfield, shown in 40, 41, 38 and 39

Patch	Directivity	Realized Gain
Air Patch	8.15 dBi	4.61 dBi
Water Patch	6.25 dBi	- 5.7 dBi

TABLE 3.5. Gain and Directivity from each Optimized Patch

Following the optimization of each patch, they were integrated to form the complete WPPA, enabling effective operation in both environments.

3.4.3 WPPA - Integration of Both Patch Antennas

The integration process of both patches was done by creating a junction between the two optimized patches, as shown in Figure 3.19 and Figure 3.20.

Before proceeding with further optimization, the results from this junction (Figure 3.41) were analyzed to assess whether the antenna was functioning as intended, even if its performance was not yet ideal.

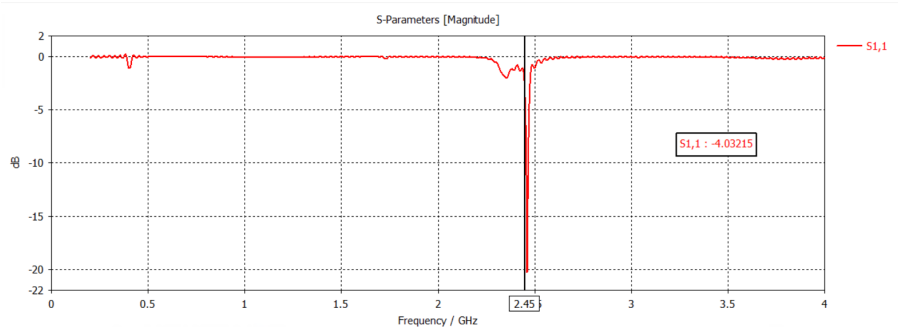


FIGURE 3.41: WPPA

The resonant frequency was slightly shifted from the 2.45 GHz. However, since the patches had been optimized in the presence of neoprene and the human body model, these two elements needed to be incorporated before proceeding with further optimization. Once the neoprene layer was added to the antenna (Figure 3.42), the resonant frequency automatically aligned with the target value, as shown in 36. This adjustment also resulted in an improvement in the reflection of the signal, by analyzing the magnitude, shifting from -4 dBi to -31 dBi and a input impedance exactly at 50Ω , as shown in 37.

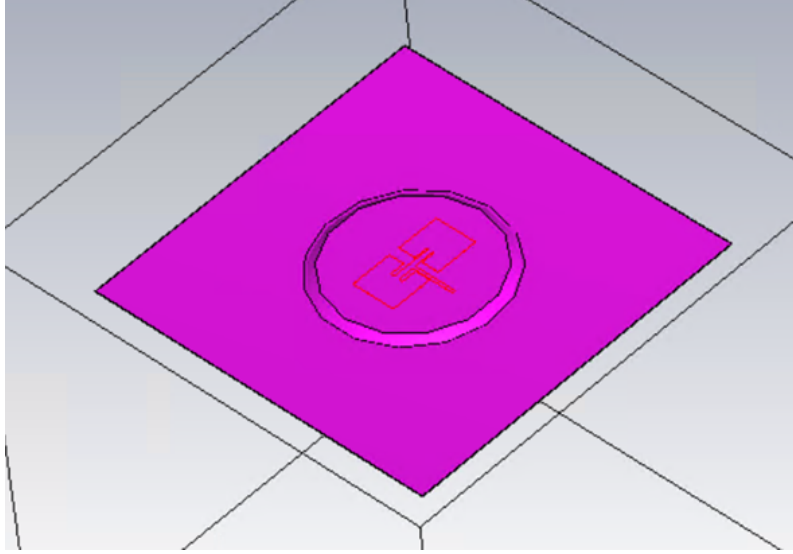
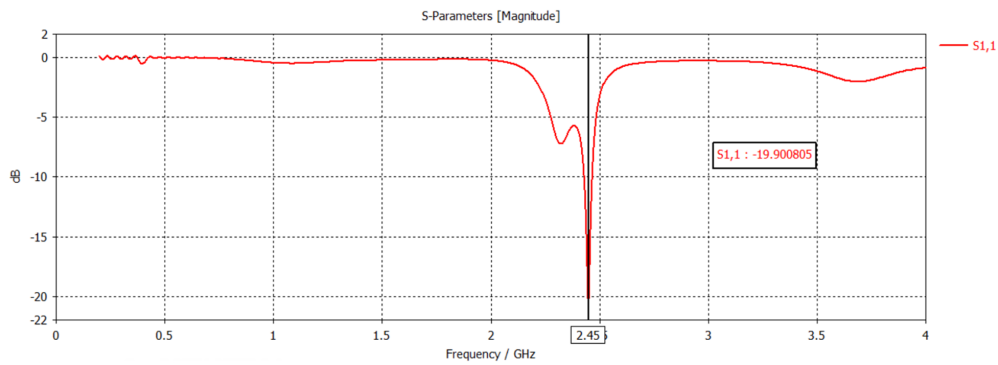


FIGURE 3.42: WPPA with a Coating of Neoprene

The human body model was then incorporated to enable the simulation of the WPPA in both environments. The antenna was placed under a 10 mm layer of water and separately, within a 10 mm layer simulating air, vacuum.

Beginning with the simulation under a water layer, Figure 3.43 shows that the antenna is functional in this environment, operating at the correct resonant frequency. Furthermore, the input impedance is approximately 50Ω , as illustrated in Figure 3.44.

FIGURE 3.43: S_{11} - Optimized WPPA in the Presence of Water, the human body model and a layer coating of neoprene

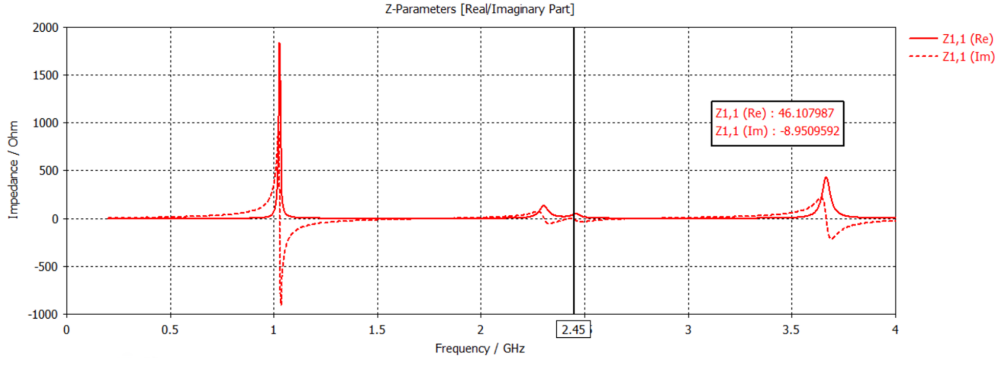


FIGURE 3.44: Input Impedance - Optimized WPPA in the Presence of Water, the human body model and a layer coating of neoprene

As for the antenna, when operating outside of water (Figure 3.45), it is visible that the magnitude decreased substantially when the human body model was added to the simulations. Nonetheless, the antenna continues to operate as intended with the input impedance remaining close to the target value (Figure 3.46).

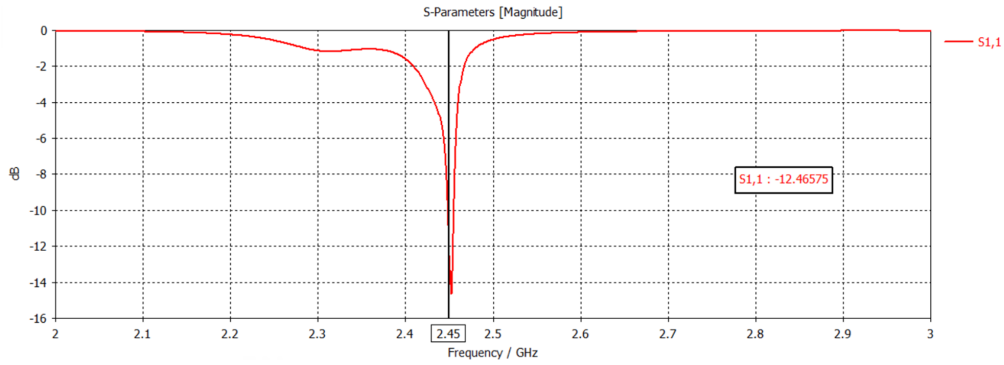


FIGURE 3.45: S_{11} - WPPA in the Presence of Air

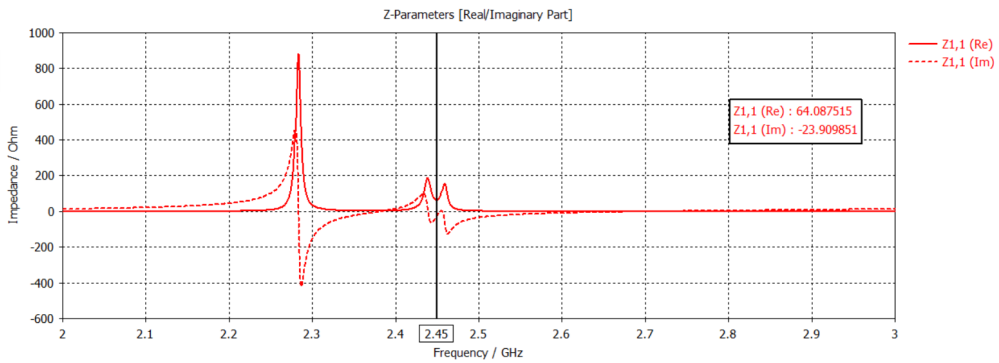


FIGURE 3.46: Input Impedance - WPPA in the Presence of Air

In addition to these factors, it was essential to verify whether the antenna's realized gain aligned with the numerical link budget, which specified a transmission

gain threshold of -15 dBi. This requirement was the reason why the first antenna considered, the Inverted-F Antenna, was excluded from the study. Therefore, evaluating the realized gain and directivity was also important to determine the suitability of the proposed one, WPPA, for this study.

	Realized Gain	Directivity
Free space	5.7 dBi	8.97 dBi
Neoprene	5.82 dBi	8.25 dBi
Body and neoprene (Air environment)	6.36 dBi	9.23 dBi
Body and neoprene (Water environment)	-5.11 dBi	7.7 dBi

TABLE 3.6. Realized Gain and Directivity for Different Test Environments

The results presented in Table 3.6 represent the final gain values obtained through the optimization process. The WPPA demonstrated higher efficiency when used in combination with the neoprene layer and the human body model, than when tested in free space or with only the neoprene coating. This improvement can be attributed to the fact that each patch was individually optimized for its specific environment. Although the performance in the water layer test was clearly less efficient than in the air environment, it still surpassed all previously studied antennas, remaining within 10 dB of the threshold.

The design of the WPPA was considered viable due to these positive evaluations and outcomes. The final parameter values that were obtained for the optimized WPPA were the following in Table 3.7, considering the design shown in Figure 3.19.

