NATIONAL UNIVERSITY OF
SCIENCE AND TECHNOLOGY
POLITEHNICA BUCHAREST

Doctoral School of Electronics, Telecommunications
and Information Technology

THESIS SUMMARY
DOCTORAL DEGREE

CONTRIBUTIONS ON THE DEVELOPMENT OF FLEXIBLE SUBSTRATE ANTENNAS AND RADIOFREQUENCY-BASED MEASUREMENT SYSTEMS

Ing. Mircea-Alexandru CĂLIN

PhD supervisor
Prof. Dr. Ing. Paul SVASTA
UNSTPB

BUCHAREST 2025

1.Introduction

This doctoral thesis explores the frontiers of wearable antenna technology, an emerging branch of electronic engineering that intersects with fields such as innovative materials, textile technology, and human-machine interfaces. In the context in which our society is becoming more and more connected, the need for efficient, sustainable and, above all, comfortably integrated communication solutions into everyday life is more pressing than ever. Therefore, this research aims to address the key challenges of the design, manufacture and implementation of wearable antennas, with a particular focus on innovation and practical applicability.

1.1 Background and relevance

In the era of ubiquitous technology, the seamless integration of electronic solutions into everyday life has become a priority for both researchers and industry. Wearable antennas, as key elements in this integration, represent a vital bridge between technological progress and its applicability in everyday contexts. The context and relevance of this work derives from the exponential increase in the need for portable communication devices, which facilitate a variety of functionalities, from health and sports activity monitoring to improved connectivity and immersive experiences in augmented and virtual reality.

By approaching this theme, I propose to study in detail, simulate and carry out practical experiments in order to design radio antennas and radio frequency circuits. The objective of these studies is to innovate new architectures of passive radio antennas with small dimensions, made specifically to be integrated into mobile radio communication systems, to improve the known methods of impedance adaptation and the way of working in order to make electrical measurements for radio antennas.

1.2 Research objectives

The research objectives of this doctoral thesis are part of an ambitious vision, aiming not only to advance technical knowledge in the field of wearable antennas, but also to encourage an innovative spirit that pushes the boundaries of what is possible. In a field where progress is often limited by technological and material constraints, this research aims to explore new horizons, test existing barriers and propose solutions that redefine how wearable antennas can be integrated and used in everyday life. One of the main objectives is to develop wearable antennas with superior performance, which offer extended bandwidth and improved efficiency, while integrating harmoniously with the wearer, ensuring comfort and discretion.

1.3 Purpose and objectives of the thesis

The aim of this doctoral thesis is to redefine the paradigm of wearable antennas by exploring and implementing innovative solutions that address both current technical challenges and the emerging needs of the ever-expanding digital society. The objectives of the thesis focus on innovation and pushing the boundaries of knowledge by developing wearable antennas capable of operating in a wide spectrum of frequencies, adapting to various usage environments, and integrating effortlessly with mobile devices and IoT platforms.

1.4 Contributions and novelty

The contributions and novelty of the doctoral thesis in the field of wearable antennas are multidimensional, addressing existing challenges and opening new directions in design, manufacturing and integration.

The first major contribution is the development of an advanced design and simulation methodology that integrates new materials and innovative manufacturing techniques, resulting in antennas with improved performance, wider bandwidths and increased adaptability.

The second contribution consists of identifying and characterizing sustainable materials for the manufacture of wearable antennas, evaluating the electromagnetic properties of textiles and plastics and developing composites with superior performance even under variable environmental conditions.

The third contribution is the implementation of new techniques for testing and evaluating performance in real scenarios, ensuring that the antennas are not only theoretically efficient, but also practically viable and ergonomically acceptable.

In addition, the thesis explores the integration of wearable antennas with emerging technologies such as augmented/virtual reality, health monitoring systems and IoT platforms, thus opening new horizons of applicability in various fields.

2. Fundamentals of Wearable Antennas

The frequent use of antennas in modern electronic applications has created an increasing need for the study and optimization of the impedance matching process, which will ultimately help improve the performance of the RF system by minimizing losses. The impedance adaptation of an antenna is considered to be a complex process, with many mysteries for most engineers working in the field of practical applications. Some of the problems encountered in this adaptation process are difficult to estimate with a simple theoretical model and are almost impossible to intuitively perceive.

2.1 Streamlining energy transfer

The concept of impedance matching is a technical process that allows the designer to optimize the performance of the RF circuit by minimizing energy loss and increasing the efficiency of the transfer from the source to the load - represented by the antenna in our case. This is done by measuring and modifying parameters or components that influence the impedance profile of the antenna and ideally a perfect match of the impedance between the components that make up the radio system will be achieved. The theory of obtaining maximum power transfer is usually described in only two ways: by obtaining an impedance at the source equal to the complex conjugate of the load impedance, or by creating complex impedances that have a null imaginary part, both for the source and for the load.

2.2 Losses in transmission lines

The problems introduced by radio circuits tend to be more complex as the working frequency is higher, so in the case of signals corresponding to the UHF radio band (300MHz – 3GHz), the length of the transmission line, the quality of the PCB printed wiring and the device housing will have a strong influence on the value of the complex impedance. Signal reflections are mostly due to discontinuities in the transmission line, as shown in Figure 2.1. These discontinuities are the main cause of power losses, frequency impedance profile variation, and nonlinearities.

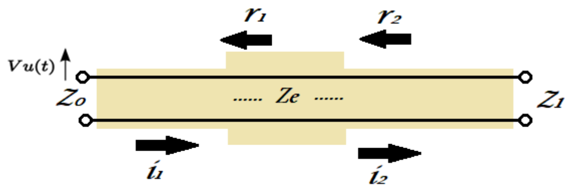

Figure 2.1 *Signal reflections caused by line discontinuities*

Electronic devices that are manufactured as discrete or integrated chips, in SMT or THT technologies, must be mounted on a PCB or other type of support material before being connected to the measurement system. This is also the case for most ceramic-based antennas, which are currently produced in a wide variety of capsules, but require a special form of adaptation when connected to the coaxial ports of a vector network analyzer (VNA). The example shown in Figure 2.1 denotes the incident signal with i1 and i2, the reflected signal with r1 and r2, Z0 being the initial impedance, and Z1 the resulting impedance at the far end of the line, as measured by the VNA connected to the end where we have Z0. By eliminating the influences of the measurement system, we are able to perform appropriate measurements with microstrip structures or in other non-coaxial circuits and can minimize the influence of the transmission medium on the actual DUT characteristics. This is further studied in the form of a VNA port calibration procedure and reference plane calibration, mentioned in the theory presented in [5] [6].

2.3 Impedance Matching

2.3.1 Calibration of the measurement reference plane

For accurate calibration of the VNA port for measurements, a number of devices known as calibration standards are used. They will be connected according to the procedure recommended by the appliance manufacturer [4].

