Printed monopoles for integration into small terminals

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To my family and friends...
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Resumo

Hoje em dia, a informação necessita de circular a enormes velocidades, sendo por isso fundamental aumentar o seu ritmo de transmissão. A importância aumenta com o tráfego global IP a quase triplicar nos próximos 5 anos, sendo os smartphones responsáveis por um terço do total, ultrapassando o tráfego de computadores.

Os monopólos impressos, sendo de pequena espessura e tamanho físico, permitem uma integração discreta em dispositivos móveis. As dificuldades surgem quando se tenta colocar um grande número de monopólos, mantendo as interações mútuas num nível aceitável. Além disso, a maioria dos serviços móveis sem fios actualmente requerem antenas com grande largura de banda ou antenas multibanda. Contudo, se estes desafios forem cumpridos, permitindo a implementação de sistemas MIMO e 4G, os monopólos são excelentes candidatos para muitos dispositivos.

Esta dissertação propõe uma antena impressa tri-banda de quatro monopólos adequada para a integração em terminais pequenos e finos. Com 4 monopólos assentes proximamente na mesma estrutura, a antena pode operar em três bandas de frequências diferentes, nomeadamente, 1.5 GHz a 2.7 GHz com 4 monopólos activos e 0.7 GHz a 1 GHz e 5 GHz a 6 GHz com 2 monopólos activos. Estes estão impressos na mesma placa de 143 × 85.2 × 0.86 mm³, o que representa actualmente um ecrã de um smartphone grande. Abrange serviços promissores como o Wi-Fi 5 GHz e bandas de baixa frequência LTE, além dos serviços ubíquos GPS, UMTS e Wi-Fi 2.4 GHz.

O projecto e optimização da antena foram realizados através do software CST. Foi fabricado e testado um protótipo do sistema de antenas. A boa concordância obtida entre as simulações e os resultados experimentais validou o procedimento de projecto e possibilitou a prova de conceito.

Palavras-chave: Monopólo impresso, Antenna tri-banda, Sistema multi-antena, Antena para 4G, Antenna de smartphone
Abstract

Information needs to circulate at huge rates nowadays, being therefore paramount to increase its transmission speed and throughput. The importance grows bigger as global IP traffic will increase nearly threefold over the next 5 years, with smartphone traffic exceeding PC traffic by 2020, and accounting for one-third in total.

Printed monopoles, of small physical thickness and size, allow for a discrete integration into mobile devices. Difficulties arise when putting many monopoles together, keeping mutual interactions negligible. Moreover, most wireless services today require wide-bandwidth or multiband antennas. However, if these challenges are met, allowing for the implementation of MIMO and 4G systems, these antennas constitute excellent candidates for many devices.

This thesis proposes a tri-band 4 monopoles printed antenna suitable for integration in thin small terminals. With 4 monopoles closely positioned in its structure, it can operate at three different frequency bands, namely, $1.5 \text{GHz}$ to $2.7 \text{GHz}$ with 4 active monopoles and $0.7 \text{GHz}$ to $1 \text{GHz}$ and $5 \text{GHz}$ to $6 \text{GHz}$ with 2 active monopoles. These are printed on the same $143 \times 85.2 \times 0.86 \text{mm}^3$ PCB representing nowadays a large screen smartphone. It covers promising services like $5 \text{GHz}$ Wi-Fi and low LTE frequency bands, besides the ubiquitous GPS, GSM, UMTS and Wi-Fi $2.4 \text{GHz}$.

The antenna system has been designed and optimized using the CST software tool. An antenna prototype was then fabricated and tested. The agreement obtained between simulation and experimental results has validated the design procedure and enhanced the proof of concept.