Parameter	Value(mm)	Parameter	Value(mm)	Parameter	Value(mm)
Wms_1	5.64	Wms_2	5.0	Win_3	3.1
Lms_1	17.5	Lms_2	21.30	Win_3	3.0
Lp_1	41	Lp_2	42.30	Lms_3	22.5
Wp_1	43	Wp_2	41.95	$Lsub$	86
Li_1	14.67	Li_2	13.28	$Wsub$	127.3
Wi_1	3.5	Wi_2	1.40	$hsub$	0.254

TABLE 3.7. Final Values of the Parameters of WPPA

3.4.4 Military Application

Beyond the use of wearable antennas in neoprene wetsuits for amphibious or aquatic missions, one relevant future application lies in the integration of this technology into the standard operational uniforms used aboard the naval ships.

These uniforms, as described in the official specification ET 0515 of the Portuguese Navy, are made of flame-retardant aramid based textile blends and designed with multiple integrated pockets. This structural design presents opportunities for embedding lightweight antennas without compromising the ergonomics or functionality of the individual.

A relevant potential application of the proposed design is the automatic detection and signaling of man overboard events. In maritime operations, particularly during nighttime navigation, where the identification of personnel who have fallen overboard presents a challenge due to reduced visibility. The WPPA developed in this study could be adapted to address this issue by integrating a textile-based antenna into the back of each crew member's uniform. In this configuration, the WPPA automatically transmits a signal to the ship upon immersion in water, enabling rapid detection and response incidents, thereby improving man-overboard rescue operations.

This application would only be feasible through the integration of an embroidered antenna into the uniform. Given that the required operating frequency would be significantly lower, the antenna dimensions would consequently be larger. Therefore, the most efficient approach to incorporating it, while preserving the ergonomics and mobility of the crew member, would be to sew the antenna directly into the fabric of the uniform.

This antenna could be designed as a dual-band, operating at both the GPS frequency of 1227.6 MHz and the Very High Frequency (VHF) band. This band is continuously monitored on naval ships for Search and Rescue (SAR) purposes, specifically on channel 16, which operates at 156.8 MHz in accordance with *Portaria n.º 630/2002*.

For the proposed military application, the adapted antenna should operate at two distinct frequencies, each serving a specific purpose. The first is the VHF frequency, dedicated to man overboard scenarios. In this mode, when a crew member falls into the water the antenna, upon immersion, would immediately transmit a distress signal on a designated VHF channel. This approach is optimal, as the individual is likely to be in close proximity to the ship at the time of the incident, ensuring reliable reception even with moderate transmission power. The second frequency would be the GPS band, enabling geolocation of the crew member for recovery operations. This method would optimize the security of the crew members.

Chapter 4

Experimental

4.1 Setup Preparation

4.1.1 Phantom Fabrication and Characterization

To facilitate the experimental validation of the designed antenna, a homogeneous phantom was developed to mimic the dielectric properties of human tissue. This phantom, shaped to approximate a torso, was adapted from the two-third phantom described by Mendes and Peixeiro 2017. It was fabricated using deionized water, agar, sodium chloride, TX-151 and polyethylene powder, similar to the composition used by Mendes and Peixeiro 2017, but with a different total volume and with specific quantities and components detailed in Table 44.

As the volume of the phantom differed from that used in previous studies, the fabrication process began by determining its total volume. Given the phantom dimensions of $350 \times 350 \times 100 \text{ mm}^3$ its volume was calculated to be 12.25 liters. To estimate the required quantities of each component for this volume, a direct proportion calculation was applied, resulting in the values shown in 4.1.

Component	Quantity (g)
Deionized water	9715.9
Agar	301.12
Sodium chloride	20.11
TX-151	86.64
Polyethylene powder	2915.06

TABLE 4.1. Components and Quantities used for Phantom Fabrication

The ingredients were carefully measured and heated under continuous agitation to ensure uniform dispersion and avoid burning the agar. TX-151 and polyethylene powder were gradually added to the mixture with appropriate safety precautions to prevent inhalation and clumping (4.1). Once homogenized, the mixture was poured into a mold with dimensions $350 \times 350 \times 100$ mm, wrapped in plastic film, to preserve moisture and structural integrity and cooled at room temperature for 24 hours.



FIGURE 4.1: Process of Making the Phantom

After 24 hours, the phantom did not exhibit the expected consistency, it remained overly gelatinous. This posed a potential issue, as variations in consistency could lead to non-uniform dielectric properties throughout the phantom, contrary to the objective of achieving a homogeneous one. This was evident by the formation of two distinct layers, a denser and more cohesive layer at the top and a lower layer that appeared more liquid, as illustrated in Figure 4.2.



FIGURE 4.2: Phantom

The fact that there were two layers, was a potential problem, so a permittivity test was carried out to check if the phantom still had the right properties to simulate human tissue for these experiments.

The human body's complex tissue interactions can be modeled using a phantom composed of common substances and mixtures, as described earlier. In the final stages of phantom fabrication it became clear that a permittivity test was necessary to assess whether the phantom remained suitable for experimental use. To measure the phantom's permittivity, an open-ended coaxial probe technique was implemented beginning with the calibration of the measurement setup.

The process began by connecting the open-ended coaxial probe to a Vector Network Analyzer (VNA), an essential equipment for RF and high frequency measurements commonly used to test and verify design simulations to make sure they work properly (Tektronix 2012). Before taking measurements, the probe was carefully calibrated using three reference standards. First the probe was measured in free space to simulate an open circuit ensuring a reflection coefficient of $\Gamma \approx 1$. Second, a short circuit was simulated using aluminium foil, ensuring that $\Gamma = -1$. Finally, the probe was placed in contact with a matched load at certain frequencies, deionized water can be considered as a matched load due to its permittivity, resulting in nearly perfect absorption and a reflection coefficient close to zero $\Gamma = 0$. After calibration, permittivity measurements of the fabricated phantom were executed in three different spots to assure homogeneity. This process was repeated three times leaving a total of nine measurements of the phantom itself.

The experimental method involved inserting the open-ended coaxial probe into the material under test, the phantom. The probe is sensitive to the phantom and a signal is reflected at the probe tip. This reflected signal was measured and analyzed using the VNA, showing the S_{11} , also known as the reflection coefficient.

4.1.2 Mathematical Basis of the Calibration Method

To estimate the complex permittivity of the phantom using the open-ended coaxial probe, the measured reflection coefficient $\rho_m(\omega)$ at the calibration plane of the VNA must be related to the intrinsic dielectric properties of the material under test, in this case the phantom.

The calibration method used in this study, based on the approach proposed by Bao et al. and refined by Bobowski et al. (Bobowski and Johnson 2012), avoids the need for prior knowledge of the probe's capacitances. It expresses the measured reflection coefficient as:

$$\rho_m(\omega) = \frac{A_2 + A_3 \left(\varepsilon_r - j \frac{\sigma_{dc}}{\omega \varepsilon_0} \right)}{A_1 + \left(\varepsilon_r - j \frac{\sigma_{dc}}{\omega \varepsilon_0} \right)} \quad (4.1)$$

where:

- ε_r is the relative permittivity of the phantom;
- σ_{dc} is the direct current conductivity of the phantom;
- ω is the angular frequency;
- ε_0 is the vacuum permittivity;
- A_1, A_2, A_3 are calibration coefficients computed from three standard terminations.

The calibration coefficients are obtained from the reflection coefficients ρ_1 , ρ_2 and ρ_3 , measured respectively with:

- a short circuit (aluminium foil) where the reflection coefficient at the tip of the probe is, $\Gamma_1 = -1$;
- an open circuit (air): $\Gamma_2 \approx 1$;
- a standard liquid load with known dielectric properties $\varepsilon_r^s, \sigma_{dc}^s$: Γ_3 is computed from impedance.

The constants are then given by:

$$A_3 = \rho_1 \quad (4.2)$$

$$A_1 = \frac{(\rho_2 - \rho_1) + (\rho_1 - \rho_3) \left(\varepsilon_r^s - j \frac{\sigma_{dc}^s}{\omega \varepsilon_0} \right)}{\rho_3 - \rho_2} \quad (4.3)$$

$$A_2 = \frac{\rho_3(\rho_2 - \rho_1) + \rho_2(\rho_1 - \rho_3) \left(\varepsilon_r^s - j \frac{\sigma_{dc}^s}{\omega \varepsilon_0} \right)}{\rho_3 - \rho_2} \quad (4.4)$$

Once A_1 , A_2 and A_3 are computed, equation (4.1) can be inverted to extract ε_r and σ_{dc} of the unknown sample. This method was used in the present study to characterize the phantom fabricated for experimental validation.

After processing the nine different permittivity and loss tangent values from each measurement, the mean and standard deviation were calculated for both parameters. It is evident that the loss tangent remained relatively consistent across all measurements, as shown in Figure 4.4. On the other hand all nine measurements of the permittivity show significant variations ranging from 30 to 45 as can be seen in Figure 4.3.

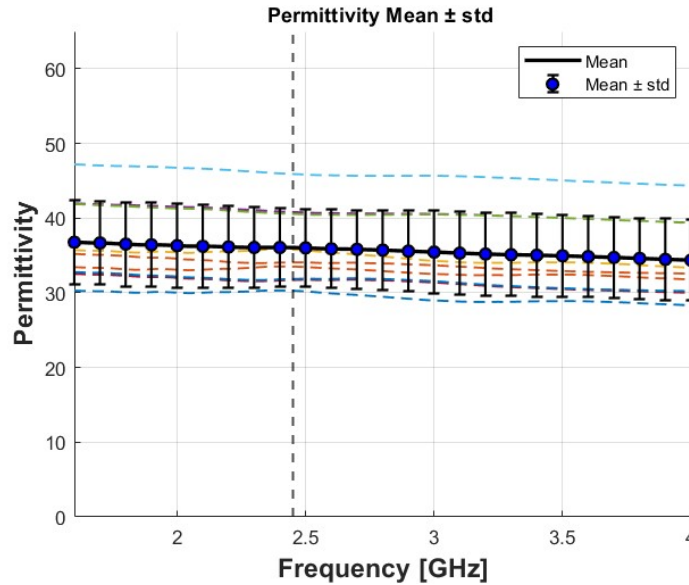


FIGURE 4.3: Permittivity Measurements

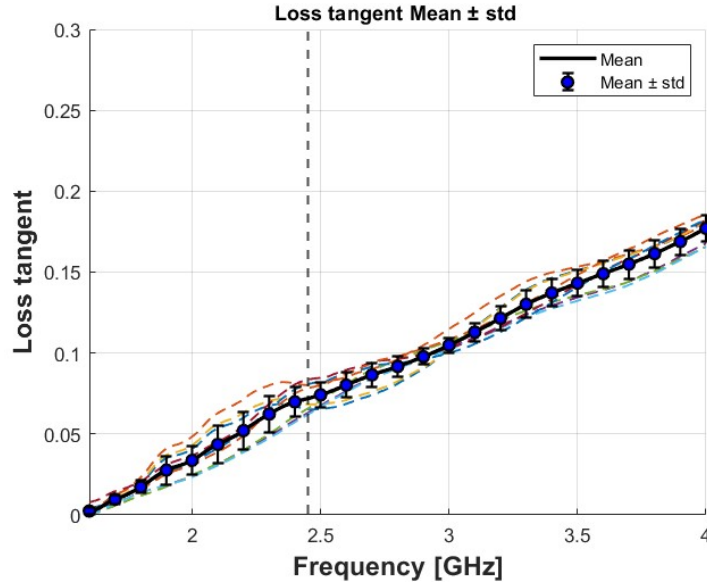


FIGURE 4.4: Loss Tangent Measurements

The mean values obtained from the nine measurements at 2.45 GHz is $\varepsilon_r = 36.1 (\pm 5.25)$ and a $\tan(\delta) = 0.0718 (\pm 0.0087)$. These results fall within acceptable limits, indicating that the phantom still exhibits the appropriate dielectric properties for conducting the experimental antenna tests. This aligns well with the theoretical values for a homogeneous phantom, reported as $\varepsilon_r = 36$ and $\tan(\delta) = 0.0718$, in Mendes and Peixeiro 2017.