This is where the novelty of this procedure comes in: we will perform an additional calibration check and an adjustment of the reference plane using the entire DUT device. Otherwise, without a precise configuration of the reference plane, the representation of the complex impedance on the Smith diagram will be erroneous and the user will not be able to perform a correct impedance matching process.

The test setup, used in the experiments presented below, was designed from the components shown in the figure. 2.2. Consisting of a VNA, a transmission line or coaxial cable (C), adapter connector (B) and DUT device (A). The physical termination planes of each component are represented by a vertical dotted line.

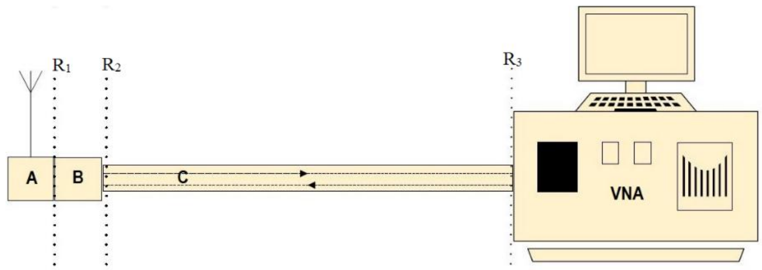

Figure 2.2 *Simplified representation of the measurement system*

With the help of this representation, we can see that the reference plane after calibrating a port is located at the boundary between the adapter and the device, i.e. the plane denoted R1. In fact, the reference plane is measured as being inside the calibration tasks or adapter connectors.

2.4 Impedance matching procedures

In the process of adapting the impedance, most of the measurements will aim to represent the complex impedance in the Cartesian format (R+jX), plotted by the VNA on a Smith diagram and additionally, the reflection coefficient |S11| measured at one of the ports. The reflection coefficient is useful in that it quantifies the percentage of reflected power from the total power injected by the network analyzer, usually due to an impedance discontinuity in the transmission line and DUT.

A disadvantage of this working style is the frequency limitations introduced by commercially available LC components. For this reason, most of the time the system using such a solution will be limited to the upper end of the UHF band – equivalent to a maximum of 3GHz. Beyond this frequency band, the parasitic capacitance and inductance introduced by the component capsule begin to dominate the nominal value of the components, this situation suggests the need to use other types of circuits.

2.5 Results

The test circuit was physically made in the form of a two-layer PCB, using FR4 TG 130-140 dielectric, with a relative permittivity of 4.3, thickness of 1.6 mm and copper plated of 30µm. Particular attention has been paid to the design of the ground plane for this PCB in order to create an area around the antenna where we do not have metal structures and to minimize the parasitic capacities introduced. To minimize RF power loss, the transmission line connecting the SMA connector to the antenna has been designed to achieve a characteristic impedance of 50 ohms. However, many of the physical changes that impact the impedance profile can be reversed during the adaptation process. The results obtained after the optimization of the 433 MHz Johansson antenna are plotted on the Smith diagram based on the data points obtained from the measurements made with the VNA. The graph of the reflection coefficient obtained after the impedance adaptation experiments is shown in figure 2.9 and confirms a very good power transfer to the antenna in a bandwidth of 8MHz. The useful frequency band was determined by taking into account a better reflection coefficient of -10dB and a center frequency of 433MHz. The best performance is achieved at the resonant frequency of 433MHz, where | S11| reaches a value of -15dB, which corresponds to a transmission efficiency of over 96%.

2.6 Additional stability experiments

The experiments were continued with the aim of evaluating the temperature dependence of the antenna impedance. In order to obtain an easily observable result in the graphical representations, the reflection coefficient was measured in a temperature range of 75 °C, starting from a room temperature of 25 °C. Reflection Coefficient Measurement |S11|, over a wide frequency range, was preferred over complex impedance, as a Smith diagram would not provide a sufficiently clear picture of the changes taking place in the antenna frequency band. The temperature variation will lead to a change in the properties for the materials that make up the substrate for the PCB and antenna, also affecting the mechanical dimensions of the material.

3.The state of technology of wearable antennas

Today, wireless communications technology requires miniaturized broadband planar antennas to be used in the design of numerous wireless devices. Therefore, they will be used mainly in the bands used for ISM (Industrial Scientific Medical), WLAN (Wireless Local Area Network), Bluetooth and mobile telephony [15]. These wireless communication technologies require high performance and the best possible level of miniaturization from the antenna that can be achieved through compact antenna systems [16].

3.1 Evolution of technology

The electronic equipment manufacturing industry is experiencing a growing demand for "wearable" devices - electronic systems attached to users' bodies. Global technical progress has enabled advanced miniaturization, transforming electronic devices into components integrated into everyday objects or even the human body through implants. A relevant example is shoes with biomedical sensors that measure vital parameters such as blood pressure or heart rate, transmitting the data instantly to mobile phones for processing.

Advances in nanotechnology, applied electronics, and the Internet of Things (IoT) have created new possibilities for in-body communication devices, used in health monitoring and integration into complex systems with global coverage. Communication components are essential for harnessing data collected by sensors and facilitating medical operations of care, diagnosis or drug administration.

3.2 Requirements and problems imposed by wearable antennas

The topic of developing antennas for *wearable* systems has been difficult for researchers to approach and is in full development, as evidenced by the numerous antenna models proposed in the literature.

Installing the antenna integrated directly on the human body, in a *wearable system*, will give rise to a number of problems. The antenna will be bent around the body, follow its movements, and may become permanently deformed. In some applications, there is also the problem of making an antenna that is waterproof or washable. There will also be a series of interactions between the antenna and the body, which will lead to changes in the electrical parameters of the antenna, the directivity and the absorption of part of the radiated energy. Also of interest is the specific absorption rate (SAR) in the body of electromagnetic energy.

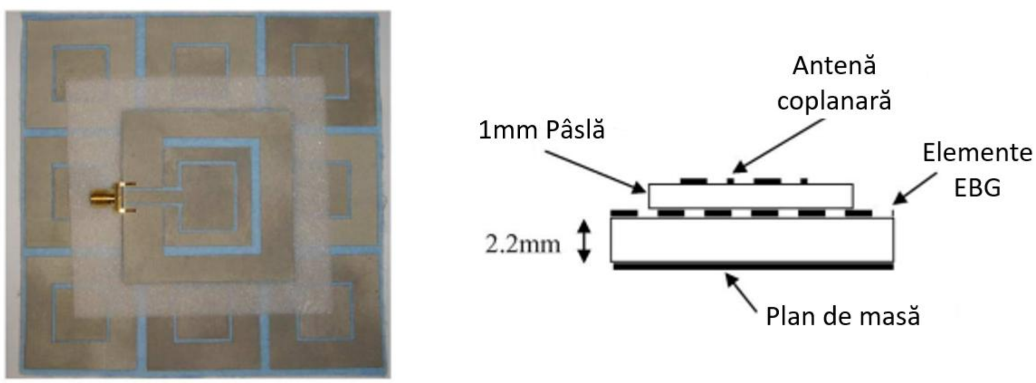

Figure 3.3 *Coplanar textile antenna with EBG plane [24]*

Designs have been made for antennas incorporating a material that blocks the electromagnetic field for a certain frequency band, these will be hereinafter referred to as EBG (*Electromagnetic band-gap*) and their design has been reported in [20] and [24]. The EBG layer, shown in Figure 3.3, offers the advantage of reducing the level of radiation emitted from the antenna to the human body and therefore a reduction in the radiation absorbed by the body.

