



UNIVERSITY OF DEUSTO

ELECTROMAGNETICALLY COUPLED
MICROSTRIP TEXTILE PATCH
ANTENNA DESIGN MODEL AND
CONSTRUCTION PROCESS FOR
SMART CLOTHING APPLICATIONS

Ph.D. Thesis Presented by

RUBEN DEL-RIO-RUIZ

Directed by

DR. JON LEGARDA and PROF. DR. HENDRIK ROGIER

Bilbao, March 2021



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within the Ph.D. Program in Engineering for the Information
Society and Sustainable Development

Directed by

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*Electromagnetically Coupled Microstrip Textile Patch Antenna Design Model
and Construction Process for Smart Clothing Applications*

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Text printed in Bilbao

First edition, March 2021

Abstract

Textile EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna)s currently face significant challenges to be considered for off-body BCWC (Body Centric Wireless Communications) applications. Research has shown that EMCMPAs are suitable for off-body communications, as they avoid the use of rigid components or galvanic soldering; they achieve high gain and radiation efficiency values in desired directions; and its ground plane reduces the negative effect of human body proximity. Nevertheless, they have two main challenges: the lack of a specific design model and their high fabrication complexity. This study aims to determine an EMCMPA design model to easily obtain its initial dimensions, and a textile fabrication process to reliably assemble them. Building on the existing work about textile EMCMPAs for off-body communications, it asks: to what extent modeling EMCMPAs with TL (Transmission Line) models can provide accurate and efficient textile antennas? In this context, TLs are simple analytical models that provide good and intuitive understanding of the initial dimensions and EM (Electromagnetic) performance of the antennas, combined with a reasonably accurate mathematical formulation.

Based on the literature, these models can predict the initial dimensions of one part of EMCMPAs, but they do not provide all antenna dimensions. In addition, few designed and measured textile EMCMPAs have been reported, with no validated fabrication techniques, nor efficient antenna results. Analysis of the results demonstrated that using the proposed combination of TL, efficient textile EMCMPAs for the 2.45 GHz ISM (Industrial, Sci-

entific and Medical) band were obtained, presenting initial values for all dimensions of the antennas, with measured resonance frequency errors below 6%, and excellent free-space and on-body measured BW (Impedance Bandwidth), maximal gains, and high radiation efficiencies. It also demonstrated that using an alignment method, based on laser-cut wood, with a fast intralayer attachment method, and thermally activated adhesive sheets to fabricate textile EMCMPAs, exhibited standard deviation results of measured resonant frequencies, BW, maximal gains, and total radiation efficiencies equal to 24.54 MHz, 14.02 MHz, 0.15 dBi, and 3.57%, respectively.

The results indicate that the obtainment of efficient textile EMCMPA prototypes, by using a novel antenna design model and a reliable fabrication process, makes them a serious candidate for future smart clothing applications.

Acknowledgements

It is my pleasure to give my deepest gratitude to my supervisor, Dr. Jon Legarda (University of Deusto, Spain) for giving me the opportunity to work under his supervision in his research group. I will always be grateful for his consistent encouragement, advice, and guidance throughout the entire journey. He guided me from the beginning very patiently and gradually exhibited the beauty of research work. His mentorship and support is of most importance in completion of this dissertation. In the same way, I also want to thank my second supervisor, Prof. Dr. Hendrik Rogier (Ghent University - imec, Belgium) for giving me his technical knowledge and creative insights which have been invaluable for the development of this work. I am also thankful to him for welcoming me to his lab, where I was able to gain crucial experience on the design, construction and measurement of fully textile antennas, and for his research group, specially Dr. Olivier, Dr. Sam A., Mr. Quinten, Mr. Kamil, Dr. Thomas, and Ms. Duygu for welcoming me to their lab, and having great discussions about antennas, electromagnetics, and most importantly, life itself. Special thanks also to Prof. Dr. Sameer Sonkusale (Tufts University, USA), for giving me the opportunity to perform a three months international stay in his lab, and for his research group, specially Mr. Aydin, Mr. Cihan, Dr. Riddha, Mr. Wenxin, Dr. Junfei, and Ms. Rachael who made me feel like at home from the first day I arrived, despite all COVID-19 limitations.

I am also thankful for all lecturers and professors from the University of Deusto that were always willing to help me with any

problem I had, and guiding me in the right direction, specially Mr. Juan-Manuel Lopez-Garde, Dr. Javier Vicente, Dr. Juan-Ignacio Angulo, and Dr. Nekane Ione-Sainz-Bedoya. Also thanks to all my colleagues in the University of Deusto, specially Dr. Timothy Otim, Ms. Teresa Redondo, Dr. Laura Arjona, Mr. Florian Muralter, and Mr. Amgad Elsayed for all the inspiring conversations we had during every single lunch-break.

Most importantly, I want to express my heartfelt gratitude to all my family and friends who lifted me up with their unending support. Specially my wife Rebekah for constantly being by my side encouraging me, helping me, listening to me, and spending her time with me while I was doing this thesis, "Special thanks for you, my love". And of course, my two beautiful daughters Haizea and Alba for been a constant source of joy and energy.

Finally, my greatest regards to the living Almighty for giving me the courage, strength and love to face the complexities of life and complete this dissertation successfully.

Thank you all! ¡Muchas gracias a todos!

Ruben Del-Rio-Ruiz

March 2021

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LIST OF ABBREVIATIONS

AMC	Artificial Magnetic Conductors
BCWC	Body Centric Wireless Communications
BW	Impedance Bandwidth
CPW	Coplanar Waveguide
CST	Computer Simulation Technology
DOI	Digital Object Identifier
EM	Electromagnetic
EMCMPA	Electromagnetically Coupled Microstrip Patch Antenna
FTBR	Front To Back Ratio
HF	High Frequency
ISM	Industrial, Scientific and Medical
MDF	Medium-Density Fibreboard
MLIN	Microstrip Line
MPA	Microstrip Patch Antenna
NFC	Near Field Communications
PCB	Printed Circuit Board
PCPTF	Pure Copper Polyester Taffeta Fabric
PDMS	Polydimethylsiloxane
PES/CO	Polyester and Cotton
PIFA	Planar Inverted F-Antenna
PPB	Phenolic Plywood Board
PVC	Polyvinyl chloride
RF	Radio Frequency
RL	Return Loss
RMS	Root Mean Square
SAR	Specific Absorption Rate
SIW	Substrate Integrated Waveguide
SMA	SubMiniature version A
STDV	Standard Deviation
TL	Transmission Line
U.FL	Hirose Ultra-small surface mount coaxial

LIST OF SYMBOLS

$f(x)$	A function of x
Z_{in}	Antenna input impedance
Z_a	Antenna impedance
R_a	Antenna input resistance
jX_a	Antenna input reactance
R_{cd}	Ohmic losses due to conductive and dielectric antenna materials
Z_g	Generator impedance
P_{in}	Total input (accepted) power
P_{rad}	Total radiated power
e_0	Total antenna efficiency
e_c	Conduction losses
e_d	Dielectric losses
e_r	Impedance losses
e_p	Polarization losses
f_r	Resonance frequency
Γ	Reflection coefficient
$G(\theta, \phi)$	Antenna gain in a given direction
$U(\theta, \phi)$	Antenna radiation intensity in a given direction
$D(\theta, \phi)$	Antenna directivity in a given direction
ϵ	Complex permittivity
ϵ_r	Relative permittivity
ϵ_0	Permittivity of vacuum
ϵ'_r	Real part of dielectric constant
ϵ''_r	Imaginary part of dielectric constant
$\tan\delta$	Loss tangent

Do justly, love mercy and walk
humbly.

Micah 6:8

1

INTRODUCTION

The first chapter introduces wearable textile antennas and highlights the motivation, objectives, background, structure and publications conducted during the thesis.

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1.1 Wearable Applications

Wearable devices have been around for longer than we might think. The first known wearable device was invented in 1961, when mathematicians Edward Thorp and Claude Shannon developed the first wearable shoe-mounted analogue device, that could predict the speed of a roulette wheel in a casino and transmit the results via radio to the wearer's earpiece [1]. From then on, different wearable devices were released, like the calculator wristwatch in 1975, the Walkman in 1979, or a wearable wireless webcam in 1994. Nevertheless, It was not until the 2000s, with the rise of wireless technology standardization, higher computer processing power and electronic component miniaturization, that the market of wearable devices seriously increased with products like, Fitbits, Google Glasses, Apple Watches, and many others [2]. These wearable devices are mainly focused on our wrists or eyes, typical body locations where we wear specific gadgets. Yet, the wearable industry is heading towards fully integrated electronics on daily garments, also defined as smart clothing [3, 4, 5]. Smart clothes can provide the wearer with new information about the activity or physiology of the human body by combining textile materials with electronics, sensors or wireless technologies.

Some potential application areas with their respective functionalities are: (1) health care, to measure burned calories, body temperature, blood pressure, glucose levels, brainwaves, body postures; (2) police and firefighters, to control vital signals, to measure oxygen and hazardous gases, temperature, body impacts and falls; and (3) sports and healthy life, to monitor physical capabilities, training progress, rehabilitation techniques, prevent injuries, improve specific movements [6, 7]. Other application areas like diet management, sexual assault prevention, car insurance, navigation, memory aid,... could also potentially become targets of future smart clothing to provide the wearers security, health, guidance, wealth... services.

The path from wearable devices to smart clothes is challenging. Nowadays, at least some products are starting to integrate sensors into textile materials: the *Levi's Commuter x Jacquard* that interacts with phone calls or music control [8]; the *Nadi X* yoga pant that senses when the yoga pose needs refining

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and interacts with small vibrations on the body part you need to modify [9]; the *Hexoskin* smart garment that precisely monitors the electrocardiogram, heartbeat, heart rate variability, and heart rate recovery [10]; the *Sensoria Fitness Socks* that detect precise data on how the foot lands [11]; the *Neviano Swimsuit* that sends alerts when ultraviolet radiation levels are too high [12]; or the *Siren's socks* that detect ulcerations which often result in amputations in people with diabetes [13].

All these examples have something in common: the electronic components for data processing and wireless communications are embedded in removable plastic devices. The need of rechargeable batteries and their incompatibility with industrial and domestic washing processes are the main reasons for removable plastic devices. Therefore, the two main challenges for the success of smart clothing are the integration of electronic functionality and wireless technologies in traditional clothes, for data processing and communications, and even energy harvesting. Particularly, within wireless technology, antennas are one of the most sensible electronic components in this integration, due to their EM susceptibility when on-body, and their high dependency on their dimensions to operate efficiently. Depending on the application, their miniaturization might not be feasible, due to their frequency band of operation, the required minimum BW or radiation diagram. For these reasons, in this research work we are going to take important steps towards the integration of antennas in textile materials for body centric wireless communications BCWC applications.

BCWC can be divided in three application domains: in-, on-, and off-body communications. In-body refers to communications from devices on the body surface to devices inside the body; on-body refers to communications between devices on the body surface; and off-body refers to communications from on body surface to external devices. This thesis is focused on off-body communication systems, in which the efficiency of the antennas is closely related with their effect when in proximity to the human body. In this application area, textile antennas have a double challenge in their path to smart clothing and off-body communications: they should be isolated from the body to efficiently

communicate with external devices, and they should be flexible enough to be correctly integrated with textile materials.

1.2 Textile Antennas

The antennas' efficiency is a key aspect for any smart cloth system to reduce power consumption and increase battery life, both when communicating with other devices or when harvesting RF (Radio Frequency) energy [14, 15, 16]. In a nutshell, an antenna performs in an efficient way for a specific application when it meets mainly two requirements. First, a good impedance matching between the antenna and the signal source that allows the maximum power transfer or reception. And second, a good antenna topology design and fabrication that maximizes the radiation towards the desired direction. Moreover, for BCWC antennas, two more requirements are added: the antenna performance must consider the effect of the human body and the mechanical (bending, crumpling, compression, washing and ironing) and aesthetic requirements of the wearer and its clothes, respectively.

This section briefly summarizes the main concepts of textile antennas to better understand the further motivation, objectives, and challenges of this thesis.

1.2.1 Antenna Efficiency

1.2.1.1 Input Impedance

The antenna is connected to a transmitter or receiver, usually through a TL. The power transferred from a generator or TL to the antenna can be expressed by the reflection coefficient Γ of the incident signal. This parameter is defined in 1.1, as the ratio between the reflected and incident power of the signal at the antenna terminals (for a single-port S-parameter of the antenna S_{11}), caused by the impedance mismatch between Z_g , the generator impedance and Z_{in} , the antenna input impedance, which is composed of: the power radiated in the far field (R_a), the power stored in the near-field (jX_a), and the power

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dissipated by dielectric and conductor losses (R_{cd}). It is usually represented by its equivalent circuit, as shown in Figure 1.1.

$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{Z_{in} - Z_g}{Z_{in} + Z_g} \quad (1.1)$$

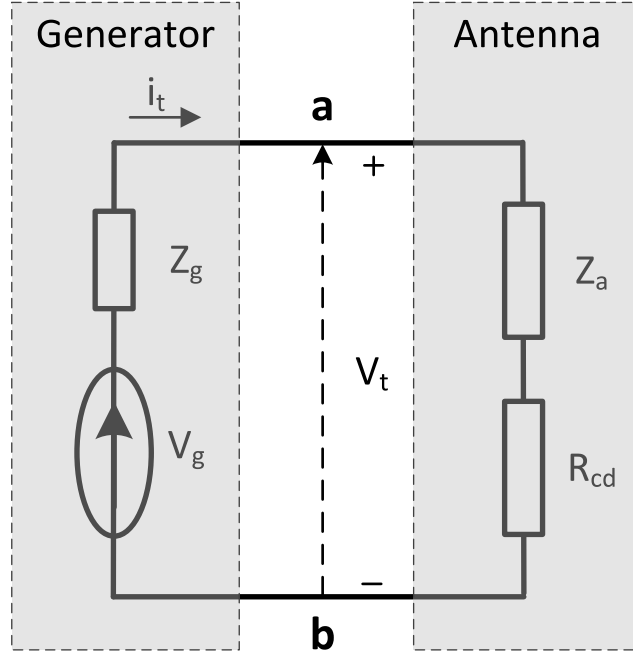


Figure 1.1: Equivalent Circuit of an antenna in transmit mode.

The reflection coefficient can also be evaluated on the logarithmic scale defined as RL (Return Loss), where

$$RL_{dB} = 20 \log_{10}(1/|\Gamma|). \quad (1.2)$$

The main two rules to obtain the desired input impedance matching in textile antennas are: a good antenna topology design and a good selection of the EM characteristics of the textile materials.

1.2.1.2 Radiation Efficiency

Another factor for BCWC antennas is to efficiently convert guided EM waves present in a wave-guide, feeder cable or TL into radiating waves traveling

between the human body and the surrounding environment and vice-versa. Their radiation efficiency can be defined as the total radiated power (P_{rad}) in relation to the total input accepted power (P_{in}) using

$$P_{rad} = e_{cd} \cdot P_{in}, \quad (1.3)$$

where e_{cd} is the antenna radiation efficiency (dimensionless) which takes into account the losses due to the conduction (e_c) and the dielectric material (e_d), but not the losses arising from impedance (e_r) and polarization (e_p) mismatches.

Yet, the radiation efficiency can also be related to the gain of the antenna and to its directional capabilities. Where its gain (in a given direction) ($G(\theta, \phi)$) is defined as the ratio of radiation intensity obtained in a given direction ($U(\theta, \phi)$), to the radiation intensity that would be obtained if the antenna source radiated isotropically. In 1.4 this is expressed as

$$G(\theta, \phi) = 4\pi \frac{\text{Radiation intensity in a given direction}}{\text{Total input (accepted) power}} = 4\pi \frac{U(\theta, \phi)}{P_{in}}. \quad (1.4)$$

When the direction is not given, the gain is usually taken in the direction of maximum radiation. Using 1.3 reduces 1.4 to

$$G(\theta, \phi) = e_{cd} \left[4\pi \frac{U(\theta, \phi)}{P_{rad}} \right] = e_{cd} D(\theta, \phi), \quad (1.5)$$

where $D(\theta, \phi)$ represents the directivity of the antenna.

Again, the main two variables to obtain a good radiation efficiency are: the antenna topology and the EM characteristics of the materials.

1.2.2 Antenna Application

Antennas have to be efficient within a determined application, generally the antennas' BW and radiation diagram.

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1.2.2.1 Impedance Bandwidth

The Z_{in} is generally frequency dependent, thus the antenna will be matched, to the interconnecting TL and other associated components, only within a BW.

The antenna's BW is defined as "the range of frequencies within which their performance, conforms to a specified standard" [17]. In this work, the BW will depend on the antennas' RL, defined as the range of frequencies, on either side of a center frequency (usually the resonance frequency), where the RL is below a certain value (in this work, -10 dB).

The main two variables to obtain the desired BW are: the antenna topology and the EM characteristics of the materials.

1.2.2.2 Radiation Pattern

An antenna radiation pattern is defined as a graphical representation of the radiation properties of the antenna as a function of space coordinates. In this work, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates. The most illustrated radiation property, published in our articles, is the two-dimensional spatial distribution of radiated energy as a function of the observer's position along a surface of constant radius. They are normalized with respect to their maximum gain value and are plotted on a logarithmic scale (dB). A convenient set of coordinates is shown in Figure 1.2.

Radiation patterns can be divided into lobes. A radiation lobe is a portion of the radiation pattern bounded by regions of relatively weak radiation intensity, as shown in Figure 1.2. The main-lobe is the region around the direction of maximum radiation. The side-lobes are smaller beams that are away from the main beam, usually radiate in undesired directions, they cannot be completely eliminated and occur between 45 and 135 degrees. Finally, the back-lobes are often radiation in the opposite direction to the main-lobe.

There are multiple types of radiation patterns depending on the type of antenna topology. This work has been focused on fully grounded planar textile antennas. Therefore, the main-lobe is perpendicular to the antenna surface

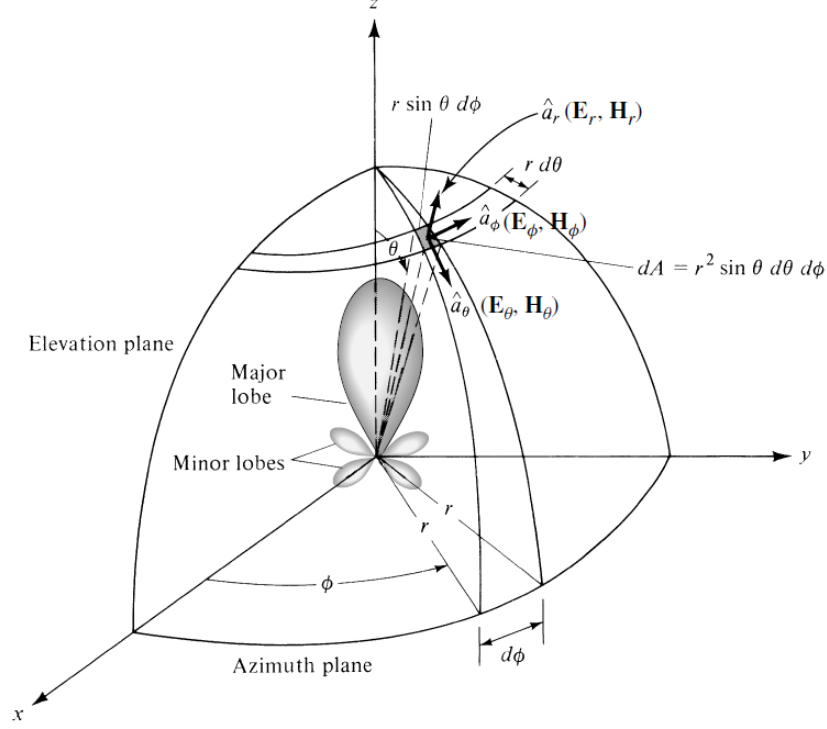


Figure 1.2: Coordinate system for antenna radiation pattern analysis.

and in the opposite direction to the body, or also called off-body communication antennas. Side- and back-lobes are undesired radiation patterns that have to be minimized to obtain low SAR (Specific Absorption Rate) levels.

The main two variables to obtain the desired BW are: the antenna topology and the EM characteristics of the materials.

1.2.3 Antenna On-Body

The antenna's susceptibility to body proximity and their thickness remain a mayor issue when integrating them in smart clothing. Additional absorption caused by a radiating antenna placed near the human body should be avoided as this could lead to health issues if radiation levels are above the standard limitations [18]. The presence of the body also affects the propagation characteristics, and careless antenna designs could result in poor link quality, depolarization, and augmented power consumption. The body might

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also de-tune the antenna's operating frequency, and deteriorate its matching characteristics and/or radiation efficiency.

The radiation patterns of off-body communication antennas have to be directed in the normal direction to the body surface. Therefore, side- and back-lobe radiation patterns have to be minimized to obtain low SAR levels.

1.2.3.1 Specific Absorption Rate

SAR is a measure of how much energy is absorbed by the human body when exposed to EM fields, which can be calculated using 1.6

$$SAR = \frac{\sigma E^2}{\rho}, \quad (1.6)$$

where σ (S/m) is a function of the tissue's conductivity, E (V/m) is the RMS (Root Mean Square) electric field within the tissue, and ρ (kg/m^3) is the specific mass density of the human tissue.

For the characterization of on-body antennas, the SAR is commonly expressed in W/kg or W/g and the measurements are integrated over a small sample volume (typically a 1 gram or 10 grams area) of body tissue. The limits set for SAR differ depending on the region. In Europe is 2.0 W/kg averaged over 10 grams of tissue [19] and in the USA is set, much more stringent, to 1.6 W/kg, averaged over 1 gram of tissue [20].

1.2.3.2 Textile Materials

Textile materials are planar fibrous materials that are largely determined by the characteristics of their fibers and the composition of their yarns. In this section, some features of textile materials that affect the efficiency of the antennas are examined:

1- The permittivity of the dielectric materials ϵ , which is a complex value parameter. It is usually expressed as a relative value ϵ_r where,

$$\epsilon = \epsilon_0 \epsilon_r = \epsilon_0 (\epsilon'_r - j\epsilon''_r). \quad (1.7)$$

ϵ_0 is the vacuum permittivity, which is 8.854×10^{-12} F/m, and ϵ'_r and ϵ''_r are the real and imaginary parts, respectively, of the relative permittivity. It is frequency dependent, therefore, all dielectric textile materials have to be characterized for their specific application. In this work, its real part and the ratio of the imaginary to the real part, known as loss tangent ($\tan\delta$), are used to quantify the textile materials' characteristics, where

$$\tan\delta = \frac{\epsilon''_r}{\epsilon'_r}. \quad (1.8)$$

The relative permittivity affects the antennas' BW and radiation efficiency. Textile material's inherited low permittivity values, caused by their high porosity, reduces their surface wave losses, allowing BW and radiation efficiency enhancements.

2- The electrical surface resistivity of conductive textile materials refers to the resistance experienced by the leakage of current along a determine surface of conductive material. It is usually reported in ohms/square (Ω/sq or $\Omega/\square$) [21, 22].

Besides the permittivity of the substrate, the choice of conductive textile material is also important to assure a good EM antenna performance to minimize the ohmic losses and thus increase the antenna efficiency.

3- The thickness of textile materials is another important parameter. Textile materials have a very narrow range of permittivity values, due to their low inherited permittivity. Therefore, the thickness becomes an important parameter, because it can have much wider variations. The thickness of textile materials can determine the BW, input impedance, and flexibility of the antenna.

For a fixed relative permittivity, the substrate thickness can be increased to enhance the planar antenna's BW. However as the thickness increases, surface waves and spurious feed radiation increase, which leads to lower radiation efficiency values. Therefore, the thickness is a trade-off between BW and radiation efficiency of the antenna [17].

4- The previous features are all dependent on the mechanical performances required by the application. Generally, off-body communications textile

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antennas have to be robust under bending, crumpling, and stretching conditions, because of the wearer's movements, washing or ironing of the garments, and to prevent from braking or malfunctioning. Other antenna factors like its light weight, low profile, and easiness to integrate in clothes should also be considered. The use of rigid components should be avoided, and soldering points should be minimized to achieve these requisites when designing planar textile antennas.

1.3 Textile Antenna Topologies

Considering the previous considerations, it is clear that the election of the antenna topology and materials are key to achieve the efficiency requirements for BCWC applications. Yet, the election of an antenna topology to enhance some antenna performance parameters, can affect undesirably other parameters like, (I) increasing the dielectric thickness to enhance the antenna BW, reduces the wearers' comfortability and its integration in clothes, (II) the addition of shorted vias or probe feeds between layers to increase antenna BW, radiation efficiency or lower FTBR (Front To Back Ratio) values, yet, increasing the amount of soldering points, reducing its flexibility and the wearers' comfortability, and increasing the overall fabrication complexity, and (III) the design of complex radiating patches to enhance the antenna BW, to modify the radiation pattern and to generate multiple resonant frequency bands, yet, increasing the antenna performance susceptibility under body-centric conditions. Therefore, the challenge is to obtain the best trade-off between the antenna topology and on-body requisites.

According to the latest literature, the most suitable BCWC antenna types are MPA (Microstrip Patch Antenna), SIW (Substrate Integrated Waveguide) and PIFA (Planar Inverted F-Antenna). This work was centered on MPA topologies, since they provide light weight, low profile, and conformability to curved surfaces [23, 24, 25]. They also avoid the use of rigid shorted vias between different layers, reducing their fabrication complexity and increasing their flexibility, in comparison to SIW and PIFA topologies.

Nevertheless, MPAs have two main challenges. First, their inherent narrow BW, mainly caused by the limited overall thickness in clothes. Many solutions have been proposed to increase their BW, like modifying the MPA topologies, patch design, feeding technique, adding parasitic elements, slots, extra layers, etc... Yet, if these solutions are applied, their fabrication complexity increases leading to their second challenge, their low fabrication repeatability factor.

In this work, a MPA feeding technique was chosen named EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna). This feeding technique increases the MPAs' inherited narrow BW [26, 27, 28, 29], and achieves high gain and radiation efficiency values in desired directions [26, 30, 31, 32]. They are specifically suitable for off-body communications, compared to other MPA alternatives, as its ground plane reduces the negative effect of body proximity [32], and they avoid the use of rigid components or galvanic soldering between radiating patches and feed lines [33], which maximize the antennas' flexibility.

Nonetheless, EMCMPAs have to make several steps forward to be seriously considered as one of the best planar textile topologies for off-body communications. Therefore, in this work we are going to focus on two main EMCMPA challenges: 1) the lack of a specific design model, to obtain their initial dimensions, and 2) their high construction complexity [34, 35], where the alignment and attachment of the multiple layers must be precise, to obtain stable EM performance.

1.4 Thesis Overview

This thesis proposes a novel textile EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) design model for efficient BCWC (Body Centric Wireless Communication) applications, which has been rigorously validated using different materials and a reliable fabrication technique for multilayer textile antennas.

It does to validate the thesis statement that is formulated as follows: "modeling textile EMCMPAs with TL models can provide accurate and efficient

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antenna designs, and with a high fabrication repeatability if combined with innovative multilayer construction techniques.”

The research work behind this thesis is divided in three main objectives to validate the thesis statement.

- OB1: To present a state of the art of the most recent planar textile off-body communication antennas. Analyzing the advantages and disadvantages of different planar antenna topologies, construction processes, antenna measurements under diverse conditions, and describing the suitability of EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) topologies for planar off-body textile applications.
- OB2: To propose a combination of transmission line (TL) models as design instruments for EMCMPAs. Validating them in flat and bending conditions in an anechoic chamber, and assessing the influence of the human body on the antennas.
- OB3: To propose a new lab-scale construction process for textile EMCMPAs. Validating its construction repeatability and EM results stability.

They have been successfully fulfilled after facing multiple technical challenges like, choosing the antenna topology and feeding technique for planar off-body textile antennas; measuring the antennas under diverse conditions; designing, simulating and fabricating EMCMPAs using rigid and textile materials; and enhancing the working frequency band of the proposed antenna design model.

1.4.1 Background and Funding

The main research activities performed in this thesis were carried out at the Faculty of Engineering, University of Deusto - DeustoTech, Spain. Certain tasks were performed elsewhere, as shown in the list below:

- **University of Deusto - DeustoTech**

Most of the work for the thesis was carried out at this facility. All the office work and some laboratory work was performed, including writing conference papers, journal articles, and the thesis itself; and performing antenna designs, EM simulations, materials characterizations, construction of solid MPAs, and conducting basic EM antenna measurements, respectively.

- **Deusto Fablab**

This facility, also located within the University of Deusto, provided installations, equipment, knowledge and resources needed to manufacture most textile antenna prototypes.

- **Ghent University - imec, Dept. Information Technology**

This center, located in the city of Ghent, Belgium, provided the installations, equipment, knowledge and resources needed to accurately measure in their anechoic chamber all the antenna prototypes.

- **Tufts University - NANOLAB**

This laboratory, located in Boston, USA, provided the installations, equipment, knowledge and resources needed to 1) design, manufacture and measure textile metamaterials in the X- and W-band, 2) propose a new lab-scale fabrication technique for one-layer textile metamaterials or circuit designs, and 3) design, assemble and test a low-cost down-to 2 GHz anechoic chamber. This work has been performed during the 3-month international stay at Prof. Sameer Sonkusale's Nano Lab.

This thesis was supported by the Department of Education of the Basque Government by fully granting a Pre-Doctoral scholarship to perform the Ph.D. Degree. Furthermore, the Department of Education of the Basque Government also granted an additional financial support for a three-month research stay at Tufts University, Boston, USA.

1. INTRODUCTION

1.4.2 Structure and General Methodology

The methodology of the research work has followed several iterative antenna design-fabrication-measurement cycles with a continuous state of the art revision thorough each cycle. The very first state of the art study came-up with the confirmation of the opportunity to use EMCMPA topologies for BCWC applications. The next cycles evidenced the necessity for an EMCMPA design model and a reliable multi-layer antenna fabrication technique using specific textile materials. The next cycles validated the accuracy and repeatability of the proposed design model and fabrication process, respectively. Finally, the last cycles validated the proposed design model for a wider frequency range.

The three objectives of the thesis are achieved with the publication of three relevant articles with a high impact factor within the engineering/telecommunications research area. Moreover, three international conference papers have been presented during the research process to report the results of some iterations.

The structure of the document follows the fulfillment of the three main objectives with the three main publications:

Chapter 2 presents a broad state of the art examining the best planar off-body textile antenna designs and their performances, construction techniques using different materials, and antenna measurements under diverse conditions for textile applications.

Chapter 3 is centered on fast and reliable design models to yield the initial dimensions of EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna)s. First, preliminary antennas are designed and constructed using rigid and textile materials like FR4, threads and fabrics, to experimentally evaluate the most suitable materials and constructions techniques for EMCMPAs. It is concluded that they can be used for textile applications, obtaining low FTBR values, wider BW, less soldering, and good on-body EM performance, among others. Then, a combination of TL models to fully design EMCMPAs in the 2.45 GHz ISM band is performed. Finally, the proposed designed model is evaluated for a wider frequency range between 1 - 10 GHz.

Chapter 4 presents lab-scale fabrication processes to construct textile MPAs. First, thread-based design and fabrication considerations are presented for textile antennas. It is concluded that easier and more stable fabrication techniques were necessary for EMCMPAs. Therefore, a lab-scale construction process for multilayer textile antennas is performed that consists in combining an alignment and attachment method, using conductive and dielectric textile fabrics.

Each of these chapters summarizes the publications that are dedicated to that same aspect. Each publication is self-contained. Therefore, each of them includes its own state of the art section, proposes its research questions, and describes the particular strategy that it applies, which is tailored to the main research questions.

1.5 Publications

In this section, the publications are listed and briefly introduced.

1.5.1 PAPER I

PAPER I (appendix A) is titled "*Planar Textile Off-Body Communication Antennas: A Survey*". It has been published in the journal "*MDPI Electronics - Special Issue on Intelligent Antennas*". This review shows the latest research literature on planar textile fully grounded antennas for off-body communications, providing a novel design guide that relates key antenna performance parameters versus topologies, feeding techniques, conductive and dielectric textile materials, as well as the behavior under diverse measurement conditions.

1. INTRODUCTION

Ruben Del-Rio-Ruiz, Juan-Manuel Lopez-Garde, Jon Legarda, "Planar Textile Off-Body Communication Antennas: A Survey," *Electronics*, vol. 8, no. 6, 2019.

Electronics JIF (2019): 2.412

Q2 in Engineering, Electrical & Electronic.

1.5.2 PAPER II

PAPER II (appendix B) is titled "*Design and Performance Analysis of a Purely Textile Proximity Fed Microstrip Patch Antenna for On-Body Wireless Communications*". It has been presented in the "*2018 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting (APS/URSI 2018)*". This paper is a step forward in new designs of purely textile EMCMPAs with flexible and robust features, in the 2.45 GHz ISM band, for BCWC applications. Their performance is successfully validated in simulation and measurement, using different materials, obtaining satisfactory results.

Ruben Del-Rio-Ruiz, Juan-Manuel Lopez-Garde, Jon Legarda, "Design and Performance Analysis of a Purely Textile Proximity Fed Microstrip Patch Antenna for On-Body Wireless Communications," 2018 APS/URSI in Boston, USA between 8th-13th July 2018.

1.5.3 PAPER III

PAPER III (appendix C) is titled "*A Combination of Transmission Line Models as Design Instruments for Electromagnetically Coupled Microstrip Patch Antennas in the 2.45 GHz ISM Band*". It has been published in the journal "*IEEE Transactions on Antennas and Propagation (TAP)*". This paper provides initial values for all dimensions of the EMCMPA, with measured resonance frequency errors below 6%. The initial design is optimized in two subsequent phases to center the resonance frequency and to increase the BW, obtaining

measured resonance frequency errors below 0.6% and BW enhancements of more than 1.2 times the original ones, respectively. The model has been validated with antenna prototypes based on rigid and textile materials, exhibiting excellent results. Moreover, very stable on-body performance is obtained, with minimal frequency detuning when deployed on the human body.

Ruben Del-Rio-Ruiz, Juan-Manuel Lopez-Garde, Jon Legarda, Olivier Caytan, Hendrik Rogier "A Combination of Transmission Line Models as Design Instruments for Electromagnetically Coupled Microstrip Patch Antennas in the 2.45 GHz ISM Band," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 1, pages 550-555 2020.

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION JIF (2019): 4.371

Q1 in Telecommunications.

Q1 in Engineering, Electrical & Electronic.

1.5.4 PAPER IV

PAPER IV (appendix D) is titled "*Towards More Accurate Design Models for Electromagnetically coupled Microstrip Patch Antennas Between 1 and 10 GHz*". It has been presented in the "*2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting (APS/URSI 2020)*". This paper gives an analytical framework approach for EMCMPAs to more accurately predict the initial antenna dimensions between 1 - 10 GHz. The proposed EMCMPA design model is validated in simulation, where a coherent error is obtained between the desired and simulated resonant frequency.

Ruben Del-Rio-Ruiz, Juan-Manuel Lopez-Garde, Jon Legarda, "Towards More Accurate Design Models for Electromagnetically coupled Microstrip Patch Antennas Between 1 and 10 GHz," 2020 Virtual APS/URSI between 5th-10th July 2020.

1. INTRODUCTION

1.5.5 PAPER V

PAPER V (appendix E) is titled *"Design and performance analysis of a purely textile spiral antenna for on-body NFC applications"*. It has been presented in the *"2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP 2017)"*. This paper gives a step forward on purely textile spiral antenna designs with flexible and robust materials for on-body applications. Their performance is successfully validated with a real bracelet, and some design and construction considerations, using conductive threads, are offered for novel textile antennas.

Ruben Del-Rio-Ruiz, Juan-Manuel Lopez-Garde, Jon Legarda, Hendrik Rogier, "Design and performance analysis of a purely textile spiral antenna for on-body NFC applications," 2017 IEEE MTT-S (IMWS-AMP) in Pavia, Italy between 20th-22nd September 2017.

1.5.6 PAPER VI

PAPER VI (appendix F) is titled *"Reliable Lab-Scale Construction Process for Electromagnetically Coupled Textile Microstrip Patch Antennas for the 2.45 GHz ISM Band"*. It has been published in the journal *"IEEE Antennas and Wireless Propagation Letters (AWPL)"*. This paper introduces a novel lab-scale construction process for EMCMPAs that consists in combining an alignment method, based on laser-cut wood frames to perform accurate layer alignments, with a fast intralayer attachment method, based on thermally activated adhesive sheets. It is validated with a textile EMCMPA design, operating in the 2.45 GHz ISM band. It has been reproduced eight times, and the results confirm that the novel lab-scale construction process provides good performance repeatability for EMCMPAs.

Ruben Del-Rio-Ruiz, Juan-Manuel Lopez-Garde, Jon Legarda, Sam Lemey, Olivier Caytan, Hendrik Rogier "Reliable Lab-Scale Construction Process for Electromagnetically Coupled Textile Microstrip Patch Antennas for the 2.45 GHz ISM Band," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, issue 1, pages 153-157 2019.

IEEE Antennas and Wireless Propagation Letters JIF (2019): 3.726

Q1 in Telecommunications.

Q1 in Engineering, Electrical & Electronic.