Phantom Permittivity - Simulated versus Experimental

On the other hand for the simulations, when the antenna was optimized for a homogeneous simulated human body with the permittivity and loss tangent based on Mendes and Peixeiro 2017, a more specific simulation was conducted with an inhomogeneous, two third phantom, mimic of the human body. A two third phantom, mentioned in Felício et al. 2016c, was taken as reference.

The analysis started off by considering the structure shown in Figure 4.5 for the simulation of the human body and considered the parameters in Felício et al. 2016c shown in Figure 4.6 to calculate the permittivity and loss tangent for skin, fat and muscle.



FIGURE 4.5: Two Third Phantom

	ϵ_∞	$\Delta\epsilon_1$	τ_1 (ps)	α_1	$\Delta\epsilon_2$	τ_2 (ns)	α_2	$\Delta\epsilon_3$	τ_3 (μ s)	α_3	$\Delta\epsilon_4$	τ_4 (ms)	α_4	σ
Skin	4.0	32.0	7.23	0.00	1100	32.48	0.20	0.0	---	---	0.0	---	---	0.0002
Fat	2.5	9.0	7.96	0.20	35	15.92	0.10	3.3×10^4	159.15	0.05	1.0×10^7	15.915	0.01	0.0350
Muscle	4.0	50.0	7.23	0.10	7000	353.68	0.10	1.2×10^6	318.31	0.10	2.5×10^7	2.274	0.00	0.2000

FIGURE 4.6: Parameters of the Human Tissue taken from Felício et al. 2016c

After analysing the parameters in 4.6 the relative permittivity and loss tangent were calculated using the multiterm Cole-Cole model, as shown in Equation 4.5. This equation calculates the complex permittivity which is used to acquire the properties needed, $\epsilon_r = \epsilon'$ and $\tan(\delta) = \frac{\epsilon''}{\epsilon'}$. The resulting values are presented in Figure 4.7a and Figure 4.7b which represents the different relative permittivity and loss tangent through 2 to 3 GHz. More specifically, the dielectric properties at 2.45 GHz are summarized in Table 4.2.

$$\epsilon' - j\epsilon'' = \epsilon_\infty + \sum_n \frac{\Delta\epsilon_n}{1 + (j\omega\tau_n)^{1-\alpha_n}} + \frac{\sigma}{j\omega\epsilon_0} \quad (4.5)$$

Tissue	ϵ'	$\tan(\delta)$
Skin	35.6085	0.0988
Fat	10.7885	0.3629
Muscle	52.0764	0.1520

TABLE 4.2. Dielectric Properties for Different Tissues

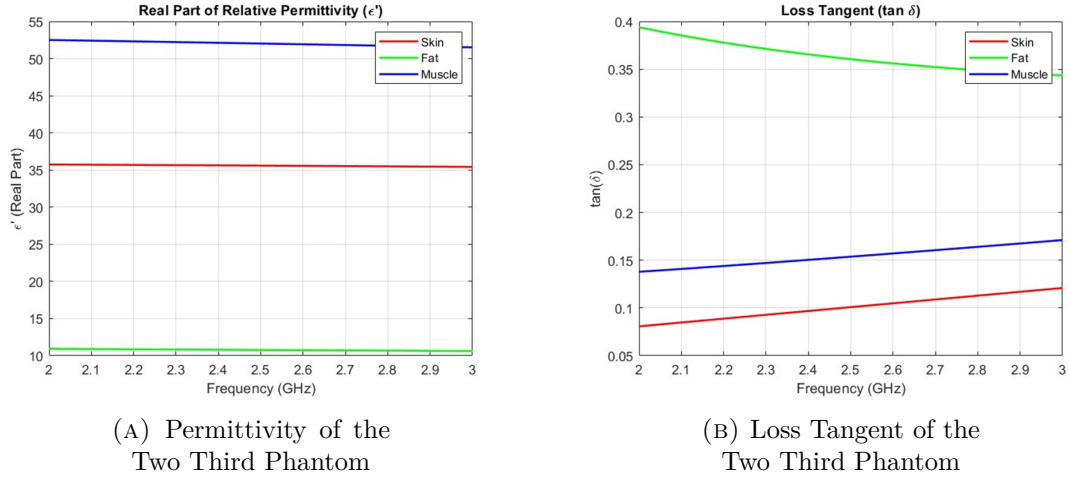


FIGURE 4.7: Relative Permittivity and Loss Tangent of the Two Third Phantom Across Frequency

After determining the dielectric properties of the two third human tissue model, a simulated body was constructed using the previously obtained results, as shown in Table 4.2. This approach was chosen because all prior simulations in CST used a homogeneous block to represent the human body. Although the inhomogeneous two-third human tissue model is more realistic, it significantly increases simulation time. Therefore, it was more practical to perform initial analyses with the simpler model and only later test the more detailed model to assess whether any substantial differences would arise. When the WPPA was optimized, the antenna was placed near a real human body (Figure 4.17) to understand if there would be a difference in the efficiency of the transmission in comparison to the antenna designed and fabricated along this study. The result obtained was rather positive as shown in Figure 4.18 and Figure 4.8.

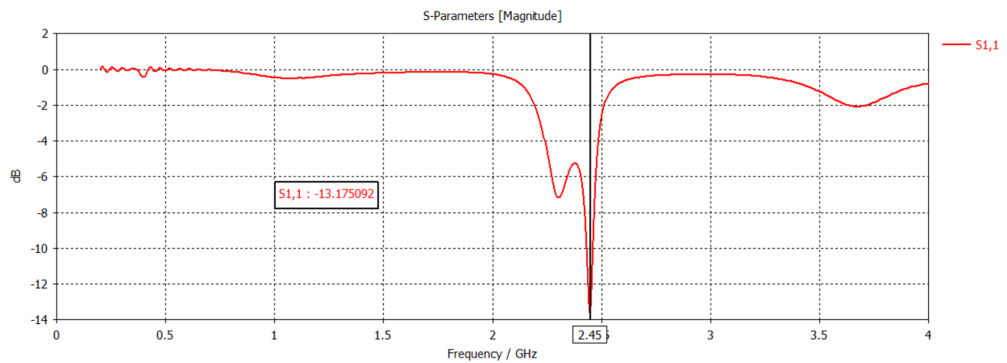


FIGURE 4.8: S_{11} of the Antenna in the Presence of Two-Third Human Tissue Model

The results clearly demonstrate that both configurations operate at the intended frequency. This indicates that the choice between them is of minor significance, as they exhibit very similar performance.

4.1.3 Neoprene Characterization

Neoprene is commonly used in wetsuits with thicknesses between 3 and 5 mm. For this study, it is important to understand how neoprene influences the transmission of the WPPA. As previously mentioned, the antenna was optimized to operate in the presence of neoprene. Therefore, it is necessary to analyze the main properties of the material and how they may affect the efficiency of the antenna.

To better evaluate these characteristics, tests were conducted to assess the permittivity of the neoprene, using both experimental measurements and simulations.

Estimating Neoprene Permittivity Through Comparison of Real and Simulated Measurements

The first step was to test the permittivity of a neoprene sample. To do this, it was necessary to obtain a commonly used wetsuit made of this material. The sample was provided by Decathlon and was taken from a surf wetsuit composed of neoprene, with a thickness varying between 2 and 3 mm. The specific sample provided had a measured thickness of exactly 2.45 mm.

After obtaining the sample, the next step was to test it using a copper transmission line that passed through one face of the neoprene, with connectors attached at both ends represented in Figure 4.9. The same experiment was then accurately replicated in the CST software using the same dimensions Figure 4.10. This approach ensured that the simulation conditions closely matched those of the physical experiment, allowing for a direct comparison of results. By iteratively adjusting the permittivity and loss tangent values in the simulation, it was possible to achieve a close fit to the experimental data. The permittivity was estimated by analysing the phase of the S_{21} parameter, while the loss tangent was determined by examining the magnitude of S_{21} .

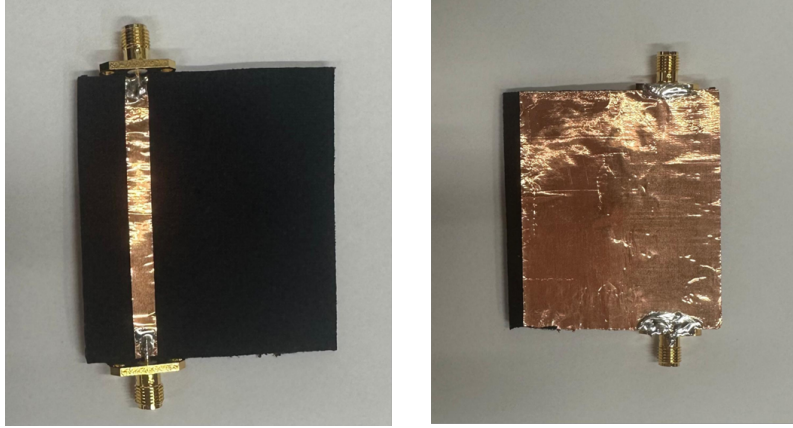


FIGURE 4.9: Real Neoprene Sample Integrated with Microstrip Line for Measurement

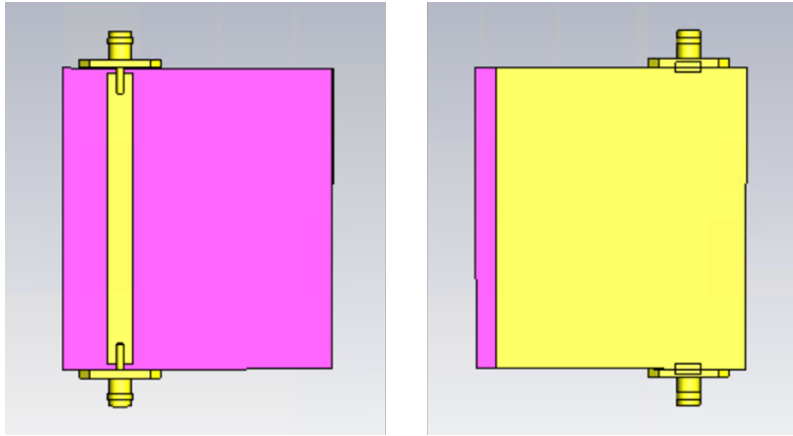


FIGURE 4.10: Simulated Neoprene With a Microstrip

The simulation began by assuming a relative permittivity for neoprene of $\epsilon_r = 5.2$ and a loss tangent of $\delta = 0.03$ as shown in Ali et al. 2023. These parameters were used to characterize the neoprene in the simulated test and the results were then compared with the experimental measurements, as shown in Figure 4.11.