3.3 Shaping the human body

The electromagnetic properties of the human body vary significantly depending on the type of tissue and the frequency of electromagnetic radiation to which it is exposed. The interaction also depends on the surface shape of the human body as it influences the degree of coupling and transmission of energy. Due to the great complexity and variety, a simplification is made by which it is considered that there are two types of surfaces: flat and curved. However, in reality, surfaces considered flat still have a certain curvature, which can be neglected from a practical point of view. To explore the properties of these surface variations and to enable the design and testing of antennas and transceiver for communications directly from the body, an approximation model for the human body must be found.

3.4 Antennas on textile substrate

Nowadays, wearable antennas are of great interest to the IoT (Internet of Things) industry due to the possibilities offered to integrate the full functionality of the electronic system into clothing. There is a growing interest in researching the technology underlying the production of antennas for smart clothing applications [34].

The antenna impedance adaptation with the radio system can be achieved mainly in two ways: by obtaining a source impedance equal to the complex conjugate of the load impedance, or by creating complex impedances that have a null imaginary part, both for the source and for the load. The first method is mostly used when adapting power amplifiers with other RF stages [38], but in the case of antennas and transmission lines it is preferable to adapt to the characteristic impedance of the line, which generally has a standard purely resistive value (50, 75, 300 ohms) [38].

Radio performance in the UHF frequency band depends on the length of the transmission line, the layout of the circuit, the objects in the vicinity of the antenna, the human body, temperature and humidity. These are the main factors that will have an influence on impedance and can greatly reduce performance if not taken into account.

3.5 Planar Antenna Design

The design and shape of the antenna have a great influence on electrical performance and compatibility with certain applications. Planar antennas are preferred in many modern communication systems due to their compact size, low weight, low cost, simple fabrication, and easy-to-set operating frequency [42].

For the conductive layers of the antenna, we chose to use a material produced by the company 3M™ under the name of *Fabric Tape CN-3190*. It is made in the form of an acrylic adhesive strip with a shielding role, which has a thickness of only 0.1 mm. The tape produced by 3M is recommended for applications such as grounding and EMI shielding of shielded equipment, components, and cameras. The tape has an adhesive material applied to one side and is covered by a removable film that allows easy cutting and handling using a mold. [41]

In our research, a variation was made for the two-corner truncation area in order to find the right dimensions for which the best electrical performance will be achieved. Also, the power point region has been modified to fine-tune the antenna input impedance and reflection coefficient.

3.6 Simulation results

The simulation analysis was performed using Ansys HFSS, a multifunctional 3D electromagnetic simulation software that allows the design of RF circuits by simulating behavior before prototype manufacturing.

The complex environment of the human body significantly influences the input impedance of the antenna, converting part of the energy into heat and generating observable losses through the variation of the reflection coefficient.

In the simulations, a custom model for human tissue was implemented, consisting of three superimposed layers: skin, fat and muscle, each with specific parameters and thicknesses. The model considers the effects of the human body up to a thickness of 20mm, because at high frequencies and low power, radiation is mostly absorbed by the upper layers. Bone structures and organs, being located at greater depths, were neglected. The simulations carried out with this model produced results consistent with the real measurements.

For performance optimization, simulation tools were used that allow parametric variations of the physical dimensions of the antenna. Although the dimensions of the radiation surface can be theoretically calculated accurately, the smaller geometric parameters required an experimental approach to determine the optimal values.

3.7 Results obtained through measurements

To validate the proposed model, several antenna prototypes were manufactured, on which a series of measurements and experiments were carried out to prove the validity of the process. The experiments focused on the UHF radio frequency band, with the help of 2.4 GHz antennas having fabric as substrate. In our experiments, performance was evaluated by measuring the reflection coefficient of the signal at the antenna input, the VSWR factor, the variation in impedance to frequency, bandwidth, and by testing all these performance factors in the vicinity of a human body.

In the experiment presented here, the projected performance of the antenna was evaluated by measuring the variation of electrical performance, in a wide frequency band, so as to encompass the 2.4 GHz band used commercially for Wi-Fi, Bluetooth and other types of communications. The implementation of the real antenna is represented in figure 3.14. It was physically assembled on a 100% cotton base material with a thickness of 0.8 mm and a relative permeability of 2.6. Particular attention was paid to achieve the precise alignment of the radiant surface and the ground plane that forms the antenna. To minimize power loss, the power path from the SMA connector to the antenna is implemented using a 50ohm coaxial line with a length of 10cm and very short solder terminals.

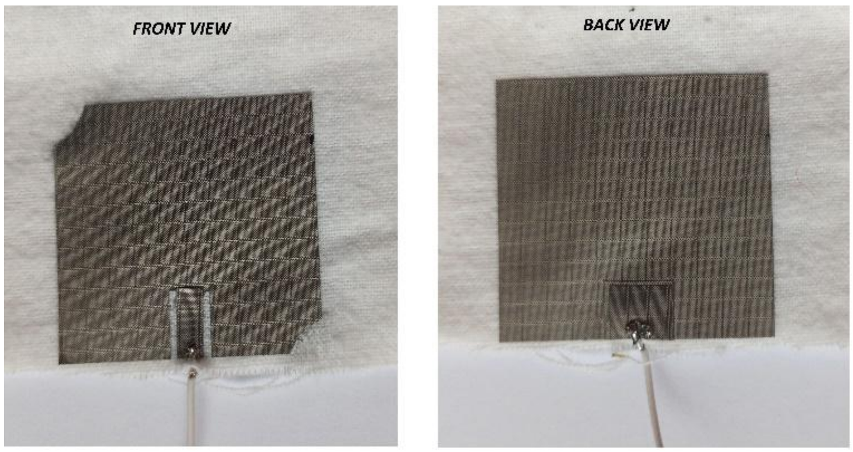

Figure 3.14 *Practical realization of the antenna on textile medium*

In the measurements made, the results are close to ideal and no intervention on the impedance profile is required, otherwise an adaptation network can be used or physical changes to the antenna model can be made to achieve the desired performance.