2

*Whoever loves instruction loves
knowledge, but whoever hates
correction is stupid.*

Proverbs 12:1

STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

*The second chapter defines the current state of art on designs, materials and
fabrication techniques for planar fully-grounded off-body communications
textile antennas.*

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2. STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

This chapter summarizes the latest research done on off-body communications textile antennas (see Appendix A) [36]. The conclusions obtained in this chapter are the foundation to the following two chapters and the overall thesis.

2.1 Introduction

Fully textile antennas are an active area of research for BCWC (Body Centric Wireless Communications) applications, as long as they fulfill a complex trade-off between EM (BW, gain, efficiency, FTBR) and mechanical (bending, crumpling, compression, washing and ironing) requirements.

This state of the art is divided into three main areas of study: 1) planar antenna topologies for off-body communications, 2) EM and mechanical properties of textile materials and their fabrication techniques, and 3) antenna EM performance under diverse usage conditions. The antenna design models have not been mentioned in this chapter, for clarity reasons, since they are studied in Chapter 3.

The first section helped us to choose the most appropriate antenna topology for textile off-body applications, and showed the challenging areas to work on. The second section helped us to choose the best balance between well-known textile materials and their fabrication techniques. Finally, the third section gave us a perspective of the required EM antenna measurements, for them to be considered as textile antennas for smart clothing.

2.2 Antenna Designs and Performance

Fully grounded planar antenna designs have been broadly used for off-body communications, because of their high body isolation, low profile, robustness, ease of fabrication, and low cost [37, 38]. Nevertheless, the main drawback of these topologies is their usually narrow BW [26, 31, 39]. Many solutions have been proposed in the literature: (I) Increasing substrate thickness [40, 41, 42], (II) designing complex radiating patches [43, 44, 45], (III) adding slots to the radiating patch [40, 46, 47], (IV) including parasitic elements [31, 44, 48], (V)

inserting AMC (Artificial Magnetic Conductors) [26, 46, 48], (VI) using SIW (Substrate Integrated Waveguide) topologies [49, 50, 51], using PIFA (Planar Inverted F-Antenna) topologies [47, 52, 53], or (VII) using different feeding techniques [37, 47, 54].

It becomes clear that choosing the right antenna design is the first key aspect to obtain the desired EM and mechanical antenna performance. Therefore, this section is first divided in two main subsections where different antenna topologies and their feeding techniques are studied. Finally, a study to characterized the most suitable planar off-body textile antennas is reported.

2.2.1 Antenna topologies

There are three main planar antenna topologies for textile off-body communications: MPA, PIFA and SIW, as shown in Figure 2.1. The coaxial feeding technique has been used for sake of visual simplicity. Some general characteristics of these topologies are their lightweight, their stable EM performance under some bending conditions, their multi-band performance, and their flexibility to choose between linear or circular polarization.

MPAs consist of a radiating patch, a dielectric substrate, a ground plane, and a feeding point, as shown in Figure 2.1(a). The shape of the radiating patch (rectangular [37, 38, 39, 40, 47, 54, 55, 56, 57], circular [58, 59, 60, 61], square [31, 42, 46, 62], and others [26, 43, 44, 45, 47, 48]), combined with the feeding technique (type, number of feeds, and their positions) mainly determines the number of frequency bands, polarization, gain and efficiency of the antenna.

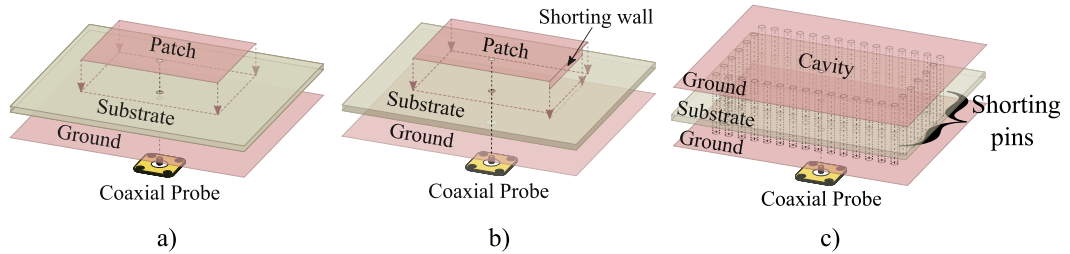


Figure 2.1: a) Microstrip patch antenna. b) Planar inverted F-antenna. c) Substrate integrated waveguide antenna.

2. STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

Textile MPAs' main disadvantage is their inherited low BW, due to the limited dielectric layer thickness. Therefore, several BW enhancement techniques are reported in the literature for MPA topologies: (I) The modification of the patch creating complex designs to combine different resonant frequency bands [26, 43, 45, 48], (II) the insertion of slots in the radiating patch [26, 46, 47, 56, 58, 63], (III) the addition of parasitic elements to the radiating patch layer [26, 43, 44, 47], and (IV) the modification of the feeding technique [31, 44, 47, 54, 64, 65].

PIFAs are an evolution of the MPA topology. They consist of a radiating patch, a dielectric substrate, a ground plane, a shorting wall, and a feeding probe, as shown in Figure 2.1(b) [47, 52, 53]. The shorting wall design and location, the feed line position, the thickness of the substrate, and the insertion of slots in the radiating patch are significant PIFA design parameters [52] to improve the BW and the multi-band antenna performance in comparison to conventional MPA [52, 53].

SIW antennas could be considered as an evolution of the PIFA topology. The single shorted area between the ground and the radiating patch in PIFAs, become periodic shorted pins of a closed shape on SIW topologies, as shown in Figure 2.1(c), creating a resonant cavity [32, 51, 66, 67]. The use of slots in the resonant cavity to enhance the BW or to obtain dual band antennas has been reported in the literature [49, 50, 67, 68, 69]. Finally, note that most SIW topologies found in literature for textile off-body communication antennas are fed with a coaxial probe, nevertheless, other feeding techniques have also been found like the microstrip line feed [68].

The main drawbacks of SIW antenna topologies are the cavity inherent limitations on the antenna size and thickness, and the lack of flexibility when constructing the cavity (conductive) walls by drilling vias. Low profile SIW cavity backed antennas have the disadvantage of narrow bandwidth for their compact sizes. Constructing textile SIW antennas using metal vias [49, 50, 51, 67, 70, 71] increases the fabrication cost and time, and decreases its flexibility. Yet, some thickness and flexibility [68] improvements have been achieved, where a 1 mm-thick SIW antenna was reported, decreasing by two-thirds the average thickness compared to other SIW antennas. Conductive threads

where sewn between the two ground layers to create the cavity, offering a better bending performance and an easier fabrication process.

2.2.2 Feeding techniques

There are several techniques available to feed EM signals to the radiating patch of a planar textile off-body antenna. The role of feeding is important to obtain good input impedance matching, wide antenna BW and low spurious radiation. The feeding techniques can be classified as contacting and non-contacting [72]. In the former one, the radiating patch is in direct contact with the feed line. The most common contacting feeding techniques are the microstrip line, microstrip line inset, CPW (Coplanar Waveguide) and the coaxial probe, as shown in Figure 2.2 and Figure 2.3(a), respectively. In the non-contacting feeding technique, the radiating patch is electromagnetically coupled with the feed line avoiding or reducing soldering points. The most common non-contacting feeding techniques are the electromagnetically (EM-CMPA or also commonly named as proximity coupled) and aperture coupled, as shown in Figure 2.3(b) and (c), respectively.

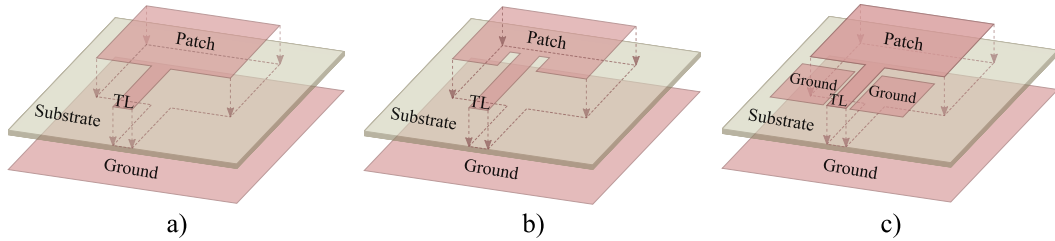


Figure 2.2: a) Microstrip line fed. b) Microstrip line inset fed. c) Coplanar waveguide fed.

The MPA topology has been chosen to illustrate the feeding techniques, because the latest literature has reported textile MPA topologies using all mentioned feeding techniques. Most textile PIFA and SIW topologies use the coaxial probe feeding technique [47, 49, 50, 51, 52, 53, 67, 69], and in few cases also the microstrip line feeding technique [68]. The only non-contacting feeding techniques reported in the literature for PIFA and SIW topologies have not used textile materials [73, 74, 75, 76, 77].

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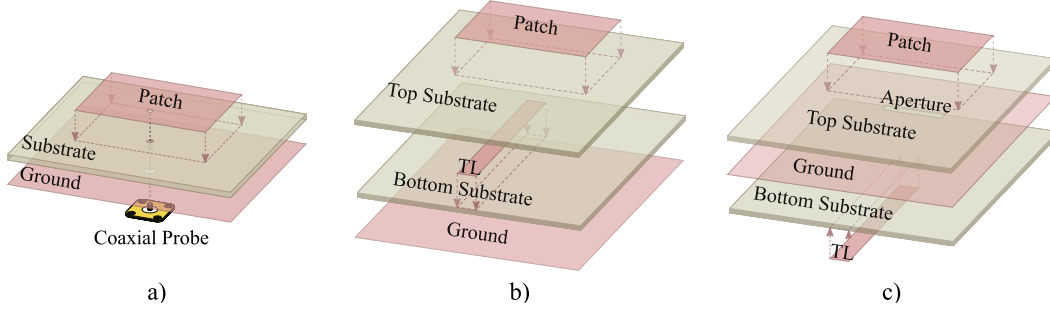


Figure 2.3: a) Coaxially fed microstrip antenna. b) Electromagnetically coupled microstrip antenna. c) Aperture coupled microstrip antenna.

Non-contacting feeding techniques provide a better textile performance than coaxial probes and microstrip fed lines, since there is no need for rigid pins going through different layers and in most cases the overall antenna size reduces.

The two basic fabrication schemes, EMCMPA and aperture coupled microstrip topologies, are shown in Figure 2.3(b) and (c), respectively. The former is composed (top to bottom) of a radiating patch, top substrate, TL (Transmission Line), bottom substrate, and ground layer. It's excited from the TL and electromagnetically coupled through the top substrate to the radiating patch. The TL is inserted between two substrate layers, the ground plane and partially the radiating patch, where any radiation from the feeding line is shielded and potentially re-radiated by the patch, leading to a good cross-polarization [27] and a good body isolation due to its full-ground plane. This topology places the radiating patch further away from the ground plane, which leads to enhanced BW and radiation efficiency values, while the feed line is closer to the ground plane to reduce its parasitic radiation. The latter is composed (top to bottom) of a radiating patch, top substrate, ground layer with an aperture, bottom substrate, and TL. It is not ideal for off-body communications since the TL is not isolated from the body [78, 79]. This creates a non-desired energy absorption and modifies the radiation pattern due to the high permittivity and losses of human skin tissue.

2.2 Antenna Designs and Performance

2.2.3 Study of the best textile antenna overall performance

The main EM antenna parameters reported to characterize textile antennas, in this study, are: (I) -10 dB $|S_{11}|$ BW (%); (II) the maximum measured gain (dBi); (III) the total radiation efficiency (%); (IV) the FTBR (dB); and (V) the SAR (W/kg).

Table 2.1: Textile antennas' designs vs. EM performances

Ref.	k	Antenna Design					EM Antenna Performance				
		Overall Size (λ) $W \times L \times h$	Feed Type	Patch Type	Topol.	BW Enhac.	Centr. Freq. (GHz)	Meas. BW (%)	Meas. Gain (dBi)	Meas. Eff. (%)	Meas. FTBR (dB)
[52]	100	$0.12 \times 0.32 \times 0.04$	Coaxial	Rectang.	PIFA	None	2.48	*44.7	1.53	77.23	*6
[52]	72.3	$0.12 \times 0.31 \times 0.04$	Coaxial	Rectang.	PIFA	Slot	2.47	*47.8	1.74	80.52	*4
[37]	61	$0.50 \times 0.61 \times 0.01$	Proxim.	Rectang.	MPA	None	2.45	15.5	0.33	-	23
[37]	35.1	$0.52 \times 0.64 \times 0.01$	Proxim.	Rectang.	MPA	None	2.45	11.8	0.41	-	21
[26]	26.9	$0.64 \times 1.07 \times 0.04$	Coaxial	Complex	MPA	Both	2.20	52	3.38	-	21
[44]	23.2	$0.66 \times 0.87 \times 0.05$	CPW	Octagone	MPA	Paras.	9.50	*108.8	**7.2	-	10
[53]	18.9	$0.22 \times 0.29 \times 0.04$	Coaxial	Triangular	PIFA	Slot	2.14	15.2	-	70.6	**5
[43]	18.9	$1.06 \times 1.16 \times 0.04$	Coaxial	Complex	MPA	Paras.	5	96.4	6.75	75	14
[47]	14	$0.32 \times 0.32 \times 0.03$	Proxim.	Rectang.	PIFA	None	2.45	*3.3	3.1	-	*15
[58]	13.2	$0.56 \times 0.56 \times 0.02$	Coaxial	Circular	MPA	Slot	2.45	3.3	5.02	**63.5	*13
[46]	10.5	$0.71 \times 0.71 \times 0.02$	Coaxial	Square	MPA	Slot	2.21	*14.3	2.5	40	*12
[47]	7.93	$0.63 \times 0.63 \times 0.05$	Proxim.	Rectang.	MPA	Slot	4.8	10	8	-	*30
[50]	7.57	$0.51 \times 0.51 \times 0.03$	Coaxial	Complex	SIW	Slot	2.45	4.8	4.2	81	*24
[51]	6.39	$0.80 \times 0.73 \times 0.02$	Coaxial	Rectang.	SIW	None	2.4	6.4	2.9	**55	*22
[49]	5.12	$0.55 \times 0.45 \times 0.03$	Coaxial	Complex	SIW	Slot	2.45	4.9	4.1	72.8	*14
[69]	4.82	$0.44 \times 0.75 \times 0.07$	Coaxial	Rectang.	SIW	Slot	5.35	*20.2	6.66	90	8
[68]	3.11	$0.79 \times 1.41 \times 0.02$	Micr.	Rectang.	SIW	Slot	5.8	*4.3	-	-	*18
[63]	3.07	$0.94 \times 0.94 \times 0.02$	Micr.	Rectang.	MPA	Slot	5.91	9.3	-2.8	17.2	9
[47]	2.44	$0.70 \times 0.70 \times 0.06$	Proxim.	Rectang.	MPA	None	5.35	*2.8	7.8	-	*20
[67]	2.32	$0.59 \times 0.38 \times 0.03$	Coaxial	Rectang.	SIW	Slot	2.45	*5.1	5.28	73	*5
[45]	1.72	$1.42 \times 1.42 \times 0.03$	Coaxial	Complex	MPA	None	2.49	17.1	-0.3	15.2	*17
[40]	0.91	$0.80 \times 0.80 \times 0.10$	Coaxial	Rectang.	MPA	Slot	5.1	*13.6	6.2	**75	*8
[61]	0.36	$0.32 \times 0.32 \times 0.01$	Coaxial	Circular	MPA	None	2.46	6.5	-7.2	24	*0

* Calculated from graph; ** Simulated result.

Table 2.1 compiles the most relevant research works done so far, to ease future designs of fully grounded textile antennas for off-body communications. A figure of merit has been used, considering the importance of having a high BW, a high FTBR, and a low antenna volume. The measured radiation efficiency of the antennas has not been considered, because of the lack of information in reported literature. Nevertheless, it should be another feature to take into account in future works. The figure of merit has been calculated using (2.1), which has been normalized to 100 in Table 2.1.

2. STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

$$k = \frac{BW(\%) \cdot FTBR(dB)}{volume(\lambda^3)} = \frac{\left(\frac{f_2-f_1}{f_c}\right) \cdot (G_f - G_b)}{W \cdot L \cdot h}, \quad (2.1)$$

where f_1 , f_2 and f_c are the minimum, maximum, and central frequencies, respectively, of an antenna with a return loss below -10 dB. G_f and G_b are the antenna gain values at its peak (bore-sight) and its opposite direction, respectively.

The overall size (λ) of the antennas has been calculated using the lowest frequency within the -10 dB $|S_{11}|$. The overall volume of the antenna has been calculated ($W \cdot L \cdot \text{Thickness}(h)$) (λ^3). The measured gain, as shown in Table 2.1, represents the maximum gain in any given direction. Most FTBR values have been obtained from the measured radiation pattern graphs, since some literature reports just illustrated the graphs, but did not give FTBR values numerically. Most literature offered measured BW results, nevertheless, there was a lack of measured antenna gain and radiation efficiency results. There are some publications that reported more than one relevant antenna implementation, in such cases, each of them has been represented in separate rows. All measured results illustrated in Table 2.1 have been obtained in free-space and flat surface scenarios. For antenna measurements under diverse conditions see Section 2.4.

The figure of merit k shows that the combination of the highest BW, the highest FTBR values, and the smallest antenna volume can be achieved using PIFA and EMCMPA topologies. PIFAs with slots and fed by a coaxial probe, report excellent BW versus volume results. EMCMPAs report excellent FTBR values versus volume results. Note that a high FTBR value, in textile off-body communication antennas, is key to obtain a low SAR and therefore, a stable antenna EM performance when on-body. SIW topologies have reported a low k in this study, because their volume is large compared to their BW. Nevertheless, their radiation efficiency and FTBR values are excellent for off-body communications. PIFAs' main drawbacks are their high substrate thickness and low FTBR values, which makes this topology complex to embed in garments. Nevertheless, their wide BW and small overall surface ($W \cdot L$) give

2.3 Antenna fabrication Techniques

them a good k value. Microstrip topologies have reported inconsistent results, nevertheless, EMCMPAs show thin substrates and excellent FTBR results.

According to the latest literature on fully grounded planar textile antennas, the best topologies for each antenna's EM parameter are as follows: (I) The highest measured impedance BW is reported on coaxially fed antennas with complex radiating patch designs, including parasitic elements and slots [26, 43]; (II) the highest gain levels are reported on complex rectangular radiating patch EMCMPAs and coaxially fed SIW topologies [43, 47, 69]; (III) the highest measured radiation efficiency levels are reported on SIW and PIFA topologies with slots [49, 52, 69]; (IV) the highest FTBR results are reported on EMCMPAs and coaxially fed microstrip patch antenna designs [37, 47, 50, 53, 57, 59]; and (V) the lowest SAR values are reported on coaxially fed slotted patch antenna designs [40, 40, 46, 48, 56, 58, 60].

It is concluded that all three, MPA, PIFA and SIW topologies have strengths in different fields. Nevertheless, in this study, EMCMPAs have been chosen for four main reasons: (1) they avoid the use of coaxial probes or vias, improving the antennas' mechanical properties, reducing spurious radiation, and avoiding soldering points, (2) they achieve high gain and FTBR values, (3) they allow an independent optimization of the feeding mechanism and the radiating patch, and (4) they are one of the best topologies according to the figure of merit k proposed in this study. Yet, their fabrication process needs to be more precise due to the required multilayer alignment and attachment techniques [37, 44, 54, 65]. Therefore, a broad study on textile antenna fabrication techniques was necessary to find dielectric and conductive textile materials that would make the assembly of EMCMPAs simpler.

2.3 Antenna fabrication Techniques

The right selection of antenna topologies and feeding techniques are the first steps to achieve the desired EM performance of a fully grounded planar antenna. However, in textile applications, the materials and the fabrication techniques also play a crucial role to obtain the desired EM and mechanical antenna performance.

2. STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

2.3.1 Textile Materials

A state of the art on materials for textile antennas can be found in [80]. Nevertheless, a brief enumeration of the latest reported dielectric and conductive materials is also given in this section:

The main reported dielectric substrates to assemble planar textile antennas are: (I) Felt [26, 40, 42, 43, 44, 46, 48, 51, 52, 53, 55, 56, 59, 61, 67, 68], (II) foam [31, 47, 49, 50, 69], (III) denim [37, 54, 55, 57], (IV) leather [45, 60, 62], (V) neoprene [62], and (VI) PDMS (Polydimethylsiloxane) [58].

The main reported conductive textile fabrics to assemble planar textile antennas are: (I) PCPTF (Pure Copper Polyester Taffeta Fabric) [37, 39, 49, 50, 52, 54, 62, 69], (II) Silver-coated nylon ripstop fabric [47, 58], (III) Nickel-copper polyester ripstop fabric [38, 57], (IV) ShieldIt Super fabric [26, 40, 43, 44, 46, 48, 51, 52, 55, 56, 67], (V) Shieldex Zell [45, 59, 60, 61, 68], and (VI) Shieldex NoraDell [42].

Conductive threads have also been reported for PIFA and SIW topologies' shorting vias, and for fully embroidered antennas: (I) Metallic wires [40], (II) 92 ShieldEx [60, 61, 68], (III) Liberator 20 [42], and (IV) ShieldEX 117f17 1-2 ply [63].

2.3.2 General Textile Antenna Fabrication Aspects

The fabrication of textile antennas can be divided in three main areas: 1) selected type of conductive materials (since the dielectric materials are commonly the same), 2) selected cutting technique for the conductive and dielectric materials, and 3) selected antenna assembling technique. Selecting the correct techniques in each of the three areas is key to obtain good EM and mechanical performance.

Regarding the first area, textile antennas can be classified as thread-based, fabric-based and ink-based antennas [81]. In this thesis, the fabric-based technique was selected for all conductive layers, because it facilitates and accelerates the manufacturing process, and does not require expensive machines or tools to create the conductive patterns. Yet, in future works the EM and

2.3 Antenna fabrication Techniques

mechanical performance of the proposed EMCMPAs could be investigated using the thread- and ink-based techniques.

The cutting technique for thread-based and ink-based conductive materials is not key, since the conductive layer does not have to be cut, and the accuracy of the dielectric layer dimensions do not usually affect the EM performance of the antennas. Yet, the cutting technique of fabric-based conductive materials is an important aspect to obtain the desired EM performance of the antennas. Two main manufacturing methods are used for shaping textile fabrics: hand- [37, 40, 43, 44, 46, 49, 51, 52, 54, 56, 58], and machine-cutting [67, 82, 83, 84]. The resolution achievable using hand-cutting is approximately 1 mm, which could even be less accurate depending on the selected fabric. Therefore, hand-cutting is not a recommended solution for complex designs. In the other hand, using a laser- or blade-plotter machine achieves a maximum resolution of approximately 0.05 mm [83]. Furthermore, these techniques have high fabrication repeatability factors, and they are ideal for large-scale productions. In this thesis, the initial textile antenna prototypes were cut hand-made to validate the antenna topology concepts. Afterwards, the laser-cutting technique was selected. In future works, the blade-cutting technique using a plotter machine could be investigated to study the cutting differences between technologies.

The antenna assembling technique is another important aspect when fabricating textile antennas, especially for multilayer topologies, like EMCMPAs. Three main assembling methods have been reported, glues, sewing and adhesive sheets. Each exhibits pros and cons, and selecting the best approach is usually a trade-off between EM and mechanical performance. The application of glues on fabrics is complex, since it can easily increase its thickness and modify the dielectric properties of the antenna's substrates in a nonuniform distribution. Attaching the antenna layers using the sewing technique also modifies the dielectric properties of the antennas' substrates where the stitches are performed, and the thickness of the antennas become nonuniform, because of the pressure applied by the stitches. The third assembling technique is based on the use of adhesive sheets, which can be uniformly deposited as a thin mesh and then thermally activated to assemble the antennas' layers.

2. STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

In this thesis all three assembling techniques have been investigated. Yet, the adhesive sheets technique has reported the best EM and mechanical results, combined with an easier and faster textile manufacturing process.

2.3.3 Fabrication Aspects for Textile EMCMPAs

The main factors when fabricating EMCMPAs have been summarized as follows: (I) the attachment of RF connectors to the textile antennas, (II) the multilayer attachment, (III) the layer alignment, and (IV) the different fabric cutting techniques.

(1) The attachment of an RF connector is necessary to evaluate the EM performance of the antennas [40, 85]. SMA (SubMiniature version A) straight RF connectors [43, 44, 47, 50, 51, 52, 58] and U.FL (Hirose Ultra-small surface mount coaxial) connectors [31, 69] have been mainly used for antenna evaluations.

The attachment between connector and conductive layers has been performed using galvanic soldering or gluing. Galvanic soldering increases the stiffness of the feeding area making it less flexible, but it provides better conductivity than most glues [38, 42, 43, 44, 53, 55]. High Frequency Silver Epoxy [31, 40, 47, 52, 58, 60, 61, 63, 68] provides a low resistivity of $<0.001 \text{ ohm} \cdot \text{cm}$ and higher flexibility rates, making it suitable for wearable antennas and fabrication processes. Nevertheless, EMCMPAs only required a soldering point at the SMA connector, for antenna characterization purposes.

(2) The over-stacking of conductive and dielectric fabrics is the most common antenna fabrication method for EMCMPAs. The layer attachment is performed using dielectric threads (sewing) or adhesives [37, 42, 52, 54, 57, 59, 60, 61, 65, 68]. The sewing of the antennas can be done hand-made [59, 68] or machine-made [37, 42, 54]. The two main reported adhesive techniques, to attach the antenna layers, are the thermally activated adhesive sheet-glue [49, 50, 62, 69] and the embedded adhesive on the conductive layer [43, 51, 52, 55, 56, 57]. Other gluing techniques have been reported, like conventional glues [39, 47, 62], bi-adhesive tape [31], PDMS [58], and spray adhesive [38]. According to the latest literature on off-body communication

2.3 Antenna fabrication Techniques

antennas, and to the best of our knowledge, evaluations of the permittivity and thickness variations that are introduced by the thermally activated adhesive sheets or the embedded adhesives have not been reported. Therefore, a brief study of the dielectric properties of a thermally activated double-sided adhesive sheet [86] is implemented. The measurements are performed using Agilent N5242A PNA-X Microwave Network Analyser, combined with the Agilent 85070E Dielectric Probe kit. Felt and cotton substrates are measured using one, two, and three layers of adhesive sheets, thermally attached to each of the textile fabrics. Two different materials are tested to obtain a better assurance of the adhesive sheet dielectric characteristics. The obtained results are shown in Fig. 2.4.

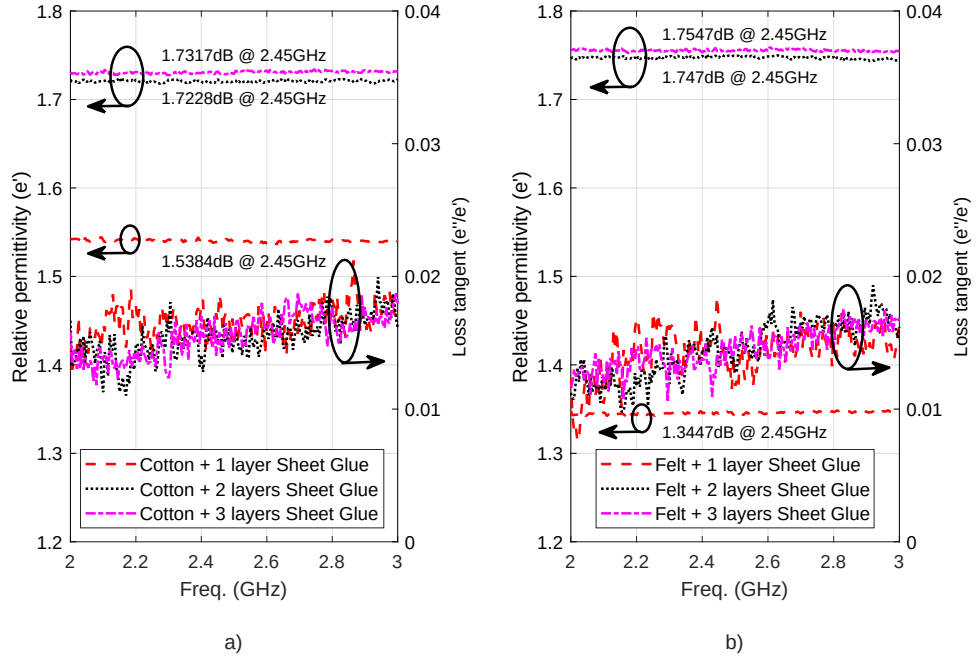


Figure 2.4: Relative permittivity and loss tangent of the adhesive sheet study. a) Cotton textile material. b) Felt textile material.

The loss tangent of both the adhesive sheets and the dielectric fabrics remain the same for each of the studies. In the other hand, the relative permittivity increases, when adding adhesive layers. The permittivity of the adhesive sheet stabilizes at 1.74-1.75 when two or more layers of adhesive sheet are applied on both dielectric substrates. Nevertheless, in simulation

2. STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

one adhesive sheet layer has been added with the corresponding relative permittivity and loss tangent shown in Fig. 2.4. It is concluded that the use of thermally activated double sided adhesive sheets [86] modify the relative permittivity of the fabrics. Therefore the EM properties of the antennas could shift between simulated and measured results, if it is not considered. It is also concluded that the loss tangent of the double sided adhesive sheet does not reduce the radiation efficiency of the antenna.

(3) There is a lack of systematic layer alignment techniques for multilayer antenna topologies, where the positioning of each layer is key to obtain the desired EM performance. Small misalignments between layers can shift the resonance frequency of the antennas, and reduce the radiation efficiency considerably. Therefore, special attention on the layer alignments for EMCMPAs has to be given.

(4) The cutting technique of the materials is another key factor for the fabrication accuracy and repeatability of EMCMPAs, especially if complex antenna shapes are designed. The main two cutting techniques are: (I) hand-made, using scissors, a blade cutter, or a scalpel [37, 40, 43, 44, 46, 49, 51, 52, 54, 56, 58]; and (II) laser-cut [38, 47, 50, 62, 63, 67, 69]. The hand-made fabrication method has been mainly used for simple antenna designs to avoid major fabrication errors [40, 43, 52]. But fabrication tolerance studies have been reported [52], and according to the latest literature, the majority of the antennas' EM performance differences between simulated and measured results have been attributed to them [43, 44, 46, 52, 54, 58]. However, laser-cutting machines have demonstrated their accuracy [38, 47, 50, 62, 69] and repetitiveness [38, 47, 69]. It reduces misalignments between slots and radiating patches [69], they increase and simplify fabrication procedures [69], and they allow the removal of single layer areas [63]. According to the literature, the main conductive fabrics that have been laser-cut are: (I) PCPTF [50, 62, 69], (II) Silver-coated nylon ripstop fabric [47], (III) Nickel-copper polyester ripstop fabric [38], and (IV) ShieldIt Super fabric [67].

2.4 Antenna Measurements under Diverse Conditions

The performance of textile antennas designed for off-body communications depend not only on ideal (flat surface, free-space) measurements, but also on-body, under bending conditions, under diverse compression levels [39], diverse crumpling shapes [87], and diverse humidity levels [69]. The antennas' performance can also vary significantly from that in free-space scenarios [40, 43, 48, 49, 51, 58, 68]. Such differences are mainly due to: (I) The ground plane size [26, 47, 48, 49, 50, 51, 52, 53, 58, 60], (II) the distance gap between the body and the antenna [26, 52, 53, 56], (III) the antenna orientation [26, 53, 56, 58], (IV) the antenna location on the body (chest [40, 43, 44, 47, 48, 49, 50, 51, 52, 53, 56, 61, 69], arm [26, 40, 44, 47, 51, 54, 58, 69], forearm [40, 47, 61], back [43, 52, 53], and thigh [40]), and (V) the bending radius [38, 40, 46, 47, 48, 49, 51, 57, 58, 59, 61, 67, 68, 69].

Typical consequences of on-body measurements are the impedance matching deterioration [40, 44, 46, 48, 49, 50, 51, 52, 53, 54, 56, 61, 69], the resonant frequency shifting [40, 44, 46, 49, 50, 52, 53, 54, 56], the radiation performance degradation [42, 48, 49, 50, 51, 52, 53, 56, 61, 69], and over the threshold SAR values [40, 46, 48, 49, 50, 51, 52, 53, 56, 67].

According to the latest literature for off-body communication textile antennas, different antenna measurements under diverse conditions have been reported, as shown in Table 2.2. The main parameters reported from the latest literature to measure textile antennas under diverse conditions are: The distance gap between the body model or phantom and the antenna under test, the bending radius of the antenna, the resonance frequency, the body model or phantom chosen to obtain on-body results, the antenna feeding technique and topology, and the antennas' reported EM results (BW, maximum gain, radiation efficiency, and FTBR), in flat free-space and on-body scenarios.

The main conclusions from this study are as follows: (I) The distance gap between the body model or phantom and the antenna under test is generally of 2 mm [49], 5 mm [61, 67] or 10 mm [46, 56, 58]. Computer aided

2. STATE OF THE ART ON PLANAR TEXTILE ANTENNAS

Table 2.2: Antenna Measurements under Diverse Conditions

Ref.	Measurement Setup				Design		BW (%)			Gain (dBi)		Eff. (%)		FTBR(dB)	
	Dis. Gap (mm)	Bend. Radii (mm)	Centr. Freq. (GHz)	Body Model	Feed Type	Topol.	Flat Free-Space	Flat Body	Bend Free-Space	Flat Free-Space	Flat Body	Flat Free-Space	Flat Body	Flat Free-Space	Flat Body
[49]	1	40	2.45	Phantom	Coax.	SIW	5	4	5	4.1	4.4	73	61	13.5	14
[49]	1	40	5.8	Phantom	Coax.	SIW	5	5	7	5.8	5.7	86	69	12.5	13.5
[50]	2	-	2.45	Phantom	Coax.	SIW	5	5	-	4.2	3.8	81	81	24	28
[46]	10	20	2.21	Phantom	Coax.	MPA	14	14	13	2.5	-	40	-	12	12
[46]	10	30	5.5	Phantom	Coax.	MPA	22	17	13	4	-	40	-	12	12
[43]	5	-	5	Phantom	Coax.	MPA	96	93	-	6.8	6.3	45	45	14	20
[67]	5	30	2.45	Hugo	Coax.	SIW	5	5	5	5.28	5.35	73	74	5	-
[58]	10	45	2.45	Phantom	Coax.	MPA	3	4	4	5.02	4.16	-	-	13	16.5
[58]	10	45	5.8	Phantom	Coax.	MPA	4	4	4	3.66	4.34	-	-	11	15.2
[68]	5	50	5.8	Duke	Micr.	SIW	4	4	-	-	3.12	-	38	18	17
[69]	-	-	5.8	-	Coax.	SIW	16	16	15	6.64	-	90	-	8.5	20
[47]	0	30	4.8	Phantom	Prox.	MPA	10	9	11	8	7.55	-	-	30	-
[53]	1	-	2.14	Hugo	Coax.	PIFA	15	13	-	-	-	71	40	-	-
[53]	1	-	5.28	Hugo	Coax.	PIFA	11	10	-	-	-	73	53	-	-
[40]	5	-	5.1	Hugo	Coax.	MPA	14	14	-	6.2	-	-	-	8	-
[40]	5	-	2.45	Hugo	Coax.	MPA	2	3	-	-3.8	-	-	-	-	-
[51]	5	40	2.4	Phantom	Coax.	SIW	6	7	-	2.9	-	-	-	22	-
[51]	5	80	5.65	Phantom	Coax.	SIW	12	12	-	5	-	-	-	10	-
[48]	15	-	2.44	Hugo	Coax.	MPA	4	2	-	5	-	-	-	-	-
[38]	-	43.2	2.44	-	Micr.	MPA	2	2	2	-	-	-	-	-	-
[42]	10	-	2.4	Phantom	Coax.	MPA	5	6	-	0	1.8	57	42	-	-
[57]	-	28.5	2.4	-	Coax.	MPA	5	6	5	-	3.8	-	-	23	-

simulations have been reported with three layer phantoms, or voxel models (Hugo [56, 67] and Duke [60, 61] models, among others), while real bodies [40, 43, 46, 48, 49, 50, 51, 52, 53, 54, 69] or phantoms [42, 58, 59, 61, 68] have been used for on-body measurements, based on the IEEE C95.1 standard. (II) The evaluation of the antennas under bending is generally performed using a solid cylinder. The bending radius reported in this literature varies from a small wrist (20 mm) [46] to the upper side of a leg (80 mm) [51]. The EM performance under bending conditions has been reported using one radius [49, 58, 67], two radii [38, 47, 57], or three radii [46, 69]). The bending of the antenna under different antenna axes has also been reported measuring one axis [38, 47, 67, 69], two axes [57, 58], or three axes [49]. The most common measured axes are x-axis, diagonally, and y-axis. (III) It has been found that the maximum gain of the antennas tends to decrease when they are on-body [43, 47, 49, 50, 58]. And (IV) the antenna efficiency also decreases when they are on-body due to the radiation absorption produced by the body [42, 49, 53, 61]. (V) The FTBR values of the antennas increase when they are on-body, because it acts as a reflector [43, 49, 50, 58, 69].

Note that the only parameter measured under bending conditions, shown in Table 2.2, is the BW. The rest of the parameters under bending conditions

were not shown because of the lack of information from the reported literature.