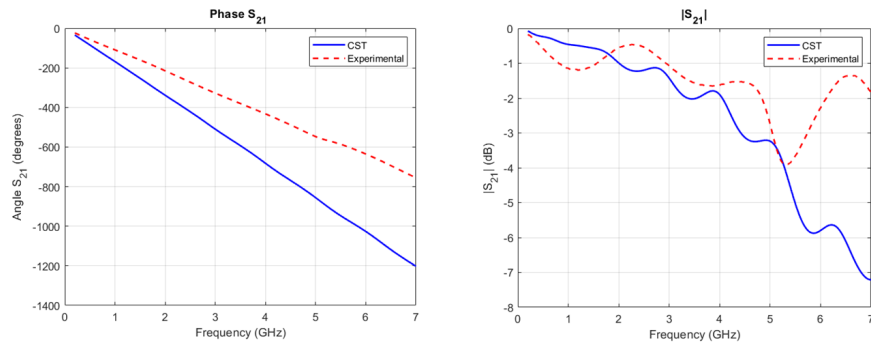


FIGURE 4.11: Comparison of Simulated and Measured Results

The initial results were not promising, as the simulated data differed significantly from the experimental measurements. This indicated that the assumed values for the relative permittivity and loss tangent did not accurately represent the actual properties of the neoprene sample. After several iterations, the best agreement was achieved with $\epsilon_r = 1.7$ and a loss tangent of $\delta = 0.0168$ as shown in Figure 4.12.

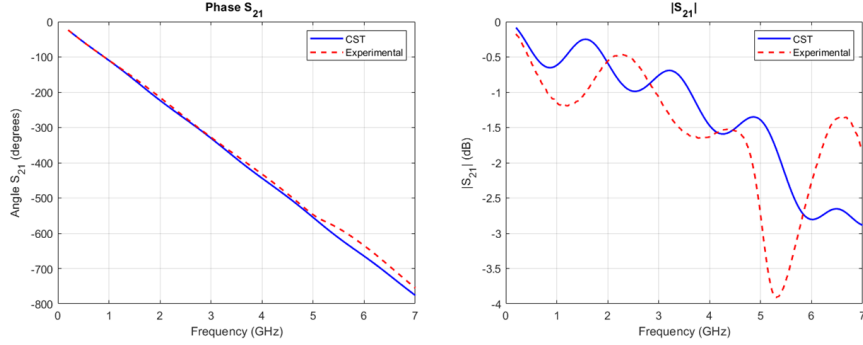


FIGURE 4.12: Comparison of Simulated and Measured Results

These final values for the relative permittivity and loss tangent were subsequently used in the simulations for the optimization of the WPPA. By incorporating these parameters into the simulated environment, it was possible to achieve a more accurate prediction of the antenna's performance in the presence of neoprene. This approach ensured that the influence of the material properties on the antenna's efficiency and overall behavior was closer to a realistic representation, thereby providing results that more closely reflect the conditions expected in practical applications.

4.2 Experimental Assessment

After the analysis presented in the previous chapter, where multiple simulations were conducted in various environments to assess the suitability of the WPPA, this chapter focuses on validating those results through real-world experiments. The fabricated antenna was tested to compare the simulated results with actual performance outcomes.

The testing begins with both the WPPA and the patch antenna, each operating at 2.45 GHz, in free space. Initially, each antenna was tested individually in free space to verify the accuracy of the simulation results. Subsequently, both antennas were evaluated simultaneously in the presence of a phantom that mimics the human body, along with a layer of neoprene, to assess their performance in more realistic conditions.

Following this, the antennas were tested in the presence of water layers of different thicknesses to evaluate whether the WPPA can effectively operate in such a lossy environment.

4.2.1 Antennas in Free Space

The process began with the fabrication of the previously mentioned antenna, the WPPA, and a patch antenna operating at 2.45 GHz that was developed specifically to represent an external antenna in this study, followed by soldering each one to a connector.

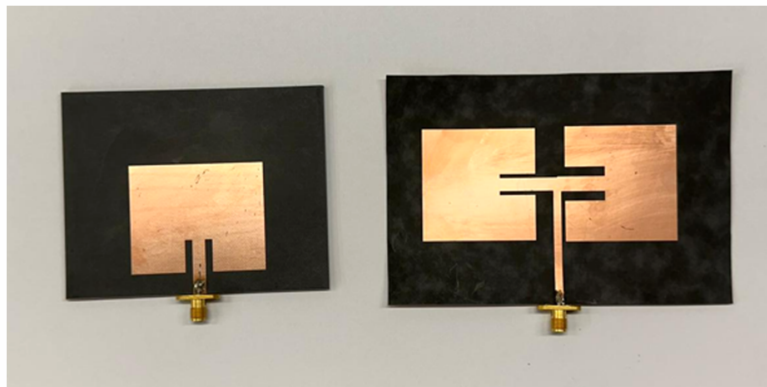


FIGURE 4.13: Patch and WPPA Operating at 2.45 GHz

Each antenna was then tested in free space and the results were compared with the corresponding simulations. The measurements cable used in these experimental tests exhibited an attenuation of -0.606 dB, identified during the calibration process. This error was not compensated for in the results presented below.

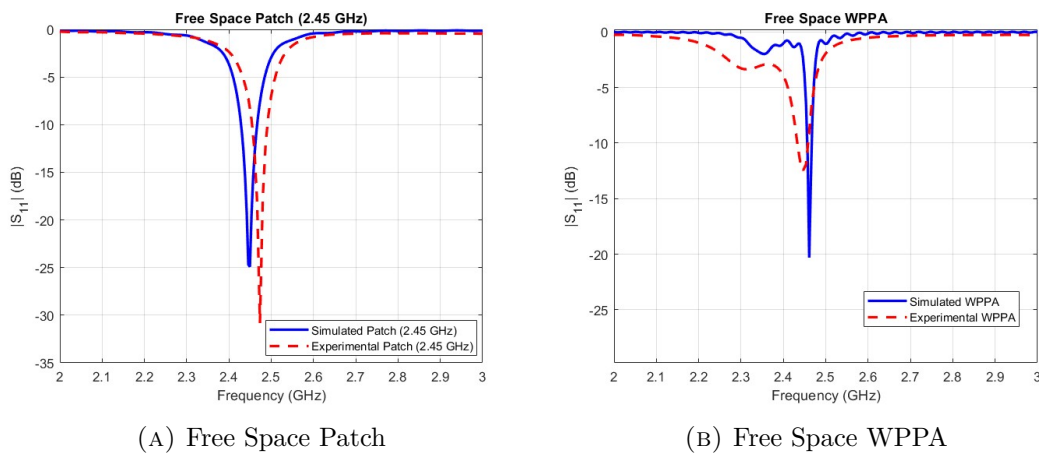


FIGURE 4.14: Simulated and Experimental S_{11} of Both Antennas in free space.

The starting point was analyzing the results for each antenna in free space, confirming that both align well with the expected performance predicted by the simulations. The wearable WPPA does not operate precisely at 2.45 GHz, as it was specifically optimized to function in the presence of neoprene. However, since its measured behavior closely matches the simulated results under these conditions, it is still considered a successful outcome. Similarly, the patch antenna designed to operate at 2.45 GHz performs as intended, having been optimized to function independently, without external influences.

The only noticeable difference was in the magnitude response of the WPPA, which showed a slight decrease during real environment testing, dropping from -21 dB to -13 dB. Nonetheless, this is still considered a satisfactory result because it is below -10 dB.

Next, a neoprene coating was added to the WPPA with 1 mm beneath the antenna, intended to be positioned between the antenna and the human body, 3.5 mm above the antenna, acting as a layer between the antenna and the water (4.15).

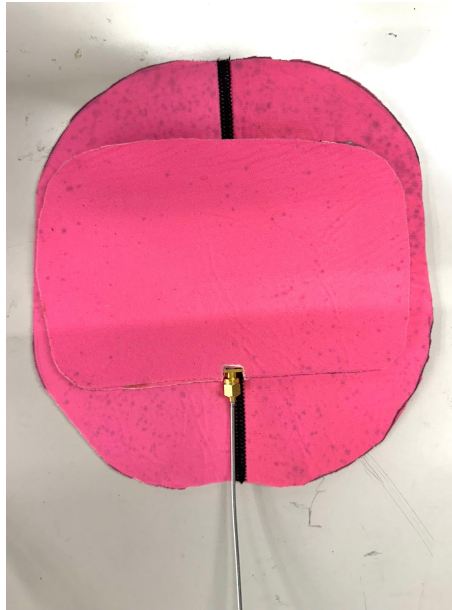
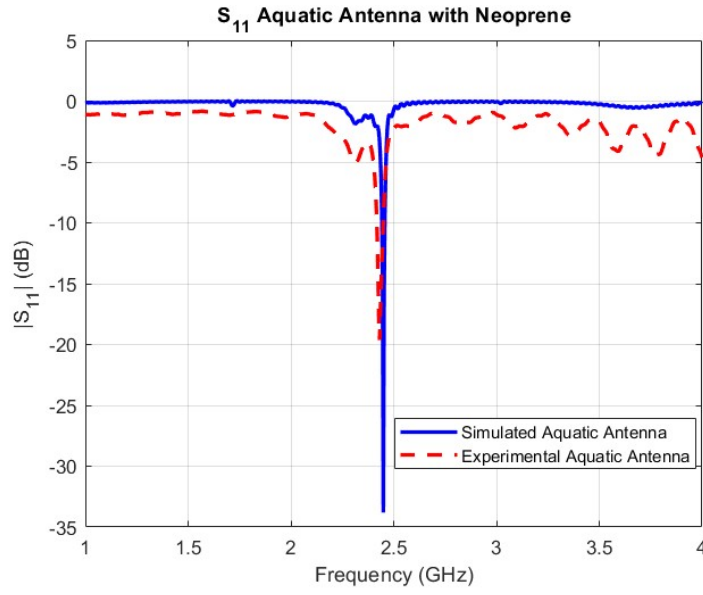


FIGURE 4.15: WPPA in the Presence of Neoprene

FIGURE 4.16: S_{11} WPPA in the Presence of Neoprene

Since the antenna was optimized to operate at 2.45 GHz in the presence of neoprene, it is expected that its performance in free space would differ slightly. The resonant frequency remains close to the intended value, but the magnitude shows a more noticeable variation. Both the simulation and the real experiment achieved satisfactory results, with S_{11} remaining below -10 dBi. However, the simulated antenna reached approximately -34 dBi, while the real experimental measurement showed a magnitude of -19 dBi as shown in 4.16.