The efficiency of the antenna can be easily quantified by evaluating the reflection coefficient. The measurements confirm a very good power transfer to the antenna in a bandwidth of 200 MHz and a center frequency of 2.45 GHz. The relative bandwidth of this antenna model has been calculated at approximately 8.2%. Displaying the VSWR factor will bring the same information as in the case of the S11 graph, but we believe that an expression in dB brings information in a more intuitive format for estimating power losses. The best performance is obtained at the resonant frequency of 2.45GHz, at this central point of the band we have a value of over -16dB for | S11|, which corresponds to a transmission efficiency of more than 96%.

4.Innovative Materials for Wearable Antennas

Renewable energy sources include antennas integrated into clothing or various objects, which capture the energy of radio emissions to be later converted and stored, thus providing an innovative and sustainable solution for powering electronic devices. In the field of medical applications, antennas and electrodes are essential for accurate electrical measurements, allowing multiple sensors to be connected to the body, such as ECG and EEG electrodes, skin electrical conductivity sensors or muscle electro-stimulators, thus helping to monitor and improve the health of patients.

4.1 Areas of application for electrically conductive textiles

RFID antennas are used in various applications for household, wearable or industrial use, facilitating automatic user identification, tracking and counting of objects, thus providing advanced solutions for resource management and data security. Organic electronic circuits such as OLED, OFET and solar cells can be integrated into textiles commonly used for clothing or other common items, thus bringing cutting-edge technology into everyday life. In sports activities, these technologies allow activity monitoring, performance measurement, muscle stimulation and sleep monitoring, helping to optimize training and improve the overall health of athletes.

4.2 Electrical characterization

Substrate materials are mainly intended to support the electrically conductive part of an antenna and improve radiation properties. So these materials will also influence the properties of the wearable antenna. In addition, most flexible materials have a high permeability factor and the tangent of the loss angle has low values, which further increases the performance of wearable antennas. In the studies conducted so far, the performance of numerous types of flexible substrates for wearable antennas has been investigated, some examples would be silk, wool, denim, Cordura, synthetic wool, felt and others [55, 56].

Various polymeric materials, such as polyamide, PET, PDMS [54] or liquid polymers (LP) [57] were used for flexible and transparent antennas, as they offered high flexibility, low losses and reduced thicknesses. In addition, polymeric materials have good electrical and mechanical properties, which guarantee good deformation behavior, an absolutely necessary condition for this type of antennas [58-59]. The use of polymeric substrates for wearable antennas or other complex projects such as liquid metal antennas is noted in studies [49].

4.3 Flexible material

The technology of conductive electrical fabrics has been known for some time, such fabrics were first manufactured by mixing a conductive powder with polymeric materials in a molten state, before the fibers from which the material is made are extruded. Such powders may include, for example, carbon particles, silver particles, or even particles coated with silver or gold. Currently, only three classes of materials are used in combination with other materials to produce conductive properties: metals, carbon allotropes, and intrinsic conductive polymers (ICPs). And for semiconductor and antistatic applications, ionomers and silicones can be used.

4.4 Conductive materials

The wearable antenna is usually composed of two conductive surfaces that are in phase opposition from an electrical point of view. The evaluation of conductive materials can be done by looking at characteristics such as electrical resistivity, conductivity, elasticity, tear strength, tensile strength and the possibility of integration with other flexible materials. There are numerous examples where various rigid conductive materials have been used to make wearable antennas. These types of materials have high conductivity, have low costs and can be integrated together with textile substrates using adhesive laminated materials without the use of mechanical fasteners or sewing techniques.

In addition, the unique characteristics of conductive polymers, such as electrical and mechanical properties, but also the possibility of being used as biodegradable, recyclable and hydrophobic materials, have allowed them to be used in various applications, such as sensors, light-emitting diodes, electric cells and accumulators, etc. [58]. In addition, polymers are low-loss materials with high stability in wet conditions due to their low moisture absorption rate, making them a suitable choice for wearable applications [59].

4.5 Adhesives and electroconductive pastes

Through this study I aimed to address the influence of electroconductive adhesives on the electrical and mechanical properties of the circuit in which they are used, to make comparisons between various types of electrically conductive paste, to study their composition in relation to electromechanical performance.

The electroconductive paste industry has developed a lot since lead-free alloys are predominantly used in the electronics manufacturing industry. It was quickly found that the interconnection technique based on lead-free alloys increased the thermal stress of the printed wiring and electronic components but at the same time kept all the well-known problems related to soldering with *SnPb* alloys (residues, gaps, short circuits, etc.).

In this study we will focus on conductive adhesives that have an isotropic distribution, i.e. they are good electrical conductors in all directions and are best suited for soldering silicon wafers, soldering chips, attaching SMD components or making electrical routes. Anisotropic conductive adhesives conduct electrical current predominantly in one direction, so they can be used for highly sensitive electronic components, such as LED devices, LCD displays, and dedicated circuits for RFID. The ratio between the conductive material and the adhesive primarily influences electrical resistivity, this is usually the most strongly affected factor and that can have a big impact on performance as interpreted by the user. To increase conductivity, a higher ratio of conductive material can be chosen, but this measure directly leads to a reduction in adhesive properties. So ideally, the amount of conductive material should be kept at an optimal level but resistivity should be improved by using higher quality materials, which will ultimately lead to increased costs.

4.6 Manufacturing methods

Manufacturing methods play a key role in the design of *wearable* antennas because they are the ones that determine the accuracy of realization, cost and execution time of the product. The latest manufacturing methods for flexible antennas use technologies such as 3D inkjet, infrared laser cutting, and hand-held tool cutting. We will now make a brief review of these manufacturing methods:

4.6.1 Template printing

It is a simple method that has been used by the electronics industry in several applications [62]. In this method, an elastic blade, usually made of silicone, is directed in a linear motion that will press the stencil into contact with the material on which the print is made. The ink will be pressed through the exposed areas of the stencil and thus reach the substrate, thus projecting an image of the stencil [63]. This method can also be used in the case of polyester or stainless steel materials. Typically, three standard stencil printing techniques are used, such as rotary, platform or cylinder.

4.6.2 Flexography

It is a printing process similar to that of letterpress printing, so it uses an embossed typographic cliché made of flexible material. Using this method, an image is generated using the printing process, as shown in Figure 4.5a.

The protrusion surface of the printing plate matrix is filled with ink, while the recessed area has no ink. For image printing, the surface of the protruding matrix contains ink and makes contact with the substrate material [68]. With this method, high throughput, clear resolution and low costs can be achieved. It requires a low-viscosity conductive ink and has been successfully used in RFID antennas.
Table 6 provides a brief comparison of the main printing processes.

4.6.3 Inkjet printing

If this printing method is used, the electrical characteristics of the antenna and RF circuits will depend on the properties of the conductive inks. Inkjet printers work by applying a small drop of ink, requiring a small amount of pico liters to produce clear and precise shapes. This method uses conductive inks, which usually contain silver nanoparticles.