2.5 Conclusions

Planar textile antennas for off-body communications have been mainly designed using MPA, SIW, and PIFA topologies with full ground planes, to achieve the desired EM performance on free-space, on-body and under bending conditions. These antenna topologies have used a variety of feeding techniques and design modifications, like the insertion of slots, resonant cavities, or the addition of parasitic elements, to obtain the desired mechanical and EM performance.

All antenna topologies have demonstrated some advantages for textile off-body communications applications, yet, in this work EMCMPAs are chosen for the following reasons: (i) the widening of MPAs' inherent narrow BW [26, 27, 28, 29], (ii) the increase of their gain and FTBR values, decreasing the degradation of their normal operation when on-body [26, 30, 31, 32], (iii) the avoidance of coaxial probes or vias, improving the antennas' comfortability and aesthetics, reducing spurious radiation, and avoiding soldering points, and (iv) according to the figure of merit k , proposed in this section, they are one of the best topologies overall for planar textile off-body communications.

Nevertheless, EMCMPA topologies have two main drawbacks: the lack of a specific design model to obtain the initial dimensions of EMCMPAs (see Chapter 3) and their high fabrication complexity [34, 35], where the alignment and attachment of multiple layers must be precise, to obtain stable EM performance (see Chapter 4).

Finally, most literature offers simulated and measured antenna BW and maximum gain results on free-space scenarios, nevertheless, there is a lack of measured FTBR and radiation efficiency results. It also has not been reported on-body and under-bending antenna measurements in most reported literature.

3

*The simple believes everything,
but the prudent gives thought to
his steps.*

Proverbs 14:15

DESIGN MODEL FOR ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCH ANTENNAS

The third chapter summarizes all the proposed EMCMPA designs.

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3. DESIGN MODEL FOR ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCH ANTENNAS

3.1 Introduction

This chapter covers all the contributions realized around the modeling of textile EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna)s. The first contribution (see Appendix B) introduces the initial design, construction and measurements of textile EMCMPAs. This work shows the necessity to improve the analytical models for EMCMPAs, to obtain the initial dimensions faster and more accurately. The second contribution (see Appendix C) is focused on validating a novel EMCMPA design model for the 2.45 GHz ISM band based on a combination of TL models. The reported results improve the state of the art and shows the great potential to cover other applications. Therefore, the last contribution (see Appendix D) suggests improvements to the proposed model to obtain more accurate designs between 1 and 10 GHz.

3.2 Initial EMCMPA Designs

MPAs are lightweight, robust, low profile, easy to fabricate, and easily conformable to different surfaces. The main disadvantage of conventional MPAs is the limited BW. EMCMPAs provide an inherent larger BW, low spurious radiation, low FTBR and less soldering points, making this MPA feeding technique suitable for wearable antennas, as discussed in Chapter 2.

As shown in Fig. 3.1, the EMCMPA is composed (top to bottom) of a radiating patch ($W_p \times L_p \times h_{cond}$), a first dielectric layer ($W_{sub} \times L_{sub} \times h_{sub}$), a feed line ($W_{line1} \times L_{line1} \times h_{cond}$), a second dielectric layer ($W_{sub} \times L_{sub} \times h_{sub}$), and a ground plane ($W_g \times L_g \times h_{cond}$).

In this contribution (see Appendix B), five EMCMPAs are presented for the 2.45 GHz ISM band, as shown in Table 3.1. First, three reference antennas are designed, simulated and constructed using well-known rigid FR4 materials, to verify the good relation between computer aided CST (Computer Simulation Technology) and measurement results. Afterwards, three textile EMCMPAs are constructed using PCPTF (Pure Copper Polyester Taffeta Fabric) [88] for the conductive layers, and flannel, cotton and felt for the dielectric layers.

3.2 Initial EMCMPA Designs

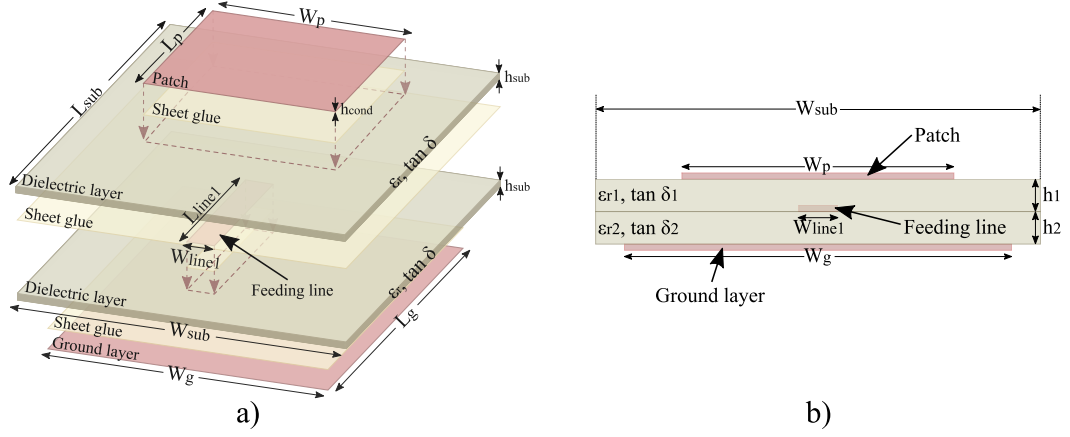


Figure 3.1: a) Perspective view of the EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) topology. For clarity, all antenna layers have been separated and labeled at the side. b) Side view of the EMCMPA.

Table 3.1: Initial EMCMPA prototypes

Name	substrate	Cond. layers	$W_p(\text{mm})$	$L_p(\text{mm})$
A001	FR4	Anneal copper	36.1	27.1
A002	FR4	Anneal copper	36.1	25.3
A003	FR4	Anneal copper	37.1	28.1
A004	Flannel	PCPTF [88]	52.4	45.3
A005	Cotton	PCPTF [88]	57.3	50.3
A006	Felt	PCPTF [88]	58.9	53.2

The initial dimensions for the radiating patch have been approximately obtained from well-known MPA design formulae [17]. The TL, ground plane and dielectric layer dimensions have been optimized using computer aided CST to achieve a reflection coefficients below -10dB in the desired frequency band.

In the first two rigid EMCMPA prototypes, mismatching results were obtained between simulation and measurement, as shown in Fig. 3.2.

It was concluded that there were four main reasons for the mismatches. First, the dimensions of the antennas were incorrect. The PCB (Printed Circuit Board) prototyping machine [89] took extra annealed copper from each conductive layer, making the antennas resonate at a higher frequency. Second, in the process of removing undesired annealed copper, it was also removed FR4

3. DESIGN MODEL FOR ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCH ANTENNAS

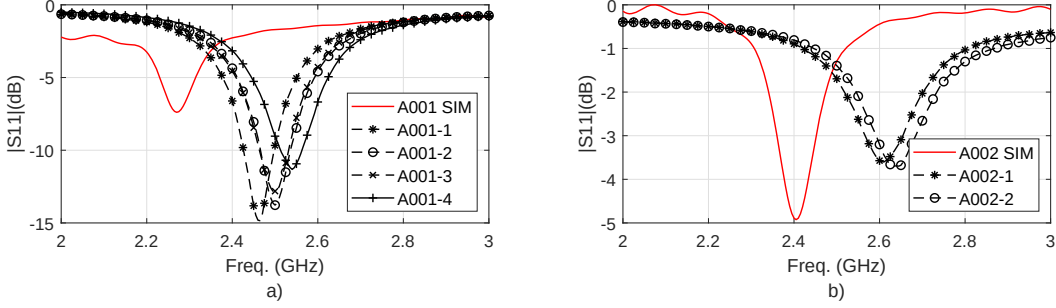


Figure 3.2: Initial Reflection coefficient results of the a) A001 and b) A002 EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) prototypes.

dielectric material, leaving air-gaps, as shown in Fig. 3.4, and reducing the overall relative permittivity of the dielectric layers. The calibration, in the z-axis, of the PCB prototyping machine determines the thickness of the extra air-gaps, therefore the PCB prototyping machine and the calibration accuracy are key to reduce the undesired air-gaps. With some PCB boards, like Rogers 4003C, it is possible to peel-off the annealed copper by hand, keeping the exact PCB dielectric layer thickness and avoiding the creation of extra air-gaps. Third, the FR4 permittivity set in the computer aided CST design was inaccurate, in the 2.45 GHz ISM band. After performing the characterization of the FR4 with the Agilent Dielectric Probe Kit [90], the permittivity was found to be between 4 and 4.4, in the 2.45 GHz ISM band. And fourth, too much galvanic soldering was added between the SMA connector and the TL, creating an extra air-gap on the TL, which modified the EM performance of the antenna.

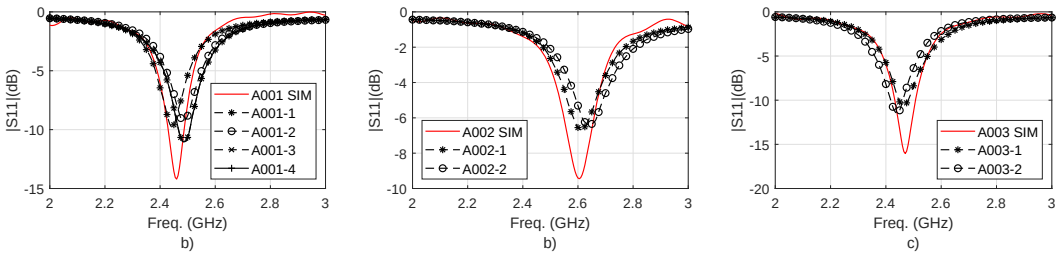


Figure 3.3: Optimized Reflection coefficient results of the a) A001, b) A002 and c) A003 EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) prototypes.

3.2 Initial EMCMPA Designs

The third rigid EMCMPA prototype demonstrated, that with these modifications, the results between simulation and measurement improved, as shown in Fig. 3.3. The simulation and soldering points of the first two prototypes were also modified obtaining an improvement between simulation and measurements.

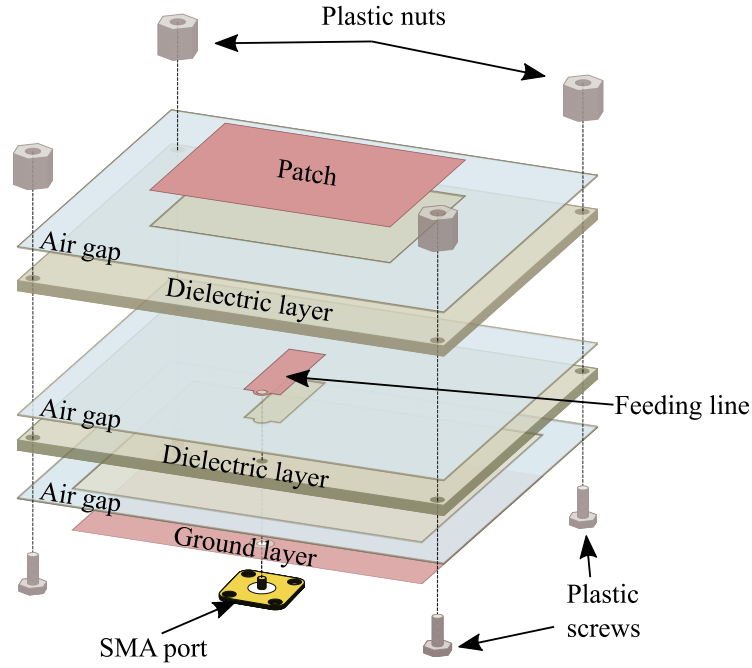


Figure 3.4: Perspective view of the rigid EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) assembling process. For clarity, all antenna layers have been separated and labeled at the side.

All rigid EMCMPAs have been assembled using plastic screws and nuts, as shown in Fig. 3.4 and 3.5. Four holes, one per corner, have been drilled in each FR4 layer, using a PCB prototyping machine [89]. The plastic screws go through the holes to align all EMCMPA layers, and the plastic nuts help keep the layers tightly secured to each other. For antenna characterization purposes, a SMA connector has been inserted from the ground plane, through the bottom dielectric layer, to feed the TL. The three rigid prototypes have been assembled, as shown in Fig. 3.5.

Next, two different textile EMCMPAs were designed, simulated, and constructed, using cotton and flannel as dielectric layers, and PCPTF as conduct-

3. DESIGN MODEL FOR ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCH ANTENNAS

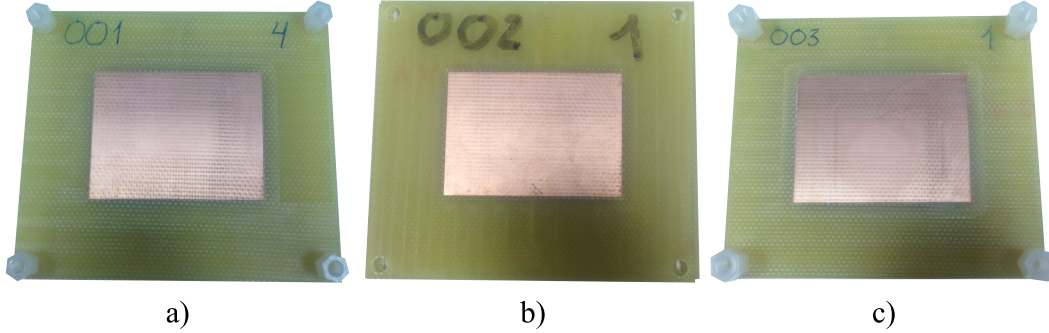


Figure 3.5: Constructed rigid EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) prototypes.

ive layers, as shown in Fig. 3.6.

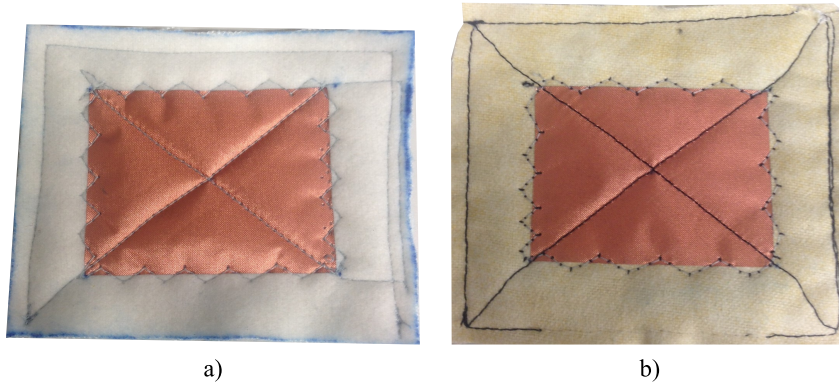


Figure 3.6: Constructed textile EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) prototypes.

All textile antennas were cut using scissors, and their layers attached by sewing cotton thread using a conventional sewing machine. This fabrication technique lead to dimension errors in the conductive fabrics, layer misalignments and unstable EM coupling between the feed line and radiating patch due to antenna thickness inconsistencies. Therefore, the reflection coefficient results mismatched between simulation and measurement, as shown in Fig. 3.7.

The main reasons for these results were: 1) the lack of a stable design model to accurately provide the right dimensions to obtain a desired simulated antenna resonant frequency, 2) the lack of a BW enhancement technique to cover the desired frequency band and 3) the lack of an accurate textile fab-

3.2 Initial EMCMPA Designs

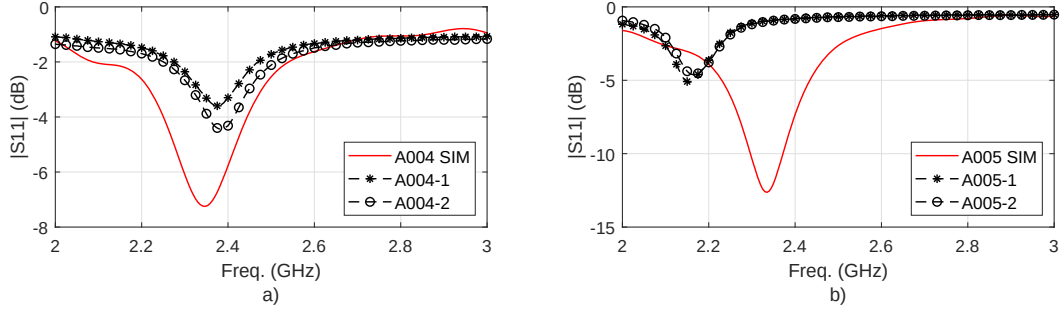


Figure 3.7: Reflection coefficient results of the a) A004, b) A005 EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) prototypes.

rication process for EMCMPA topologies to obtain matching simulated and measured reflection coefficient results.

Finally, 1.5 mm-thick felt and PCPTF as dielectric and conductive layers were designed, assembled and measured. The conductive layers were laser-cut, obtaining more accurate and stable dimensions. The EMCMPAs' layers were assemble using conventional textile glue, cure at 80°C for 20 minutes. Seven prototypes were fabricated to study their fabrication repeatability factor, as shown in Fig. 3.8.

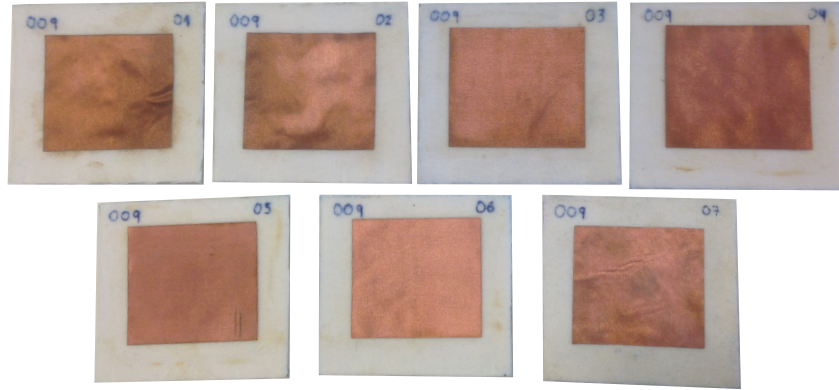


Figure 3.8: Constructed textile A006 EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) prototypes.

The reflection coefficient results improved compared to the two previous textile prototypes, as shown in Fig. 3.9. The simulation and measurement results matched in five of seven constructed prototypes. The results of prototypes

3. DESIGN MODEL FOR ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCH ANTENNAS

A006-2 and A006-7 were not as expected, because of layer misalignments, and galvanic soldering inaccuracies between the port connection and TL.

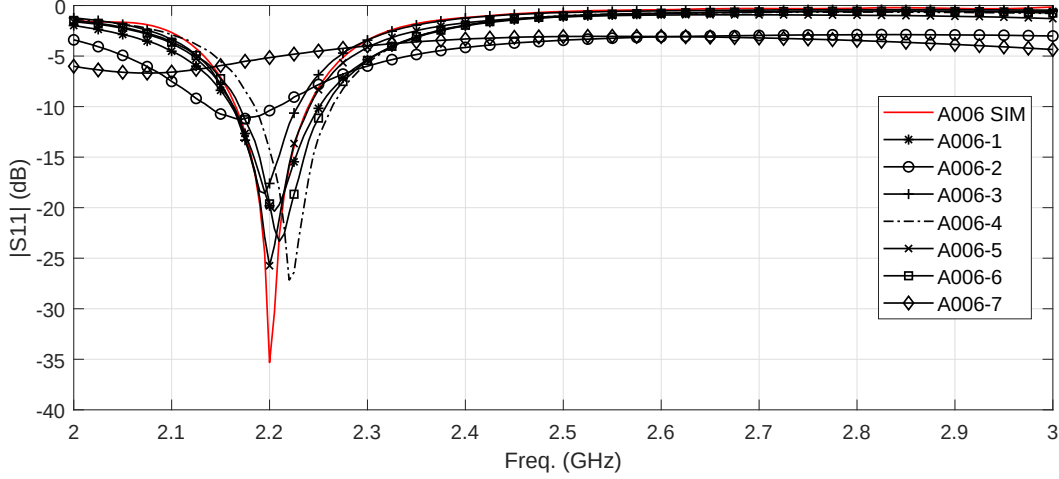


Figure 3.9: Reflection coefficient results of the A006 EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna) prototypes.

The A006 prototypes reported matching reflection coefficient results between simulation and measurements. Yet, the curing process of the conventional textile glue, modified the radiation patch patterns and surfaces, leaving them nonuniform, as shown in Fig. 3.8, and the overall fabrication process became time consuming and complex. Therefore, in the following section a simpler and more repeatable fabrication technique for multilayer textile antennas is presented.

3.3 EMCMPA Design Model

This section presents an analytical framework that combines TL models for the design of EMCMPAs in the 2.45 GHz ISM band (see Appendix C). It provides initial values for all dimensions of the antenna, with measured resonance frequency errors below 6%. The model is validated with antenna prototypes based on rigid and textile materials, exhibiting excellent free-space measured BW, maximal gains, and radiation efficiencies. Moreover, very stable on-body performance is also obtained, with minimal frequency detuning when deploying the textile antenna on the human body.

3.3.1 Analytical Prediction Models

The use of analytical prediction models to accurately calculate the substrate thickness and the dimensions of the radiating patch, the feed line and the ground plane of EMCMPAs is complex due to the electromagnetic coupling between the feed line and the radiating patch.

There are several design models for EMCMPAs, which can be categorized in two groups: simple analytical models and rigorous numerical models. The latter, involves extensive numerical procedures which, in most cases, do not avoid round-off errors and experimental modifications to the theoretical results. In [91], a full-wave spectral-domain technique and the method of moments is chosen to analyze EMCMPAs. In [92], the method of moments is applied for the determination of the current distribution along the antenna and feed line. In [93], the Green functions of the two-layer microstrip structure are determined, and the surface current densities are calculated by the method of moments. These techniques involve extensive numerical procedures, and moreover, no experimental validations have been found in literature.

On the other hand, simple analytical models can provide a good and intuitive understanding of EMCMPAs' EM performance, combined with a reasonably accurate mathematical formulation. These models use the TL model to predict the initial dimensions of at least one part of the EMCMPAs, but they do not provide all antenna dimensions. Table 3.2 shows the main literature that present TL models for EMCMPAs.

In [54], only the radiating patch of a textile EMCMPA is modeled based on equations from [17], and they do not provide values of the resonant frequency deviation between model and real measurements. However, the impedance BW and FTBR values achieved, in the 2.45 GHz ISM band, are the best of the table, despite the antenna's radiation efficiency not being reported. In [27], an analytical model is presented to partially model a dual stub feed line of a EMCMPA for 10 GHz applications, but the resonant frequency deviation between model and measured results is not reported. Yet, an excellent BW of 8.4% is achieved for that frequency band, despite the efficiency and FTBR values not being reported. In [33], a partial model is presented for non

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Table 3.2: Comparison between literature and proposed electromagnetically coupled microstrip antenna models

							This Work	
Reference		[54]	[27]	[33]	[94]	[95]	RIG_3	TEX_3
Overall (λ_0)	size	0.514x	0.389x	NA	0.518x	0.511x	0.446x	0.579x
		0.595x	0.389x		0.588x	0.559x	0.36x	0.524x
		0.011	0.069		0.119	0.029	0.023	0.019
Patch (λ_0)	size	0.381x	0.257x	0.336x	0.518x	0.351x	0.309x	0.464x
		0.335	0.257	0.341	0.324x	0.399	0.222	0.409
Textile		Yes	NA	No	NA	Yes	No	Yes
Intra layers		Sewn	NA	NA	NA	Spray	Screw	Glue
Modeled		Partial	Partial	Partial	No	No	Full	Full
Anechoic Chamber		Yes	NA	Yes	NA	Yes	Yes	Yes
BW (%)		11.2	8.4	5	22	3.9	4	5.12
Min. (GHz)	Freq.	2.33	9.65	2933	3.885	2.395	2.398	2.379
Max. (GHz)	Freq.	2.61	10.5	3068	4.845	2.49	2.499	2.504
Meas. (dBi)	Gain	0.40	4.8	NA	10	8.1	4.28	7.33
Meas. (%)	Eff.	NA	NA	NA	NA	73	62.4	71.8
Meas. (dB)	FTBR	18	NA	11	35	NA	10.5	10.9
Model (%)	error*	NA	NA	7.7	NA	NA	5.33	2.87

λ_0 : free space wavelength at the lowest operating frequency.

*Resonance frequency as reference.

textile RT Duroid based EMCMPAs, which guarantees a maximum resonant frequency deviation of 7.7%. However, the frequency band does not cover the 2.45 GHz ISM band, and gain and efficiency values are not reported. In [95]

and [94] novel textile EMCMPAs are presented. They do not use analytical models but some of their performance can be considered as a reference for EMCMPAs. In [94] very good BW and FTBR values are obtained, despite its overall thickness being high, compared to the average textile antenna thickness reported, and its resonance frequency not centered at 2.45 GHz. Finally, in [95] an EMCMPA is reported, in the 2.45 GHz ISM band and with a reduced thickness, compared to the average textile antenna thickness reported. Gain and efficiency values are a good reference for textile EMCMPAs in this band, yet, it does not provide FTBR values. Table 3.2 also shows the results obtained in this work. It stands out the fact that this work presents a complete analytical model for the design of all dimensions of an EMCMPA, in the 2.45 GHz ISM band, with a lower error than that reported in previous works. In addition, the performance of textile antennas, designed with this model for BCWC applications, are equal to or better than those in literature.

3.3.2 Proposed EMCMPA Design Model

The aim of the proposed analytical model is to easily obtain all the dimensions of an EMCMPA, yielding a resonance frequency as close as possible to the desired value. Moreover, the model also attempts to maximize BW without increasing the overall thickness. The model is suitable to design both rigid and textile based EMCMPAs, providing high radiation efficiencies and good antenna performance in free-space and on-body scenarios.

The analytical model combines several TL model equations. First of all, the conventional TL model represents the MPA by two radiating slots (Fig. 3.10(a)), each described by a parallel equivalent impedance Z_r (with resistance R_r and capacitance C_r), as shown in Fig. 3.10(b) [17], and separated by a low-impedance transmission line (TL_1 and TL_2) of total length L_p . The dimensions L_p and W_p of the rectangular microstrip patch are obtained using [17]

$$W_p = \frac{c}{2f_r \sqrt{(\epsilon_r + 1)/2}} \quad (3.1)$$

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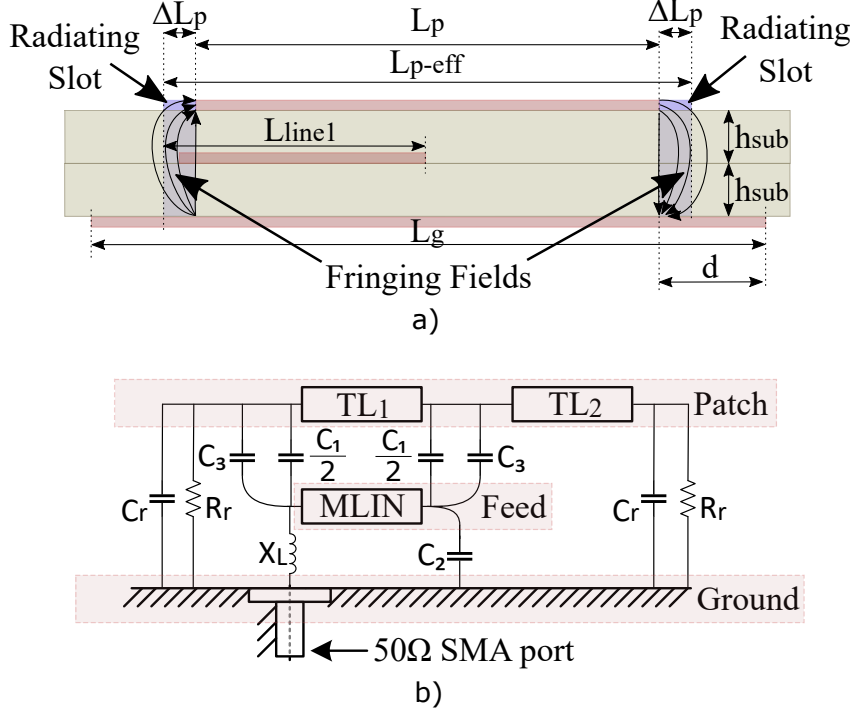


Figure 3.10: a) Physical and effective lengths, and b) equivalent circuit model of EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna)s [96].

$$L_p = \frac{c}{2f_r\sqrt{\epsilon_{reff}}} - 2\Delta L_p, \quad (3.2)$$

where f_r is the antenna's desired resonance frequency, ΔL_p is the extension of the patch length at each end caused by the fringing effects of the radiating slots, and ϵ_{reff} is the effective relative permittivity [17].

Second, the feed line of an EMCMPA can be modeled as a MLIN (Microstrip Line) [33], which is buried under TL_1 , as shown in Fig. 3.10(b). C_1 represents the coupling capacitance between the feed line and the radiating patch, modeled as two capacitors of equal value on either side of MLIN [96]. The feed line exhibits fringing fields, whose effect results in a small increase in its length. This creates extra capacitance, modeled by C_2 , from the open-ended MLIN to the ground, and C_3 , from both sides of MLIN to the radiating patch, which modifies its input impedance, yet the resonance frequency remains constant [96]. The 50Ω SMA connector is represented in the EM-

3.3 EMCMPA Design Model

CMPA's equivalent circuit model by an inductive reactance X_L connected to MLIN. This model suggests a quarter-wavelength feed line using

$$L_{line1} = \frac{c}{f_r \sqrt{\epsilon_{reff}} \cdot 4} \quad (3.3)$$

with the open-end at $L_p/2$ and equal substrate thicknesses, as shown in Fig. 3.10(a). The characteristic impedance of the feed line is set to $Z_0 = 50\Omega$. It is approximately calculated using (3.4) and (3.5) reported by [34] on page 773, where $Z_0 \sqrt{\epsilon_{reff}} \leq 89.91$.

$$W_{line1} = \frac{2 \cdot h_{sub}}{\pi} \cdot \left(B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \right) \cdot \left(\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right) \quad (3.4)$$

$$B = \frac{60\pi^2}{Z_0 \sqrt{\epsilon_r}} \quad (3.5)$$

The ground plane dimensions are modeled using $X_g = X_p + 12 \cdot h_{sub}$, where X_g and X_p correspond to either the width (W) or length (L) of the ground and patch, respectively. To ensure that the resonance frequency of the antenna remains almost identical as in an infinite ground plane scenario, the ground plane dimensions must also fulfill the design rule $d \geq \lambda_0/20$ [97], with d being the ground plane extension, as illustrated in Fig. 3.10(a). In case of conflict the later takes precedence.

The substrate dimensions are obtained by adding 12 mm to the ground plane, to ease the layer-alignment process. Nevertheless, it has been verified that the antenna performance remains identical when the ground and substrate dimensions are equal.

The proposed analytical model is the first step in a three step process to obtain the desired antenna design in a single construction attempt, where the third step is only necessary if the desired BW is not fully covered. It provides the initial dimensions of all EMCMPA layers for a given resonance frequency, input impedance and dielectric materials.

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This initial design is optimized in two subsequent phases to center the resonance frequency and increase the BW to the desired band. These two optimization steps are performed using the time-domain solver of CST. The first optimization step is necessary to better adjust the resonance frequency to the desired band. This work proposes to modify only the length of the antenna patch (L_p) to tune the antenna to the desired resonance frequency, without altering the EM performance of the antenna significantly, yielding a similar BW and $|S_{11}|$ amplitude. The second optimization is based on a ram-horn shaped feed line to enhance the antenna's BW. The line widths and lengths of the quarter-wavelength feed line and of the two half-wavelength open-ended stubs are calculated to match Z_{line} to the 50Ω input impedance [27]. Afterwards, a computer-aided optimization of the ram-horn shaped feed line is performed using CST.

3.3.3 Validation of the EMCMPA Design Model

The proposed analytical model is validated for both rigid and textile materials. The rigid antenna uses 1.43 mm-thick FR4 as dielectric layer and a $35\ \mu\text{m}$ -thick annealed copper sheet. The textile antenna uses 1.2 mm-thick felt as dielectric layer and $80\ \mu\text{m}$ -thick PCPTF as conductive layer. The preliminary values for the permittivity and loss tangent are measured using the Agilent 85070E Dielectric Probe Kit [90], and the substrate parameters are obtained after a conventional design, simulation and measurement process [98, 99].

The proposed analytical model is validated using an antenna with a resonance frequency of 2.44 GHz, an input impedance of 50Ω and the material parameters described in Appendix D. The resonance frequency errors between proposed model and simulation, simulation and measurement, and proposed model and measurement are shown in Table 3.3, which are designated as RIG_X and TEX_X . The first three letters are denoted by the dielectric layer of the antennas (RIG_X stands for the FR4-based rigid antenna and TEX_X stands for the Felt-based textile antenna), and the following number by the design phase (1 - 3).

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Table 3.3: Proposed model, simulation, and measurement error ratios

Code	Model vs. Sim.	Sim. vs. Meas.	Model vs. Meas.
RIG_1	4.92%	0.43%	5.33%
TEX_1	2.25%	0.63%	2.87%
RIG_2	0%	0.05%	0.05%
TEX_2	0%	0.41%	0.41%
RIG_3	0.37%	0.04%	0.33%
TEX_3	0.57%	0.24%	0.33%
$TEX_{3(Onbody)}$	0.45%	0.16%	0.62%

The error between simulation and measurement in both antennas is below 0.63%, which validates the fabrication process reliability for both FR4 and textile antennas (see Chapter 4 and Appendix F). The error ratios between the analytical model's center frequency and the measured resonant frequency in the RIG_1 and TEX_1 antennas are 5.33% and 2.87%, respectively, with a measured BW ($|S_{11}| < -10dB$) of 3.08% and 3.32%, respectively. The error ratios achieved with the proposed analytical model are better than those reported in literature [33, 96], providing a good first design approach for EMCMPAs.

3.3.4 EM Results under Diverse Conditions

The final aim of any designed textile antenna is to perform efficiently when it is placed in a garment. Therefore, they should be robust under diverse harsh conditions like, bending, crumpling, stretching, washing, ironing, among others.

In this thesis, the EMCMPAs are fabricated and tested in free-space, in flat and bent surfaces, and on-body conditions to validate their EM performance. The antenna measurements are performed with an Agilent N5242A PNA-X Microwave Network Analyzer, with the antennas placed in an anechoic chamber, as shown in Fig. 3.11.

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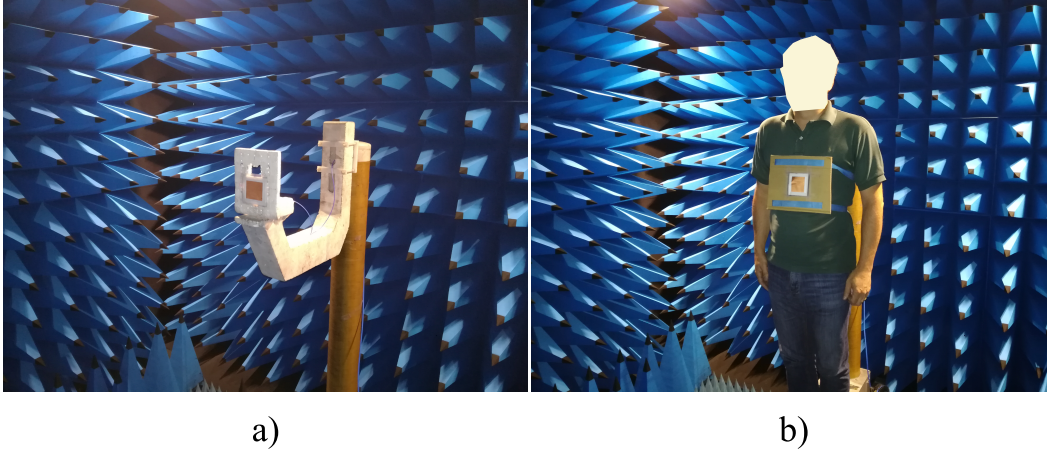


Figure 3.11: Anechoic chamber setup for a) free space and b) on-body measurements.

The free-space simulated and measured reflection coefficients of the rigid and textile antennas are shown in Fig. 3.12. Excellent agreement is observed between simulated and measured results. Both RIG_3 and TEX_3 antennas are centered at 2.44 GHz and cover the entire 2.45 GHz ISM band (2.4 - 2.4835 GHz), with a measured BW ($|S_{11}| < -10dB$) of 4% and 5.12%, respectively.

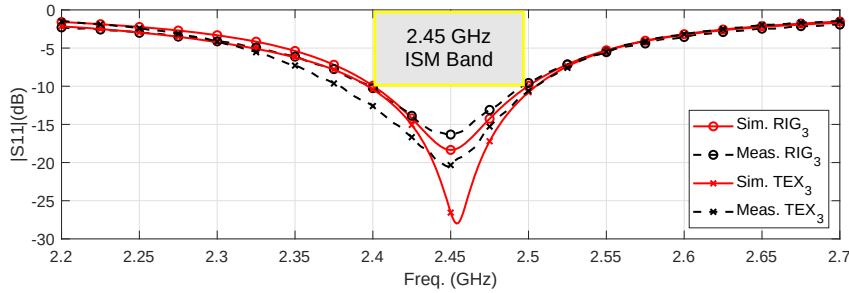


Figure 3.12: Simulated and measured reflection coefficient results in free space for RIG_3 and TEX_3 electromagnetically coupled microstrip patch antennas, using FR4 and felt dielectric layers.