After confirming that the antenna performed well when tested with neoprene, a volunteer was used to evaluate the antenna's behavior in a real life scenario in the presence of a human body 4.17.



FIGURE 4.17: Experimental Test with the WPPA covered by neoprene and a Human Body

The results were very promising in terms of magnitude. Although there was a slight downward shift in frequency compared to the simulated data, this deviation was minimal, only a few hundredths, and therefore not considered significant 4.18.

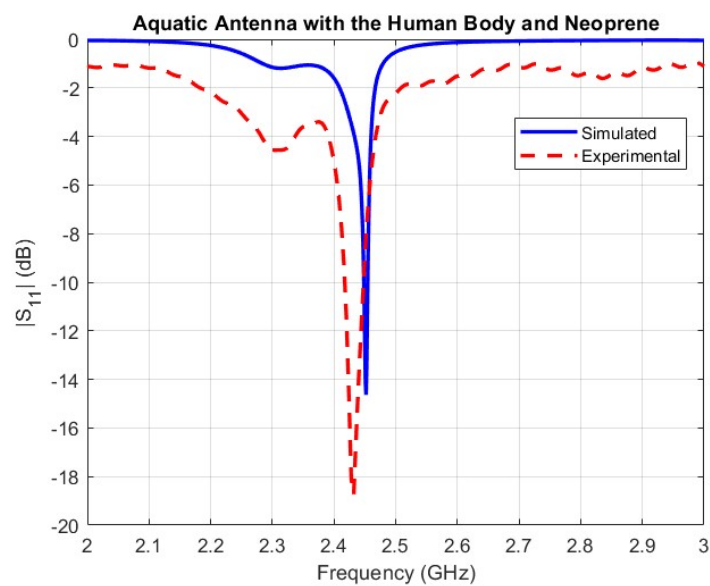


FIGURE 4.18: WPPA with Neoprene and a Simulated / Human Body

After these preliminary tests, the experimental setup was configured to perform transmission measurements at various angles (4.19b), both in the presence of water and in dry conditions, as illustrated in Figure 4.19a.

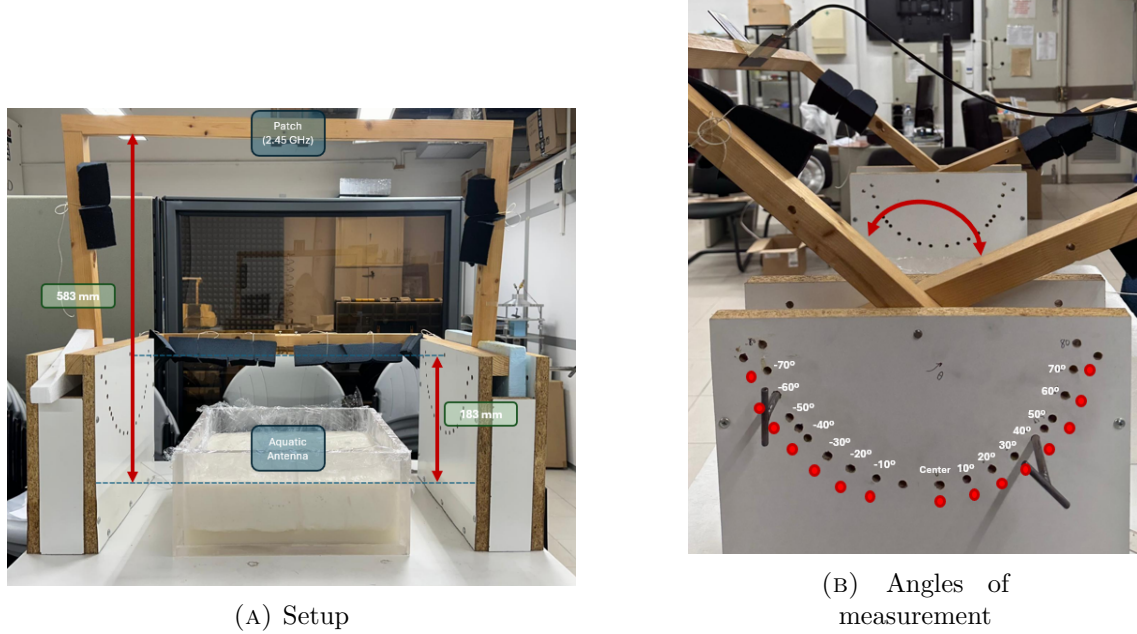


FIGURE 4.19: Experimental setup and measurement angles of the signal transmitted between both antennas

First, the wearable WPPA was placed on top of the phantom, while the patch antenna was positioned vertically above it at a distance of 583 mm, as shown on the right side of Figure 4.20.

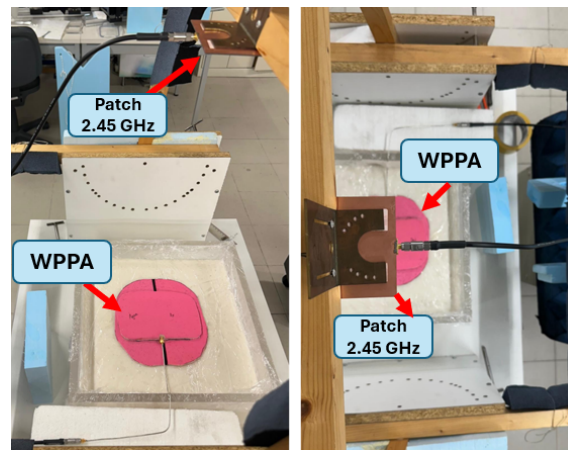


FIGURE 4.20: Setup and placement of both antennas

Following the simulations of the antenna in a non-aquatic environment, additional simulations were conducted to assess the impact of varying water layer

4.2. Experimental Assessment

thicknesses on the WPPA's performance. As part of the experimental setup, a thin plastic bag, selected for its negligible influence on signal transmission, was placed over the phantom. Two solid bricks were then positioned on top of the neoprene layer, without coming into direct contact with the antenna, as shown in Figure 4.21. This setup was implemented to secure the patch in its intended position throughout the testing process.

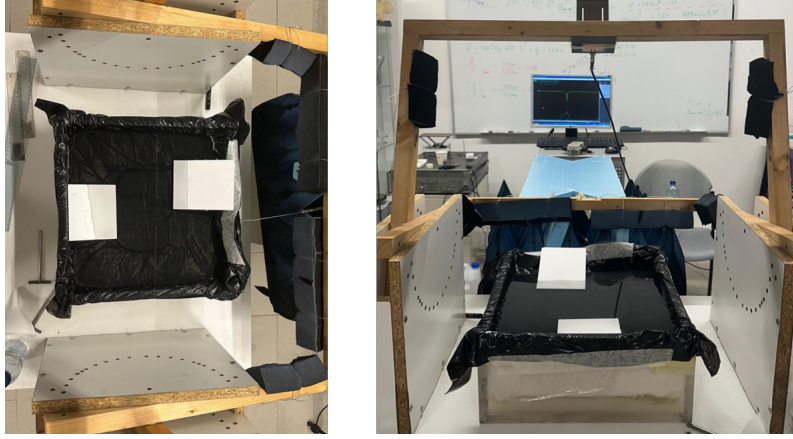


FIGURE 4.21: Setup in the Presence of Water

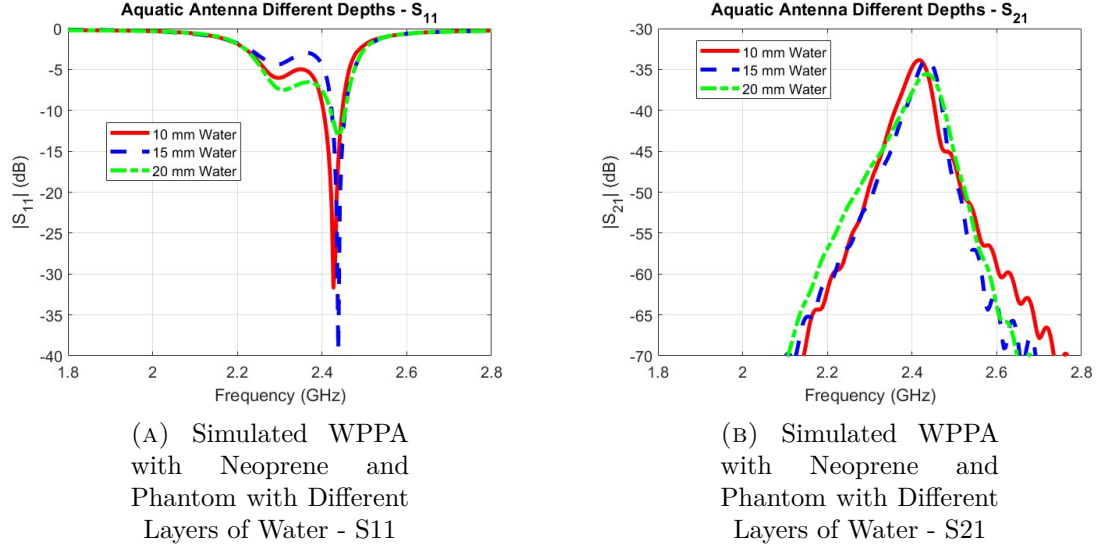


FIGURE 4.22: WPPA at Different Water Depths

The experimental results showed slight deviation from the simulated results. Specifically, the experimental tests indicated the experimental tests indicated a greater signal degradation compared to the simulations.