The inkjet printing method can be achieved by two methods, continuous inkjet or droplet controlled. When receiving control pulses, the inkjet ends apply pressure pulses to the ink using a piezoceramic actuator or thermocouple, to release a drop of ink through a nozzle.

4.6.4 Sewing and embroidery

The sewing process is a simple but effective method of making a textile antenna, compatible with the requirements of the wearable field. In addition to the actual realization of the radiant system, sewing and embroidery processes can be used to design various auxiliary metal components such as "via" connections, quarter-wave transformers, transmission lines, or interconnections using conductive fabrics and threads [70].

In [71] the sewing technique was used to connect copper surfaces onto a polyester-taffeta conductive fabric, acting as a substrate, to make inverted F-type planar antenna (PIFA). In another study [73], conductive threads were used to form conductive paths on fabrics, or cross-stitch embroidery, as exemplified in Figure 4.6a.

Similar to sewing, an antenna design can be made on textiles using conductive threads. With the evolution of technology, computer-aided embroidery machines are now available for the production of antennas by embroidery, as shown in Figure 4.6b [75].

5.Study of materials for the realization of radiofrequency structures

In order to make improvements in the ergonomics of clothing, there are numerous studies regarding the realization of textile transmission lines[86] and antennas made on textile substrate. The new scientific field dealing with the implementation of these types of transmission lines and various types of modern electronic systems for textiles has been called *Textronics* [87] in some works.

5.1 Electrical Characterization of Materials

Regarding the way to implement a transmission line in a textile substrate, there are several types of construction [87]:

1. Direct application of conductive transmission lines in the form of conductive yarns (individually insulated) or electrically conductive yarns at the production process resulting in flat textile products such as fabrics and knitwear;
2. Printing an electroconductive medium on the surface of the fabric;
3. Spraying or depositing an electroconductive medium on a planar fabric;
4. Incorporation of electrically conductive materials using sewing or embroidery methods;
5. Bonding conductive surfaces, made of metals;

5.2 Experimental analysis and simulation

In the first phase we used the planar capacitor method in measurements because it allows the realization of simple and mechanically stable structures. The initial experiments were carried out by building 5 capacitors based on different dielectric materials: 3 textiles and two types of plastic mainly used in 3D printing. Textiles P1, P2 and P3 are composed of various types of fabrics, synthetic and natural in the proportions shown in Table 9. Thus, the P1 material is made entirely of natural cotton, and the P2 and P3 samples are synthetic materials [87].

The P4 material could not be used in these experiments because it contains conductive paths with silver wires, which does not make it unsuitable in applications where a material with low electrical conductivity is required. However, I wanted to mention this material because it is worth studying with other methods and could be the subject of transmission line applications, ESD protection or for the transport of large electric currents on textile surfaces.

This report compares the electrical performance of several materials used in transmission lines, namely P1, P2, P3, ABS and PLA. The P3 material, made on the basis of

Kermel, stands out for its good performance at high frequencies, having a lower level of losses compared to P1 and P2, and the reflection coefficient indicates a very good operation up to frequencies of 2.5GHz.

The ABS material has lower performance than the other materials, the level of transmission losses being very high, and the S21 coefficient increases almost linearly with frequency. For the transmission line made on a P2 type substrate, the reflection coefficient indicates a very good operation up to frequencies of 2.7GHz, but the transmission losses increase proportionally with the frequency and are slightly higher than those obtained for the P1 material. On the other hand, the PLA plastic-type material has a good behavior up to almost 3GHz, which makes it a better option than the ABS plastic variant, which is also used for 3D printing surfaces.

The P1 material, made entirely of cotton, stands out for its low level of losses and the reflection coefficient indicates a very good operation up to frequencies of 3GHz. The S11 coefficient increases linearly, which is a normal behavior for such a material and indicates that there are no losses introduced by other components of the measurement system.

Further we continued the investigations on the performance of these materials by evaluating antenna structures made on leather, plastic or textile substrates. The simulations were performed using the HFSS program produced by the company Ansys, which is a specialized tool for simulating the behavior of complex structures at high frequency.

In order to study the influence of small geometric changes in the way the structures are made, we made a comparison between the simulation results for an antenna structure with straight edges and with rounded edges. The differences can be seen especially from the numerical performance, where an improvement to the version that uses rounded corners stands out.

6.Case Studies

6.1 Design and simulation of a wearable antenna model

In this study, a compact antenna is simulated, built and measured, specially designed to be fully integrated into a leather strap. We set out to create a triple-band antenna concept so that it is useful for Wi-Fi applications. The architecture of the radiant element is made from a series of circular areas, and the table plan will contain several structures with cutouts, known in the literature as DGS (*defected ground structures*). The design of the antenna has been chosen and optimized both from an electromagnetic point of view and from a manufacturing point of view so that it can be fully integrated into a leather strap, placed on the waist of the body.

6.1.1 Proposed topology

Most often, antennas that are small from an electrical point of view narrow the bandwidth in which we have impedance adaptation, reduce performance related to gain or directivity. The situation is similar for a planar antenna model, which although they offer a small mechanical profile and are preferred for mobile communications, introduce a challenge in terms of bandwidth improvement.

In the proposed architecture, we opted for a planar antenna array that uses a single microstrip transmission line, located in the same plane as the radiant elements. The theory of operation and calculation methods are already presented in other published works [93], so we will focus on optimizing for the best performance and introducing a novel concept that can be achieved on a leather belt.

6.1.2 Results obtained by simulation

In the simulated experiments, emphasis was placed on the graphical representation of the reflection coefficient for different variations of the mechanical parameters in order to optimize the shape and dimensions of the elements that make up the antenna. With the help of this optimization technique, parametric simulation was performed for the radius of the circles, the length of the transmission line to the feeding point, the length and position of the DGS structures. In order to investigate the effect introduced by the presence of several DGS structures in the plane of the antenna on the ground, we studied the distribution of current at different frequencies, each from different frequency bands, but in the same phase position.

The representation of the simulated reflection coefficient of the proposed antenna as a function of frequency will provide an accurate indication of the electrical behavior and useful frequency bands. This graph shows two main points of resonance that underlie the 2.4GHz and 5GHz bands – high and low. The reflected power level is very low (less than -20dB), which corresponds to a very good power transfer (considering a reflection coefficient better than -10dB) at the antenna input in a bandwidth of 100MHz for the 2.4GHz band and 920MHz for the two 5GHz bands.

In order to be able to optimise performance, additional simulation scenarios were created, in which the length of the DGS structure is varied from 23 mm to 27 mm. Similar results were obtained following the parametric simulation for the location point of DGS structures, with small steps, from 5 mm to 7 mm. It can be seen that variations in the location of the DGS may have influences on the electrical properties, mainly on the resonant frequency for frequency bands above 5GHz. Optimal performance in all three desired frequency bands was achieved for a 5 mm location point value.