The free-space simulated and measured maximum antenna gain and total antenna efficiency, between 2.4 GHz and 2.5 GHz, are plotted in Fig. 3.13. The maximum measured antenna gains for the RIG_3 and TEX_3 antennas equal 4.28 dBi and 7.33 dBi, respectively. The maximum measured antenna

3.3 EMCMPA Design Model

efficiencies for the RIG_3 and TEX_3 antennas equal 63.4% and 71.8%, respectively. There is a good agreement between the measured and simulated RIG_3 antenna results, while the textile antenna has a difference of less than 10% due to slight variations in the felt dielectric properties.

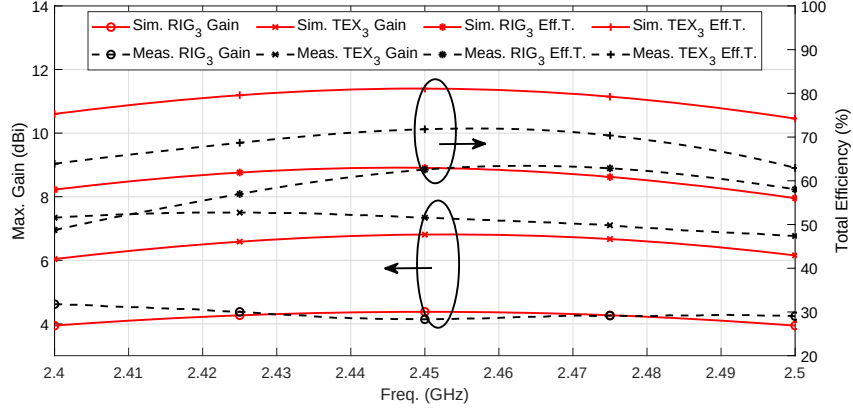


Figure 3.13: Simulated and measured maximum gain and total antenna efficiency results in free space for RIG_3 and TEX_3 electromagnetically coupled microstrip patch antennas, using FR4 and felt dielectric layers.

The TEX_3 textile antenna is also measured under bending conditions. The antenna is attached to a 45 mm-radius PVC (Polyvinyl chloride) cylinder, and bent in its x-axis. A brief comparison study between flat and bent conditions for both the reflection coefficient and radiation diagram in the E- and H-planes is shown in Fig. 3.14.

The reflection coefficient under bending conditions remains below -10 dB, in the entire 2.45 GHz ISM band, but with a slight increase of its resonant frequency, as shown in Fig. 3.14(a). The far-field radiation patterns are also compared in the E- and H-planes at 2.45 GHz, as shown in Fig. 3.14(b). The radiation patterns agree well both in shape and absolute values when under flat or bent conditions, which means that the proposed topology provides a good performance for BCWC applications.

The TEX_3 textile antenna is also simulated and measured on the torso of an average adult person. The simulation uses a three layer (skin-fat-muscle) body phantom. The on-body measurement is performed with a person of size 1.75 m and weight 85 kg inside the anechoic chamber, as shown in Fig. 3.11(b).

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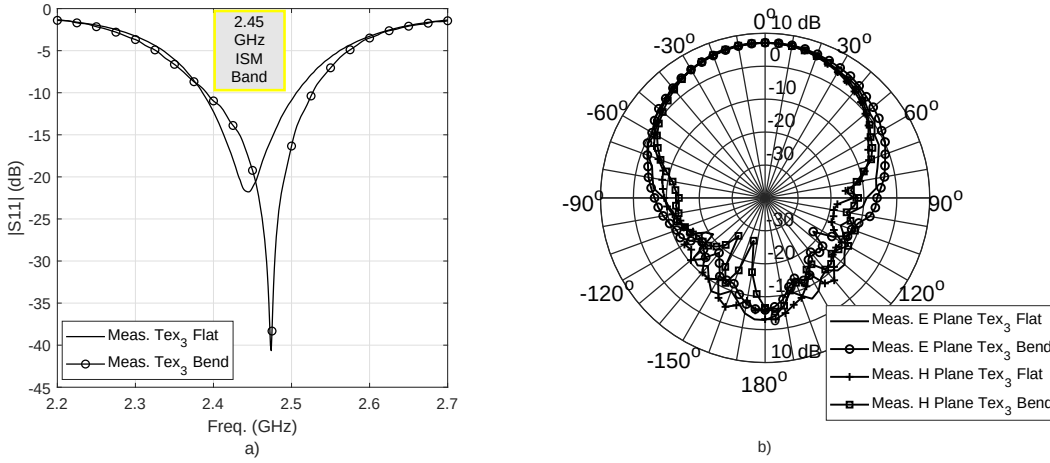


Figure 3.14: a) Reflection coefficient and b) radiation diagram of TEX_3 textile antenna's comparison study between flat and bent measurement conditions.

In both cases, the antenna is placed 2 mm away from the simulated phantom and measured body. The simulated and measured reflection coefficients in on-body and free-space scenarios are compared in Fig. 3.15. The reflection coefficients remain below -10 dB, in the entire 2.45 GHz ISM band, and the simulation and measurement differences between on-body and free-space scenarios are negligible.

The 3D measurement of the antenna performance on the torso of a person inside the anechoic chamber is not possible. Therefore, the antenna is reoriented to measure the far-field radiation patterns in the E- and H-planes at 2.45 GHz. Fig. 3.16 shows the co- and cross-polarization results, where the maximum gain is 5.5 dBi. The measured cross-polarization in the E- and H-plane remains below -13.2 dBi. The patterns in the E- and H-planes at 2.45 GHz agree well both in shape and absolute values when placed on the body, which proves that the proposed topology provides also a good performance for BCWC applications.

Finally, the SAR values are simulated, obtaining maximum SAR values at 2.45 GHz of 0.323 W/kg, which are below the 1.6 W/kg limit given by standard IEEE C95.3, with an input power of 0.5 W (rms), and averaged over 1 g of biological tissue. These results are coherent with the values shown in Fig. 3.16, which indicate that most of the radiation is directed away from the

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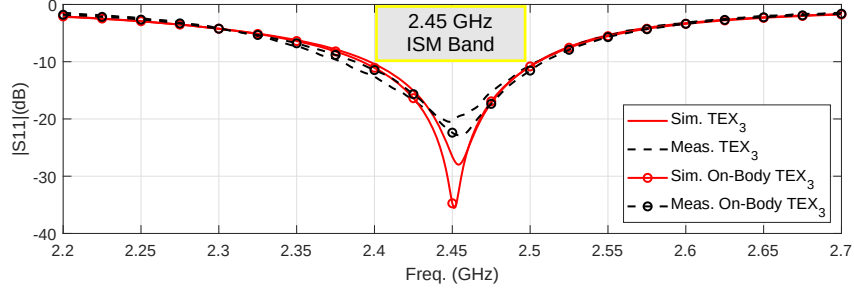


Figure 3.15: Simulated and measured on-body reflection coefficient results for the TEX_3 electromagnetically coupled microstrip patch antennas, using felt dielectric layers.

body, owing to the presence of a ground plane and a shielded feed line.

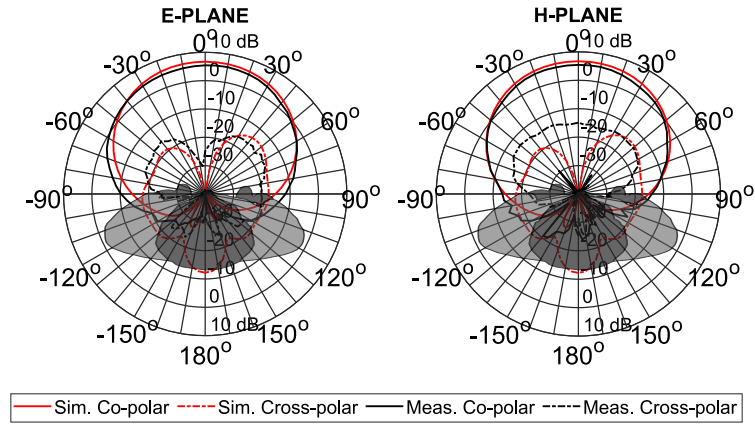


Figure 3.16: Simulated and measured on-body co- and cross-polarization patterns for the TEX_3 electromagnetically coupled microstrip patch antenna, using felt dielectric layers, at 2.45 GHz.

In future works, the proposed textile antenna prototypes should be evaluated under other harsh conditions, like different bending directions, stretching, washing and ironing. The proposed EMCMPA has been evaluated under bending conditions in the x-axis. Yet, if the antenna was to be bent in the y-axis and in some degree diagonally, it would shift the resonant frequency of the antenna, since the resonating slots of the patch are in the y-axis. One solution could be to increase the BW of the antenna to reduce the effects when bent in these directions.

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The proposed EMCMPAs have not been measured under stretching conditions. Yet, if this condition was to be evaluated, first, stretching materials would have to be selected [100, 101, 102]. Stretching the proposed EMCMPA would modify the radiating patch and transmission line dimensions, which would alter the electromagnetic coupling energy transfer. Therefore, the antenna would have to be designed to efficiently radiate in the stretched or loosed position.

Washing and ironing conditions would have to be considered when the smart fabrics are intended to be reused. The proposed EMCMPAs would have to be coated [103, 104, 105, 106] to prevent from detachments while washing and changes on the dielectric properties of the antenna substrates when in contact to water or high air-humidity levels. The attachment of coating layers to the EMCMPA would have to be simulated, carefully fabricated not to modify the thickness of the antenna, and measured to validate the good EM performance of the coated EMCMPA. The permittivity of the coating layer could slightly shift the resonant frequency of the antenna, and the loss tangent could slightly reduce the antenna's radiation efficiency.

The proposed EMCMPAs have been assemble by applying heat on the antennas' different layers to activate the adhesive sheets. Therefore, these prototypes are temperature resistance to a certain degree. Yet, more measurements would have to be performed to validate the proposed EMCMPAs under ironing conditions, since the movement of the iron combined with the increase of heat could miss-align the antenna layers.

3.4 Towards an EMCMPA Design Model between 1-10 GHz

In the previous section, an EMCMPA design model for the 2.45 GHz ISM band was presented. Yet, the model's accuracy could be improved and it's working frequency range increased, to provide antenna designers with a more complete EMCMPA design model. Therefore in this section, we present the current and future work on the EMCMPA design model, between 1-10 GHz (see

3.4 Towards an EMCMPA Design Model between 1-10 GHz

Appendix D).

This contribution presents a simulation study between 1-10 GHz using the initial dimensions of the proposed EMCMPA design model, as shown in Table 3.4. The proposed design model is validated using a well characterized rigid material, Rogers 4003C, with a permittivity of 3.604 and loss tangent of 0.0027 at 2 GHz, to reduce material uncertainties. This implementation serves as a good validation prior to considering actual textile materials. The conductive layer is a 35 μm -thick anneal copper conductive sheet, and each substrate layer is 1.524 mm-thick. Both dielectric layers are assembled using plastic nuts and screws.

The dimensions obtained from the proposed model for each frequency are inserted in CST. In Table 3.4 the simulation results are presented, where the S_{11} and total antenna efficiencies are obtained. The simulated resonant frequency is calculated where the S_{11} amplitude is maximum for each of the designs. It can be observed a shift in frequency for every design between the desired and simulated resonant frequencies. Nevertheless, the frequency deviations compared with the previous designs have a coherent tendency. An excellent total antenna efficiency is obtained in all simulated designs between 80 and 95%.

Afterwards, five RO4003C EMCMPA prototypes were fabricated between 2 and 4 GHz to validate the computer aided CST results. The measured reflection coefficient results slightly shifted in frequency compared to the simulation, but the amplitude and BW differences between simulation and measurement were negligible. Therefore, several improvements have been performed in the EMCMPA design model to reduce the mismatches between simulation and measurement results.

First, fringing fields on both ends of the TL are considered, reducing its length and obtaining a better EM coupling between the TL and the radiating patch, as shown in Fig. 3.17(a). Its effect results in a small increase in its length. This creates extra capacitance, modeled by C_2 , from the open-ended MLIN to the ground, and C_3 , from both sides of MLIN to the radiating patch, as shown in Fig. 3.17(a). Therefore, it is suggested that

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Table 3.4: Computer-Aided Results of the Proposed EMCMPA Model

Model Freq. (GHz)	Sim. Freq. (GHz)	Sim. Max. S_{11} (dB)	Sim. Total Eff. (%)	Deviation (MHz)	Error Model (%)
1	0.965	-32	80.4	-35	3.5
1.5	1.435	-28.4	88.1	-65	4.3
2	1.901	-21.1	90.9	-99	5
2.5	2.366	-20.5	92.5	-134	5.4
3	2.831	-25.3	94	-169	5.6
3.5	3.291	-26	94.5	-209	6
4	3.754	-28.1	95	-246	6.2
4.5	4.218	-28	95.1	-282	6.3
5	4.677	-28.9	95.1	-323	6.5
5.5	5.13	-31.6	95.5	-370	6.7
6	5.578	-34	95.5	-422	7
6.5	6.003	-33	95.4	-497	7.6
7	6.428	-27.2	95.7	-572	8.2
7.5	6.848	-22.5	95.5	-652	8.7
8	7.276	-19.4	95	-724	9.1
8.5	7.7	-17.3	94.3	-800	9.4
9	8.117	-15.8	93.9	-883	9.8
9.5	8.526	-14.5	93	-974	10.3
10	8.927	-13.4	91.9	-1073	10.7

$$L_{line1} = \frac{c}{f_r \sqrt{\epsilon_{reff}} \cdot 4} - 2\Delta L_p, \quad (3.6)$$

where,

$$\Delta L_p = 0.412 \cdot h_{sub1} \cdot \frac{\epsilon_1 + 0.3}{\epsilon_1 - 0.258} \cdot \frac{w_{line1}/h_{sub1} + 0.264}{w_{line1}/h_{sub1} + 0.8}, \quad (3.7)$$

3.4 Towards an EMCMPA Design Model between 1-10 GHz

with the open-end at $L_p/2 - \Delta L_p$, and ε_1 and h_{sub1} as the bottom dielectric layer permittivity and thickness, respectively, as shown in Fig. 3.17(a).

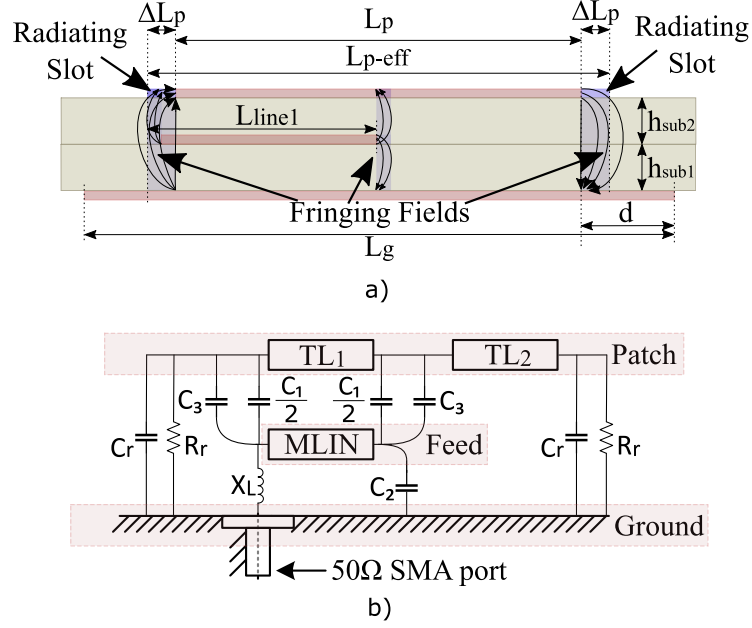


Figure 3.17: a) Physical and effective lengths, and b) equivalent circuit model of electromagnetically coupled microstrip patch antennas [96].

RO4003C is a well characterized material over a wide frequency band, which guarantees that the dimensions and EM parameters introduced in the computer aided designs are correct. Therefore, the computer aided CST simulation setups were studied. First, the general mesh of the CST design setups were increased, which lead to slight improvements on the results, but with a high cost on the simulation time. For this reason, specific high dense meshes were created instead, in key regions of the EMCMPA design, allowing the general mesh density to be reduced, as shown in Table 3.5, which reduced the simulation time, while obtaining more accurate resonance frequency results, as shown in Fig. 3.18.

Table 3.6 shows the final specific mesh parameters added to the computer aided CST designs.

Four key specific mesh areas were selected: (1) the air-gap left between dielectric layers when the annealed copper is removed, which increases the

3. DESIGN MODEL FOR ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCH ANTENNAS

Table 3.5: CST General Mesh Set-Up Comparison

Mesh Setup	Maximum Cell								Minimum Cell	
	Cells/ λ				Cells/Max. Model Box Edge				Fraction of Max. Cell	
	Near Model	to	Far Model	from	Near Model	to	Far Model	from	Near Model	to
Initial	15		15		20		1		20	
Improved	12		12		10		1		10	

Table 3.6: CST Specific Mesh Set-Up

	Axis	Air-gap	Patch	SMA connector	Soldering Air-gap
Volume Refinement Settings	x	0	50	0.5	0
	y	0	100	0.5	0
	z	0.01	0.3	1	0.15
Extend Around Boundary	x	0	10	0	0
	y	0	40	0	0
	z	0	35	0	0

mesh density in the z-axis, (2) the radiating patch, which increases the mesh density in all axes and also around its boundaries to take into account the fringing effects, but with a higher mesh density in the direction of the resonant slots, the y-axis, (3) the SMA connector, to accurately obtain its inductance, and finally (4) the galvanic soldering air-gap created on the top dielectric layer to assure that the soldering point does not create an air-gap between the TL and the top dielectric layer.

A reflection coefficient comparison study, between the initial simulation, the measured prototypes and the final improved simulation results, is shown in Fig. 3.18.

The reflection coefficient mismatches between simulated and measured results are reduced in all frequency bands, after applying all previously mentioned modifications, as shown in Fig. 3.18. At lower frequencies, up to 2.5GHz, the simulated and measured results agree well both in frequency and amplitude. Yet, above 2.5GHz, the mismatches increase, due to the proposed simulation setup and antenna design accuracy, and the dielectric properties inaccuracies

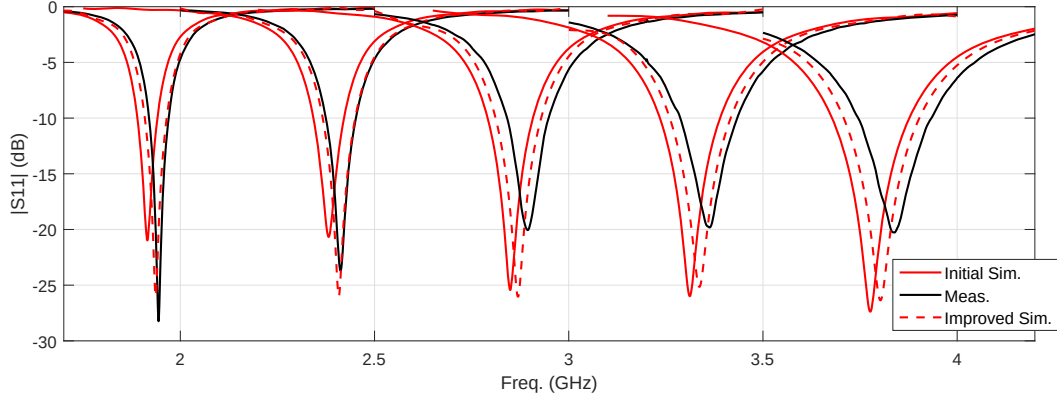


Figure 3.18: Reflection coefficient comparison study between the initial simulation setup, the measurements and the improved simulation setup results.

of the materials at higher frequencies. Therefore, in future works there is a need to reduced these mismatches to avoid modifying the length of the radiating patches, to center their resonance frequencies.

3.5 Conclusions

The use of EMCMPAs in textile applications is validated, obtaining low FTBR, wide BW, less soldering points, and using simple construction designs and structures. The PCB and textile prototypes showed good simulated and measured results. Then, an analytical model is proposed to quickly and reliably yield the initial dimensions of an EMCMPA. Two subsequent simulation phases which modify a single design variable in each phase are presented, achieving a centered resonance frequency and BW enhancement, respectively. This design instrument enables the realization, in a single attempt, of an EMCMPA for the 2.45 GHz ISM band on both rigid and textile materials. The textile antennas designed with this procedure have a high flexibility owing to their small thickness, and an excellent radiation performance in BCWC applications, with antenna gains and efficiencies of 7.33 dBi and 71.8%, respectively, and SAR values lower than 0.4 W/kg. Afterwards, a computer aided antenna design framework to initially yield the first dimensions of EMCMPA is presented between 1 GHz and 10 GHz, obtaining a simulated resonance frequency

3. DESIGN MODEL FOR ELECTROMAGNETICALLY COUPLED MICROSTRIP PATCH ANTENNAS

error of less than 10% and a minimum total simulated antenna efficiency of 80%. The obtained results are the first step towards more accurate and reliable EMCMPA design instruments to easily obtain their initial dimensions. Finally, five rigid EMCMPAs are fabricated between 2 and 4 GHz, every 500 MHz, using well characterized RO4003C, to validate the initial simulation results, where design model and simulation improvements are introduced to obtain better matching results between simulation and measurements.

4

*I can do all this through Him
who gives me strength.*

Philippians 4:13

EMCMPA FABRICATION TECHNIQUES

*The fourth chapter proposes a lab-scale construction process for
electromagnetically coupled microstrip textile patch antennas.*

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4. EMCMPA FABRICATION TECHNIQUES

Textile antennas have been an intense research topic for the last years as they are a key component in many e-textile applications. They face many design, construction and characterization challenges when they are intended to provide a specific EM performance. This chapter focuses on another important challenge for textile EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna)s, the fabrication technique.

As it has been discussed in previous chapters, the EMCMPA is based on a multilayer MPA feeding technique. Its fabrication process, when using textile materials, is complex [34, 35]. The imprecise alignment of multilayer textile antennas has been a source of uncertainty in many research works [44, 46, 47, 107, 108]. So much so, that fabrication tolerance analyses have been performed to predict the effects of mechanical inaccuracies in their designs [31, 52], and the application of complex antenna topologies have been avoided to reduce such fabrication uncertainties [40].

Therefore, this chapter studies different fabrication techniques to optimally construct textile EMCMPAs. First, it introduces a contribution (see Appendix E), where some design and fabrication considerations are offered for sewn antenna designs with conventional sewing machines. This contribution helped us understand different thread-based fabrication techniques and guided us towards easier and more stable EMCMPA fabrication methods. Then, the last main contribution that forms this dissertation is summarized (see Appendix F) [83], where a lab-scale construction process for multilayer microstrip textile patch antennas is validated, which consists in combining an alignment and attachment method, using conductive and dielectric textile fabrics.

4.1 Thread-Based Fabrication Technique

This contribution (see Appendix E), designs, constructs and measures three HF (High Frequency) (13.56 MHz) square spiral antennas using different conductive and dielectric materials. Its final purpose is to validate the thread-based fabrication technique. One rigid (FR4) and three textile (PES/CO

4.1 Thread-Based Fabrication Technique

(Polyester and Cotton), Flannel and Leather-felt) dielectric materials are evaluated in the process, as shown in Table 4.1.

Table 4.1: Properties of the Dielectric Materials

Material	Permittivity	Loss Tangent	Thickness (mm)
FR4	4.7	0.014	1.2
PES/CO	2	0.08	0.3
Flannel	1.8	0.06	0.3
Leather-Felt	1.3	0.03	1.3

The overall dimensions, gaps between turns and shape of the antenna are determined by the application and its placement in the garment. In this work, the antenna is designed to be embedded in a bracelet, therefore, a square shape design is chosen, with the overall dimensions of the antenna smaller than an average adult size wrist, and with a line thickness equal to the gap between lines to ensure antenna performance when on-body, as shown in Fig. 4.1.

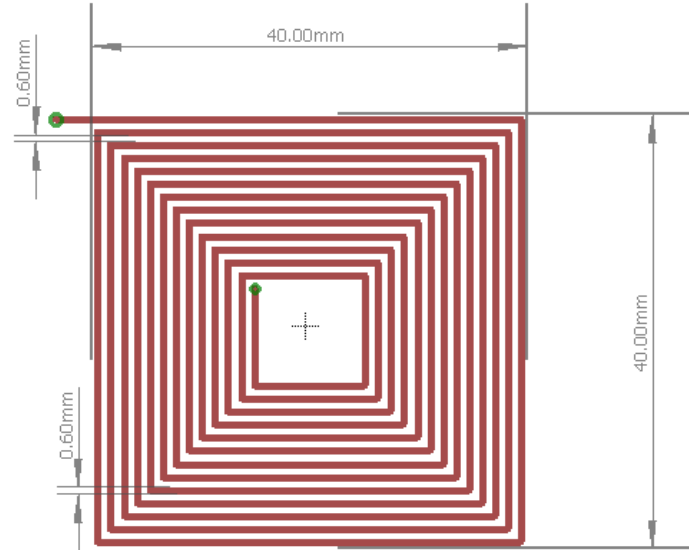


Figure 4.1: Layout and dimensions of the square shaped coil antenna.

First, a spiral antenna is designed and fabricated in a 1.2 mm-thick FR4 PCB, to obtain a reference prototype, as shown in Fig. 4.2(a). The layout includes

4. EMCMPA FABRICATION TECHNIQUES

a SMA connector to test the antenna performance and a three pin-out port to connect the NFC (Near Field Communications) chip. The PCB layout is designed using computer aided Autodesk Eagle PCB Design Software. It was fabricated using the PCB prototyping LPKF ProtoMat S62 machine.

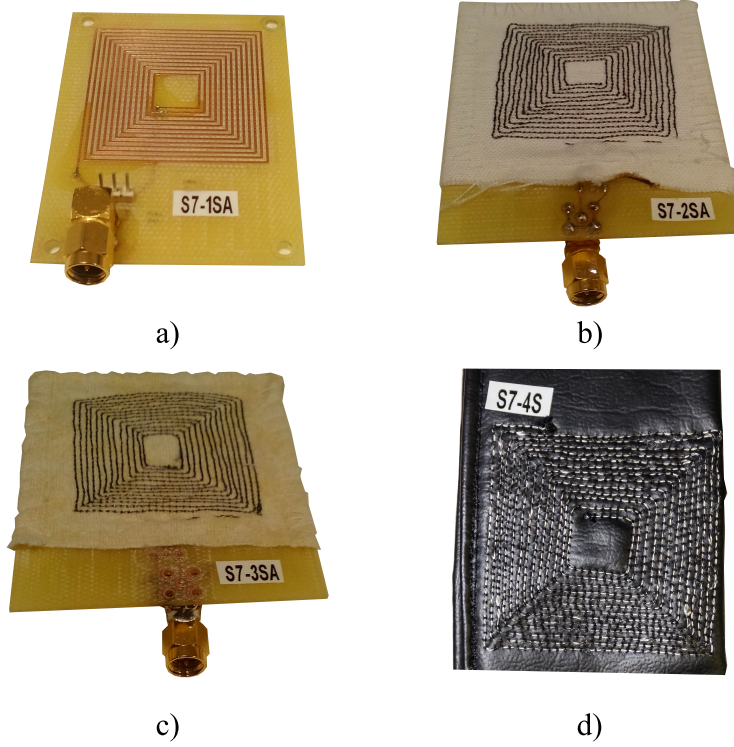


Figure 4.2: Coil antennas constructed with a) FR4 PCB, b) polyester and cotton, c) flannel, and d) leather-felt dielectric substrates.

Second, two textile antennas are designed and fabricated with a 0.2 mm-thick conductive two ply thread [109] sewn into a flannel and PES/CO fabric, as shown in Fig. 4.2(b) and (c), respectively.

A PCB antenna holder is fabricated to provide the textile antennas with equal mechanical characteristics (flatness and distributed tension) and stable measurements. It also makes the connection with the SMA and three pin-out ports simpler and more repeatable. The PCB holders are designed for testing purposes only, afterwards, they are removed from the textile antenna.

Finally, a leather-felt-based antenna is designed, where a university's NFC access card chip is embedded, to create a textile bracelet to open NFC-based

4.2 Fabric-Based Fabrication Technique

doors, as shown in Fig. 4.2(d). This antenna is fabricated to evaluate the antennas' fabrication performance, durability, and flexibility. It is embedded in a bracelet with a NFC chip and used in real-life operation for three years.

It is concluded that the reading time and distance was the same as in a conventional contact-less identification card. The bracelet underwent normal and harsh conditions (bending, crumpling and moist environments) with satisfactory results. The use of conductive threads sewn into flannel, PES/CO and leather-felt fabrics was proven to be a feasible fabrication technique for spiral antennas. Yet, this and other sewing techniques were tested on MPAs (see Appendix B), mainly to attach all MPAs' layers, with non-satisfactory results. The sewing process (with threads going through all the layers) modified the EM characteristics of the dielectric layers, making the permittivity, loss tangent and the overall thickness of the thread-based MPAs inconsistent. This modified the efficiency, BW, and resonance frequency of the antennas in unpredictable ways. Therefore, it is concluded that thread-based fabrication techniques are not suitable for textile MPAs, instead, fabric-based fabrication techniques were studied ((see Appendix A)) and selected for the construction of textile EMCMPAs. The use of an adhesive sheet to join fabric-based multilayer antenna topologies provided a constant thickness, permittivity and loss tangent along the entire surface of the antennas. Moreover, it was easily modeled in simulation, to assess its influence on the antennas' reflection coefficient and total radiation efficiency.

4.2 Fabric-Based Fabrication Technique

The misalignment of one layer can modify undesirably the resonant frequency, the BW and the radiation pattern of a textile antenna. Many fabric-based fabrication techniques have been proposed for different antenna structures and materials [47, 81, 107, 110, 111]. Nevertheless, the performance repeatability of the construction techniques has not been extensively validated, since typically only one or two prototypes are constructed and characterized. Therefore, to the best of our knowledge, this is the first reliable lab-scale construction process that assures the performance repeatability of fabric-based EMCMPAs.

4. EMCMPA FABRICATION TECHNIQUES

This section, based on a contribution (see Appendix F), presents the design, laser patterning, alignment and assembly fabrication phases for the proposed EMCMPA design, as shown in Fig. 4.3. Afterwards, the fabrication technique is validated by fabricating and measuring eight EMCMPAs, and analyzing their EM performance, standard deviation and average results.

4.2.1 Design Phase

The EMCMPA design phase comprises four steps, as shown in Fig. 4.3. First, the EMCMPA topology and materials (see Appendix C) are defined. The antenna topology comprises three conductive and two dielectric layers. The dielectric layers of the antenna are made of 1.2 mm-thick felt textile and the conductive layers are made of PCPTF. Then, the computer-aided design is performed using CST, leading to the final antenna dimensions, which are optimized to cover the 2.4-2.4835 GHz band, with a reflection coefficient below -10 dB. Finally, the alignment frames are designed, serving as template guides during the multilayer attachment process. They are tailored to the antenna dimensions.

Fig. 4.4 shows the layout of the alignment frames and the antenna layers. Alignment frame 1 (outer frame) must have a greater thickness than the inner frames, to hold steady all these alignment frames and antenna layers. The thickness difference between inner and outer frames is determined by the EMCMPA's total thickness, which in this case is $h_{total} \approx 2.4$ mm. Therefore, an outer frame thickness of 5 mm is established.

4.2.2 Laser Patterning Phase

An Epilog Fusion32 CO_2 laser-cutter is used to accurately pattern the antenna layers and wood-based alignment frames. 3 mm-thick MDF (Medium-Density Fibreboard) and 5 mm-thick PPB (Phenolic Plywood Board) are chosen, nevertheless, other materials can be used if they can be accurately patterned to the required thicknesses. To reduce the construction time and to guarantee that each PCPTF layer is perfectly adhered, an adhesive sheet is glued to the

4.2 Fabric-Based Fabrication Technique

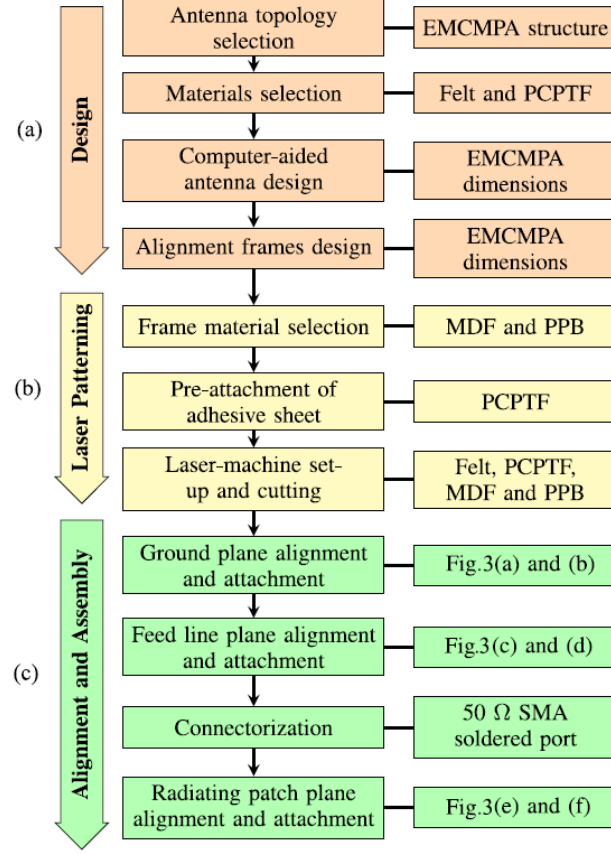


Figure 4.3: Proposed construction phases for multilayer textile antennas: a) Design phase, b) laser patterning phase and c) alignment and assembly phase.

PCPTF before it is patterned. The laser-cut machine set-up for each material is shown in Table 4.2.

Table 4.2: Laser-Cut Machine Set-Up

Material	Speed (%)	Power (%)	Frequency*
Felt	85	10	85
PCPTF	80	20	85
MDF	8	90	85
PPB	15	85	85

* Number of laser pulses fired per inch of travel, from 1 to 100.

4. EMCMPA FABRICATION TECHNIQUES

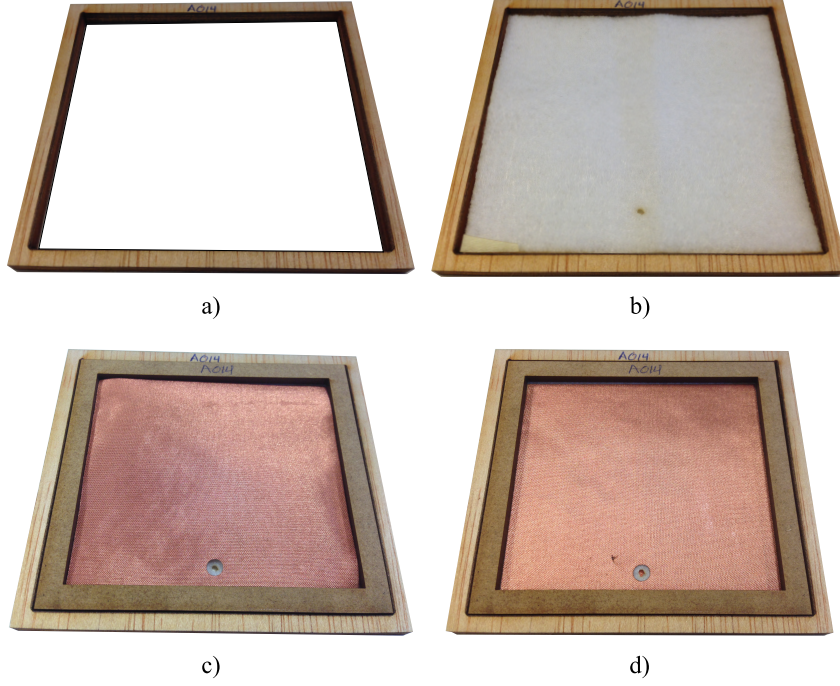


Figure 4.4: Ground plane alignment process: a) 5 mm-thick frame-1, b) introducing felt based bottom layer, c) introducing 3 mm-thick frame-2 and pure copper polyester taffeta fabric-based ground plane and d) gluing the ground plane by thermal activation.

This lab-scale construction process suggests a double-sided adhesive sheet for textile applications [86]. It is thermally activated by applying 100-150° C for 5-15 seconds, and it includes a high temperature resistant paper (carrier sheet) to facilitate the gluing.

The laser-cutting process is performed efficiently, accurately and quickly. A waste of less than 2% of material has been achieved, while the laser-cut error between desired and cut routes is less than 0.05 mm, as shown in Fig. 4.5.