Thickness (mm)	$ S_{11} $ (dB)	Freq (GHz)	$ S_{21} $ (dB)	Freq (GHz)
10	-27.93	2.418	-33.85	2.415
15	-26.97	2.441	-33.78	2.434
20	-25.32	2.435	-35.54	2.434

TABLE 4.3. Simulated Results: $|S_{11}|$ and $|S_{21}|$ for Different Water Layer Thickness

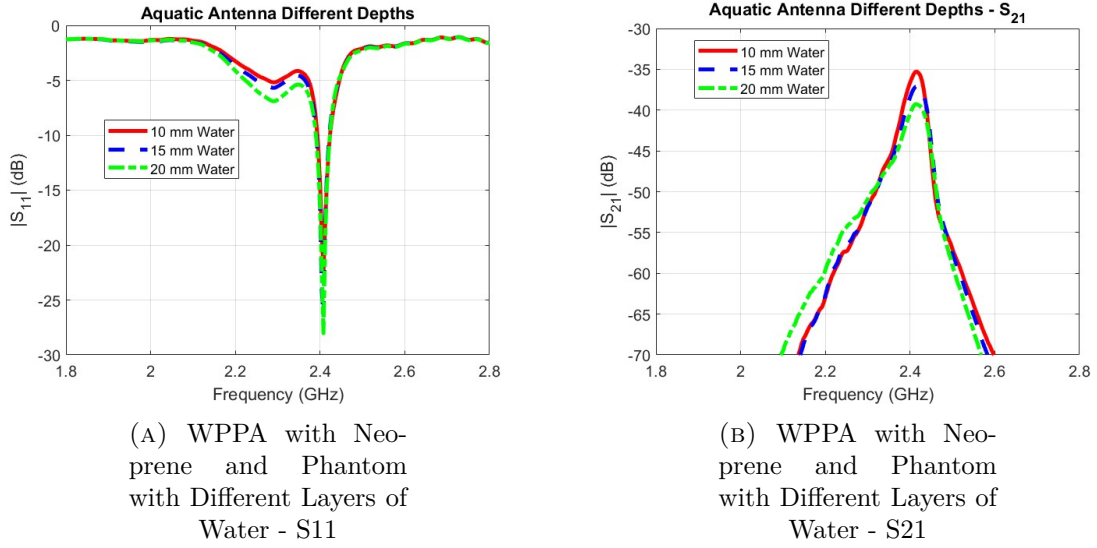


FIGURE 4.23: WPPA at Different Water Depths

Thickness (mm)	$ S_{11} $ (dB)	Freq (GHz)	$ S_{21} $ (dB)	Freq (GHz)
10	-26.10	2.434	-35.28	2.416
15	-29.18	2.421	-37.13	2.416
20	-32.61	2.419	-39.28	2.412

TABLE 4.4. Experimental Results: $|S_{11}|$ and $|S_{21}|$ for Different Water Layer Thickness

The results from the measured angles of the signal transmitted between both antennas created a farfield radiation pattern for each test environment. The setup configuration for these tests is shown in 4.19b and the results are shown in Figure 4.25 (with water) and in Figure 4.24 (without water).

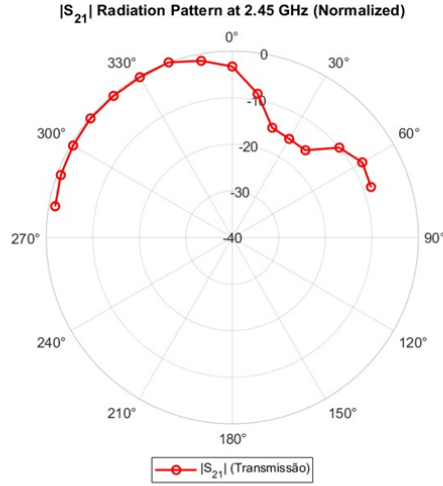


FIGURE 4.24: Experimental farfield from the measurement angles of the signal transmitted between both antennas

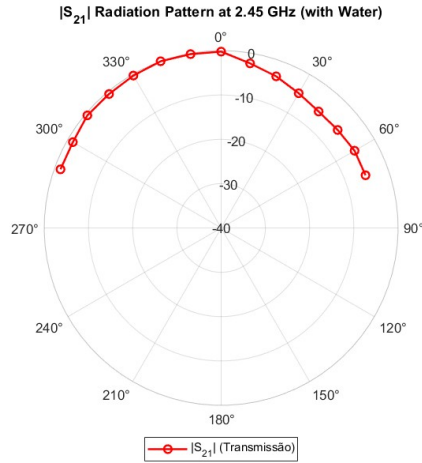


FIGURE 4.25: Experimental farfield from the measurement angles of the signal transmitted between both antennas with the layers of water

The farfield radiation patterns are asymmetric, with higher transmission on one side as shown in Figure 4.25 and Figure 4.24.

4.2.2 Communication between antennas using ESP32-CAM

The ESP32-CAM is a compact, low-power microcontroller board that combines WiFi/Bluetooth connectivity with a OV2640 camera module, shown in Figure 4.26. Which was not used in this study. The idea was to connect each one of the ESP32 to the patch antenna that operates at 2.45 GHz and the WPPA.

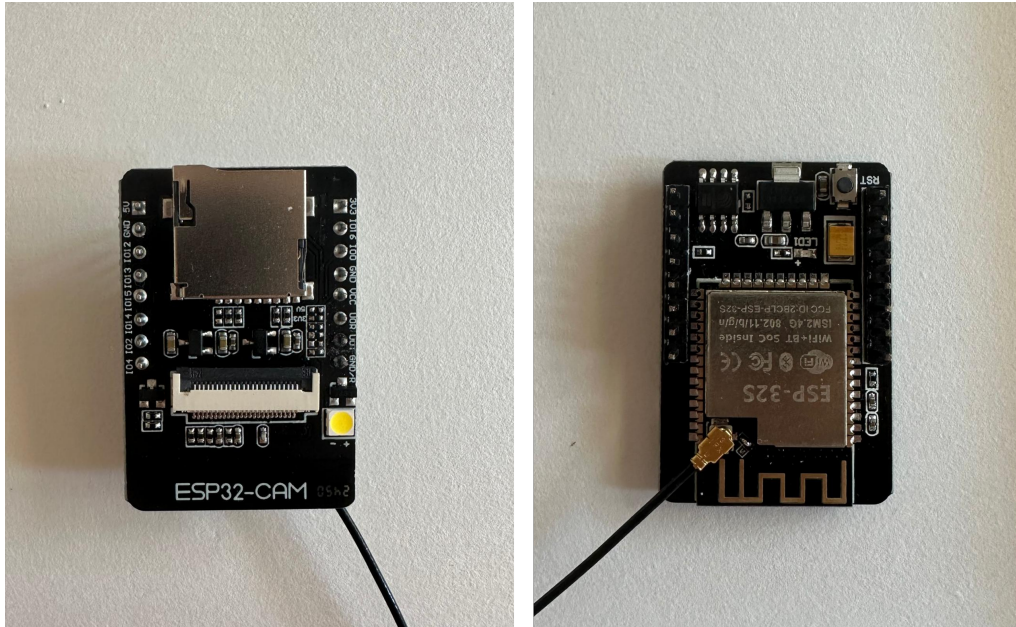


FIGURE 4.26: ESP32-CAM

In order to understand the real time data transmission between the wearable antenna and the external antenna, a two preliminary tests were conducted.

The objective of these tests is to prove that it is possible to transmit data from the wearable antenna to the external antenna through ESP32-CAM. In this study, the only focus was to identify the distance between both ESP32 and consequently the RSSI at the wearable antenna and the RSSI at the external antenna.

In this context, the master is the main node that initiates communication and estimates distance that corresponds to the external patch antenna. While the slave is the remote node that responds to the master's request by reporting its local signal measurements.

The master enables the ESP-NOW with a broadcast peer to send messages to neighbor nodes. Every 100 ms, it sends a *PING* packet with a sequence number and, upon receiving a *PONG*, it reads both the RSSI of the *PONG* at the master's receiver and the RSSI of the *PING* as measured by the slave. Both RSSI values are smoothed using an exponential moving average $\alpha = 0.2$ and then averaged to reduce noise.

The slave continuously "listens" to ESP-NOW on the same channel and whenever it receives a *PING*, it measures the RSSI of that *PING* and immediately responds with a *PONG*. Basically the slave, the wearable antenna acts as a reflector, it simply returns the local signal strength measurement back to the master. This

4.2. Experimental Assessment

allows the master to estimate, with the *PONG*'s RSSI and the *PING*'s RSSI, the distance between them.

The material used for these experimental tests were the following shown in Figure 4.27.

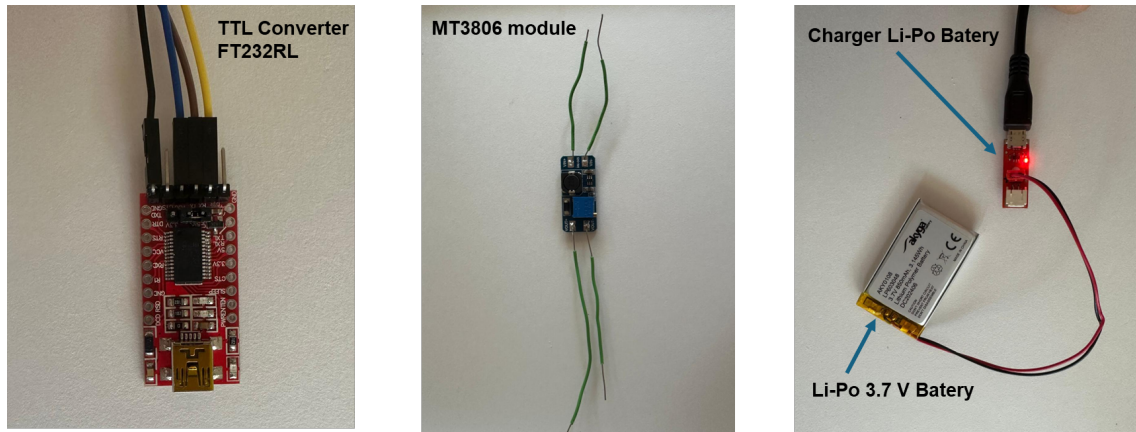


FIGURE 4.27: Equipment used to execute the tests

The first test was carried out in a dry environment, where both antennas were operated (Figure 4.28). The external antenna was connected to the computer and functioning as the "master". This antenna was positioned 3.5 meters away from the wearable antenna, WPPA, which was tested with only the neoprene coating.

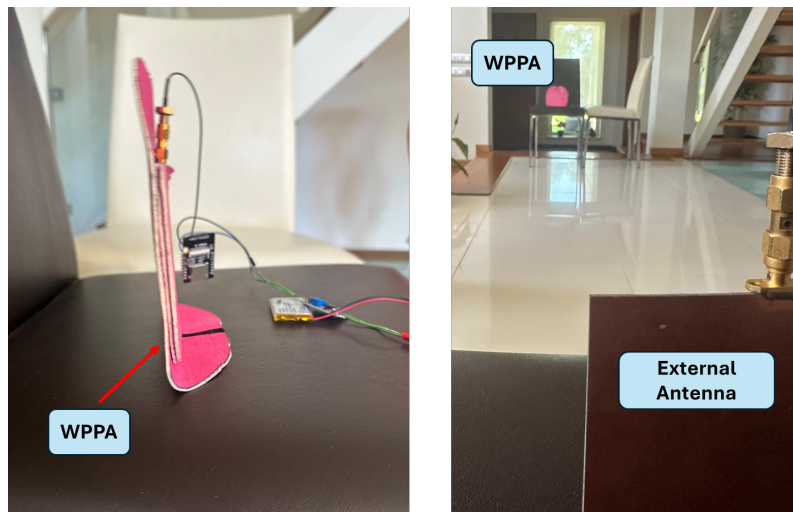


FIGURE 4.28: First Test - Antennas aligned in front of each other, 3.5 meters apart

The analysis began by evaluating the estimated distance between antennas in real time, in order to verify whether the values corresponded to the actual distance of 3.5 meters.