6.1.3 Results obtained by measurements

The prototype of this antenna was manufactured on a 100% natural leather strap, which has a thickness of 3.5 mm, a relative permittivity of 1.8 and a loss coefficient of 0.05. The conductive layers are made using 3M 1181 copper foil shielding tape, which has a thickness of 36µm and an electrical conductivity of only 8 µΩ/cm2.

This antenna design has a very good impedance performance, with a reflection coefficient of no more than -10 dB in the WLAN bands 2.4GHz/Bluetooth (2.4 – 2.48GHz), the lower band 5GHz (5.15 – 5.35GHz) and the upper band 5GHz (5.725 – 5.825GHz). In our experiments, performance was evaluated by measuring power losses caused by reflections when the signal entered the antenna. They basically represent the variation of impedance with respect to frequency, usable bandwidth and can also check the stability of electrical performance under the influence of temperature or in the presence of other conductive bodies.

The reflection coefficient variation curve highlights two main points of resonance, which make up the 2.4 GHz and 5GHz bands - high and low. The reflected power level drops to a minimum of -14dB, which corresponds to a very good efficiency in terms of power transfer, if we take into account an acceptable reflection coefficient better than -10dB. The measured bandwidth has a value of approximately 110MHz for the 2.4GHz band and 750MHz for the 5GHz bands. These results show similar performances to those obtained in the simulation without any notable differences for the mechanical dimensions of the elements that constitute the antenna.

The study was carried out by electromagnetic simulations in Ansys HFSS to optimize the antenna parameters, followed by the implementation of a real prototype using standard conductive materials and natural leather as a substrate. The performance was evaluated both by simulations and by experimental measurements, with the antenna placed on a human body. The results confirm its applicability in areas such as IoT, home appliances, medical and military applications, especially for WLAN communications.

An important contribution was the design of a compact triple-band antenna, integrable in a leather strap, intended for WBAN (Wireless Body Area Networks) and Wi-Fi applications. The design included planar circular structures and the use of DGS (Defected Ground Structures) technology to improve bandwidth and optimize electromagnetic characteristics. The parametric simulations allowed the adjustment of the antenna dimensions and the selection of the optimal configuration for the operating frequencies, improving the reflection coefficient and the impedance adaptation.

6.2 Definition and importance of pH in the study of liquids

pH measurement is one of the most common and significant evaluations performed in various fields, including industry and drinking water quality monitoring. pH measurement can provide essential information about the chemical and physical characteristics of a liquid, having a significant impact on its qualitative assessment and potential uses. The relationship between pH and the electrical potential produced by a pH probe is shown in Figure 6.15.

The pH value is among the few chemical parameters, ubiquitous in water quality measurements and at the same time, one of the most important fundamental parameters that dictate the outcome of a wide range of chemical and biological reactions. The pH parameter is also important for governing the normal function of the human body or for controlling certain industrial processes.

6.2.1 Current pH measurement techniques

Optical pH probes generally use pH-sensitive materials that change their UV absorption and optimize their optical properties based on pH levels, such as refractive index, polarization, absorption [102], and in one study [103] a pH-dependent fluorescent indicator was injected into a microfluidic coil. This fluorescent signal was recorded in the pH range of 2.5-9; however, the sensitivity is not stable, but increases from 6 mV/pH at baseline to 43 mV/pH at the acidic pH level.

6.2.2Electronic system for pH measurement in liquids

To carry out verifications on the test substances, I used a commercial measuring device, specialized for water, but I also chose to produce my own instrument, made on the basis of a commercial sensor (similar to the one in figure 6.16), together with a microcontroller with an 8-bit architecture. The software program is designed to facilitate the operation and reading of a pH sensor, model SEN-0161, which is an analog pH sensor.

The cut-off frequency is low enough to eliminate noise and allow data to be updated quickly enough. Protection, shielding, and insulation from other components are other best practices to be used to minimize eddy currents that can influence the AD8603's high-impedance input. The typical values and the mode of variation of the voltage generated by the pH electrode are shown in Figure 6.1. Based on the Nernst equation, the total voltage at the probe can range from ±414 mV (±59.14 mV/pH) at 25°C to ±490 mV (±70 mV/pH) at 80°C.

6.2.3 RF probes for pH measurement in liquid solutions

The main idea presented in this paper is to stimulate the sensor electrodes by immersing them in standard solutions, with known pH values that will allow quantifying the results based on the already known pH values. The presence of the liquid will lead to a change in the dielectric constant of the sensor and produce a change in its resonant frequency.

The sensor first shows a change in the resonance frequency of about 50 MHz between distilled water and the standard solution with the highest pH (strongly basic), when the sensor is completely submerged, and a deviation of about 100 MHz between the most acidic solution and the most alkaline solution. A small amount of solution can be used for tests and the height of the liquid matters more than the volume itself. Thus, a volume of 50ml, prepared in a glass container, is enough to allow the sensor to be submerged and stable results to be obtained.
This study compares the performance of a traditional pH probe with Ag/AgCl electrodes and an innovative radio wave-based method for measuring the pH of a liquid. Accurate pH measurement is essential in various fields, such as analytical chemistry, medicine, environmental technologies and agriculture.

The pH probe with Ag/AgCl electrodes is an electrochemical standard due to its stability and sensitivity, based on the potential difference formed at the interface of the electrode with the analyzed solution. Its advantages include robustness and high accuracy, but it can be affected by chemical interference, requires frequent recalibration, and has a slower response time.

In contrast, the radio wave-based method uses a resonant structure immersed in solution, recording variations in S11 and S21 parameters to determine the pH level. It offers a faster response time and is less influenced by chemical interference, but can be affected by electromagnetic interference and requires more complex equipment. The choice of the optimal method depends on the specific requirements of the application.

6.3 Flexible antennas for embedded devices

With the development of virtual reality (VR) technology and the improvement of the way human-computer interaction is carried out, the use of natural and efficient methods of interaction in virtual environments has become an intense subject of research. The aim is for HCI devices to be able to capture the movements of the human body through as many degrees of freedom as possible and to associate them directly with those in video games.

6.3.1 CAD modeling for device and antenna

Through this work we have developed a design that allows manipulation and interpretation of gestures with one hand, thus we have created a small and light circular shape, similar to a ball.

Given the device's small internal dimensions and specific shape, we couldn't use a standard external antenna. In this case, an integrated plastic antenna was designed, simulated, produced and placed in the upper half of the case.