4.2.3 Alignment and Assembly Phase

The alignment and assembly phase steps are listed in Fig. 4.3. First, the ground plane is aligned using the bottom dielectric layer positioned within the alignment frame-1 and -2 (Fig. 4.4(c)). Through thermal activation, both layers are attached by means of the adhesive sheet that has been previously

4.2 Fabric-Based Fabrication Technique

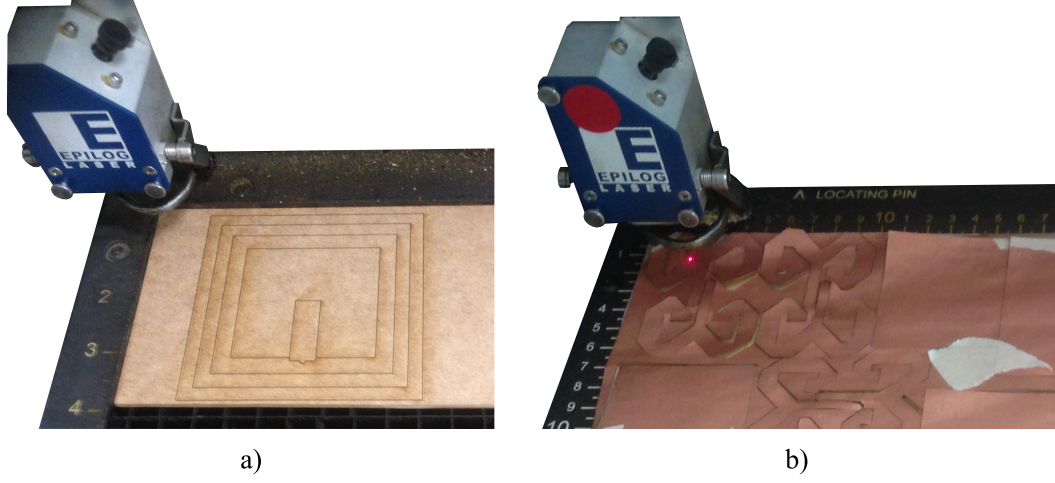


Figure 4.5: Epilog Fusion32 CO_2 laser-cutter: a) 3 mm-thick MDF frames and b) pure copper polyester taffeta fabric-based ground plane, TL and radiating patch patterns.

added to the conductive layer, during the cutting phase (Fig. 4.4(d)). In every step where a conductive layer is added, after aligning it, the layers are assembled by thermally activating the adhesive sheets. Fig. 4.6 illustrates the ground plane assembly process.

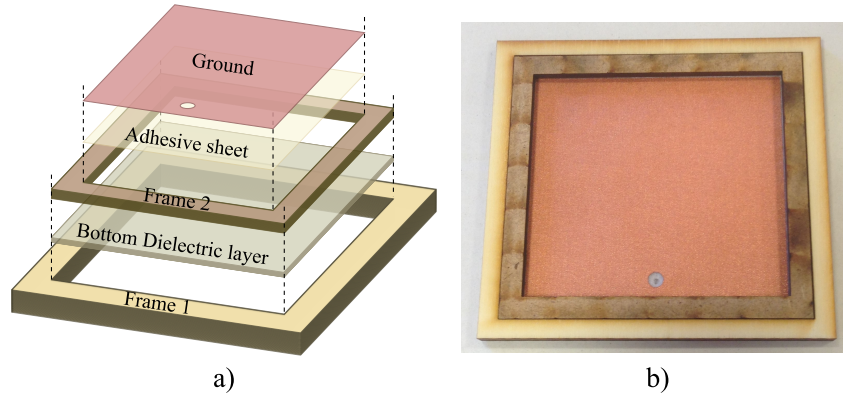


Figure 4.6: Proposed layer alignment method for a electromagnetically coupled microstrip patch textile antenna. a) Perspective view and b) final result of the ground plane alignment process. For clarity, the layers in (a) have been separated and named at the side.

The second step starts by flipping upside down the previously attached bottom dielectric layer and aligning the TL now on the top face with frames-

4. EMCMPA FABRICATION TECHNIQUES

1, -2, -3 and -4, as shown in Fig. 4.7.

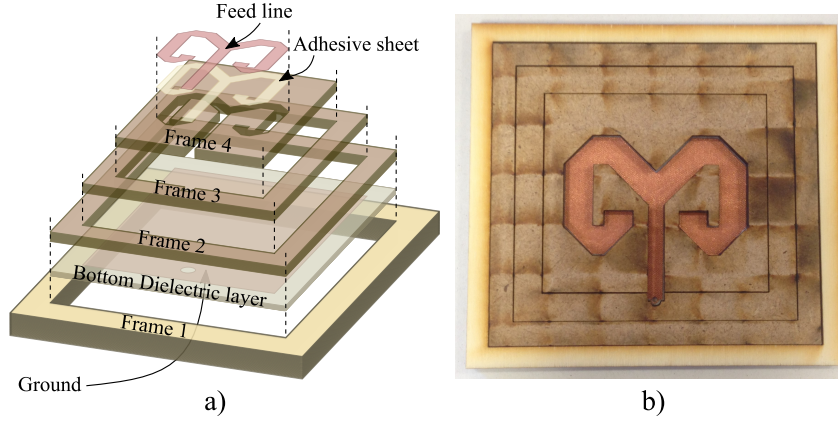


Figure 4.7: Proposed layer alignment method for a electromagnetically coupled microstrip patch textile antenna. a) Perspective view and b) final result of the TL plane alignment process. For clarity, the layers in (a) have been separated and named at the side.

The third step consists on connecting a 50Ω SMA connector to the TL and the ground layer to characterize the antenna prototypes. A galvanic soldering procedure is used. This is a critical step, since PCPTF is not resistant to high temperatures. The main two factors for this procedure to be successful are: first, to set the soldering machine to the minimum required temperature, and second, to perform the galvanic soldering in the least amount of time.

The fourth step involves the attachment of the top dielectric layer on top of the previously attached TL. The alignment is carried out with frame-1 and the attachment is performed with a pre-cut adhesive sheet that is thermally activated, as shown in Fig. 4.8.

Finally, the radiating patch is aligned with the top dielectric layer using frames-1, -2 and -3, as shown in Fig. 4.9.

4.2.4 Validation

The proposed fabrication process is validated by implementing eight EMCMPA prototypes, and measuring, with a vector network analyzer, in an anechoic chamber the EM performance of each prototype.

4.2 Fabric-Based Fabrication Technique

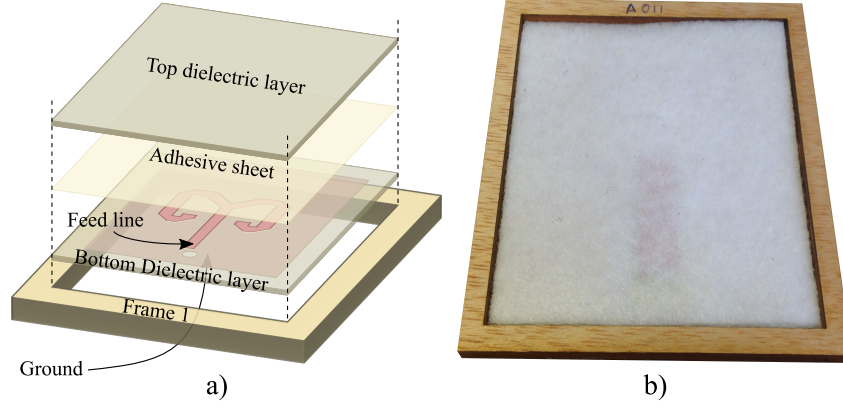


Figure 4.8: Proposed layer alignment method for a electromagnetically coupled microstrip patch textile antenna. a) Perspective view and b) final result of the top dielectric plane alignment process. For clarity, the layers in (a) have been separated and named at the side.

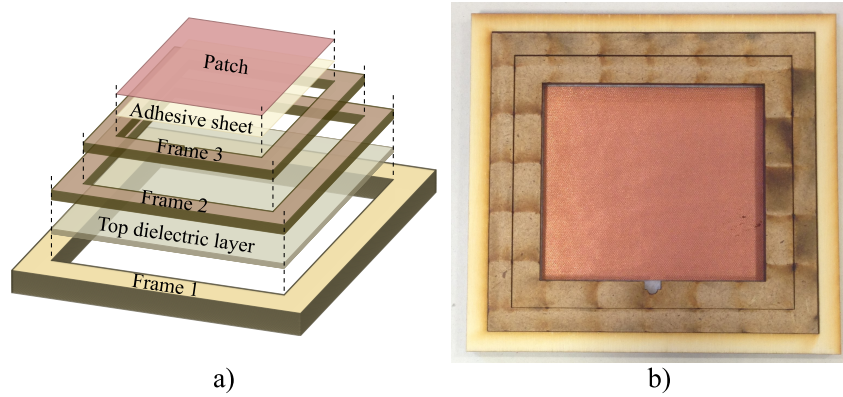


Figure 4.9: Proposed layer alignment method for a electromagnetically coupled microstrip patch textile antenna. a) Perspective view and b) final result of the radiating patch alignment process. For clarity, the layers in (a) have been separated and named at the side.

The simulated and measured reflection coefficients for all constructed prototypes are shown in Fig. 4.10. The solid line represents the reflection coefficient of the simulated antenna in CST. The other lines represent the reflection coefficients for each of the constructed prototypes using the proposed construction process. The frequency shifts in the antennas' resonance frequency are up to 48 MHz, due to the handmade SMA connectorization and inhomogeneities in the substrate's dielectric properties, which are in agreement with values

4. EMCMPA FABRICATION TECHNIQUES

found in literature [52, 108, 111]. These values are acceptable provided that for all prototypes the reflection coefficient remains below -10 dB in the entire 2.45 GHz ISM band.

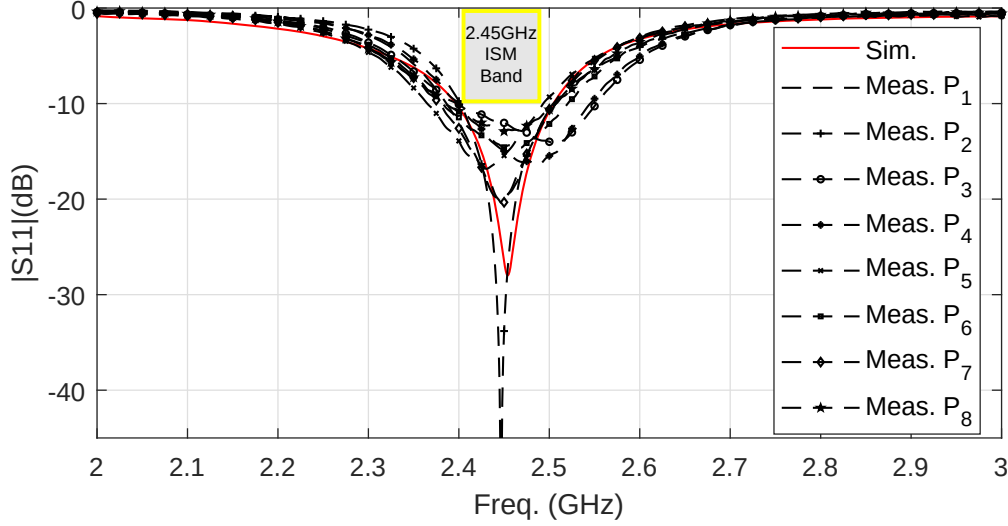


Figure 4.10: Simulated and measured reflection coefficients of all constructed electromagnetically coupled microstrip patch textile antennas.

To ensure that all prototypes radiate most of their emitted power away from the human body, their far-field radiation patterns were simulated and measured. The results at 2.45 GHz are shown in Fig. 4.11. In all cases, measured and simulated results are in excellent agreement, showing a radiation pattern with an average measured FTBR of 10.7 dB. The antenna has negligible cross-polarization, which is not presented for brevity.

The gain and radiation efficiency results for the simulation and all measured prototypes are shown in Table 4.3. The measurements were performed at 2.4 GHz, 2.45 GHz and 2.5 GHz, to validate that the antennas' EM performance remained constant in the desired band. The measured peak gain varies from 6.2 dBi to 7.8 dBi for all constructed prototypes. Moreover, the measured total efficiency varies from 54.4 % to 77.8 %.

For the different radiation characteristics, the average value and STDV (Standard Deviation) were calculated, as shown in Table 4.4, to verify the tolerance of the proposed construction process. An average result and STDV

4.2 Fabric-Based Fabrication Technique

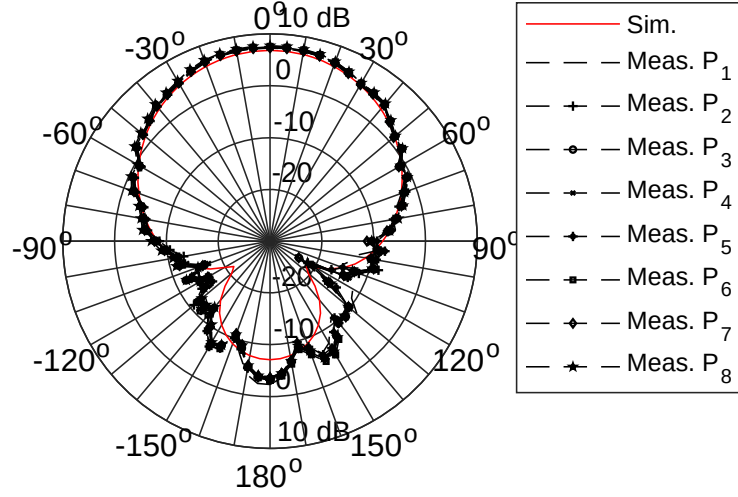


Figure 4.11: Simulated and measured radiation pattern at 2.45 GHz of all constructed electromagnetically coupled microstrip patch textile antennas.

Table 4.3: Simulated and Measured Antenna Gains and Total Efficiencies

Antenna	2.4 GHz		2.45 GHz		2.5 GHz	
	Gain (dBi)	Eff. T.* (%)	Gain (dBi)	Eff. T.* (%)	Gain (dBi)	Eff. T.* (%)
Sim.	6.1	57.4	6.8	66.3	6.2	55.6
Meas. P ₁	7.2	63.3	7.4	71.1	6.9	66.2
Meas. P ₂	7.1	64.8	7.4	74	7.2	69.1
Meas. P ₃	7.3	55.7	7.5	66.7	7.3	69.2
Meas. P ₄	7.5	67.3	7.3	69	6.8	62.1
Meas. P ₅	6.8	54.4	7.2	66.5	7	63.6
Meas. P ₆	7.6	65.6	7.6	69.1	7.3	66.5
Meas. P ₇	7.3	63.9	7.3	71.8	6.8	63
Meas. P ₈	7.8	67.7	7.7	77.8	7.7	70.4

* Total efficiency of the antenna.

of the resonant frequency of 2460 MHz and 24.54 MHz, respectively were achieved. This shift and variation in resonance frequency were due to variations in substrate permittivity and SMA connectorization. A STDV BW of

4. EMCMPA FABRICATION TECHNIQUES

14 MHz is achieved, which may be caused by variations in substrate thickness.

Table 4.4: Simulated Results, Measured Standard Deviations and Average Values of the Constructed Prototypes

	Freq. min. (MHz)	Freq. res. (MHz)	Freq. max. (MHz)	S_{11} max. (dB)	BW (MHz)	Eff. T.* @ 2.45 GHz (%)	Gain @ 2.45 GHz (dBi)
Sim.	2397	2454	2505	-28	108	66.3	6.8
Avg.	2387	2460	2516	-20.8	129.5	70.75	7.4
STDV	11.75	24.54	19.57	11.8	14	3.57	0.2

* Total efficiency of the antenna.

The minimum and maximum frequency values shown in Table 4.4 are obtained considering a reflection coefficient of -10 dB.

4.3 Conclusions

The use of thread-based fabrication techniques have been proven as a feasible construction method for NFC square spiral purely textile on-body antennas. The mechanical properties of the developed prototype, such as stress, crumpling and bending, have been successfully tested for more than three years of real life use. Yet, the same fabrication techniques were tested on MPA at 2.45 GHz with non-satisfactory results. The sewing process added uncertainty on the permittivity, loss tangent and the overall thickness of the antenna. This modified the efficiency, BW, and resonance frequency in unpredictable ways.

Therefore, fabric-based fabrication techniques were studied for the construction of textile MPAs. A lab-scale construction process for planar textile antennas was presented, where a combination of laser-cut wood frames alignment method and a fast intralayer attachment was validated. Eight identical textile EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna)s were constructed. The anechoic chamber results showed very good agreement between the eight constructed antennas and the simulation results. The an-

tenna construction process exhibited constant EM performance in terms of resonant frequency, maximum S_{11} , BW, gain and radiation efficiency.

The proposed textile multilayer fabrication technique has been validated using EMCMPAs operating in the 2.45 GHz ISM band. Yet, in future works it could be applied for other textile multilayer antenna topologies, like the aperture coupled microstrip patch antenna, or simpler textile antenna topologies that require precise antenna patterns, like microstrip patch antennas with parasitic elements, slots or complex radiating patches.

It could also be applied for antennas operating in different frequency bands. Yet, the fabrication technique would have to be re-evaluated for antennas operating at higher frequency bands for two main reasons. 1) The increase on frequency is directly related with a decrease on the antenna dimensions. Therefore, the minimum resolution for the fabrication technique would have to be studied. 2) The increase on frequency also increases the susceptibility of the antennas' cutting and layer alignment technique, and the dielectric and conductive layers' inhomogeneities, which could lead to higher frequency shifts, lower radiation efficiencies, and lower fabrication repeatability levels.

5

*Where there is no guidance, a
people falls, but in an abundance
of counselors there is safety.*

Proverbs 11:14

CONCLUSIONS AND OUTLOOK

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5.2	Future Work	86

5. CONCLUSIONS AND OUTLOOK

This Ph.D. thesis had the objective to validate an hypothesis that claims that "modeling textile EMCMPA (Electromagnetically Coupled Microstrip Patch Antenna)s with transmission line models can provide accurate and efficient antenna designs, and with a high repeatability if combined with innovative multilayer construction techniques." The main conclusion is that such statement is true: it is possible to easily design efficient textile EMCMPAs and to fabricate them with a reliable lab scale technique. They are rigorously validated using different materials and fabricating several prototypes. Many technical conclusions have been arisen during the realization of the research work, to validate the thesis hypothesis. This chapter summarizes them according to the contributions of each chapter. Then, an outlook is presented for potential applications and future research.

5.1 General Conclusions

In the near future, it is expected that fully integrated electronics on daily garments, also defined as smart clothing, will change the way we experience our surroundings, by providing new information about the activity or physiology of our bodies. The two main challenges for their success are the integration of electronic functionality and wireless technologies in traditional clothes.

The work presented in this Ph.D. thesis focuses on wireless technologies, particularly on the antennas, which are one of the most exposed electronic components in this integration, due to their EM susceptibility when they are integrated on-body and their high dependency on their dimensions to operate efficiently.

Chapter 2 presented a broad state of the art examining the best planar off-body textile antenna topologies, construction techniques and antenna measurements under diverse conditions. It is concluded that EMCMPA topologies are most suitable for planar off-body applications because of: (i) the widening of MPA's inherent narrow BW, (ii) the increase of their gain and FTBR values, and (iii) the avoidance of coaxial probes or vias, which improves their flexibility.

Chapter 3 presented fast and reliable design models to yield the initial dimensions of EMCMPAs. First, preliminary antennas were designed and constructed using rigid and textile materials, to experimentally evaluate them, obtaining low FTBR, wide BW, less soldering points, and using simple construction designs and structures. The rigid and textile prototypes reported good simulated and measured results. Then, a combination of transmission line models to quickly and reliably yield the initial dimensions of an EMCMPA in the 2.45 GHz ISM band was performed. Two subsequent simulation phases which modify a single design variable in each phase were presented, achieving a centered resonance frequency and BW enhancement, respectively. This design instrument enables the realization, in a single attempt, of an EMCMPA for the 2.45 GHz ISM band on both rigid and textile materials. Antenna gains and radiation efficiencies of 7.33 dBi and 71.8%, respectively, and SAR values lower than 0.4 W/kg were obtained. Finally, the proposed designed model was evaluated for a wider frequency range, from 1 - 10 GHz, obtaining a simulated resonance frequency error of less than 10% and a minimum total simulated antenna efficiency of 80%. Five rigid EMCMPAs were fabricated between 2 and 4 GHz, every 500 MHz, using well characterized RO4003C. The reflection coefficient results showed very good agreement between the constructed antennas and the simulation results.

Chapter 4 presented a lab-scale fabrication process to construct textile MPAs. First, thread-based design and fabrication considerations were presented for textile antennas. It was concluded that easier and more stable fabrication techniques were necessary for EMCMPAs. Therefore, fabric-based fabrication techniques were chosen for the construction of textile EMCMPAs. A lab-scale construction process for planar textile antennas was presented, where a combination of laser-cut wood frames alignment method and a fast intralayer attachment was validated. Eight identical EMCMPAs were constructed. The anechoic chamber results showed very good agreement between the constructed antennas and the simulation results. The antenna construction process exhibited stable EM performance in terms of resonant frequency, maximum S_{11} , BW, gain and radiation efficiency.

5. CONCLUSIONS AND OUTLOOK

5.2 Future Work

The research performed in this dissertation forms a solid basis for future work. Yet, many improvements and progress can still be made.

In particular, the combination of the proposed antennas with electronics and sensors embedded in textile materials for smart clothing applications. To this day, the interconnects between rigid electronics and flexible antenna remains as the main challenge for smart clothing systems, as they have the tendency to fail over time, due to friction, bending, and twisting caused by the wearers' movements. Yet, the connection of these electronics with EMCMPAs would be performed at the feed line, which is between the two dielectric layers, increasing the electronics' durability under these conditions.

Another area of improvement related to EMCMPAs is shifting the design and fabrication techniques towards higher frequency bands. Obviously, this brings along additional challenges, as interconnections become more susceptible to undesired interference, losses increase and fabrication tolerances decrease.

The EMCMPA model presented in this work is a solid foundation for simple rectangular radiating patches and TLs, and have more than adequate performance to meet the requirements of current wireless protocols, such as Wi-Fi, Bluetooth, and ZigBee. This foundation combined with the proposed fabrication technique, can enable the development of more complex radiating patches, TLs, parasitic element designs, to easily enhance the EM performance of EMCMPAs: in this work the TL design, of the proposed initial EMCMPA design, was modified, increasing its complexity, to enhance its BW, using the same fabrication technique. The fabrication of array antennas, feed lines and ground planes can be easily developed using the proposed fabrication process for many applications like more efficient communications, or to harvest more RF energy from the ambient. Interesting research can also be performed into obtaining the fabrication technique's maximum accuracy, by reducing the design dimensions, and increasing its complexity.

Finally, the proposed EMCMPA textile topology could be measured under other harsh environments, like higher bending angles, crumpling, washing and

ironing cycles, which are typical use environments of textile antennas.

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APPENDIX



Paper I

Planar Textile Off-Body Communication Antennas: A Survey

This paper has been published in the journal “*MDPI Electronics - Special Issue on Intelligent Antennas*”, on June 24th, 2019. Its DOI (Digital Object Identifier) is 10.3390/electronics8060714. It is published as Open Access and can be accessed online through the MDPI Electronics journal website. The published version is appended here. © 2019 by the authors. Licensee MDPI, Basel, Switzerland. This publication is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Review

Planar Textile Off-Body Communication Antennas: A Survey

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Received: 31 May 2019; Accepted: 20 June 2019; Published: 24 June 2019



Abstract: Fully textile smart wearables will be the result of the complete integration and miniaturization of electronics and textile materials. Off-body communications are key for connecting smart wearables with external devices, even for wireless power transfer or energy harvesting. They need to fulfill specific electromagnetic (EM) (impedance bandwidth (BW), gain, efficiency, and front to back radiation (FTBR)) and mechanical (bending, crumpling, compression, washing and ironing) requirements so that the smart wearable device provides the required performance. Therefore, textile and flexible antennas require a proper trade-off between materials, antenna topologies, construction techniques, and EM and mechanical performances. This review shows the latest research works for textile and flexible planar, fully grounded antennas for off-body communications, providing a novel design guide that relates key antenna performance parameters versus topologies, feeding techniques, conductive and dielectric textile materials, as well as the behavior under diverse measurement conditions.

Keywords: textile antennas; off-body communications; fully-grounded planes

1. Introduction

The convergence of electronics and conductive textiles (e-textiles) to create smart wearable devices remains challenging in several application areas such as medical, sport, art, military, or aerospace. They will be capable of sensing data, controlling actuators, communicating with external devices, and even being recharged wirelessly. Miniaturization and integration of electronics into smart textiles are key for this revolution. Nevertheless, the performance of certain components like sensors [1,2], energy harvesters [3–5], or antennas is dependent on their dimensions and cannot be miniaturized.

Off-body communication antennas are used in smart textile devices to communicate with other external devices. The topology and materials of these antennas play a key role in the smart textile devices' efficiency, manufacturing cost, and mechanical performance (bending, crumpling, washing, and ironing). There have been reported many textile antenna topologies, but off-body communication antennas require the minimization of front-to-back radiation (FTBR) levels (to avoid the negative effects of the human body, and the degradation of the antennas' performance), while having the required impedance bandwidth (BW), high radiation efficiency, and low antenna volume. On the other hand, the inherent proximity of the human body to the antenna gives special concern to the wearers' health safety, and therefore the specific absorption rate (SAR) [6,7] is also a key aspect to take into consideration.

Antennas with full-ground planes are good candidates to enhance the FTBR and SAR values for body-worn applications. Recent literature on fully-grounded planar topology antennas constructed with non-textile materials show promising electromagnetic (EM) performances in terms of measured BW, maximum peak gain, radiation efficiency, and FTBR [8–17]. They are normally based on

well characterized dielectric and conductive materials, like Rogers Duroid 5880 [8–10,14,18–25], Rogers 4003 [12], Rogers 3003 [14], and F4B [16] and FR4 Microwave [26–29], which lead to consistent results between simulations and measurements. The thinness of the substrates used (between 0.5 mm and 2 mm) [8,10,12,13,16,18–20,24–26,28,30] offers good BW and radiation efficiencies, giving some clues about their potential for textile applications. They also allow for a plethora of design alternatives to improve the EM performances, normally based on three patch shapes, like rectangular [8,9,11–13,15,18,20,22,24–26,29,30], circular [21,23,31], and square [14,19], combined with different slotted patch configurations like linear [8,12,16,19,20,26,28,30], meandered [18], ramp [18], circular-ring [21], complex [17,22], L-shaped [29], and U-shaped [24]. Feeding techniques are also relevant when they are used for textile applications—coaxial fed [11,12,14,16,17,21,23–26,28,31], microstrip line fed [9,10,22,30], microstrip inset line fed [8,9,19,20], aperture-coupled fed [13], and L-shaped line fed [15] antennas. Finally, antennas for single-band [8–20,23–26,28,30,31], dual-band [29], and reconfigurable bands [21,22,25] have been reported, which is sometimes also also desirable in textile applications.

This is the reason why this survey is focused on analyzing textile antennas with a full-ground plane for off-body communications, combining the potential of fully grounded topologies with the challenges of textile materials. These antennas can be thin, lightweight, robust, and easily manufactured. They can even be used for energy harvesting as the available space over the textile surface is high. But greater dimensions require solutions based on textile materials that guarantee comfortable and aesthetically acceptable designs and robust performance against bending, crumpling, washing, and ironing. Moreover, EM characteristics of textile materials are crucial for good antenna performance. For instance, the permittivity, loss tangent, and thickness of the substrates are main factors for good BW and radiation efficiency of the antennas.

The structure of this survey is as follows: Section 2 presents an analysis on the latest literature on planar off-body textile antenna designs and their EM performance on ideal scenarios (flat surface and free-space), describing their feeding techniques and antenna topologies. Section 3 describes the latest reported textile antenna construction techniques, and their main dielectric and conductive materials. Section 4 discusses the EM performance of textile antennas under diverse conditions (on-body, bending, crumpling, compression, humidity). Finally, Section 5 gives the main conclusions and future work.

2. Antenna Designs and Performance

Fully grounded planar antenna topologies have been broadly used for off-body communications because of their high body isolation, low profile, robustness, ease of fabrication, and low cost [32,33]. Textile materials add a better bending performance, lower permittivity, lighter weight, and lower costs, which—combined with fully grounded planar topologies—make them ideal for off-body communications. Nevertheless, the main drawback of these topologies is their usually narrow BW [34–36]. The research within this type of textile antennas has recently been focused on the enhancement of the BW with different feeding techniques and design topologies. Many solutions have been proposed in the literature: (I) Increasing substrate thickness [37–39], (II) designing complex radiator patches [7,40,41], (III) adding slots to the radiator patch [6,37,42], (IV) including parasitic elements [34,40,43], (V) inserting Artificial Magnetic Conductors (AMC) [6,36,43], (VI) using Substrate Integrated Waveguide (SIW) topologies [44–46], using Planar Inverted F-Antennas (PIFA) topologies [42,47,48], or (VII) using different feeding techniques [32,42,49].

AMC planes are made of metamaterial emulating a magnetic conductor over a limited frequency band dependent on its design. They are implemented on planar antennas, forming a reflector and reducing the FTBR, they can be designed for wide-band or dual-band applications, and they can replace the usual ground plane [6,36,43,50]. AMC planes consist of periodic structures (square [6], ring [43], cross [36], and complex [50]) in arrays (4×4 [6], 3×5 [43], 3×3 [36] and 2×2 [50]).

The addition of slots in the radiator patch modifies the current on the patch [6,45,47,51], leading to better antenna performance: (I) BW enhancement [6,36,43,44,47,52], (II) dual-band or

multi-band resonant frequencies [44,51–54], (III) miniaturization of the overall antenna size [6,36,45,53], (IV) antenna frequency tuning [45,51–55], and (V) circular polarization [54].

This section analyzes and organizes the most recent literature reported on textile antenna designs and EM performance into four areas: (I) The feeding techniques, (II) antenna topologies used in fully grounded planar antennas for off-body communications, (III) their main EM parameters in ideal conditions (flat surface and free-space), and (IV) some final conclusions regarding a new figure of merit that is proposed.

Note that figures shown in this section have been designed with rectangular radiator patches, nevertheless circular [52,54,56,57], square [6,34,39,58], and other complex shapes [7,36,40,41,43,44,48] have been found in the latest literature.

2.1. Feeding Techniques

2.1.1. Coaxially Fed Antennas

The coaxial probe feeding technique is well implemented in off-body communications textile antennas. The basic scheme is shown in Figure 1a. The outer conductor of the coaxial probe is connected to the ground plane, and the inner connector to the radiator patch. The coaxial probe introduces an inductance, which depends on its length and is determined by the substrate's thickness of the antenna [59]. Their fabrication at lab scale is simple, their compactness in terms of the overall volume is good, and their impedance matching is easily obtained with capacitive coupling radiator patches [7] or adjusting the position of the feeding point [41,44,52,53,55]. The main BW enhancement techniques that do not change the antenna topology are based on slots in the radiator patch [6,37,44,45,47,48,50,52,53,55] or on parasitic elements close to the radiator patch [7,36,43]. This feeding technique is not ideal for real textile applications that are expected to be flexible and comfortable, since the rigid coaxial probe is part of the antenna and can not be removed after antenna testing.

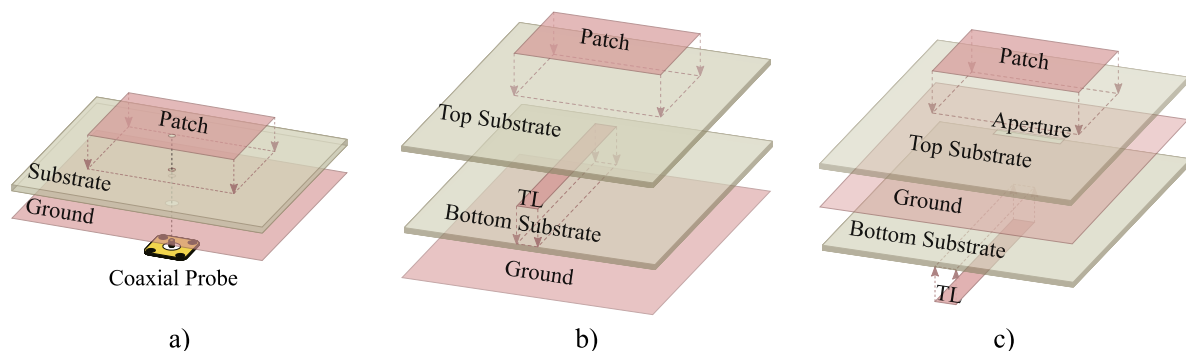


Figure 1. (a) Coaxially fed microstrip antenna. (b) Electromagnetically coupled microstrip antenna. (c) Aperture-coupled microstrip antenna.

2.1.2. Multilayer Feeding Techniques

Ideally, multilayer feeding techniques provide a better textile performance than coaxial probes, since there is no need for rigid pins going through different layers, and the connector can be removed after the antenna evaluation is performed. There are two main multilayer feeding techniques, based on electromagnetic (proximity) and aperture coupling. Their basic construction schemes are shown in Figure 1b,c, respectively. The former is composed (from bottom to top) of a ground layer, bottom substrate, transmission line (TL), top substrate, and radiator patch. The latter is composed (from bottom to top) of a TL, bottom substrate, ground layer with an aperture, top substrate, and radiator patch.

The proximity coupled microstrip antenna is excited from the TL and electromagnetically coupled through the top substrate to the radiator patch. The TL is inserted between two substrate layers, the ground plane and partially the radiator patch, where any radiation from the feeding line is shielded and potentially re-radiated by the patch, leading to a good cross-polarization [60] and a good body

isolation. On the other hand, aperture-coupled fed microstrip antennas [61,62] are not ideal for off-body communications since the TL is not isolated from the body. This creates a non-desired energy absorption and modifies the radiation signal pattern due to the high permittivity and losses of human skin tissue.

Multilayer microstrip feeding techniques increase the BW of the antennas, they are robust to bending, but the manufacturing process needs to be more precise due to the required multilayer alignment [32,40,49,63]. According to the latest literature, there have not been any designs found with parasitic elements or slots in the radiator patch.

2.1.3. Microstrip Line Feeding Techniques

The microstrip line feeding technique is also widely used for textile applications. It consists of a radiator patch with a TL, a dielectric substrate, and a ground plane, as illustrated in Figure 2a. They do not have any coaxial probe going through the layers or multilayer structures, which decreases the manufacturing complexity and improves the antenna's flexibility. The impedance matching is made possible by modifying the width and length of the TL [64–66] or by creating an inset gap in the patch [33,67], as shown in Figure 2b. With this feeding technique, array antennas can be easily implemented—modifying the TL length and width to obtain the required input impedance for each antenna element [32,49,68]. On the other hand, the increase of TL length also increases the losses, the overall size of the antenna, and the impedance matching complexity. According to the latest literature, slotted radiator patches fed with a TL have also been proposed [51,69].

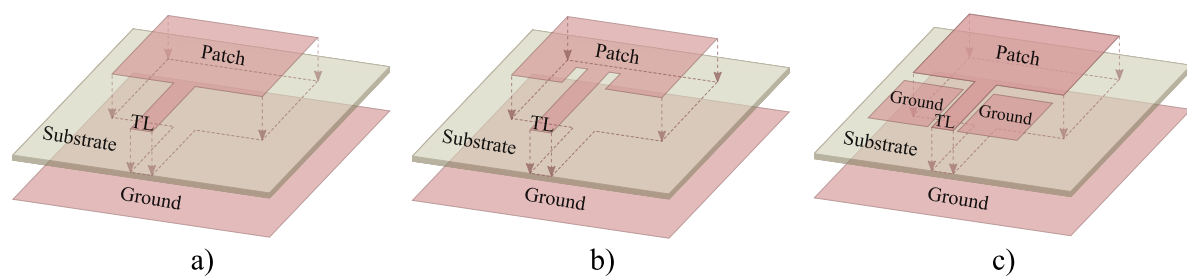


Figure 2. (a) Microstrip line fed. (b) Microstrip line inset fed. (c) Coplanar waveguide fed (CPW).

2.1.4. Coplanar Waveguide Fed Antennas

The coplanar waveguide (CPW) fully grounded feeding technique is based on the microstrip line feeding technique, but with a truncated ground plane close to the TL [40,70,71]. Two equal planar ground planes are placed symmetrically on each side of the CPW line, as shown in Figure 2c. The impedance matching of the CPW feeding technique is achieved by optimizing the width of the TL and the gap between the TL and ground planes. This feeding technique is designed on three layer antenna structures (ground, substrate, and radiator patch), but multilayer antennas have also been used [40].

2.2. Antenna Topologies

There are three main planar antenna topologies for textile off-body communications—the microstrip antenna, the planar inverted F-antenna (PIFA), and the substrate integrated waveguide (SIW) antenna. They are shown in Figure 3, and the coaxial feeding technique has been used for sake of visual simplicity. Some general characteristics of these topologies are their light weight, their stable EM performance under bending conditions, their multi-band performance, and their flexibility to choose between linear or circular polarization.

2.2.1. Microstrip Antenna

The microstrip antenna, as shown in Figure 3a consists of a radiator patch, a dielectric substrate, a ground plane, and a feeding point that can be implemented with different techniques. The radiator patch dimensions (width (W_p), length (L_p), and thickness (h)) determine the resonant frequency, BW, and efficiency of the microstrip antenna. The shape of the radiator patch (rectangular [32,33,35,37,42,49,50,72,73], circular [52,54,56,57], square [6,34,39,58], and others [7,36,40–43]) combined with the feeding technique (type, number of feeds, and their positions) determines the number of frequency bands, polarization, BW, and gain of the antenna.

Several BW enhancement techniques have been proposed for microstrip antenna topologies: (I) The modification of the patch creating complex designs to combine different resonant frequency bands [7,36,41,43], (II) the insertion of slots in the radiator patch [6,36,42,50,52,69], (III) the addition of parasitic elements to the radiator patch layer [7,36,40,42], and (IV) the modification of the feeding technique [34,40,42,49,63,74].