It is visible that the estimation doesn't stabilize at 3.5 meters. For most of the measurement period, it remains below the true distance, as shown in Figure 4.29.

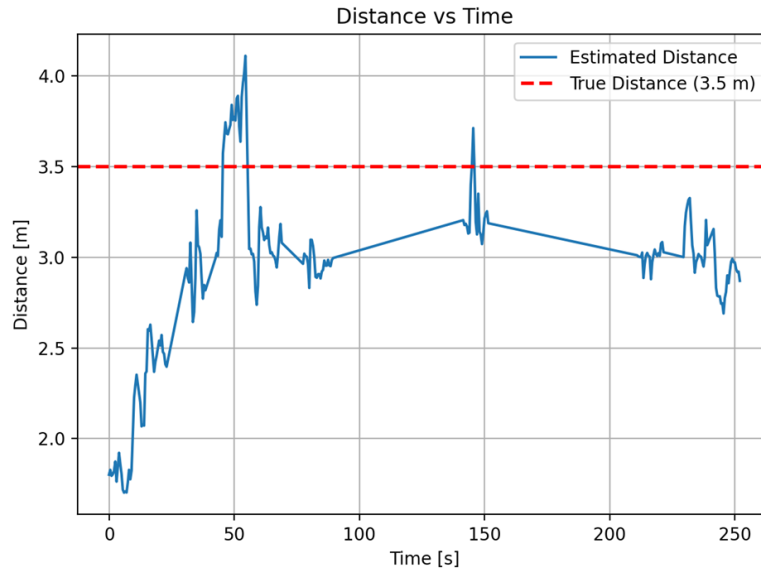


FIGURE 4.29: Estimated distance between both antennas in real time 3.5 m apart

Regarding the RSSI values of both the external antenna and the wearable antenna, it is evident that the external antenna exhibits a worse RSSI compared to the wearable antenna, WPPA, indicating that there was loss of signal during transmission, as shown in Figure 4.30.

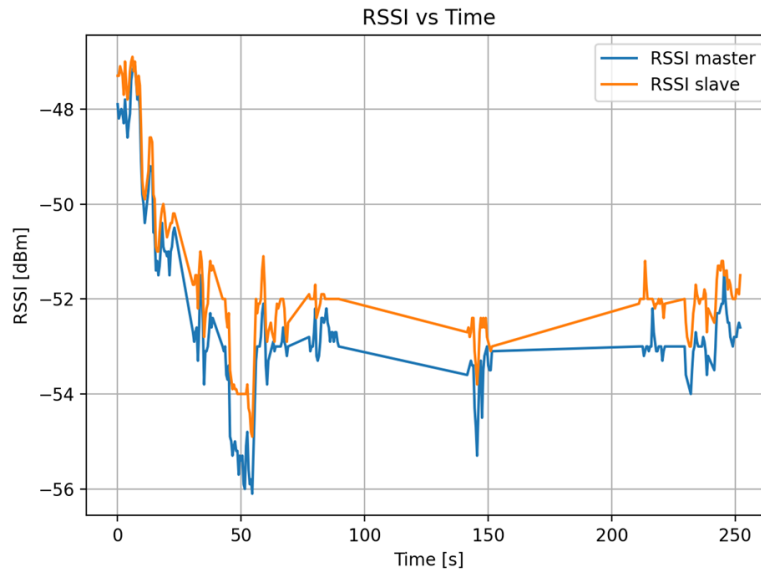


FIGURE 4.30: RSSI of both antennas in real time 3.5 m apart

The second test that was conducted, the wearable antenna was in the presence of a neoprene coating and a human body in a dry environment and the two antennas were positioned 25 meters away from each other. The external antenna was connected to the computer (Figure 4.31) while the wearable antenna was connected to the Li-Po battery (Figure 4.32).



FIGURE 4.31: External antenna connected to the computer

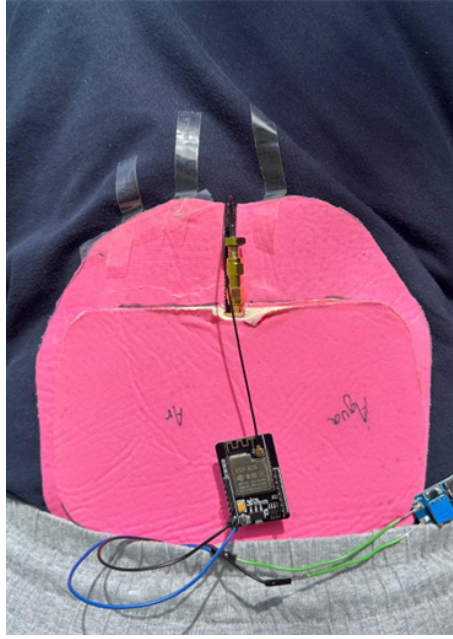


FIGURE 4.32: WPPA Connected to the Li-Po Battery

The results were not particularly promising, especially regarding the RSSI values of both the external and wearable antenna, as shown in Figure 4.34. It is important to understand that the antenna's positioning and alignment is important. These results could also be associated with the wearable antenna's asymmetric farfield radiation pattern that forcefully is stronger on one side than the other.

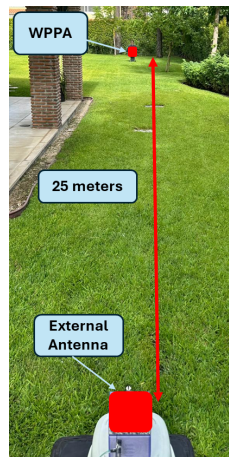


FIGURE 4.33: Distance Between both Antennas

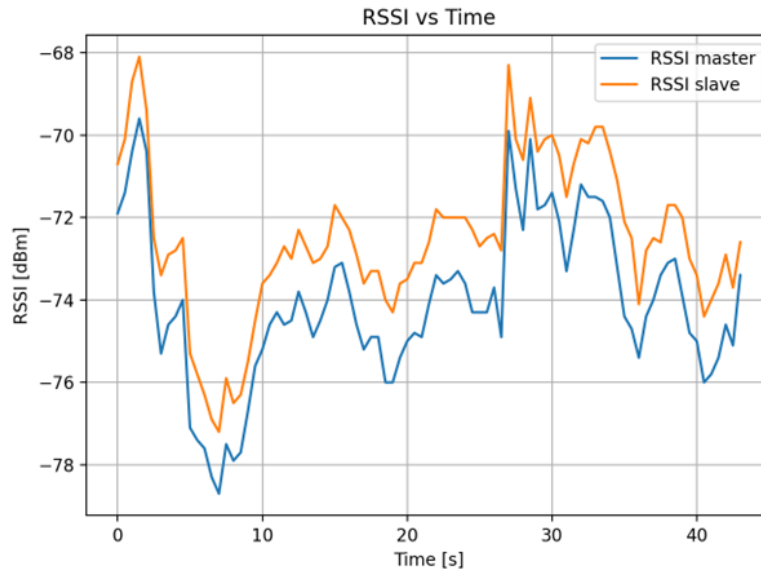


FIGURE 4.34: RSSI of both antennas in real time 25 m apart

The estimated real-time distance between the two antennas deviated from the actual distance, likely due to the positioning of the antennas.

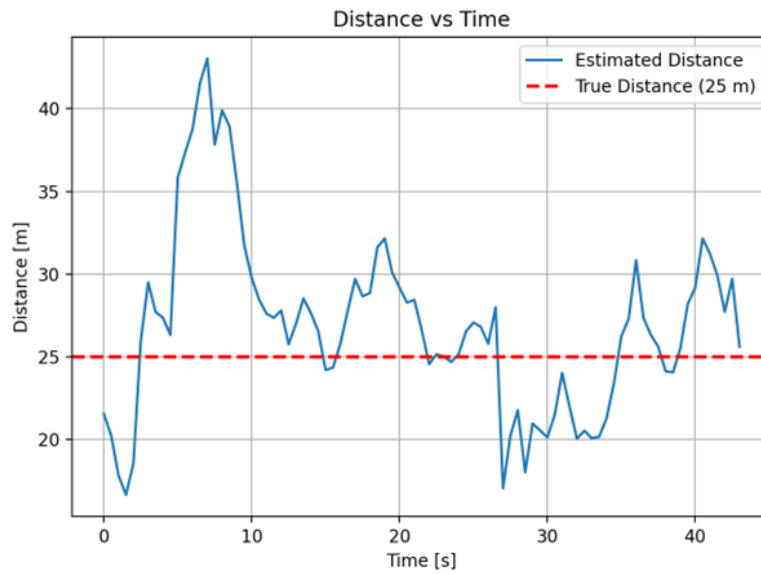


FIGURE 4.35: Estimated distance between both antennas in real time 25 m apart

It is important to highlight that these were preliminary tests, intended to provide an initial understanding of how the data can be transmitted from one antenna to the other. Further study is required, particularly in more realistic conditions, such as water environments. Further studies should also explore additional

factors, such as the positioning and orientation of each antenna, to better assess their impact on transmission quality. These results serve as a starting point for more detailed studies.

Conclusion

This dissertation has explored the development of a wearable antenna designed to enable transmission in aquatic environments. The motivation for this research stems from the growing demand for real-time, wireless data communication in settings where mobility, comfort and environmental constraints severely limit traditional communication methods, such as competitive swimming, maritime rescue operations and amphibious military applications.

The study was conducted through a comprehensive approach that integrated theoretical concepts, CST simulations, material characterization and experimental validation. A strong emphasis was placed on understanding the complex interactions between electromagnetic waves and high-loss media, such as water and human tissue, both of which exhibit high permittivity and conductivity. The challenges posed by these materials were addressed through a optimization of the antenna for the operating frequency (2.45 GHz, within the ISM band), by changing the antenna's geometry.

Initial link budget analyses and wave propagation studies confirmed that although the 2.45 GHz frequency experiences considerable attenuation in water, it remains suitable for very short-range communication, particularly in shallow or partially submerged scenarios. While lower frequencies such as 400 MHz or 900 MHz allow deeper penetration, they come with significant trade-offs in antenna size and integration complexity, making them less suitable for compact, wearable systems.

The design phase focused initially on comparing two antenna topologies: the Inverted-F Antenna (IFA) and the Slotted Patch Antenna. The IFA was discarded due to insufficient gain and unsatisfactory performance near the human body. In contrast, the Slotted Patch Antenna, adapted from Musa et al. 2023, demonstrated a more favorable response but was not successfully optimized for dual-mode operation, it was efficient in air but posed problems when layers of water were added in aquatic environments at 2.45 GHz frequency. Parametric simulations using CST Studio Suite identified critical geometric factors affecting both impedance matching and the resonant frequency, especially in proximity to lossy materials.