The connection between the antenna and the microcontroller is made through a small diameter coaxial cable, using a U.FL connector to the microcontroller PCB. A thin strip of Kapton was used for the antenna substrate, a material known for its very good dielectric, mechanical and thermal properties. Kapton is a material used in many fields, including in the manufacture of flexible RF antennas, due to a number of outstanding properties

In the measurements presented here, we can see that the antenna embedded in the PCB is quite limited in terms of maximum communication distance, and our proposed plastic embedded design performed better than the commercial omnidirectional antenna, not only at short distances, but also at long distances, so we determined that it is suitable for communication at medium to long distances

In this sub-chapter we have proposed a 3D printed HCI device, made of PLA/ABS materials and equipped with affordable electronic components, which makes it easy to build and suitable for multiple applications, such as video games, virtual reality and robotic arm control with four degrees of freedom.

A major advantage of the design is the elimination of physical connections between the user and the computer, thanks to a built-in plastic antenna and a Li-Ion battery. The experiments confirmed the optimization of the antenna design, and the RSSI measurements indicate efficient communication over long distances via Bluetooth. The device provides reliable data, making it ideal for interacting with virtual and augmented reality applications.

7.Contributions and conclusions

This doctoral thesis explores wearable antenna technology, addressing essential aspects such as design, materials and their integration into everyday life. A fundamental contribution was made in the initial stage of the research, where the investigation methodology, study directions and strategic objectives were clearly defined. Through a rigorous review of the literature, technological gaps and current challenges have been identified, thus laying a solid foundation for the development of innovative solutions.

In addition, the research process has been efficiently structured by selecting the appropriate simulation, design and testing methods, ensuring a systematic and reproducible approach. Theoretical models were developed to optimize the performance of the antennas, and the experimental planning included the development of prototypes and their evaluation in real conditions of use. Thus, this contribution allowed not only an efficient management of the research stages, but also the validation of applicable technological solutions, relevant to the progress of the field.

The second chapter makes significant contributions in the field of RF engineering, focusing on optimizing energy transfer and adapting impedance for wearable antennas, a topical topic in the context of the exponential growth of wearable devices in modern applications.

This section explains in detail the challenges and solutions associated with impedance adaptation, an essential process for maximizing energy transfer and minimizing losses. Through this paper I have proposed some practical methods, addressing the theoretical limitations and common errors encountered in real calibrations. Through meticulous analysis of the factors influencing the impedance matching process, this paper contributes to improving the performance of wearable devices through a better understanding and implementation of adaptive techniques.

The experimental studies described highlight the effect of high frequencies (UHF) on line parameters and emphasize the importance of using accurate measurement systems such as vector network analysis. By treating the relationship between electrical length and impedance variation in detail, this section helps to reduce errors and improve signal quality in wearable devices.

One of the key contributions is the introduction of a validated method for the precise calibration of the reference plane of the devices under test (DUT). The chapter develops a procedure that includes additional calibration checks using the entire device, thus reducing errors arising from additional connectivity. This approach extends existing methodologies through a practical perspective, directly applicable to the engineering of wearable antennas, and fills a gap identified in the literature.

Regarding impedance adaptation, a structured methodology is proposed for the representation and adjustment of complex impedance using the Smith diagram and LC components, emphasizing the scenarios encountered at high frequencies. The contribution consists in detailing the working methods and the parasitic influence of the components, providing solutions for optimizing adaptation in special cases and critical frequencies, above the limit of 3 GHz. This section is particularly valuable for antenna designers who want to minimize losses and extend the applicability of the solutions to new generation devices.

The main purpose of the study carried out in the third chapter was to perform simulations using *Ansys HFSS* for the process of optimizing the antenna parameters and then to implement the project resulting from the simulations in a real scenario. We proposed a simple construction method, by using standard conductive fabric on a substrate made from normal cotton materials, generally used for clothing. This construction method does not necessarily require a sewing machine, resulting in a cost-effective implementation that can be used on a wide variety of small antenna circuits. Performance was evaluated through simulation, measurements under ideal conditions and real-life scenarios. The results obtained in the experiments confirm that this type of antenna is suitable for IoT, home appliances, medical or military applications that require radio communications in the free bands of 433MHz and 2.4GHz.

In order to highlight the behavior of some of the materials presented in these studies, a transmission line section was made in microstrip topology. The conductors used for the surfaces were idealized from the point of view of electrical conductivity because only the influence of the material used to make the substrate was pursued. A central aspect of my research was the evaluation and optimization of antenna performance using textile substrates and unconventional materials. We designed a transmission line in microstrip topology to analyze the behavior of different materials used as substrate.

In the simulations, several types of materials were modeled and the performances were compared by measuring and graphically representing the parameters S11/S22 and S12/S22, these pairs of quantities will have the same variation because the transmission line and ports are symmetrical. The reflection coefficient, represented by the parameter S11 and S22, indicates the degree of adaptation between the ideal impedance of the generator and the characteristic impedance of the line.

The parameters S12 and S21, which represent the transmission coefficients, will indicate the level of losses when transporting energy through the transmission line, being correlated with the tangent of the loss angle, specific to each material. We proposed the use of textiles with integrated EBG layers, which significantly reduce the SAR (Specific Absorption Rate) – a crucial issue for the safety of wearable antennas. My studies show that an EBG layer can reduce SAR by up to 97% while improving antenna gain. In addition, we have detailed methods for optimizing microstrip line sizes to achieve accurate impedances at specific frequencies (2.4 GHz), relevant for WiFi and Bluetooth applications.

Having different dielectric properties, the dimensions of the microstrip line have been recalculated for each type of material so as to obtain a standard value of 50 ohms at the working frequency of 2.4GHz. A fairly high frequency was chosen to be able to evaluate the performance for a future antenna made for communication technologies in this band, especially Wi-Fi and Bluetooth. Design problems arise related to the thickness of the material when using materials that have a low value dielectric constant, thus resulting in high values for the width of the path. The solution consists in reducing the thickness for the material, so that the desired value for the impedance is obtained and the width of the path remains within a range of practical values, up to 2-3 mm.

In the research, we considered the complex effects of antenna-body interaction, using both numerical (voxel phantoms) and physical models. It has been shown that electromagnetic interaction can be controlled by using optimized insulation layers and dielectric materials, reducing losses. From the simulations performed, a correlation between the transmission coefficient and the tangent of the loss angle can be observed. Thus, for materials already known for their dielectric performance, better performance is obtained in terms of the level of losses introduced by the line. On the other hand, there was no variation in the impedance variation profile as a function of losses, which depended more on the geometric dimensions and the location of the component surfaces of the line.

The contributions of chapter five consist in the development of an innovative method for measuring the dielectric characteristics of textiles and plastics, using planar capacitors as the main evaluation technique. This method allows obtaining precise and efficient data on the behavior of materials under the influence of electromagnetic fields, having applicability in various fields, such as radio frequency communications, 3D printing technologies or electromagnetic protection. The proposed technique is based on simple but highly relevant measurements, allowing clear relationships to be established between the geometry of the material, its permittivity and the loss factor. By applying this model, researchers and engineers can quickly assess the performance of materials without the need for sophisticated measuring equipment or additional costs.