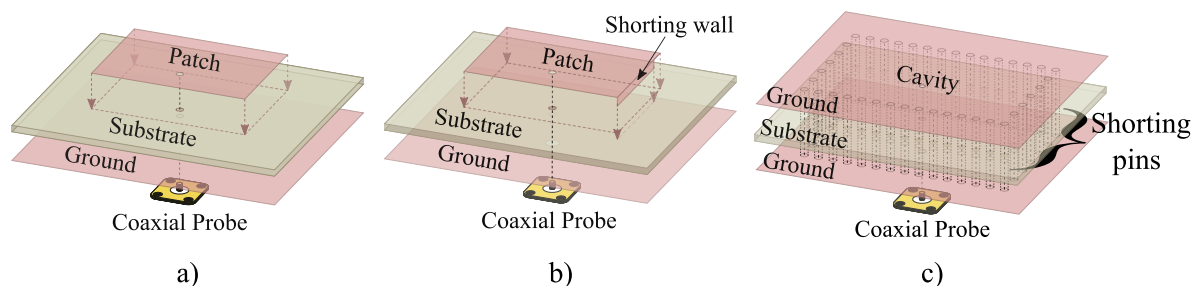


Figure 3. (a) Microstrip antenna. (b) Planar inverted F-antenna (PIFA). (c) Substrate integrated waveguide (SIW) antenna.

2.2.2. Planar Inverted F-Antenna

The PIFA antenna is an evolution of the microstrip antenna. It consists of a radiator patch, a dielectric substrate, a ground plane, a shorting wall, and a feeding probe, as shown in Figure 3b [42,47,48]. The shorting wall design and location, the feed line position, the thickness of the substrate, and the ground plane size are significant PIFA parameters [47] in order to improve the impedance BW and the dual-multi band performance compared to conventional microstrip antennas.

The main impedance BW enhancement techniques proposed for PIFA topologies are the insertion of slots in the radiator patch [47,48]. The utilization of other feeding techniques is not an option, and the addition of parasitic elements or the design of complex radiator patches have not been found in the recent literature for PIFA textile off-body communication antennas.

2.2.3. Substrate Integrated Waveguide Antenna

The SIW antenna could be considered as another evolution of the PIFA topologies. The single or specific shorted area between the ground and the radiator patch of PIFA topologies becomes periodic shorted pins of a closed shape, creating a resonant cavity, as shown in Figure 3c. The SIW structure consists of two conductive layers separated by a dielectric substrate, where the top conductive layer is usually fed with a coaxial probe. The advantages of these topologies are: (I) The increased isolation between antenna and wearer without the need for a large ground plane, (II) low-cost and low-loss implementation, (III) being compact and low profile [44], and (IV) their miniaturization possibilities by exploiting the symmetry of the field distribution of the resonant modes, like a half-mode or quarter-mode SIW [45]. The body isolation is significantly increased when compared to conventional microstrip antennas with larger ground planes and smaller dimensions [53].

The use of slots in the resonant cavity to enhance the impedance BW or to obtain dual band antennas has been reported in the recent literature [44,45,51,53,55]. Finally, note that most SIW

topologies found in the literature for textile off-body communication antennas are fed with a coaxial probe, nevertheless, other feeding techniques have been found like the microstrip lines [51].

2.3. EM Antenna Performance

The main EM antenna performance parameters reported in this survey, as shown in Table 1 are: (I) -10 dB $|S_{11}|$ BW (%); (II) the maximum measured gain (dBi); (III) the total efficiency (%) of an antenna, as the ratio between the power radiated by the antenna and the power delivered to the antenna; (IV) the front To back radiation (FTBR) (dB), as the ratio between the power radiated in the main radiation lobe and the power radiated in the opposite direction; and (V) the Specific Absorption Rate (SAR) (W/kg), which is the absorbed RF energy by human tissue.

According to the latest literature: (I) The highest measured impedance BW are found on coaxially fed antennas with complex radiator patches, including parasitic elements and slots [7,36]; (II) the highest gain levels are reported on proximity fed rectangular and complex patch microstrip antennas, and on coaxially fed SIW topologies [7,42,55]; (III) the best measured antenna efficiencies are reported on SIW and PIFA topologies with slots [44,47,55]; (IV) the highest FTBR results are reported on proximity and coaxially fed microstrip patch antennas [32,42,45,48,57,73]; and (V) the lowest SAR values are found on coaxially fed slotted patch microstrip antennas [6,37,37,43,50,52,54].

Table 1. Textile antenna's design vs. electromagnetic (EM) performance.

Ref.	k	Antenna Design					EM Antenna Performance				
		Overall Size (λ) $W \times L \times h$	Feed Type	Patch Type	Structure	BW Enhancement	Centr. Freq. (GHz)	Meas. BW (%)	Meas. Gain (dBi)	Meas. Eff. (%)	Meas. FTBR (dB)
[47]	100	$0.12 \times 0.32 \times 0.04$	Coaxial	Rectang.	PIFA	None	2.48	*44.7	1.53	77.23	*6
[47]	72.3	$0.12 \times 0.31 \times 0.04$	Coaxial	Rectang.	PIFA	Slot	2.47	*47.8	1.74	80.52	*4
[32]	61	$0.50 \times 0.61 \times 0.01$	Proxim.	Rectang.	Micr.	None	2.45	15.5	0.33	-	23
[32]	35.1	$0.52 \times 0.64 \times 0.01$	Proxim.	Rectang.	Micr.	None	2.45	11.8	0.41	-	21
[36]	26.9	$0.64 \times 1.07 \times 0.04$	Coaxial	Complex	Micr.	Both	2.20	52	3.38	-	21
[40]	23.2	$0.66 \times 0.87 \times 0.05$	CPW	Octagone	Micr.	Parasitic	9.50	*108.8	**7.2	-	10
[48]	18.9	$0.22 \times 0.29 \times 0.04$	Coaxial	Triangular	PIFA	Slot	2.14	15.2	-	70.6	**5
[7]	18.9	$1.06 \times 1.16 \times 0.04$	Coaxial	Complex	Micr.	Parasitic	5	96.4	6.75	75	14
[42]	14	$0.32 \times 0.32 \times 0.03$	Proxim.	Rectang.	PIFA	None	2.45	*3.3	3.1	-	*15
[52]	13.2	$0.56 \times 0.56 \times 0.02$	Coaxial	Circular	Micr.	Slot	2.45	3.3	5.02	**63.5	*13
[6]	10.5	$0.71 \times 0.71 \times 0.02$	Coaxial	Square	Micr.	Slot	2.21	*14.3	2.5	40	*12
[42]	7.93	$0.63 \times 0.63 \times 0.05$	Proxim.	Rectang.	Micr.	Slot	4.8	10	8	-	*30
[45]	7.57	$0.51 \times 0.51 \times 0.03$	Coaxial	Complex	SIW	Slot	2.45	4.8	4.2	81	*24
[46]	6.39	$0.80 \times 0.73 \times 0.02$	Coaxial	Rectang.	SIW	None	2.4	6.4	2.9	**55	*22
[44]	5.12	$0.55 \times 0.45 \times 0.03$	Coaxial	Complex	SIW	Slot	2.45	4.9	4.1	72.8	*14
[55]	4.82	$0.44 \times 0.75 \times 0.07$	Coaxial	Rectang.	SIW	Slot	5.35	*20.2	6.66	90	8
[51]	3.11	$0.79 \times 1.41 \times 0.02$	Micr.	Rectang.	SIW	Slot	5.8	*4.3	-	-	*18
[69]	3.07	$0.94 \times 0.94 \times 0.02$	Micr.	Rectang.	Micr.	Slot	5.91	9.3	-2.8	17.2	9
[42]	2.44	$0.70 \times 0.70 \times 0.06$	Proxim.	Rectang.	Micr.	None	5.35	*2.8	7.8	-	*20
[53]	2.32	$0.59 \times 0.38 \times 0.03$	Coaxial	Rectang.	SIW	Slot	2.45	*5.1	5.28	73	*5
[41]	1.72	$1.42 \times 1.42 \times 0.03$	Coaxial	Complex	Micr.	None	2.49	17.1	-0.3	15.2	*17
[37]	0.91	$0.80 \times 0.80 \times 0.10$	Coaxial	Rectang.	Micr.	Slot	5.1	*13.6	6.2	**75	*8
[56]	0.36	$0.32 \times 0.32 \times 0.01$	Coaxial	Circular	Micr.	None	2.46	6.5	-7.2	24	*0

* Calculated from graph; ** Simulation result.

2.4. Conclusions

Textile off-body communication antennas have a wide variety of design alternatives related to the feeding techniques (coaxial, proximity, aperture, microstrip line, microstrip inset line, and CPW) and antenna topologies (microstrip, PIFA, and SIW). Other alternative designs have been reported in the literature for BW enhancement, like the insertion of slots in the radiator patch or resonant cavities, or the addition of parasitic elements. Table 1 compiles the most relevant research works done so far in order to ease future designs of fully grounded textile antennas for off-body communications. A figure of merit has been used, considering the importance of having a high impedance BW, a high FTBR, and a low antenna volume. The measured efficiency of the antenna has not been taken into account, because of the lack of information in the reported literature. Nevertheless, it should be another feature

to take into account in future surveys. The figure of merit has been calculated using (1), which has been normalized to 100 in Table 1.

$$k = \frac{BW(\%) \cdot FTBR(dB)}{volume(\lambda^3)} = \frac{\left(\frac{f_2 - f_1}{f_c}\right) \cdot (G_f - G_b)}{W \cdot L \cdot h}, \quad (1)$$

where f_1 , f_2 and f_c are the minimum, maximum, and central frequencies of an antenna with return losses below -10 dB, respectively. G_f and G_b are the antenna gain at its peak (bore-sight) and its opposite direction, respectively.

The overall size (λ) of the antennas has been calculated using the lowest frequency of the -10 dB $|S_{11}|$ band. The overall volume of the antenna has been calculated ($W \cdot L \cdot \text{Thickness}(h)$) (λ^3). The measured gain, as shown in Table 1, represents the maximum gain in any given direction. Most FTBR values have been obtained from the measured radiation pattern graphs, since most of the reported literature just illustrate the graphs, but do not numerically describe the FTBR values. Most literature offers measured BW results, nevertheless, there is a lack of measured gain and efficiency parameters of the antennas. When a publication reports more than one relevant antenna implementation, each of them could be represented in separate rows in the table. All measured results illustrated in Table 1 have been obtained in free-space and flat surface scenarios. Antenna measurements under diverse conditions have been described in Section 4.

The figure of merit k shows that the combination of the highest BW, the highest FTBR, and the smallest antenna volume can be achieved using PIFA and proximity fed microstrip topologies. PIFA with slots and fed by a coaxial probe, reports excellent BW versus volume results. Proximity fed microstrip antennas, report excellent FTBR versus volume results. Note that a high FTBR in textile off-body communication antennas is key to obtain a low SAR and a low disturbance of the EM performance of the antenna due to the body proximity.

SIW topologies have reported a low k in this survey's figure of merit, because their volume is large compared to their BW. Nevertheless, their radiation efficiency and FTBR are excellent for off-body communications. PIFA's main drawbacks are their high substrate thickness and low FTBR, which makes this topology complex to embed in garments. Nevertheless, their wide BW and small overall surface ($W \cdot L$) give them a good k value. Microstrip topologies have reported inconsistent results, nevertheless, proximity fed microstrip antennas show thin substrates and excellent FTBR results.

3. Antenna Construction Techniques

The right selection of feeding, antenna topology, or the BW enhancement techniques are the first steps to achieving the desired EM performance of a fully grounded planar antenna. However, in textile applications, the construction techniques and materials are also crucial, and are sometimes even more restrictive. A state of the art regarding materials for textile antennas can be found in [75]. Nevertheless, a brief enumeration of the latest reported dielectric and conductive materials is given in this survey. The main dielectric substrates are: (I) Felt [6,7,36,37,39,40,43,46–48,50,51,53,56,57,72], (II) foam [34,42,44,45,55], (III) denim [32,49,72,73], (IV) leather [41,54,58], (V) neoprene [58], and (VI) Polydimethylsiloxane (PDMS) [52]. The main conductive textile fabrics are: (I) Pure Copper Polyester Taffeta Fabric (PCPTF) [32,35,44,45,47,49,55,58], (II) silver-coated nylon ripstop fabric [42,52], (III) Nickel–copper polyester ripstop fabric [33,73], (IV) ShieldIt Super fabric [6,7,36,37,40,43,46,47,50,53,72], (V) Shieldex Zell [41,51,54,56,57], and (VI) Shieldex NoraDell [39]. Conductive threads have also been reported for PIFA and SIW antennas' shorting vias and for fully embroidered antennas: (I) Metallic wires [37], (II) 92 ShieldEx [51,54,56], (III) Liberator 20 [39], and (IV) ShieldEX 117f17 1-2 ply [69].

This section introduces the state of the art of how the latest literature deals with (I) the attachment of RF connectors to the textile antennas, (II) the multilayer attachment, (III) alignment, and (IV) the different cutting techniques of the fabrics.

(1) The attachment of an RF connector is necessary to evaluate the EM performance of the antennas [37,76]. SubMiniature version A (SMA) straight RF connectors [7,40,42,45–47,52] and

Hirose Ultra-small surface mount coaxial connector (U.FL) [34,55] have been used for antenna evaluations, according to the recent literature. SMA connectors are bulky and degrade the flexibility of the antenna [37,46], but have a pin which serves as a feed for the coaxial probe, decreasing the manufacturing process complexity compared to U.FL connectors [55]. The addition of a planar and rigid structure like a shim of brass to increase the connector's robustness has been used in [69]. On the other hand, U.FL connectors provide better antenna flexibility performance and robustness during washing [37,46], but the connector attachment complexity increases the resonance frequency error between simulation and measurement, and reduces the expected measured BW [55].

The attachment between connector and conductive layers has been performed using galvanic soldering or gluing. Galvanic soldering increases the stiffness of the feeding area making it less flexible, but it provides better conductivity than most glues [7,33,39,40,48,72]. High Frequency Silver Epoxy [34,37,42,47,51,52,54,56,69] provides a low resistivity of $<0.001 \text{ ohm}\cdot\text{cm}$ and higher flexibility rates, making it suitable for wearable antennas and construction processes.

(2) The over-stacking of conductive and dielectric fabrics is the most common antenna construction method. Nonetheless, a few embroidered techniques have been reported in the latest literature for off-body communication antennas [64,77]. The layer attachment is performed using glue or dielectric threads (sewing) [32,39,47,49,51,54,56,57,63,73]. The sewing of the antennas can be hand-made [51,57] or machine-made [32,39,49]. The two main reported gluing techniques to attach the antenna layers are the thermally activated adhesive sheet-glue [44,45,55,58] and the embedded adhesive on the conductive layer [7,46,47,50,72,73]. Other gluing techniques have been reported, like conventional glues [35,42,58], bi-adhesive tape [34], PDMS [52], and spray adhesive [33]. According to the latest literature on off-body communication antennas, and to the best of our knowledge, an evaluation of the permittivity and thickness variations that are introduced by the thermally activated adhesive sheets or the embedded adhesive has not been reported.

(3) There is a lack of systematic layer alignment techniques for multi-layer antenna topologies or for complex radiator patches with parasitic elements [42,55]. Complex off-body communication antennas need layer alignment techniques: (I) Multilayer structures, where the positioning of each layer is key to obtain the desired EM performance; (II) parasitic elements, where the distance to the radiator patch and its orientation is key to obtain the desired coupling; and (III) PIFA or SIW topologies, where the positioning of each shorted wall, the thickness of the vias, and its distance are also key aspects.

(4) The cutting technique for each antenna layer determines the manufacturing accuracy and repeatability. This survey separates two main techniques: (I) hand-made using scissors, a blade cutter, or a scalpel [6,7,32,37,40,44,46,47,49,50,52]; and (II) laser-cutting [33,42,45,53,55,58,69]. The hand-made fabrication method has been mainly used for simple antenna designs to avoid mayor fabrication errors [7,37,47]. But fabrication tolerance studies have been reported [47], and, according to the latest literature, the antenna's EM performance difference between simulated and measured results have been attributed to them [6,7,40,47,49,52]. On the other hand, laser-cutting machines have demonstrated their accuracy [33,42,45,55,58] and repetitiveness [33,42,55], they prevent miss-alignments between slots and the patch [55], they increase and simplify the fabrication procedure [55], and they allow to remove single layer areas [69]. As main drawbacks, the first setup and calibration time of the machine is time consuming, and the heat of the laser cures the edge of the material leaving the edge not as clean as a knife's cut [55].

The conductive textile fabrics that have been laser-cut are: (I) PCPTF [45,55,58], (II) silver-coated nylon ripstop fabric [42], (III) Nickel-copper polyester ripstop fabric [33], and (IV) ShieldIt Super fabric [53].

To the best of our knowledge, and according to the latest reported literature on off-body communication textile antennas: (I) PIFA topologies have mainly used high conductive silver epoxy to attach the RF connectors to the feeding point, embedded adhesive to attach the layers [42,47], and the hand-made cutting technique [47,48], as shown in Table 2. (II) SIW topologies have used galvanic soldering for their RF connectors and thermally activated adhesive sheet to attach the

antenna layers [44–46,53,55]. (III) Coaxially fed microstrip antennas have been cut using hand-made techniques. (IV) ShieldIt Super conductive fabric and Nylon ripstop fabric materials are the only reported conductive fabric that have embedded adhesives [7,42,46–48,52]. (V) The thinnest dielectric fabric reported in this survey is Denim, with a unitary thickness of 0.7mm, as shown in Table 2. Nevertheless, it has been used for proximity fed microstrip antennas [32], which uses a multilayer feeding technique with a total of 5 layers (2 dielectric layers and 3 conductive layers). (VI) an embroidered antenna [69] which uses the laser-machine cutting technique to create a slot, by removing one layer after the antenna is constructed.

Table 2. Antenna Construction Techniques and Materials.

Ref.	Materials			Antenna Design			Construction Method				
	Diel. Name	Unit. Thick. (mm)	Cond. Name	Feed Type	Structure	# of Total Layers	Port Attach. Method	Port Glue Type	Layer Attach. Method	Layer Glue Type	Cutting Method
[47]	Felt	6	ShieldIt Sup.	Coax.	PIFA	3	Glue	Ag Epoxy	Glue	Emb.	Man.
[47]	Felt	6	PCPTF	Coax.	PIFA	3	Glue	Ag Epoxy	Sewn	-	Man.
[48]	Felt	6	ShieldIt Sup.	Coax.	PIFA	3	Galv.	NA	Glue	Emb.	Man.
[42]	Foam	1.6	Nylon Rips.	Prox.	PIFA	5	Glue	Ag Epoxy	Glue	Emb.	Laser
[45]	Foam	3.7	PCPTF	Coax.	SIW	3	Galv.	NA	Glue	Adh. Sheet	Laser
[46]	Felt	3	ShieldIt Sup.	Coax.	SIW	3	Galv.	NA	Glue	Emb.	Man.
[44]	Foam	3.9	PCPTF	Coax.	SIW	3	Galv.	NA	Glue	Adh. Sheet	Man.
[55]	Foam	4	PCPTF	Coax.	SIW	3	Galv.	NA	Glue	Adh. Sheet	Laser
[53]	Felt	3	ShieldIt Sup.	Coax.	SIW	3	Galv.	NA	Glue	-	Laser
[32]	Denim	0.7	PCPTF	Prox.	Micr.	5	Galv.	NA	Sewn	-	Laser
[32]	Denim	0.7	PCPTF	Prox.	Micr.	5	Galv.	NA	Sewn	-	Man.
[42]	Foam	1.6	Nylon Rips.	Prox.	Micr.	5	Glue	Ag Epoxy	Glue	Ag Epoxy	Laser
[36]	Felt	3	ShieldIt Sup.	Coax.	Micr.	3	-	-	Glue	-	Man.
[7]	Felt	3	ShieldIt Sup.	Coax.	Micr.	3	Galv.	NA	Glue	Emb.	Man.
[52]	PDMS	-	Nylon Rips.	Coax.	Micr.	3	Glue	Ag Epoxy	Glue	PDMS	Man.
[6]	Felt	1.5	ShieldIt Sup.	Coax.	Micr.	3	-	-	Glue	-	Man.
[37]	Felt	6	ShieldIt Sup.	Coax.	Micr.	3	Glue	Ag Epoxy	Glue	-	Man.
[56]	Felt	1	Zell	Coax.	Micr.	3	Glue	Ag Epoxy	Sewn	-	Man.
[39]	Felt	1	NoraDell	Coax.	Micr.	3	Glue	-	Sewn	-	Man.
[69]	PET-PES	0.025	117f17	Micr.	Micr.	3	Glue	Ag Epoxy	Sewn	-	Laser
[40]	Felt	2	ShieldIt Sup.	CPW	Micr.	5	Galv.	NA	Glue	-	Man.

4. Antenna Measurements under Diverse Conditions

It is assumed that the performance of textile antennas designed for off-body communications depend not only on ideal (flat surface, free-space) scenarios, but also body-proximity, bending conditions, diverse compression levels of the substrate [35], diverse crumpling shapes [78], and diverse humidity levels [55]. The antenna performance can vary significantly from that in free-space scenarios [7,37,43,44,46,51,52]. Such differences can mainly vary based on: (I) The ground plane size [36,42–48,52,54], (II) the distance gap between the body and the antenna [36,47,48,50], (III) the antenna orientation [36,48,50,52], (IV) and the antenna location on the body (chest [7,37,40,42–48,50,55,56], arm [36,37,40,42,46,49,52,55], forearm [37,42,56], back [7,47,48], and thigh [37]), and (V) the bending radius [6,33,37,42–44,46,51–53,55–57,73].

The typical consequences of body-proximity evaluations are the impedance matching deterioration [6,37,40,43–50,55,56], the resonant frequency detuning [6,37,40,44,45,47–50], the radiation performance degradation [39,43–48,50,55,56], and a non-acceptable SAR value [6,37,43–48,50,53]. The literature uses computer aided CST Hugo [50,53] and Duke voxel models [54,56], phantoms [40,44,46,50] based on the IEEE C95.1, and the distance gaps used between the body and antenna are 2 mm [44], 5 mm [53,56], and 10 mm [6,50,52].

To the best of our knowledge, and according to the latest literature for off-body communication textile antennas, different antenna measurements under diverse conditions have been reported, as shown in Table 3. (I) The distance gap between the body model or phantom, and the antenna under test is normally between 1 and 10 mm. Computer aided simulations have been done with 3 layer phantoms, or voxel models (Hugo and Duke models), while real bodies [6,7,37,43–49,55] or phantoms [39,51,52,56,57] have been used for on-body measurements. (II) The evaluation of

the antennas under bending is done with a solid cylinder. The bending radius reported in this literature varies from a small wrist (20 mm) [6] to the upper side of a leg (80 mm) [46]. The EM performance under bending conditions has been studied using 1 radius [44,52,53], 2 radii [33,42,73], and 3 radii [6,55]. The bending of the antenna under different antenna axes has also been reported measuring 1 axis [33,42,53,55], 2 axes [52,73], or 3 axes [44]. The most common measured axes are x-axis, diagonally, and y-axis. (III) It has been found that the maximum gain of the antennas tends to decrease when they are on-body [7,42,44,45,52]. (IV) The antenna efficiency also decreases when they are on-body due to the absorption produced by the body [39,44,48,56]. (V) the FTBR of the antennas increase when they are on-body, because it acts as a reflector [7,44,45,52,55].

Note that the only parameter measured under bending conditions shown in Table 3 is the impedance BW. The rest of the parameters under bending conditions were not shown because of the lack of information from the reported literature.

Table 3. Antenna Measurements under Diverse Conditions

Ref.	Measurement Setup				Design		BW (%)			Gain (dBi)		Eff. (%)		FTBR(dB)	
	Dis. Gap (mm)	Bend. Radii (mm)	Centr. Freq. (GHz)	Body Model	Feed Type	Structure	Flat Free-Space	Flat Body	Bend Free-Space	Flat Free-Space	Flat Body	Flat Free-Space	Flat Body	Flat Free-Space	Flat Body
[44]	1	40	2.45	Phantom	Coax.	SIW	5	4	5	4.1	4.4	73	61	13.5	14
[44]	1	40	5.8	Phantom	Coax.	SIW	5	5	7	5.8	5.7	86	69	12.5	13.5
[45]	2	-	2.45	Phantom	Coax.	SIW	5	5	-	4.2	3.8	81	81	24	28
[6]	10	20	2.21	Phantom	Coax.	Micr.	14	14	13	2.5	-	40	-	12	12
[6]	10	30	5.5	Phantom	Coax.	Micr.	22	17	13	4	-	40	-	12	12
[7]	5	-	5	Phantom	Coax.	Micr.	96	93	-	6.8	6.3	45	45	14	20
[53]	5	30	2.45	Hugo Mod.	Coax.	SIW	5	5	5	5.28	5.35	73	74	5	-
[52]	10	45	2.45	Phantom	Coax.	Micr.	3	4	4	5.02	4.16	-	-	13	16.5
[52]	10	45	5.8	Phantom	Coax.	Micr.	4	4	4	3.66	4.34	-	-	11	15.2
[51]	5	50	5.8	Duke Mod.	Micr.	SIW	4	4	-	-	3.12	-	38	18	17
[55]	-	-	5.8	-	Coax.	SIW	16	16	15	6.64	-	90	-	8.5	20
[42]	0	30	4.8	Phantom	Prox.	Micr.	10	9	11	8	7.55	-	-	30	-
[48]	1	-	2.14	Hugo Mod.	Coax.	PIFA	15	13	-	-	-	71	40	-	-
[48]	1	-	5.28	Hugo Mod.	Coax.	PIFA	11	10	-	-	-	73	53	-	-
[37]	5	-	5.1	Hugo Mod.	Coax.	Micr.	14	14	-	6.2	-	-	-	8	-
[37]	5	-	2.45	Hugo Mod.	Coax.	Micr.	2	3	-	-3.8	-	-	-	-	-
[46]	5	40	2.4	Phantom	Coax.	SIW	6	7	-	2.9	-	-	-	22	-
[46]	5	80	5.65	Phantom	Coax.	SIW	12	12	-	5	-	-	-	10	-
[43]	15	-	2.44	Hugo Mod.	Coax.	Micr.	4	2	-	5	-	-	-	-	-
[33]	-	43.2	2.44	-	Micr.	Micr.	2	2	2	-	-	-	-	-	-
[39]	10	-	2.4	Phantom	Coax.	Micr.	5	6	-	0	1.8	57	42	-	-
[73]	-	28.5	2.4	-	Coax.	Micr.	5	6	5	-	3.8	-	-	23	-

5. Conclusions

Planar textile antennas for off-body communications have been mainly designed using microstrip, SIW, and PIFA topologies with full ground planes, to achieve the desired EM performance on-body scenarios and under bending conditions. These antenna topologies have used a variety of feeding techniques (coaxial, proximity, microstrip line, microstrip inset line, and CPW) to obtain the desired mechanical and EM performance. Different BW enhancement techniques have been also reported, like the insertion of slots in the radiator patch or resonant cavities, or the addition of parasitic elements.

It is concluded (in flat surface and free-space measurement scenarios) that PIFA and proximity fed microstrip topologies are the best candidates if the goal is a combination of the highest BW, the highest FTBR, and the smallest antenna volume. PIFA with slots and fed by a coaxial probe showed an excellent BW versus volume results. Proximity fed microstrip antennas have reported excellent FTBR versus volume results. Last but not least, SIW topologies have achieved high radiation efficiencies and high FTBR levels.

Nevertheless, the performance of textile antennas designed for off-body communications depend not only on ideal (flat surface, free-space) scenarios, but also depends on the body-proximity, bending conditions, compression levels of the substrate, crumpling shapes, and humidity levels. The ability to control the ground plane size, the distance gap to the body, the orientation, and the bending radius of the antennas determine the robustness of the antenna prototypes under diverse conditions. Typical

consequences of on-body antennas are the impedance matching deterioration, resonant frequency detuning, radiation performance degradation, and non-acceptable safety requirements (SAR above standard threshold). Nonetheless, computer aided voxel models and phantoms, and real on-body measurements using volunteers or phantoms have been found to evaluate and optimize the EM performance of textile off-body communication antennas under such conditions.

The construction techniques of planar textile antennas are key to obtain the desired EM performance with an acceptable repeatability factor. Therefore, it has been concluded that 4 major steps need to be considered for the construction of planar textile antennas: (I) The attachment of the RF connector to the antenna. SMA and U.FL connectors have been connected using galvanic soldering or gluing. Galvanic soldering increases the stiffness of the feeding area making it less or even not flexible, but it offers better conductivity than most glues. High Frequency Silver Epoxy provides higher flexibility rates, making them more suitable for wearable antennas and manufacturing processes. (II) The attachment of the antenna layers. This is performed using glue or dielectric threads (sewing). The sewing can be hand-made or machine-made, and the gluing is done using thermally activated adhesive sheet glue or using embedded adhesive on the conductive layer. (III) The layer alignment technique is mainly required for multi-layer antenna structures and for complex radiator patches with parasitic elements, since the positioning of each layer is key to obtain the desired EM performance. The distance to the radiator patch and its orientation are key to obtain the desired coupling, and the positioning, thickness, and distance of the shorting vias of PIFA and SIW topologies also need accurate alignment. Finally, (IV) the cutting technique for each antenna layer are hand-made and laser-cutting made, where the hand-made fabrication method has been mainly used for simple antenna designs to avoid mayor fabrication errors, and laser-cutting made to provide higher cutting accuracy and repetitiveness for more complex antenna designs.

Finally, it has been concluded that most literature usually offers the simulated and measured data (BW and gain) of the antennas on free-space scenarios, nevertheless, there is a lack of information in other fields. Most FTBR values have been obtained from the measured radiation patterns graphs. Simulated and measured results of the radiation efficiency of the antennas are not reported. On-body and under-bending results are missing in most of the reported literature. The effects of the permittivity and thickness variations that are introduced by the thermally activated adhesive sheets or the embedded adhesives on the antennas have also not been found.

Author Contributions: R.D.-R.-R. contributed to the conceptualization, investigation, resources, and the overall research. J.-M.L.-G. contributed to the investigation, resources, writing—review and editing. J.L. contributed to the writing—review and editing, supervision and project administration.

Funding: This research was funded by the Collaborative Research in Strategic Areas 2018, Department of Economic Development and Infrastructure of the Basque Government. LangileOK: Advanced technologies to support the workers of Industry 4.0. File No.: KK-2018/00071.

Acknowledgments: This research was supported by the Department of Education of the Basque Government, by granting a Pre-Doctoral scholarship to Ruben Del-Rio-Ruiz.

Conflicts of Interest: The authors declare no conflict of interest.

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APPENDIX

B

Paper II

Design and Performance Analysis of a Purely Textile Proximity Fed Microstrip Patch Antenna for On-Body Wireless Communications

This paper was presented in the symposium “*2018 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting (APS/URSI 2018)*” in Boston, Massachusetts, USA between July 8th-13th, 2018. Its DOI is 10.1109/APUSNCURSINRSM.2018.8608986. It can be accessed online through the IEEE Xplore Digital Library. The published version is appended here. © 2018 IEEE. Reprinted, with permission.

Design and Performance Analysis of a Purely Textile Proximity Fed Microstrip Patch Antenna for On-Body Wireless Communications

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Abstract—Novel combinations of materials and construction techniques are key for the development of new textile antenna configurations for on-body applications. Stretchable, flexible and conformable features of textile antennas are one of the hot research topics nowadays. This work gives a step forward with new designs of purely textile proximity coupled microstrip patch antennas with flexible and robust features at 2.44GHz, on-body applications. Their performance is successfully validated in different materials, both simulated and constructed, and obtaining positive results.

I. INTRODUCTION

In the last decades, the microstrip patch antenna (MPA) has been researched and developed extensively in both the military and commercial sector. Because of its light weight, planar profile, robustness, ease of fabrication, and conformability with a shaped surface, this class of antennas are being merged with textile technologies in body-centric wireless communications (BCWC) [1]. However, the disadvantage of conventional MPA is the limited frequency bandwidth. BCWC systems such as wearable health monitoring systems potentially improve the quality of life by providing a low cost and real-time health status sensing and alerting in cases of emergencies, for instance. Antennas designed for wearable computing are, therefore, meant to operate in/on or close to the human body [2]. These Antennas need to be comfortable, aesthetically acceptable to be worn, and be shielded from the body to avoid safety risks.

Most MPA's disadvantage is the narrow frequency bandwidths obtained. Therefore, most textile ultra-wideband (UWB) antennas obtain their bandwidth by using aperture MPA, increasing the thickness of the substrates, introducing slots, or by implementing partial ground planes [3], [4]. The main drawback of these solutions is that they have high-back radiation, and this is undesirable for body worn communications. Proximity coupled MPA provides large bandwidth, low spurious radiation, low-back radiation and less soldering, making this type of MPA structure suitable for worn antennas.

In this work, five proximity coupled antennas are presented for on-body communications. The originality of this work lies in the fact that the results of the designed, simulated, and constructed antennas are coherent with each other, making this work a solid base for future works with more efficient and optimized all-textile proximity coupled MPA.

II. PROXIMITY COUPLED MPA DESIGN AND SIMULATION

A 2.44 GHz proximity coupled MPA has been designed. The configuration of the proposed MPA is shown in Figure 1 and 2, which is based (top to bottom) of a radiating patch, a substrate, a transmission line, a second substrate, and a ground layer to shield the transmission and patch layer.

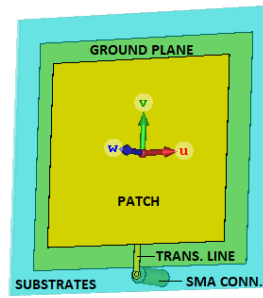


Fig. 1. 3D view of the structure of a proximity coupled MPA.

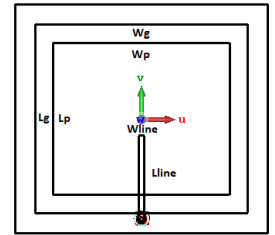


Fig. 2. Main dimension variables of the antennas.

Five different designs have been performed as shown in Table I. Three reference antennas, using well-known materials and constructing techniques have been developed using a Printed Circuit Board (PCB). Once the reference antennas were verified, the other two antennas have been made of different textile materials and dimensions.

TABLE I
MICROSTRIP COUPLED MPA PROTOTYPES

Name	substrate	Cond. layers	Wp(mm)	Lp(mm)
MPA-001	FR4	copper anneal	36.1	27.1
MPA-002	FR4	copper anneal	36.1	25.3
MPA-003	FR4-2	copper anneal	37.1	28.1
MPA-004	Frannel	copper Taffeta [7]	52.4	45.3
MPA-005	Cotton	copper Taffeta	57.3	50.3

The dimensiones for the radiating patch have been obtained from well-known MPA design formulas [5]. The obtainment of the ground dimensions are given by Equation 1.

$$Xg = 6 * h + Wp \quad (1)$$

Where h is the total thickness of the antenna, Xg is either the width or the length of the ground layer, and Wp the width of the patch. The transmission line width was calculated for 2.44GHz and an impedance of 50 Ohms the length of the line was optimized to achieve the most optimum return loss for each antenna. In Table II the properties of the materials used for this work are presented.

TABLE II
DIELECTRIC AND CONDUCTIVE MATERIAL PROPERTIES

Name	ϵ'	Loss T.	Cond. (S/m)	Thickness(mm)
FR4	4.8	0.027		1.5
FR4-2	4.5	0.01		1.4
Coppeal anneal			4.7e+7	0.035
Copper Taffeta			4.7e+6	0.08
Flannell	1.75	0.057		0.45
Cotton	1.3	0.03		1.75

III. DESIGN RESULTS AND MEASUREMENTS

To simulate the antenna designs, Computer Simulator Technology (CST) software was used. Nevertheless, the return loss obtained from the first simulated antenna (MPA-001) did not match the desired frequency band, as is can be seen in Graph 3. Therefore, the length of the radiation patch and the transmission line were modified to center de desired frequency band to 2.44GHz (MPA-002) as illustrated in 4. After constructing both antennas, the conclusion obtained was that the issue was on the parameters introduced in the simulator. As shown in Graph 3 and 4, both antenna designs shift to higher frequencies between 150-200MHz. After the changes of MPA-002 were made, the S11 was centered around 2.42GHz, while the measured antenna was centered at 2.6GHz. Four identical MPA-001 antennas were constructed with a total deviation of 90MHz and 3dB. Two MPA-002 antennas were constructed with a total deviation of 20MHz and 0.5dB.

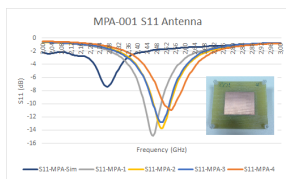


Fig. 3. Return loss of MPA-001 PCB Antenna.

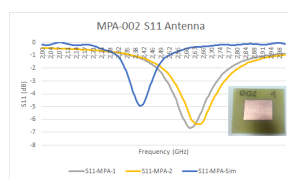


Fig. 4. Return loss of MPA-002 PCB Antenna.

After doing some reasearch both in the simulator and the constructed antennas, it was concluded that there were two main issues for the mismatch between the simulator and the real measurements gap. The first problem was the thickness of the PCB's substrate. The machine that produced them, took 0.1mm of FR4 substrate from each layer, making the antenna resonate at a higher frequency that it was supposed to. The second problem was found at the permittivity of the FR4. The manufacturer datasheet specified the permittivity around 4.8

at 1MHz, but after performing the characterization of the FR4 with the Dielectric Probe Kit of Agilent [6], the permittivity was between 3.8 and 4.5 (upon surface roughness) between 2-3 GHz. After including this changes in the design formulas, new dimensions were obtained, therefore antenna MPA-003 had to be simulated and constructed. The results between the simulator and real measurement match as shown in Figure 5. The last procedure was to design, simulate, and construct the textile antennas as shown if Figure 6.