This observation highlighted the need to develop an entirely new antenna structure better adapted for aquatic's, highly conductive, environment. As a result, a third antenna design, the WPPA, was conceived and developed. This new configuration was designed based on the lessons learned from all previous simulations and was specifically modeled for operation in a neoprene coated, body-worn environment, with robustness against water attenuation.

Integration with neoprene introduced additional design challenges. While the material is well suited for wearable use due to its flexibility and water resistance, its dielectric properties alter the antenna's resonant behavior. Experimental permittivity evaluation of the neoprene sample using a microstrip transmission line led to the estimation of its permittivity and loss tangent, enabling realistic simulation adjustments. Optimizing the antenna in the presence of this material proved essential to ensure that the antenna maintained acceptable performance even when embedded in wetsuits of varying thicknesses.

In the course of testing, the human body didn't present to be a critical variable. Through both simulation and experimental testing, it was confirmed that the human body didn't significantly affect antenna performance, especially at 2.45 GHz.

To experimentally validate the design, a two-third phantom mimicking the dielectric properties of human tissue was fabricated. Although the phantom displayed some layering inconsistencies, permittivity measurements confirmed that its overall properties remained within acceptable limits for simulation fidelity. Tests using a Vector Network Analyzer and an open-ended coaxial probe supported the validation of the experimental setup.

The final version of the WPPA, embedded in neoprene and evaluated through multiple configurations, was then tested in free space, on the back of a human body and under several water depths. The results demonstrated consistent alignment with simulations, confirming satisfactory impedance matching and efficient transmission. The antenna maintained functionality within expected margins for near-surface, short range communication, validating the effectiveness of this final antenna design. In addition both antennas were connected to two ESP32-CAM each to validate the possibility of transmitting data from the WPPA to the external antenna.

Beyond the technical validation, this dissertation also outlined several relevant application scenarios. In sports, such antennas could enable real-time biometric monitoring and performance tracking. In military contexts, their integration into

operational uniforms opens the door to various applications, particularly in environments that demand real-time communication, mobility and situational awareness. The automatic detection of man-overboard incidents is a key example, enhancing crew safety on naval ships during both day and night operations.

In conclusion, this study has demonstrated that it is possible to design, simulate and experimentally validate a compact, wearable antenna for aquatic communication using neoprene as the support material. The development of the WPPA represents the culmination of an iterative design process informed by analytical modeling, simulation and practical testing. While several challenges remain, including optimizing performance at greater depths, integrating sensor modules and ensuring energy autonomy, the findings presented here offer a promising foundation for future research and real-world implementation.

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Appendix

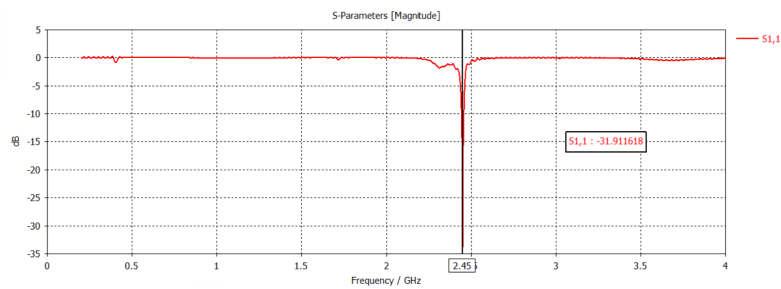


FIGURE 36: S_{11} - WPPA with neoprene

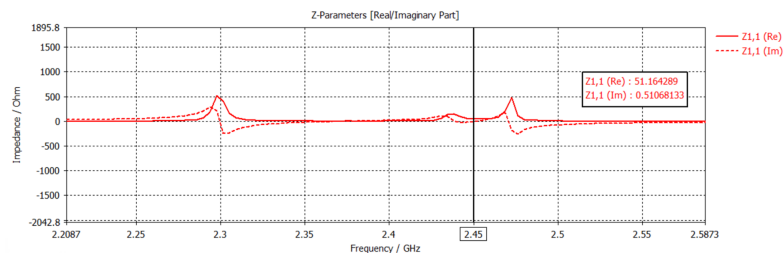


FIGURE 37: Input Impedance - WPPA with neoprene

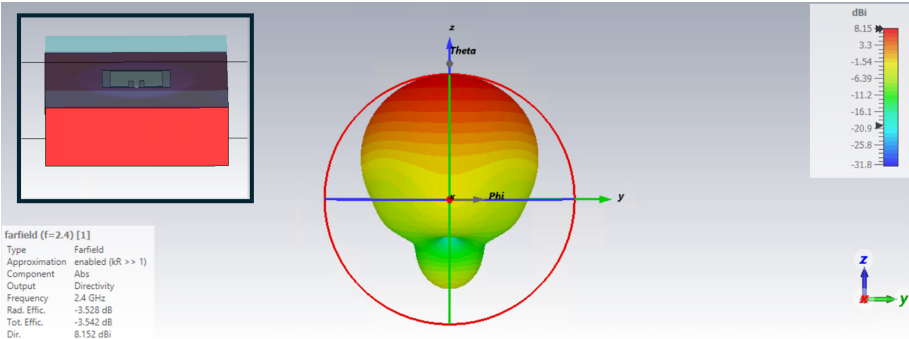


FIGURE 38: Farfield of the Air Patch - Front View

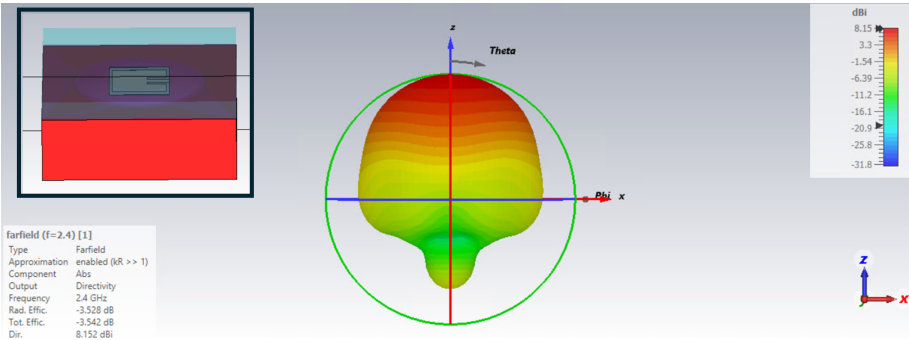


FIGURE 39: Farfield of the Air Patch - Side View

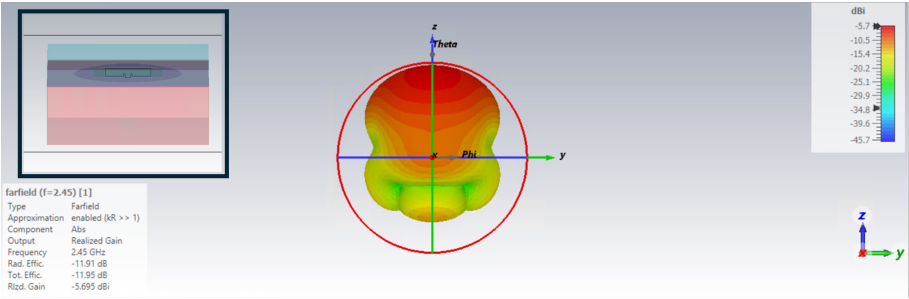


FIGURE 40: Farfield of the Water Patch - Front View

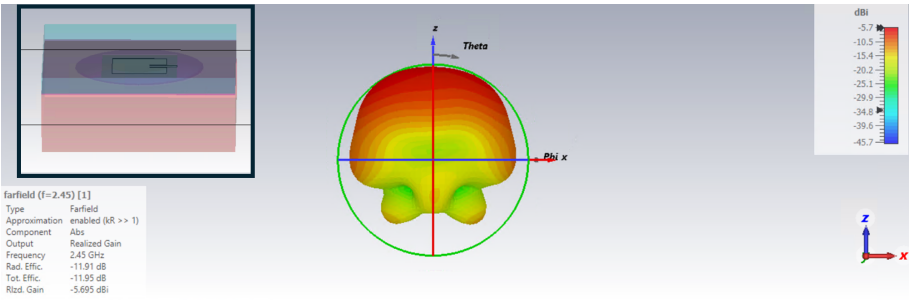


FIGURE 41: Farfield of the Water Patch - Side View

Annex

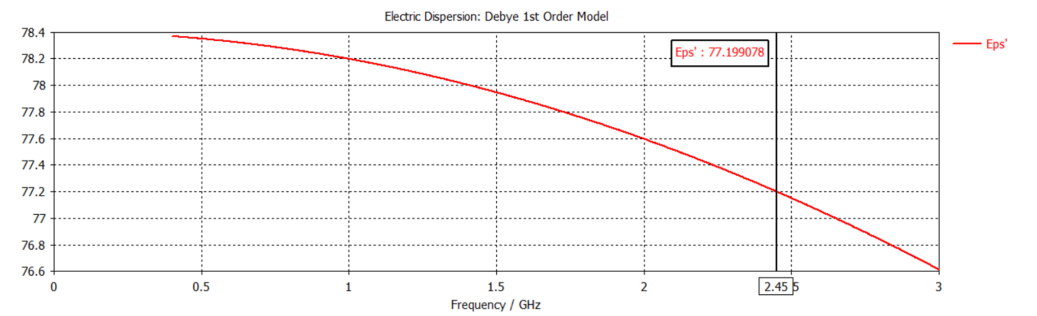


FIGURE 42: Relative Permittivity of Water - CST Results

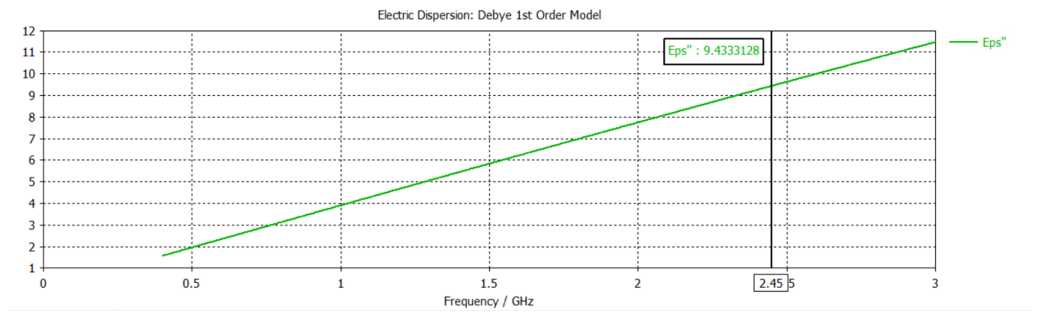


FIGURE 43: Imaginary Permittivity of Water - CST Results

Ingredient	Amount [g]
Deionized water	8937.8
Agar	277.0
Sodium chloride	18.5
Sodium azide	5.3
TX-151	79.7
Polyethylene powder	2681.6

FIGURE 44: Ingredients used in Mendes and Peixeiro 2017