Also, another important contribution of the work consists in the comparison and detailed analysis of the dielectric characteristics of various types of textiles and plastics, which provides a solid basis for the selection of materials in radio frequency applications. In the experiment, three textiles with different compositions – natural cotton and synthetic fibers – and two types of plastic were studied, and the results obtained were compared with the theoretical values for permittivity and the loss factor. These comparisons allow the identification of types of materials that can be successfully used in specific fields, but also in optimizing the manufacturing processes of electronic and telecommunications equipment.

Another innovative aspect is the application of this model for 3D printed plastics, a technology that is constantly expanding. 3D printing offers great flexibility in the production of complex structures, and research in this field is essential for adapting materials to the increasingly diverse requirements of the market.

Also, the work carried out in this study provides an in-depth understanding of how various types of materials, natural or synthetic, influence the performance of low and medium frequency communication systems. This is an important step towards developing more efficient solutions for materials used in telecommunications, and future research will be able to extend these observations to higher frequencies relevant to modern communications.

The study carried out in chapter six used primarily by electromagnetic simulation using the *Ansys HFSS* program, in order to optimize the physical parameters of the antenna aiming to increase the electrical performance. In the second phase, a real prototype was implemented, using standard conductive materials and a substrate made of natural leather, as used in the manufacture of clothing belts. The performance was evaluated by simulation and the measurements were made with the prototype placed on a human body. The results obtained from our experiments indicate that this antenna model can be useful for the field of IoT, home appliances, medical or military applications, which carry out WLAN or similar band communications. Within the research described in this chapter, we have made contributions in several stages of the antenna development process, from conception to prototyping and their evaluation through simulation and experimental measurements.

My goal was to develop a functional antenna for Wi-Fi, which would have high performance, adapted to the modern requirements of bandwidth and versatility in the use of different frequency bands. In terms of antenna design, we proposed an architecture based on planar circular structures and used defective DGS (Defected Ground Structures) to improve the bandwidth and optimize the electromagnetic characteristics of the antenna. These choices have proven essential for improving antenna performance, given that modern requirements require broadband antennas capable of operating on multiple frequency bands. Thanks to this innovative design, I was able to extend the antenna's bandwidth and improve impedance matching, achieving good results in all three frequency bands specific to Wi-Fi applications.

An important aspect of the research was to carry out simulations to optimize the antenna geometry. We performed detailed parametric simulations, varying the dimensions of the radiant elements, as well as the DGS structure, in order to efficiently adjust the antenna performance according to the operating frequencies. These simulations helped me identify the best size configurations so that I could achieve optimal performance, especially in terms of reflection coefficient and bandwidth. We also tested various material combinations and selected conductive copper foil for the radiant layers and table top, which simplified the manufacturing process and reduced prototype costs.

As for the experimental measurements, we evaluated the performance of the built antenna by measuring the reflection coefficient and bandwidth at different frequencies. The experimental results confirmed the validity of the simulations and demonstrated that the built prototype meets the performance requirements for Wi-Fi applications, with a very low reflection coefficient (-10 dB or less) in the desired frequency bands. These measurements were essential for the validation of the concept and to ensure that the antenna can be used efficiently in real-world conditions. Further measurements were also made to verify the electrical behaviour of the materials used, such as the leather substrate, and we obtained accurate values of the effective permittivity, which were used to correct the measured data and improve the theoretical predictions. The contributions in carrying out this research were essential for the development of a functional, innovative and well-optimized product, capable of meeting the modern requirements of wireless networks and wearable applications.

The pH probe with Ag/AgCl electrodes has been a benchmark in the field of electrochemistry for a long time due to its stability and sensitivity. It works based on the potential difference that forms at the interface of the electrode with a solution whose pH is to be measured. The advantages of this method include robustness, accuracy, and relatively high sensitivity. In contrast, the radio-wave-based pH probe injects radiofrequency signals to record variations in the parameters S11 (reflection coefficient) and S21 (transmission coefficient). This is achieved by immersing a resonant structure in solution and monitoring changes in S-parameters. The method is largely independent of chemical interference and can have a faster response time than methods that measure electrical potential, without requiring frequent recalibrations. However, this type of probe may be sensitive to other types of interference, such as electromagnetic interference, and may require more sophisticated measurement equipment. The choice between the two measurement methods depends largely on the specific requirements of the application.

We proposed an HCI device based on a simple construction to a 3D printed, using conventional PLA/ABS materials and affordable electronic components, resulting in a device that is easy to make, but can be used in a wide range of applications, such as video games, virtual reality or even manipulating robotic arms with four degrees of freedom. A great advantage of our design is that it does not require any physical connections between the user and the computer or mobile terminal, thanks to the wireless communication implemented based on the built-in plastic antenna and the included Li-Ion battery. The results obtained from the antenna experiment certify that our design is well optimized for use in the HCI device, and the measured RSSI values obtained indicate that the communication module works efficiently and at long distances, compared to the performance of the Bluetooth protocol.

7.2 Conclusions and development prospects

The prospects for further development of the research are the optimization of manufacturing technologies and the integration of new advanced materials. Studies have shown that textiles and plastics can be successfully used to make antenna substrates, but exploring hybrid or composite materials with improved dielectric properties can lead to higher performance. Also, the integration of nanomaterials, such as graphene or metal nanoparticles, could improve the conductivity and flexibility of antennas, allowing the development of more efficient and sustainable devices.

Another key aspect is the development of advanced modeling and simulation methods for the analysis of antenna-body interaction. Current research has used numerical models and voxel ghosts to assess the impact of the human body on the performance of wearable antennas. A future direction of research could include the use of techniques based on artificial intelligence and machine learning for the automatic optimization of antenna geometry, thus reducing the time and costs associated with the design and testing process.

In terms of impedance adaptation and energy transfer optimization, experimental studies have demonstrated the importance of using precise calibration and measurement methods. Future research could explore techniques for automatic impedance adjustment in real time, using adaptive circuits and dynamic tuning algorithms, so that circuits that receive high-frequency energy can adapt their performance according to the use environment and operating parameters.

Expanding the applicability of wearable antennas in areas such as healthcare, the medical industry or next-generation communications is another direction of interest. For example, integrating these antennas into wearable medical devices for continuous patient monitoring could contribute to the development of advanced telemedicine systems. At the same time, exploring the compatibility of wearable antennas with 5G and 6G networks could open up new perspectives for applications in the field of mobile communications and the Internet of Things (IoT).

Finally, an innovative aspect to investigate is the optimization of antennas to reduce the impact on users, by reducing the specific absorption of radiation (SAR). Preliminary research has shown that the use of integrated EBG structures can significantly reduce SAR, but a more detailed exploration of different configurations and materials could lead to more effective solutions for user safety.