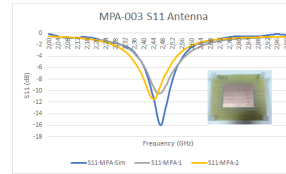


Fig. 5. Return loss of MPA-003 PCB Antenna.

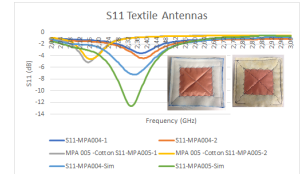


Fig. 6. Return loss of MPA-004 and MPA-005 textile Antennas.

This antennas still need to be improved in order to obtain better S11 (<-10dB) performance. Nevertheless, the simulation and real results were coherent for the MPA-004 antenna. Since antenna MPA-005 is made of Cotton, which is more flexible than flannell, the thickness of the substrate changed making the antenna thickness increase. Different substrate attachment methodologies will be investigated in order to prevent future inconsistencies.

IV. CONCLUSION

The use of proximity coupled MPA can be used in textile technologies, obtaining low back radiation, wider frequency bandwidths, less soldering, and simple construction structures. The PCB antenna prototypes showed coherence between design, simulation and construction results, creating a solid base for the development of purely textile antennas in the upcoming publications.

Open issues for future work are related to textile connectivity procedures, stretchable designs and other novel construction methods, as layer glueing, and digital laser cut.

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APPENDIX

C

Paper III

A Combination of Transmission Line Models as Design Instruments for Electromagnetically Coupled Microstrip Patch Antennas in the 2.45 GHz ISM Band

This paper has been published in the journal “*IEEE Transactions on Antennas and Propagation (TAP)*”, on June 17th, 2020. Its DOI is 10.1109/TAP.2020.3001668. It can be accessed online through the IEEE Xplore Digital Library. The published version is appended here. © 2020 IEEE. Reprinted, with permission.

Communication

A Combination of Transmission Line Models as Design Instruments for Electromagnetically Coupled Microstrip Patch Antennas in the 2.45 GHz ISM Band

Ruben Del-Rio-Ruiz^{ID}, Juan-Manuel Lopez-Garde^{ID}, Jon Legarda^{ID}, Olivier Caytan^{ID}, and Hendrik Rogier^{ID}

Abstract—This communication presents an analytical framework that combines transmission line models for the design of electromagnetically coupled microstrip patch antennas for the 2.45 GHz industrial, scientific, and medical band. It provides initial values for all dimensions of the antenna, with measured resonance frequency errors below 6%. The initial design is optimized in two subsequent phases to center the resonance frequency and to increase the impedance bandwidth (BW), obtaining measured resonance frequency errors below 0.6% and BW enhancements of more than 1.2 times the original ones, respectively. The model has been validated with antenna prototypes based on rigid and textile materials, exhibiting excellent free-space measured BW of 4% and 5.12%, maximal measured gains of 4.28 and 7.33 dBi, and radiation efficiencies of 63.4% and 71.8%, respectively. Moreover, very stable on-body performance is obtained, with minimal frequency detuning when deploying the textile antenna on the human body. The measured maximum on-body gain for the textile antenna equals 5.5 dBi, with a simulated specific absorption rate of 0.323 W/kg at 2.45 GHz.

Index Terms—Design methodology, electromagnetic (EM) coupling, flexible structures, microstrip textile antennas, transmission line (TL) models.

I. INTRODUCTION

Microstrip patch antennas (MPAs) have been extensively developed for military [1] and civil [2] applications. Their main characteristics of lightweight, planar profile, robustness, ease of fabrication, and conformability make them suitable for textile material implementations in body-centric wireless communication (BCWC) systems [3].

Recent work has focused on three of the main challenges associated with textile MPAs used for BCWC: 1) widening their inherent narrow impedance bandwidth (BW) [4], [5]; 2) increasing their front to back ratio (FTBR) to avoid the degradation of their normal operation due to body proximity [1], [2], [6]; and 3) realizing them in a comfortable and esthetically pleasing manner.

The electromagnetically coupled microstrip rectangular patch antenna (EMCMPA) offers a good performance tradeoff in terms of these three challenges [4], [7]–[11]. Nevertheless, the implementation of analytical prediction models to accurately fix the substrate thickness and the dimensions of the radiating patch, the feed line, and the ground plane of an EMCMPA is complex due to the electromagnetic (EM) coupling between the feed line and the radiating patch.

Manuscript received December 29, 2019; revised June 3, 2020; accepted June 5, 2020. Date of publication June 17, 2020; date of current version January 5, 2021. The work of Ruben Del-Rio-Ruiz was supported by the Basque Country Government by fully granting a Predoctoral scholarship for his Ph.D. Degree. (Corresponding author: Ruben Del-Rio-Ruiz.)

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Digital Object Identifier 10.1109/TAP.2020.3001668

There are several design models for EMCMPAs, which can be categorized in two groups: simple analytical models and rigorous full-wave models. The latter involves extensive computational processing, which in most cases does not account for fabrication tolerances or other modifications to the realized prototypes compared to the simulated designs [12], [13]. On the other hand, simple analytical models can provide a good and intuitive understanding of the EM performance of the EMCMPA, combined with a reasonably accurate mathematical formulation. These models typically use the transmission line (TL) model to predict the initial dimensions of at least one part of the EMCMPA, but they do not provide all antenna dimensions.

In [8], only the radiating patch of a textile EMCMPA is modeled based on equations from [14], and they do not analyze the deviation between model and measured resonance frequency. However, excellent impedance BW and FTBR values are achieved for the 2.45 GHz industrial, scientific, and medical (ISM) band, even though the antenna's radiation efficiency is not simulated nor measured. In [4], a partial analytical model is presented for a dual stub feed line of an EMCMPA in the 10 GHz band, but the deviation in resonance frequency between model and measurements is not specified. Yet, an excellent BW of 8.4% is achieved, although the radiation efficiency and FTBR values are not provided. In [15], a partial model is presented for a nontextile RT/Duroid-based EMCMPA, which obtains a maximum deviation in resonance frequency of 7.7%. However, the frequency band is not centered at the 2.45 GHz ISM band, and the gain and radiation efficiency values are not available. In [7] and [9], novel textile EMCMPAs are presented. No analytical models are applied in the design phase, but their performance can be considered as a reference for EMCMPAs. Ooi [9] shows very good BW and FTBR values, although the overall thickness is high and the BW is not centered at the 2.45 GHz ISM band. Finally, Adami *et al.* [7] presents a textile EMCMPA for the 2.45 GHz ISM band, with a relatively small thickness. Gain and radiation efficiency values are a good reference for textile EMCMPAs in this band, although no FTBR values are given.

Therefore, this communication presents an analytical design instrument that approximately fixes all dimensions of an EMCMPA, with a given substrate, in the 2.45 GHz ISM band, and with an error lower than that reported in previous publications.

II. ANTENNA DESIGN

A. Antenna Topology and Principle of Operation

As shown in Fig. 1, the EMCMPA is composed (top to bottom) of a radiating patch ($W_p \times L_p \times h_{cond}$), a first dielectric layer ($W_{sub} \times L_{sub} \times h_{sub}$), a feed line ($W_{line1} \times L_{line1} \times h_{cond}$), a second dielectric layer ($W_{sub} \times L_{sub} \times h_{sub}$), and a ground plane ($W_g \times L_g \times h_{cond}$).

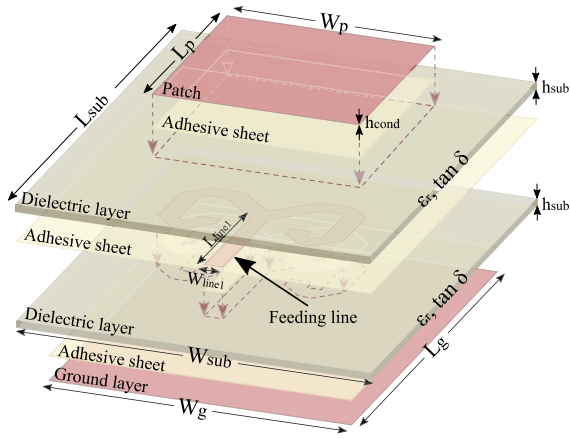


Fig. 1. Perspective view of the electromagnetically coupled microstrip patch textile antenna structure. For clarity, all the antenna layers have been separated and labeled at the side.

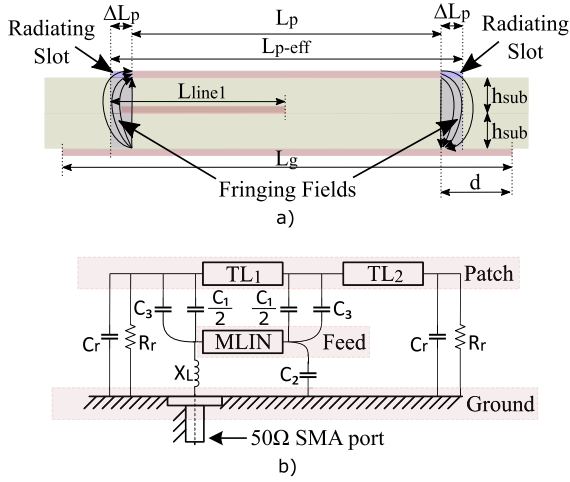


Fig. 2. (a) Physical and effective lengths and (b) equivalent circuit model of EMCMPAs [16].

The EMCMPA is excited by the microstrip feed line, which is electromagnetically coupled through the top substrate to the radiating patch. The feed line is located between the ground plane and the radiating patch, such that any radiation from the feed line is shielded and potentially reradiated by the patch, leading to a good cross-polarization [4]. This topology places the radiating patch further away from the ground plane [Fig. 2(a)], which leads to enhanced BW and efficiency values, while the feed line is closer to the ground plane to reduce its parasitic radiation.

B. Analytical Model

The aim of the proposed analytical model is to easily obtain all the dimensions for the preliminary design of an EMCMPA, yielding a resonance frequency as close as possible to the desired value. Moreover, the model also attempts to maximize BW without increasing the overall thickness. The model is suitable to design both rigid and textile-based EMCMPAs, providing high radiation efficiencies and good antenna performance in close body proximity.

The analytical model combines several TL model equations. First of all, the conventional TL model represents the MPA by two radiating slots [Fig. 2(a)], each described by a parallel equivalent impedance Z_r (with resistance R_r and capacitance C_r), as shown

in Fig. 2(b) [14], and separated by a low-impedance TL (TL_1 and TL_2) of total length L_p . The dimensions L_p and W_p of the rectangular microstrip patch are obtained using [14]

$$W_p = \frac{c}{2f_r \sqrt{(\epsilon_r + 1)/2}} \quad (1)$$

$$L_p = \frac{c}{2f_r \sqrt{\epsilon_{reff}}} - 2\Delta L_p \quad (2)$$

where f_r is the antenna's desired resonance frequency, ΔL_p is the extension of the patch length at each end caused by the fringing effects of the radiating slots, and ϵ_{reff} is the effective relative permittivity [14].

Second, the feed line of an EMCMPA can be modeled as a microstrip line (MLIN) [15], which is buried under TL_1 , as shown in Fig. 2(b). C_1 represents the coupling capacitance between the feed line and the radiating patch, modeled as two capacitors of equal value on either side of MLIN [16]. The feed line exhibits fringing fields, whose effect results in a small increase in its length. This creates extra capacitance, modeled by C_2 , from the open-ended MLIN to the ground, and C_3 , from both sides of MLIN to the radiating patch, which modifies its input impedance, yet the resonance frequency remains constant [16]. The 50 Ω subminiature version A (SMA) connector is represented in the EMCMPA's equivalent circuit model by an inductive reactance X_L connected to MLIN.

As reported in [12], [17], and [18], the optimum EM coupling is obtained when the patch is centered over the end of the feed line and located above it, if the overall thickness $2 \cdot h_{sub}$ is at a certain critical value [17]. In this communication, the overall thickness is fixed and below the critical value. Therefore, the feed line and patch are over-coupled, which slightly decrements its matching performance [17]. Yet, in these publications, the radiating elements are half-wavelength long dipoles, which leads to quarter-wavelength feed lines, as described in [17]. Therefore, our model suggests a quarter-wavelength feed line using

$$L_{line1} = \frac{c}{f_r \sqrt{\epsilon_{reff}} \cdot 4} \quad (3)$$

with the open-end at $L_p/2$ and equal substrate thicknesses, as shown in Fig. 2(a). In this communication, the feed line's fringing fields are neglected, since the input impedance's variation is negligible, mainly due to the substrate's small thicknesses and low permittivities. Nevertheless, they should be considered if different dielectric substrates are chosen.

The characteristic impedance of the feed line is set to $Z_0 = 50 \Omega$, as shown in Fig. 3(a). It is approximately calculated using (4) and (5) reported by Garg *et al.* [19, p. 773], where $Z_0 \sqrt{\epsilon_{reff}} \leq 89.91$

$$W_{line1} = \frac{2 \cdot h_{sub}}{\pi} \cdot \left(B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \cdot \left(\ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right) \right) \quad (4)$$

$$B = \frac{60\pi^2}{Z_0 \sqrt{\epsilon_r}} \quad (5)$$

Employing a quarter-wavelength feed line allows to cover the desired BW, although in a tight way (2.4–2.485 GHz) in the case of the proposed antenna prototypes due to their small substrate thickness. Resonance frequency shifts up to 50 MHz in textile antennas have been reported due to manual SMA connectorization and inhomogeneities in the substrate's dielectric properties [20]. Therefore, to better guarantee that the textile antennas cover the entire 2.45 GHz ISM band, a ram-horn-shaped feed line is proposed as an alternative design to enlarge the EMCMPA's BW [4]. The ram-horn feed line is a combination of quarter-wavelength feed line and two

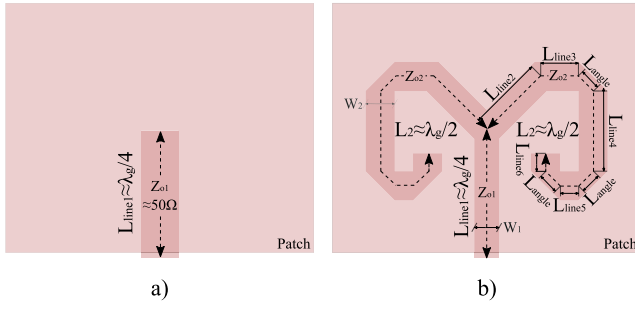


Fig. 3. Proposed feed lines for the EMCMPAs. (a) Quarter-wavelength feed line. (b) Ram-horn-shaped feed line [4].

symmetric half-wavelength open-ended stubs connected at $L_p/2$, as shown in Fig. 3(b), that use impedance transformations to achieve greater BW. The initial dimensions of the ram-horn-shaped line are obtained from [4], where L_{Line1} is a quarter-wavelength long with characteristic impedance Z_{o1} , and L_2 is a half-wavelength long with characteristic impedance Z_{o2} . The input impedance Z_{line} of the ram-horn shaped feed line is

$$Z_{line} \simeq jZ_{o1} \left\{ \frac{2 \cdot Z_{o1}}{Z_{o2}} \right\} \cdot \tan(\beta \cdot L_2) - \cot(\beta \cdot L_{line1}). \quad (6)$$

The ground plane dimensions are modeled using $X_g = X_p + 12 \cdot h_{sub}$, where X_g and X_p correspond to either the width (W) or length (L) of the ground and patch, respectively. To ensure that the resonance frequency of the antenna remains almost identical as in an infinite ground plane scenario, the ground plane dimensions must also fulfill the design rule $d \geq \lambda_0/20$ [21], with d being the ground plane extension, as illustrated in Fig. 2(a). In the case of conflict the later takes precedence.

The substrate dimensions are obtained by adding 12 mm to the ground plane, to ease the layer-alignment process. Nevertheless, it has been verified that the antenna performance remains identical when the ground and substrate dimensions are equal.

C. Antenna Materials

The proposed analytical model is validated for both rigid and textile materials. The rigid antenna uses FR4 as a dielectric layer because its loss tangent is similar to that of textile substrates, and manufacturing with this material is fast and cost-effective by means of a milling-machine [22]. Therefore, a rigid antenna implemented with this material serves as a good validation prior to constructing the textile antennas. The conductive layer is a 35 μm -thick annealed copper sheet. Both dielectric layers are assembled using plastic nuts and screws. All computer-aided FR4 antenna design models include air gaps and extra FR4 removal gaps to model the removal process of the anneal copper. The extra FR4 removal gaps depend on the prototyping machine's accuracy, which in some cases could be negligible. The textile antenna uses felt as dielectric layer and pure copper polyester taffeta fabric (PCPTF) as conductive layer with a thickness of 80 μm and a surface density of 80 g/m^2 . Table I summarizes these parameters.

The preliminary values for the permittivity and loss tangent, shown in Table I, are measured using the Agilent 85070E Dielectric Probe Kit, and the substrate parameters are obtained after a conventional design, simulation, and measurement process [23], [24].

The textile antennas are constructed according to the process explained in [20]. A total of four double-sided thermally activated adhesive sheets (approximate thickness of 20 μm , $\epsilon_r = 1.74$ and

TABLE I
MATERIAL PROPERTIES OF THE TWO PROPOSED ANTENNAS

Code	Substrate	Thickness (mm)	ϵ'_r	Loss T.	Conductor	Sheet Res. Ω/sq
RIG_x	FR4	1.43	4.08	0.01	Annealed copper	0.0005
TEX_x	Felt	1.2	1.25	0.003	PCPTF	0.05

ϵ'_r : optimized relative permittivity at 2.45 GHz.

TABLE II
ANTENNA DIMENSIONS PROPOSED BY ANALYTICAL MODEL

Code	W_p	L_p	W_g	L_g	W_{sub}	L_{sub}	W_{line1}	L_{line1}
RIG_1	38.57	29.49	55.73	46.65	67.73	58.65	2.89	16.07
TEX_1	57.96	52.45	72.36	66.85	84.36	78.85	5.2	27.75

Units: mm

$\tan \delta = 0.015$) are required to assemble all the EMCMPA layers, as shown in Fig. 1.

III. ANTENNA IMPLEMENTATION

The proposed analytical model is the first step in a three step process to obtain the desired antenna design in a single construction attempt, where the third phase is only necessary if the desired BW is not fully covered. It provides the initial dimensions of all EMCMPA layers for a given resonance frequency, input impedance and dielectric materials. This initial design is optimized in two subsequent phases to center the resonance frequency and increase the BW to the desired band. These two optimization steps are performed using the time-domain solver of CST Microwave Studio. Although the proposed design process is intended to avoid manufacturing prototypes until all three steps are completed, in this communication the antennas are simulated, manufactured, and measured after each phase to see the error evolution between the analytical model and each of the prototypes.

A. Model Implementation

The proposed analytical model is applied to design an antenna with a resonance frequency of 2.44 GHz, an input impedance of 50 Ω and the material parameters described in Table I. The initial dimensions obtained for rigid and textile antennas are shown in Table II, which are designated as RIG_1 and TEX_1 . The first three letters are denoted by the dielectric layer of the antennas (RIG_1 stands for the FR4-based rigid antenna and TEX_1 stands for the Felt-based textile antenna), and the following number by the design phase (1)–(3).

The resonance frequency errors between proposed model and simulation, simulation and measurement, and the proposed model and measurement are shown in Table III, using the following equation:

$$\text{Model versus Meas. (\%)} = \left| \frac{f_{r\text{model}} - f_{r\text{meas.}}}{f_{r\text{model}}} \right|. \quad (7)$$

In addition, there are two effects derived from the construction process that are considered in the simulation, although their influence on the results is minimal. The first effect is the influence of h_{air} in rigid antennas, which represents the air layer between the FR4 dielectric layers and the copper conductors due to the tolerance of the milling machine. This air layer (0.1 mm) causes a decrease of 0.3 to 0.5 dB in the $|S_{11}|$ due to the difference in permittivity between FR4 and air. The second effect is due to the adhesive sheet layer h_{glue} that is used in textile antennas to assemble all layers.

TABLE III

PROPOSED MODEL, SIMULATION, AND MEASUREMENT ERROR RATIOS

Code	Model vs. Sim.	Sim. vs. Meas.	Model vs. Meas.
RIG_1	4.92%	0.43%	5.33%
TEX_1	2.25%	0.63%	2.87%
RIG_2	0%	0.05%	0.05%
TEX_2	0%	0.41%	0.41%
RIG_3	0.37%	0.04%	0.33%
TEX_3	0.57%	0.24%	0.33%
$TEX_3(Onbody)$	0.45%	0.16%	0.62%

This layer causes an amplitude variation of about 1 to 3 dB and a frequency shift between 2 and 4 MHz, due to the higher permittivity of the adhesive and the increase of the total thickness, respectively.

The error between simulation and measurement in both antennas is below 0.63%, which validates the fabrication process reliability for both FR4 and textile antennas [20]. The error ratios between the analytical model's center frequency and the measured resonant frequency in the RIG_1 and TEX_1 antennas are 5.33% and 2.87%, respectively, with a measured BW ($|S_{11}| < -10$ dB) of 3.08% and 3.32%, respectively. The error ratios achieved with the proposed analytical model are better than those reported in the literature [15], [16], providing a good first design approach for EMCMPA.

B. Design Optimization

A first optimization step is necessary to better adjust the resonance frequency to the desired band. This communication proposes to modify only the length of the antenna patch (L_p) in order to tune the antenna to the desired resonance frequency. The new dimensions of L_p for the RIG_2 and TEX_2 antennas are 27.8 and 51.1 mm, respectively, which cause a resonance frequency shift of 120 and 60 MHz, respectively, centering the peak at 2.44 GHz. Slightly modifying the length of the radiating patch does not alter the EM performance of the antenna significantly, yielding a similar BW and $|S_{11}|$ amplitude. The RIG_2 and TEX_2 antennas are simulated, manufactured and measured, where a measured BW ($|S_{11}| < -10$ dB) of 3.29% and 3.49% is achieved, respectively. The proposed one-step one-variable optimization process provides a maximum resonant frequency error below 0.41%. Nevertheless, as the 2.45 GHz ISM band is tightly covered, a third optimization step is required.

C. BW Enhancement

A ram-horn-shaped feed line is proposed to enhance the antenna's BW, as shown in Fig. 3(b). The line widths and lengths of the quarter-wavelength feed line and of the two half-wavelength open-ended stubs are calculated to match Z_{line} to the 50 Ω input impedance [4]. Afterward, a computer-aided optimization of the ram-horn shaped feed line is performed using CST Microwave Studio. Application of the design procedure [4] on the RIG_2 and TEX_2 prototypes should yield a BW of 1.4 and 1.6 times the original 3.29% and 3.49% BW, respectively. Yet, slightly lower measured BW increments of 1.2 and 1.5 are obtained in RIG_3 and TEX_3 , respectively, which are in line with the measured increments obtained in [4]. The resonant frequency of RIG_3 and TEX_3 antennas is centered at 2.44 GHz and the BW fully covers the 2.45 GHz ISM band, as shown in Fig. 4. The optimized ram-horn-shaped feed line dimensions of the antennas are shown in Table IV.

TABLE IV

RAM-HORN SHAPED FEED LINE DIMENSIONS

Code	W_1	W_2	L_{line1}	L_{line2}	L_{line3}	L_{line4}	L_{line5}	L_{line6}	L_{angle}
RIG_3	3.06	4.1	38.57	29.49	55.73	46.65	67.73	58.65	5.79
TEX_3	3.68	7.43	57.96	52.45	72.36	66.85	84.36	78.85	10.4

Units: mm

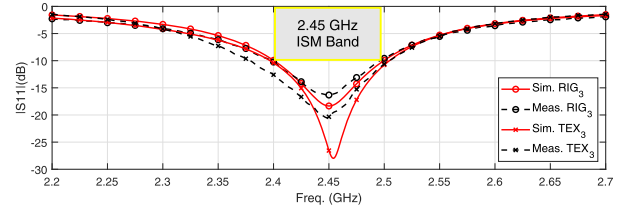


Fig. 4. Simulated and measured reflection coefficient results in free space for RIG_3 and TEX_3 EMCMPAs, using FR4 and felt dielectric layers.

IV. FINAL EXPERIMENTAL VALIDATION

The electromagnetically coupled ram-horn-shaped fed MPAs are fabricated and tested under free space and on-body conditions to validate their EM performance. The antenna measurements are performed with an Agilent N5242A PNA-X Microwave Network Analyzer, with the antennas placed in an anechoic chamber.

A. Free Space Performance

The simulated and measured reflection coefficients of the rigid and textile antennas are shown in Fig. 4. Excellent agreement is observed between simulated and measured values. Both RIG_3 and TEX_3 antennas are centered at 2.44 GHz and cover the entire 2.45 GHz ISM band (2.4–2.4835 GHz), with a measured BW ($|S_{11}| < -10$ dB) of 4% and 5.12%, respectively.

Cross sections of the radiation pattern of the antennas in the E- and H-planes are measured in the anechoic chamber at 2.45 GHz, as shown in Fig. 5. Again, there is an excellent agreement between the measured and simulated results. The maximum measured copolarization gains for the RIG_3 and TEX_3 antennas are 4.11 and 7.33 dBi, respectively. The cross-polarization is very small, both in simulations and measurements. Their deviations are due to effects by the mounting fixtures of the measurement system and to positioning and measurement errors.

The simulated and measured maximum antenna gain and the total antenna efficiency between 2.4 and 2.5 GHz are plotted in Fig. 6. The maximum measured antenna gains for the RIG_3 and TEX_3 antennas equal 4.28 and 7.33 dBi, respectively. The maximum measured antenna efficiencies for the RIG_3 and TEX_3 antennas equal 63.4% and 71.8%, respectively. There is a good agreement between the measured and simulated RIG_3 antenna results, while the textile antenna has a difference of less than 10% due to slight variations in the felt dielectric properties.

B. On-Body Performance

The TEX_3 textile antenna is simulated and measured on the torso of an average adult person. The simulation uses a three layer (skin-fat-muscle) body phantom. The dielectric properties of the phantom layers are obtained from the Hugo voxel model from the CST material library. The two main phantom thickness setups [2], [25] are simulated to obtain a better accuracy, with an overall thicknesses of 22 and 70 mm, respectively. The measurement is performed with

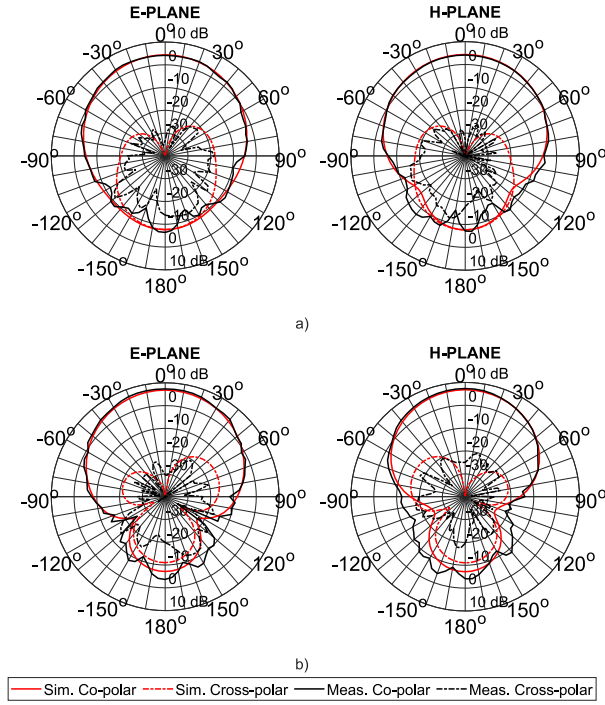


Fig. 5. Simulated and measured co- and cross-polarization patterns in free space for (a) RIG_3 and (b) TEX_3 EMCMPAs, using FR4 and felt dielectric layers, respectively.

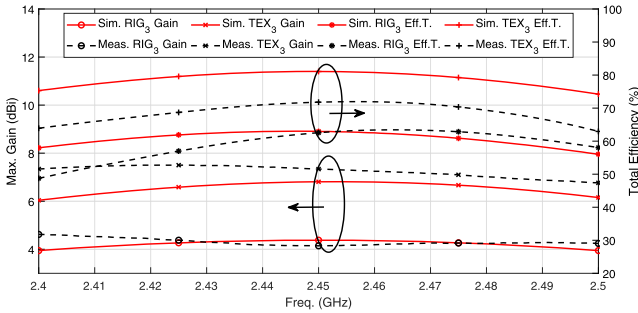


Fig. 6. Simulated and measured maximum gain and total antenna efficiency results in free space for RIG_3 and TEX_3 EMCMPAs, using FR4 and felt dielectric layers.

a person of size 1.75 m and weight 85 kg inside the anechoic chamber. In both cases, the antenna is placed 2 mm away from the simulated phantom and measured body. The simulated and measured reflection coefficients in on-body and free space scenarios are compared in Fig. 7. The reflection coefficient remains below -10 dB in the entire 2.45 GHz ISM band and the simulation and measurement differences between on-body and free-space scenarios are negligible.

The 3-D measurement of the antenna performance on the torso of a person inside the anechoic chamber is not possible. Therefore, the antenna is reoriented to measure the far-field radiation patterns in the E- and H-planes at 2.45 GHz. Fig. 8 shows the co- and cross-polarization results, where the maximum gain is 5.5 dBi. The measured cross-polarization in the E- and H-plane remains below -13.2 dBi. The patterns in the E- and H-planes at 2.45 GHz agree well both in shape and absolute values when placed on the body, which means that the proposed design method provides also a good performance for BCWC applications.

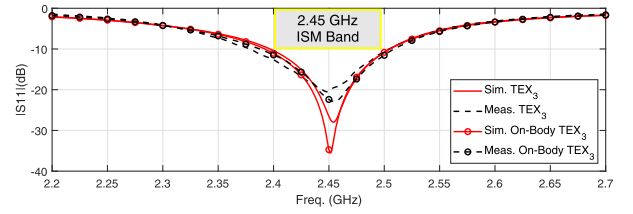


Fig. 7. Simulated and measured on-body reflection coefficient results for the TEX_3 EMCMPAs, using felt dielectric layers.

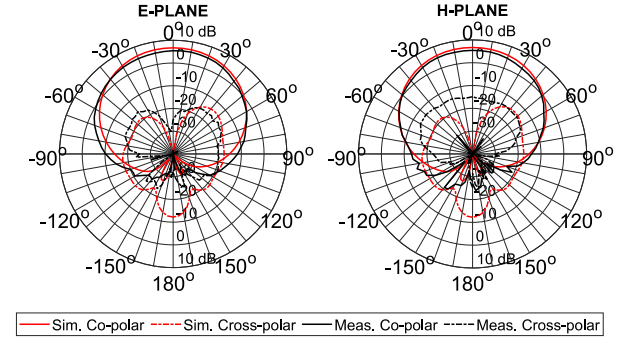


Fig. 8. Simulated and measured on-body co- and cross-polarization patterns for the TEX_3 EMCMPA, using felt dielectric layers.

Finally, the specific absorption rate (SAR) values are simulated using the proposed phantom properties and thicknesses [2], [25], obtaining maximum SAR values at 2.45 GHz of 0.199 and 0.323 W/kg, respectively, which are well below the limit of 1.6 W/kg, according to standard IEEE C95.3, with an input power of 0.5 W (rms), and averaged over 1 g of biological tissue. These results are coherent with the values shown in Fig. 8, which indicate that most of the radiation is directed away from the body, owing to the presence of a ground plane and a shielded feed line.

V. CONCLUSION

The analytical model proposed in this communication quickly and reliably yields the initial dimensions of an EMCMPA. Two subsequent simulation phases which modify a single design variable in each phase are presented, achieving a centered resonance frequency and BW enhancement, respectively. This design instrument enables the realization, in a single attempt, of an EMCMPA antenna for the 2.45 GHz ISM band on both rigid and textile materials. The textile antennas designed with this procedure have a high flexibility owing to their small thickness, and an excellent radiation performance in BCWC applications, with antenna gains and efficiencies of 7.33 dBi and 71.8%, respectively, and SAR values lower than 0.4 W/kg.

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APPENDIX

D

Paper IV

Towards More Accurate Design Models for Electromagnetically coupled Microstrip Patch Antennas Between 1 and 10 GHz

This paper was presented online in the symposium “*2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting (APS/URSI 2020)*”, between July 5th-10th, 2020. Its DOI is yet to be given. It can be accessed online through the IEEE Xplore Digital Library. The published version is appended here. © 2020 IEEE. Reprinted, with permission.

Towards More Accurate Design Models for Electromagnetically-Coupled Microstrip Patch Antennas between 1 and 10 GHz

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Abstract—This work presents an analytical framework approach for electromagnetically-coupled microstrip patch antennas (EMCMPA) to more accurately predict the initial antenna dimensions between 1 - 10 GHz. The proposed EMCMPA design model is validated in simulation, where a coherent error is obtained between the desired and simulated resonant frequency. A minimum simulated antenna efficiency of 80% and initial resonance frequency errors smaller than 10% are achieved in all tested frequencies.

Index Terms—Design model, electromagnetically-coupled feed line, microstrip antennas.

I. INTRODUCTION

Electromagnetically-coupled microstrip rectangular patch antennas (EMCMPA) offer a good performance trade-off in terms of the following three antenna challenges: (i) widening their inherent narrow impedance bandwidth (BW) [1]–[4], (ii) increasing their front to back ratio (FTBR) to avoid the degradation of their normal operation due to body proximity [1], [5]–[7], and (iii) realizing them in a comfortable and aesthetically pleasing manner.

A perspective view of its topology is shown in Fig. 1. This type of antenna is particularly suitable for off-body communications as its ground plane reduces the negative effect of body proximity [7]. Its feed structure avoids rigid components or galvanic soldering between radiating patches and feed lines [8], thereby maximizing the antenna's flexibility. The feed line and radiating patch can be positioned on thin and thick dielectric layers, respectively [2], thereby providing better radiation efficiencies and higher BWs. The absence of turns, junctions and other discontinuities in the feed line also reduces spurious radiations [9]. Moreover, the addition of stubs in the feed line [2], parasitic elements, or slots in the radiating patch increase its BW. One of the main drawbacks of EMCMPA topology is the complex layer alignment in the construction process. However, recent work has solved this problem on a laboratory scale [10], which definitely opens up the application of this topology for textile applications.

The implementation of analytical prediction models to accurately fix all EMCMPA dimensions is complex due to the electromagnetic-coupling between the feed line and the radiating patch. Therefore, in this work an EMCMPA design

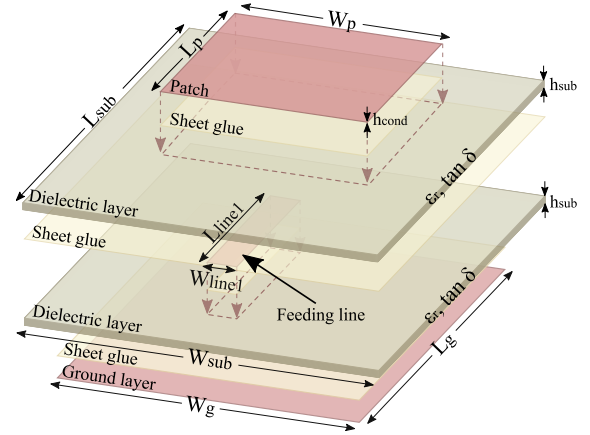


Fig. 1. Perspective view of the electromagnetically-coupled microstrip patch textile antenna structure. For clarity, all the antenna layers have been separated and labeled at the side.

approach is presented to predict the initial dimensions of the antennas for a wide range of frequencies.

II. ANTENNA DESIGN AND ANALYTICAL FRAMEWORK

The EMCMPA is composed (top to bottom) of a radiating patch ($W_p \times L_p$), a dielectric layer ($W_{sub} \times L_{sub}$), a feed line ($W_{line1} \times L_{line1}$), a second dielectric layer ($W_{sub} \times L_{sub}$), and a ground layer ($W_g \times L_g$), as shown in Fig. 1. The antenna's overall assembly comprises three conductive layers with a thickness of h_{cond} each, and two dielectric layers with a thickness h_{sub} each.

The dimensions L_p and W_p of the rectangular microstrip patch are obtained using [9] on pages 816-826. The feed line is modeled using a 50Ω quarter-wavelength feed line. The optimum electromagnetic coupling is obtained when the patch is centered over the end of the feeding line and located above it, if the overall thickness $2 \cdot h_{sub}$ is at a certain critical value [11]. In this conference paper, the overall thickness is fixed and below the critical value. Therefore, the feed-patch match is over-coupled, which slightly decrements its matching performance [11].

To reduce material uncertainties, the proposed design model is validated using a well characterized rigid material. Therefore, Rogers 4003C material as dielectric layer is chosen, with a permittivity of 3.604 and loss tangent of 0.0027 at 2 GHz. The implementation of this model using this material serves as a good validation prior to considering actual textile materials. The conductive layer is a 35 μm thick anneal copper conductive sheet, and each substrate layer is 1.524mm thick. Both dielectric layers are assembled using plastic nuts and screws.

III. DESIGN AND SIMULATION RESULTS

The proposed design model is validated in simulation using computer aided CST Microwave Studio simulation tool from 1 GHz to 10 GHz. The results are shown in Table. I.

TABLE I
COMPUTER-AIDED RESULTS OF THE PROPOSED EMCMPA MODEL

Model Freq. (GHz)	Sim. Freq. (GHz)	Sim. Max. S_{11} (dB)	Sim. Total Eff. (%)	Deviation (MHz)	Error Model (%)
1	0.965	-32	80.4	-35	3.5
1.5	1.435	-28.4	88.1	-65	4.3
2	1.901	-21.1	90.9	-99	5
2.5	2.366	-20.5	92.5	-134	5.4
3	2.831	-25.3	94	-169	5.6
3.5	3.291	-26	94.5	-209	6
4	3.754	-28.1	95	-246	6.2
4.5	4.218	-28	95.1	-282	6.3
5	4.677	-28.9	95.1	-323	6.5
5.5	5.13	-31.6	95.5	-370	6.7
6	5.578	-34	95.5	-422	7
6.5	6.003	-33	95.4	-497	7.6
7	6.428	-27.2	95.7	-572	8.2
7.5	6.848	-22.5	95.5	-652	8.7
8	7.276	-19.4	95	-724	9.1
8.5	7.7	-17.3	94.3	-800	9.4
9	8.117	-15.8	93.9	-883	9.8
9.5	8.526	-14.5	93	-974	10.3
10	8.927	-13.4	91.9	-1073	10.7

The dimensions obtained from the proposed model for each frequency are inserted in the computer-aided design. In Table I the simulation results are presented, where the S_{11} and total antenna efficiencies are obtained. The simulated resonant frequency is calculated where the S_{11} amplitude is maximum for each of the designs. It can be observed a shift in frequency for every design between the desired and simulated resonant frequencies. Nevertheless, the frequency deviations compared with the previous designs have a coherent tendency. An excellent total antenna efficiency is obtained in all the band between 80 and 95%. The proposed design model error is below 10%, which is in agreement with values found in literature [8], [12]–[14].

IV. CONCLUSION

This work presents a basic antenna design framework to initially yield the first dimensions of EMCMPA, with a resonance frequency error of less than 10% and a minimum total efficiency of 80%, between 1 GHz and 10 GHz.

The obtained results are the first step towards more accurate and reliable EMCMPA design instruments to easily obtained their initial dimensions. In future work, a full EMCMPA design model with lower resonant frequency errors will be presented, using different substrates both rigid and textile, which shall be simulated and measured to accurately validate the models.

ACKNOWLEDGEMENT

This work was supported by the Basque Country government by fully granting Ruben Del-Rio-Ruiz a Pre-Doctoral scholarship to perform the Ph.D. Degree.

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APPENDIX

E

Paper V

Design and performance analysis of a purely textile spiral antenna for on-body NFC applications

This paper was presented in the workshop “*2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*” in Pavia, Italy, between September 20th-22nd, 2017. Its DOI is 10.1109/IMWS-AMP.2017.8247427. It can be accessed online through the IEEE Xplore Digital Library. The published version is appended here. © 2017 IEEE. Reprinted, with permission.

Design and Performance Analysis of a Purely Textile Spiral Antenna for On-Body NFC Applications

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Abstract—Novel combinations of materials and construction techniques are key for the development of new textile antenna configurations for on-body applications. Stretchable, flexible and conformable features of textile antennas are one of the hot research topics nowadays. This work gives a step forward with new designs of purely textile spiral antennas with flexible and robust features for Near Field Communications (NFC) on-body applications. Their performance is successfully validated with a real NFC chipset, and some design and construction considerations are offered for novel textile materials.

I. INTRODUCTION

The design of textile antennas has gained much popularity in the last few years, specifically on new designs, textile materials and construction methodologies for new applications [1], [2]. The existing textile antenna designs are based on sewing, embroidery and gluing of conventional threads and fabrics, but new challenges arise when flexibility, stretchability, conformability and robustness characteristics become key for on-body applications. The implementation of textile conductive fabrics, threads, paints or glues to obtain some of these properties are being used by most authors giving good results [3], [4]. Nevertheless, the combination of these textile materials with innovative designs can lead to, for example, more flexible antennas keeping their Electromagnetic (EM) characteristics.

Near field spiral antennas are highly attractive for body-centric and wearable applications. Due to the growing of RFID technology in garments, the tag antenna design becomes one of the most interesting research topics for body centric environments. NFC and RFID tags extract their power from the field received from the reader and the efficient transfer of energy depends on the loop antenna, which must be tuned to the carrier frequency. RFID technologies are generally classified into four frequency ranges; i.e., LF (125-134.2 kHz), HF (13.56 MHz), UHF (433, 860-960 MHz) and microwave frequencies (2.45, 5 GHz).

This work shows the performance and comparison of three LF square spiral antennas (13.56 MHz) utilizing different

conductive and dielectric materials. First, a classic spiral antenna has been designed and developed in a FR4 printed circuit board. Secondly, two designs have been developed, one with a conductive textile thread sewn into a flannel fabric, and another with polyester/cotton fabric. Thirdly, the performance of all antennas has been analyzed and compared, and relevant conclusions are presented. Finally, the designed coil with an embedded NFC chip has been sewn in a leather fabric bracelet, and its functionality and durability were tested.

II. SPIRAL ANTENNA DESIGN AND CONSTRUCTION

A 13.56 MHz coil antenna has been designed using a square shape, because of its simpler construction on textile layers. The overall dimensions and gaps between turns of the antenna are determined by the application and its placement in the garment. The designed antenna's purpose is to be embedded in a textile bracelet by sewing a conductive thread on it.

The line width of the coil antennas is as close as possible to the widths of the conductive threads, commonly between 0.1 mm and 0.6mm.

The equivalent model of the NFC system is divided into the chip circuits and the antenna. The NFC chip is represented by R_{chip} showing its current consumption, in parallel with C_{tag} representing its internal tuning capacitance and parasitics.

The antenna circuit includes three components in parallel:

- C_{ant} : Overall capacitance of the coil antenna.
- R_{ant} : Resistive loss of the coil antenna.
- L_{ant} : Self inductance of the coil antenna.

The resulting antenna impedance is given by Equation 1.

$$Z_{ant} = C_{ant} | R_{ant} | L_{ant} \quad (1)$$

The stray capacitance is generally in a range of few pF for typical NFC antennas and its actual value must be measured once the antenna is constructed, in order to perform the fine tuning. L_{ant} is calculated in two different ways to verify

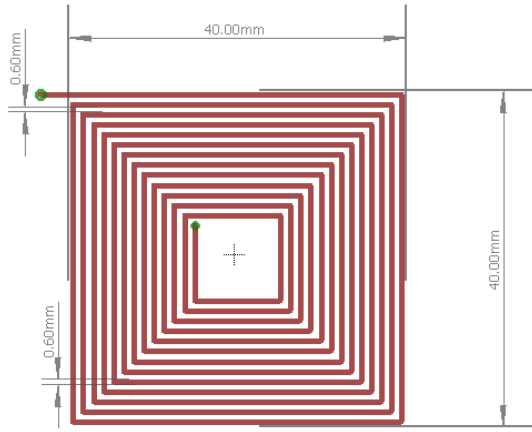


Fig. 1. Layout of the square shaped coil antenna.

the obtained result more accurately. On the one hand, using Equation 2 [8].

$$L_{ant} = K_1 \cdot \mu_0 \cdot N^2 \cdot \frac{d}{1 + K_2 \cdot p} = 4,63uH \quad (2)$$

On the other hand, using eDesignSuite antenna design tool, which takes into consideration more variables, such as the material's properties and thickness. The result obtained is $L_{ant} = 5,04uH$. This method will be chosen since its more accurate and the difference is not too far from the one calculated in Equation 2.

In order to verify the antenna's internal capacitance and the tuning frequency, a prototype needs to be produced. A network analyzer with an ad-hoc probe and the contact-less method has been chosen to characterize the coil antennas.

Three pairs of antennas have been constructed using 3 different dielectric and two conductive materials. The first pair of antennas have been constructed on FR4 PCB boards. The other two pairs of antennas, use purely textile layers, with the same conductive thread but different dielectric fabrics. Table II shows each pair of antennas, named with a unique code, and their constitutive materials.

TABLE I
SPIRAL ANTENNA CONSTRUCTION MATERIALS

Code	Conductive material	Dielectric material
S7-1SA-B	PCB Copper	FR4
S7-2SA-B	2 ply conductive thread [5]	PES/CO
S7-3SA-B	2 ply conductive thread [5]	Flannel

Different conductive threads [6], [7] have been sewn on the fabrics giving negative results, such as, breaking the thread while being sewn, threads touching each other because of the thread thickness, overlapping threads on the fabric and high modification of the textile's flexibility. Therefore, the 2 ply conductive thread [5] has been chosen to construct the textile antennas.

In Table II and III the coil material's EM properties are shown.

TABLE II
ANTENNAS' CONDUCTIVE MATERIALS PROPERTIES

Material	Resistivity $\Omega/inch$	Thickness (mm)
PCB Copper	0.042	0.035
2 ply conductive thread	1.3	0.2

The permittivity and loss tangent of the flannel and polyester/cotton (PES/CO) materials shown in Table III have been obtained with Agilent 85070E Dielectric Probe Kit.

TABLE III
ANTENNAS' DIELECTRIC MATERIALS PROPERTIES

Material	Permittivity	Loss Tangent	Thickness (mm)
FR4	4.7	0.014	1.2
PES/CO	2	0.08	0.3
Flannel	1.8	0.06	0.3

The next phase was to construct the PCB for the reference antenna, and the PCB textile coil holder as shown in Figure 2 and Figure 3 respectively. Both layouts include a SMA and a 3 pin-out connectors (to attach the NFC chip). The layouts were performed with Autodesk Eagle PCB Design Software and the PCB were constructed with the LPKF ProtoMat S62.

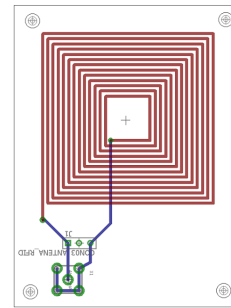


Fig. 2. PCB Layout of S7-1SA-B coil antennas.

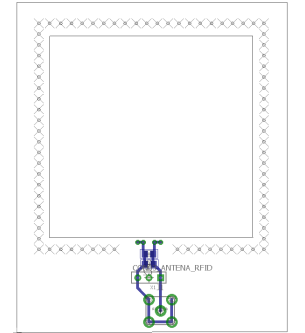


Fig. 3. PCB Layout of S7-2SA-B and S7-3SA-B coil antenna holders.

The PCB textile holder provides the textile coils with equal mechanical characteristics (flatness, and distributed tension), and easy connectivity with the SMA and 3 pin-out connectors, as it can be seen in Figure 3 and 4. Two PCB vias per end have been included in the textile antenna holders in order to attach the conductive threads to the PCB lines.

III. RESULTS

The reflection coefficient of six square spiral antennas have been characterized by using an Agilent N5242A Microwave Network Analyzer (PNA) and an ad-hoc constructed single loop antenna connected to one of the PNA ports. The coil antennas have been tuned for their resonance frequency to be

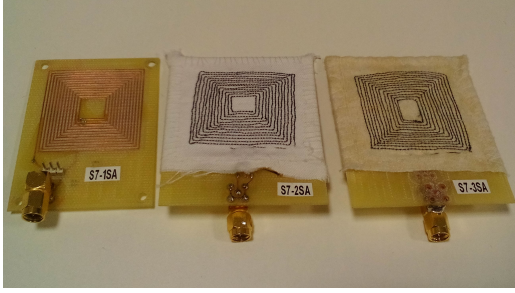


Fig. 4. Coil antennas constructed in PCB (S7-1SA), in polyester and cotton (PES-CO)(S7-2SA), and in franela (S7-3SA)

centered at 13.56MHz. In order to do so, the C_{ant} has been measured, and taking into account C_{tag} , an external capacitor of 6.83pF has been introduced.

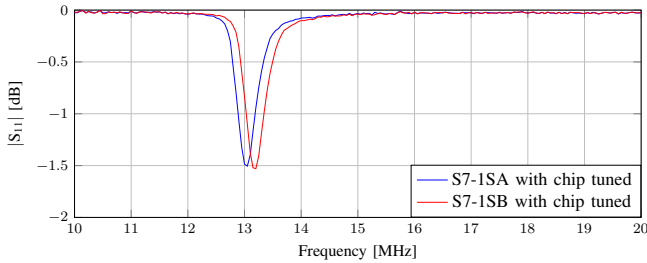


Fig. 5. Measured input reflection coefficient of the S7-1SA and S7-1SB antennas with tuning capacitor.

The antenna prototypes have been measured using 10pF instead of 6.83pF, as this capacitor value was not available. Nevertheless, the actual resonant frequency of S7-1SA-B antennas, as shown in Figure 5, match if we take into account the actual C_{tun} used. The resonant frequencies of S7-2SA-B and S7-3SA-B antennas are shifted up around 0.8 to 1MHz compared with the S7-1SA-B antennas, as shown in Figure 6. This means that the antenna's internal capacitance generated by the textile materials (both dielectric and conductive) is different to the S7-1SA-B loop antennas.

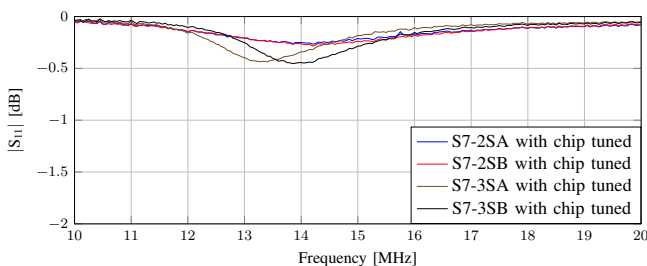


Fig. 6. Measured input reflection coefficient of the S7-2SA-B and S7-3SA-B antennas with tuning capacitor.

The reflection coefficient levels of S7-3SA-B antennas have better performance (-0.45dB) than the S7-2SA-B antennas (-0.25dB) due to the higher permittivity of the dielectric layers.

In order to evaluate the textile coil's performance, durability, and flexibility, it has been embedded in a leather bracelet with a NFC chip and used in real-life operation for a year. The results obtained show that the reading time and distance is the same as commercial MIFARE contact-less (Figure 8) cards in 100% of the times even in harsh conditions (bending, crumpling, moist environments). The prototyped bracelet is shown in Figure 7.



Fig. 7. Designed textile coil embedded in a leather bracelet.



Fig. 8. MIFARE contact-less Deusto card.

IV. CONCLUSION

The use of conductive threads sewn into flannel, PES/CO and leather fabrics has been proved as a feasible construction method for NFC square spiral, purely textile on-body antennas. The mechanical properties of the developed prototype, such as stress, crumpling and bending, have been successfully tested for more than one year of real life use.

Open issues for future work are related to textile connectivity procedures, stretchable designs and other novel construction methods, such as ink-jet and screen printing techniques.

ACKNOWLEDGMENT

Ruben Del-Rio-Ruiz's scholarship for PhD students has been granted by the Department of Education of the Basque Government. The authors would also like to mention Textil Santanderina for their help with the manufacturing of the antennas.

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APPENDIX

F

Paper VI

Reliable Lab-Scale Construction Process for Electromagnetically Coupled Textile Microstrip Patch Antennas for the 2.45 GHz ISM Band

This paper has been published in the journal “*IEEE Antennas and Wireless Propagation Letters (AWPL)*”, on November 28th, 2019. Its DOI is 10.1109/LAWP.2019.2956238. It can be accessed online through the IEEE Xplore Digital Library. The published version is appended here. © 2019 IEEE. Reprinted, with permission.

Reliable Lab-Scale Construction Process for Electromagnetically Coupled Textile Microstrip Patch Antennas for the 2.45 GHz ISM Band

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Abstract—A precise layer alignment is crucial to ensure performance repeatability of multilayer microstrip antennas. We introduce a novel lab-scale construction process for multilayer microstrip textile patch antennas that consists in combining an alignment method, based on laser-cut wood frames to perform accurate layer alignment, with a fast intralayer attachment method, based on thermally activated adhesive sheets. This lab-scale construction process is validated with an electromagnetically coupled microstrip rectangular patch textile antenna operating in the 2.45 GHz ISM band. It has been reproduced eight times to validate the proposed construction process. The differences between desired simulated versus measured average values of the resonant frequencies, impedance bandwidths, gains, and total efficiencies equal 6.25 MHz, 21.5 MHz, 0.6 dBi, and 4.45%, respectively. Moreover, the standard deviations of measured resonant frequencies, impedance bandwidths, gains, and total efficiencies equal 24.54 MHz, 14.02 MHz, 0.15 dBi, and 3.57%, respectively. These results confirm that the novel lab-scale construction process provides good performance repeatability of multilayer microstrip textile patch antennas.

Index Terms—Construction process, electromagnetically coupled microstrip antenna, textile materials.

I. INTRODUCTION

TEXTILE antennas have been an intense research topic for the last few years as they are a key component in many e-textile applications. They face many design, construction, and characterization challenges when they are intended to provide a specific electromagnetic (EM) performance. This letter focuses on another important challenge in textile antennas, which is the construction process. The imprecise alignment of multilayer textile antennas has been a source of uncertainty in many research works [1]–[5], so much so that fabrication tolerance analysis have been performed to predict the effects of mechanical inaccuracies in their designs [6], [7]. Moreover, the application

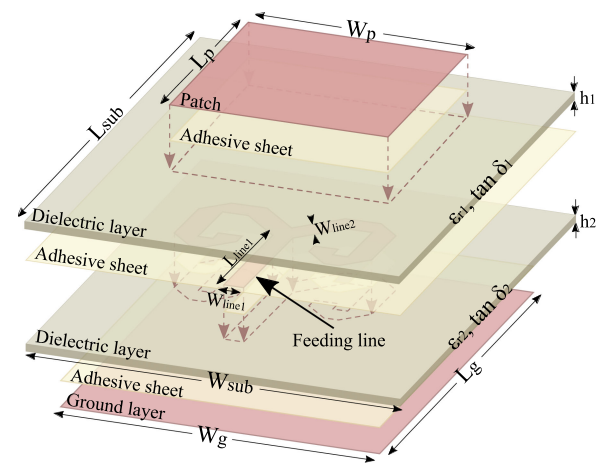


Fig. 1. Perspective view of the EMCMPA structure. For clarity, all the antenna layers have been separated and named at the side.

of complex antenna topologies has been avoided to reduce such uncertainties [8].

The misalignment of one layer can modify undesirably the resonant frequency, the impedance bandwidth (BW), and the radiation pattern of a textile antenna. Many lab-scale construction techniques have been proposed for different antenna structures and materials [1], [2], [9]–[11]. Nevertheless, the performance repeatability of the construction techniques has not been extensively validated, since typically only one or two prototypes are constructed and characterized. Therefore, to the best of our knowledge, this is the first reliable lab-scale construction process that assures the performance repeatability of multilayer textile antennas. This construction process combines an alignment method, based on laser-cut wood frames to implement accurate layer alignment, with a fast intralayer attachment method based on thermally activated adhesive sheets. Moreover, the textile dielectric and conductive layers are laser-cut, providing a repetitive and accurate patterning method.

This lab-scale construction process has been validated by implementing an electromagnetically coupled microstrip patch textile antenna (EMCMPA), as shown in Fig. 1. It is specifically suitable for off-body communications as its ground plane reduces the negative effect of body proximity [12], and it avoids the use of rigid components or galvanic soldering between

Manuscript received September 30, 2019; revised November 12, 2019; accepted November 21, 2019. Date of publication November 27, 2019; date of current version January 20, 2020. The work of R. Del-Rio-Ruiz was supported by the Basque Country government for fully granting a Predoctoral scholarship for the Ph.D. degree. (Corresponding author: Ruben Del-Rio-Ruiz.)

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Digital Object Identifier 10.1109/LAWP.2019.2956238

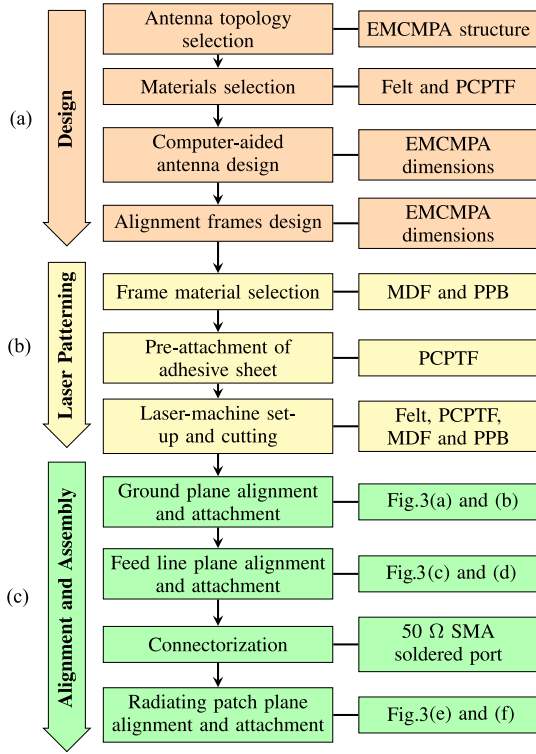


Fig. 2. Proposed construction phases for multilayer textile antennas. (a) Design phase. (b) Laser patterning phase. (c) Alignment and assembly phase.

radiating patches and feedlines [13]. The feed and patch can be positioned on thin and thick dielectric layers, respectively [14], thereby providing better radiation efficiency and higher BW. The absence of turns, junctions, and other discontinuities in the feedlines also reduces spurious radiation [15].

This letter is organized as follows. After the introduction, the following three sections correspond to each main phase of the proposed lab-scale construction process. The different steps are summarized in Fig. 2. Section II describes the design phase, Section III the laser patterning phase, and Section IV the alignment and assembly phase. Section V provides the validation of this process with the main EM parameter measurements, standard deviations, and average results of the eight antennas that are constructed. Finally, conclusions are given in Section VI.

II. DESIGN PHASE

The EMCMPA is composed (top to bottom) of a radiating patch ($W_p \times L_p$), a dielectric layer ($W_{\text{sub}} \times L_{\text{sub}}$), a double horn-shaped stub feedline [14] ($W_{\text{line1}} \times L_{\text{line1}} \times W_{\text{line2}} \times L_{\text{line2}}$), a second dielectric layer ($W_{\text{sub}} \times L_{\text{sub}}$), and a ground layer ($W_g \times L_g$), as shown in Fig. 1. The antenna's overall assembly comprises three conductive layers with a single thickness of h_{cond} and two dielectric layers of thickness h_1 and h_2 . The EMCMPA is excited by a microstrip feedline, which is electromagnetically coupled through the top substrate to the radiating patch. The feedline is located between the ground layer and the radiating patch, such that any radiation from the feedline

TABLE I
EMCMPA DIMENSIONS

W_p	W_g	h_1	h_{glue}	W_{line1}	L_{line1}
58	72.4	1.2	0.02	4.1	$\approx \lambda/4$ [14]
L_p	L_g	h_2	h_{cond}	W_{line2}	L_{line2}
51.1	65.5	1.2	0.08	7.4	$\approx \lambda/2$ [14]

Units in mm.

is shielded and potentially re-radiated by the patch, leading to a good cross polarization [14].

The dielectric layers of the antenna are made of 1.2 mm thick felt textile with a permittivity ϵ' and loss tangent $\tan \delta$ at 2.45 GHz of 1.25 and 0.003, respectively. Preliminary values for the permittivity and loss tangent have been measured using the Agilent 85070E Dielectric Probe Kit, and the substrate parameters have been obtained after a conventional design, simulation, and measurement process [16], [17]. The conductive layers are made of pure copper polyester taffeta fabric (PCPTF), which exhibits a low surface resistivity of $0.05 \Omega/\text{sq}$ at 2.45 GHz. PCPTF is a plain woven fabric, coated with pure copper. It has a thickness of $80 \mu\text{m}$ and an estimated weight of 80 g/m^2 , making it suitable for the construction of textile EMCMPA.

The computer-aided design is performed using CST Microwave Studio 2019, leading to the final EMCMPA dimensions shown in Table I. The dimensions are optimized to cover the 2.4–2.4835 GHz band, with a reflection coefficient below -10 dB .

The last step is the design of the alignment frames, serving as templates guide during the multilayer attachment process. They are tailored to the antenna dimensions.

Fig. 3 shows the layout of the alignment frames and the antenna layers. Alignment frame 1 must have a greater thickness than the inner frames, to hold steady all these alignment frames and antenna layers. The thickness difference between inner and outer frames is determined by the EMCMPA's total thickness, which in this case is $h_{\text{total}} \approx 2.4 \text{ mm}$. Therefore, an outer frame thickness of 5 mm is established.

III. LASER PATTERNING PHASE

Frames made out of wood have been chosen, because they can be easily and accurately laser-cut. For the alignment of frames, 3 mm thick medium-density fibreboard (MDF) and 5 mm thick phenolic plywood board (PPB) have been chosen. Nevertheless, other materials can be used if they can be accurately patterned and cut to the required thicknesses. To reduce the construction time and to guarantee that each PCPTF layer is perfectly adhered, an adhesive sheet is glued to the PCPTF before it is laser-cut.

This lab-scale construction process suggests a double-sided adhesive sheet for textile applications [18]. It is thermally activated by applying 100°C – 150°C for 5–15 s, and it includes a high-temperature resistant paper (carrier sheet) to facilitate the gluing.

The antenna radiating patch, feedline, and ground plane may either be patterned manually with a scalpel [12], a blade-cutter [19], scissors [20], or by a laser cutting machine [21].

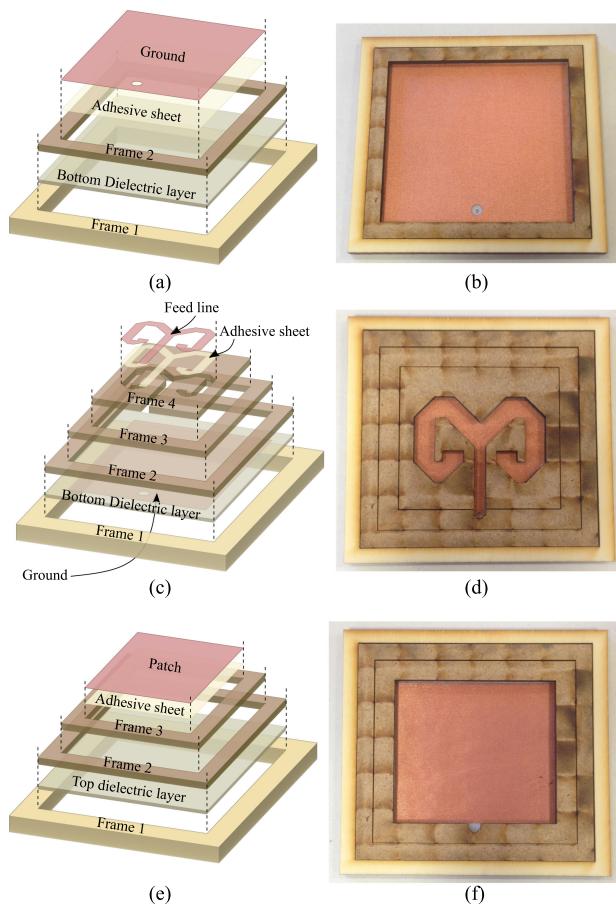


Fig. 3. Proposed layer alignment method for an EMCMPA. (a) Perspective view and (b) final result of the ground plane alignment process. (c) Perspective view and (d) final result of the feedline plane alignment process. (e) Perspective view and (f) final result of the patch plane alignment process. For clarity, the layers in (a), (c), and (e) have been separated and named at the side.

TABLE II
LASER-CUT MACHINE SETUP

Material	Speed (%)	Power (%)	Frequency*
Felt	85	10	85
PCPTF	80	20	85
MDF	8	90	85
PPB	15	85	85

*Number of laser pulses fired per inch of travel, from 1 to 100.

In this letter, an Epilog Fusion32 laser-cutter has been used to pattern the antenna and alignment layers. The laser-cut machine setup for each material is shown in Table II.

The laser-cutting process is performed efficiently, accurately, and quickly. A waste of less than 2% of material has been achieved, while the laser-cut error between desired and cut routes is less than 0.05 mm. Moreover, it takes approximately 20 s to laser-cut all PCPTF and felt layers of one antenna.

IV. ALIGNMENT AND ASSEMBLY PHASE

The two main techniques to assemble textile layers is by sewing conductive threads [19], [20] or by gluing [21]. The

sewing process (with threads going through all the layers) adds uncertainty on the permittivity, loss tangent, and the overall thickness of the antenna. This modifies the efficiency, BW, and resonance frequency of the antenna in an unpredictable way. This attachment technique is very time-consuming for multilayered antenna structures. In contrast, the use of an adhesive sheet to join multilayer structures provides a constant thickness, permittivity, and loss tangent along the entire surface of the antenna. Moreover, it can be easily modeled to assess its influence on the antennas reflection coefficient and the total radiation efficiency. In addition, the alignment becomes easier when each layer is glued individually. Nevertheless, the thermal activation of the adhesive sheet needs to be performed carefully, because most textile materials are not heat-resistant and could be damaged or their properties may change during the process.

The alignment and assembly phase is shown in detail in Fig. 3. The ground plane is aligned using the bottom dielectric layer positioned within the alignment frames 1 and 2. Through thermal activation, both layers are attached by means of the adhesive sheet that has been previously added to the conductive layers during the cutting phase. In every step where a conductive layer is added, after aligning it, the layers are assembled by appropriate thermally activated sheets. Fig. 3(a) and (b) show this first step where the ground plane is on the top face. The second step starts by flipping upside down the previously attached bottom dielectric layer and aligning the feedline now on the top face with frames 1, 2, 3, and 4, as shown in Fig. 3(c) and (d). The third step consists of connecting a 50 Ω SubMiniature version A (SMA) connector to the feedline and the ground layer to characterize the antenna prototypes. A galvanic soldering procedure is used. This is a critical step, since PCPTF is not resistant to high temperatures. The fourth step involves the attachment of the top dielectric layer on top of the feed layer. The alignment is carried out with frame 1, and the attachment is performed with a precut adhesive sheet that is thermally activated. This step is not shown in Fig. 3 because of its simplicity. Finally, the radiating patch is aligned with the top dielectric layer using frames 1, 2, and 3, as shown in Fig. 3(e) and (f).

V. MEASURED RESULTS

Eight prototypes with the dimensions listed in Table I were fabricated and measured with a vector network analyzer in an anechoic chamber to validate the construction process. The simulated and measured reflection coefficients for all constructed prototypes are shown in Fig. 4. The solid line represents the reflection coefficient of the simulated antenna in CST. The other lines represent each of the constructed prototypes using the proposed construction process. The frequency shifts in the antennas' resonance frequency are up to 48 MHz, due to the handmade SMA port connectorization and inhomogeneities in the substrate's dielectric properties, which are in agreement with values found in literature [3], [6], [11]. These values are acceptable provided that for all prototypes the reflection coefficient remains below -10 dB in the entire 2.45 GHz ISM band.

To ensure that all prototypes radiate most of their emitted power away from the human body, their far-field radiation

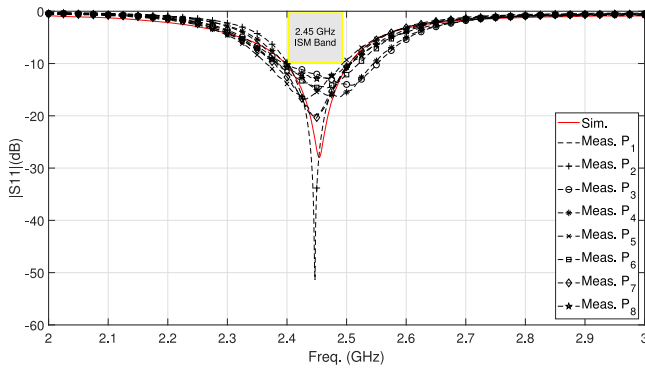


Fig. 4. Simulated and measured reflection coefficients of all constructed EMCMPA.

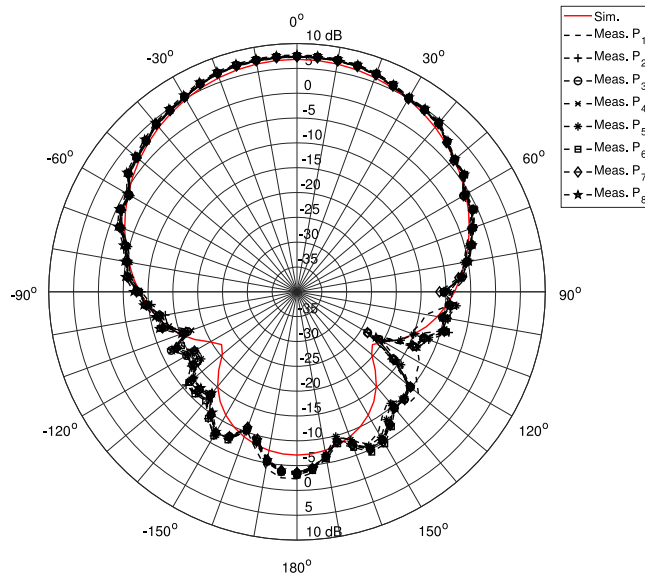


Fig. 5. Simulated and measured radiation pattern at 2.45 GHz of all constructed EMCMPA.

patterns were simulated and measured. The results at 2.45 GHz are shown in Fig. 5. In all cases, measured and simulated results are in excellent agreement, showing a radiation pattern with an average measured front-to-back ratio of 10.7 dB. The antenna has negligible cross polarization, which is not presented for brevity.

The gain-efficiency results for the simulation and all the measured prototypes are shown in Table III. The measurements were performed at 2.4, 2.45, and 2.5 GHz, to validate that performance remains constant in the desired band. The measured peak gain varies from 6.2 to 7.8 dBi for all constructed prototypes. Moreover, the measured total efficiency varies from 54.4% to 77.8%.

For the different radiation characteristics, the average value and standard deviation (STDV) were calculated in Table IV to verify the tolerance of the proposed constructions process. An average result and STDV of the resonant frequency of 2460 and 24.54 MHz, respectively, is achieved. This shift and variation in resonant frequency may be due to variations in substrate

TABLE III
SIMULATED AND MEASURED ANTENNA GAINS AND TOTAL EFFICIENCIES

Antenna	2.4 GHz		2.45 GHz		2.5 GHz	
	Gain (dBi)	Eff. T.* (%)	Gain (dBi)	Eff. T.* (%)	Gain (dBi)	Eff. T.* (%)
Sim.	6.1	57.4	6.8	66.3	6.2	55.6
Meas. P ₁	7.2	63.3	7.4	71.1	6.9	66.2
Meas. P ₂	7.1	64.8	7.4	74	7.2	69.1
Meas. P ₃	7.3	55.7	7.5	66.7	7.3	69.2
Meas. P ₄	7.5	67.3	7.3	69	6.8	62.1
Meas. P ₅	6.8	54.4	7.2	66.5	7	63.6
Meas. P ₆	7.6	65.6	7.6	69.1	7.3	66.5
Meas. P ₇	7.3	63.9	7.3	71.8	6.8	63
Meas. P ₈	7.8	67.7	7.7	77.8	7.7	70.4

*Total efficiency of the antenna.

TABLE IV
SIMULATED RESULTS, MEASURED STANDARD DEVIATIONS, AND AVERAGE VALUES OF THE CONSTRUCTED PROTOTYPES

	Freq. min. (MHz)	Freq. res. (MHz)	Freq. max. (MHz)	S_{11} max. (dB)	BW (MHz)	Eff. T.* @ 2.45 GHz (%)	Gain @ 2.45 GHz (dBi)
Sim.	2397	2454	2505	-28	108	66.3	6.8
Avg.	2387	2460	2516	-20.8	129.5	70.75	7.4
STDV	11.75	24.54	19.57	11.8	14	3.57	0.2

*Total efficiency of the antenna.

permittivity and SMA connectorization. An STDV impedance BW of 14 MHz is achieved. This variation in BW may be due to variations in substrate thickness.

The minimum and maximum frequency values shown in Table IV are obtained considering a reflection coefficient of -10 dB.

VI. CONCLUSION

A lab-scale construction process for planar textile antennas is presented in this letter. A combination of laser-cut wood frames alignment method and a fast intralayer attachment is explained and validated. Eight identical EMCMPA are constructed. The anechoic chamber results show very good agreement between the eight constructed antennas and the simulation. The antenna construction process exhibits constant EM performance in terms of resonant frequency, maximum S_{11} , BW, gain, and efficiency. Its implementation in planar textile antennas will definitely help in obtaining repeatable EM results.

In future work, the direct connection of the SMA to the microstrip line in the same plane will be studied to reduce the prototypes' resonance frequency shift. The frequency dependence of the proposed construction process will also be studied to reach a wider range of communication applications.

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Declaration

I herewith declare that I have produced this work without the prohibited assistance of third parties and without making use of aids other than those specified; notions taken over directly or indirectly from other sources have been identified as such. This work has not previously been presented in identical or similar form to any examination board.

The dissertation work was conducted from 2015 to 2021 under the supervision of Dr. Jon Legarda Macon and Prof. Dr. Hendrik Rogier from the University of Deusto and the University of Ghent, respectively.

Bilbao, Friday 12th March, 2021

This dissertation was finished writing in Bilbao on Friday 12th March, 2021

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