**Keywords:** Printed monopole, Tri-band antenna, MIMO antenna system, 4G antenna, Smartphone antenna.
# Contents

Acknowledgments ................................................................. v
Resumo ................................................................. vii
Abstract ................................................................. ix
List of Tables ................................................................. xv
List of Figures ................................................................. xix
Glossary ................................................................. xxii

1 Introduction ................................................................. 1
  1.1 Motivation ................................................................. 1
  1.2 Objectives ................................................................. 2
  1.3 Contributions ................................................................. 3
  1.4 Thesis structure ................................................................. 3

2 State-of-the-art ................................................................. 5
  2.1 Introduction ................................................................. 5
  2.2 Antennas for small terminals ................................................................. 6
  2.3 Types of printed monopoles ................................................................. 7
     2.3.1 Simple planar monopole ................................................................. 8
     2.3.2 Multi-branch planar monopoles ................................................................. 8
     2.3.3 3D monopoles ................................................................. 9
     2.3.4 UWB monopoles ................................................................. 9
     2.3.5 Examples of planar monopoles ................................................................. 9
        2.3.5.1 Monopoles with slits ................................................................. 9
        2.3.5.2 Rectangular spiral monopole ................................................................. 10
        2.3.5.3 Inverted F-monopole ................................................................. 10
        2.3.5.4 Fractal monopoles ................................................................. 11
     2.3.6 Examples of 3D monopoles ................................................................. 12
        2.3.6.1 Wrapped monopoles ................................................................. 12
        2.3.6.2 Folded monopole ................................................................. 12
        2.3.6.3 Branched patch monopoles ................................................................. 13
        2.3.6.4 L-shaped ground ................................................................. 13
2.4 Multiband printed monopoles ................................................................. 14
  2.4.1 Single feed ................................................................. 14
  2.4.2 Multiple feed .......................................................... 15
  2.4.3 Reduced feeds ......................................................... 16
2.5 Multiband printed monopoles for small terminals ......................... 17
2.6 Diversity and MIMO antenna systems ............................................. 18
  2.6.1 Spatial diversity ....................................................... 19
  2.6.2 MIMO antennas ....................................................... 19
  2.6.3 Diversity-MIMO trade-off ........................................... 20

3 Design and optimization ................................................................. 23
  3.1 Introduction ................................................................. 23
  3.2 Antenna specifications ....................................................... 24
    3.2.1 Frequency bands ................................................... 24
    3.2.2 Number of monopoles ............................................. 24
    3.2.3 Return loss .......................................................... 25
    3.2.4 Directivity and gain .............................................. 25
    3.2.5 Antenna size ........................................................ 26
  3.3 Antenna configuration ........................................................... 26
    3.3.1 Area and volume of the small terminal ......................... 27
    3.3.2 Current devices on the market ................................ 28
    3.3.3 Number and place of the monopoles ......................... 28
    3.3.4 Specific geometry of the monopoles ......................... 29
  3.4 Optimization procedure .......................................................... 30
    3.4.1 Algorithms and solvers used ................................... 31
    3.4.2 Sensitivity analysis ................................................ 32
      3.4.2.1 Parameters which don’t affect S-plots ................ 33
      3.4.2.2 Changing S11 parameters ................................ 34
      3.4.2.3 Changing S44 parameters ................................ 34
      3.4.2.4 Changing overall parameters ......................... 35
    3.4.3 Outcome .............................................................. 35
      3.4.3.1 Front ............................................................ 36
      3.4.3.2 Back ............................................................ 36
      3.4.3.3 Side ............................................................ 38
  3.5 Simulation results ............................................................... 38
    3.5.1 S-Parameters ........................................................ 38
      3.5.1.1 Symmetries .................................................... 38
      3.5.1.2 Input reflection coefficient results .................... 39
      3.5.1.3 Mutual coupling .......................................... 41
4 Antenna fabrication and test

4.1 Introduction ........................................... 48
4.2 Fabrication process ..................................... 49
4.3 Measurement techniques ................................ 50
  4.3.1 S-parameters ...................................... 50
  4.3.2 Radiation patterns ................................ 51
4.4 Comparison of simulation and experimental results ................. 54
  4.4.1 S-Parameters ...................................... 54
    4.4.1.1 Input reflection coefficient .................. 54
    4.4.1.2 Mutual coupling ............................... 55
  4.4.2 Envelope correlation coefficient .................... 57
  4.4.3 Radiation patterns ................................ 57

5 Conclusions .............................................. 59
  5.1 Future work .......................................... 61

References .................................................. 68

A LTE and 5 GHz Wi-Fi bands ................................ 69

B Solvers and algorithms .................................... 71
  B.1 Solvers .............................................. 71
    B.1.1 Transient solver ................................ 71
    B.1.2 Frequency domain solver ......................... 71
    B.1.3 Eigenmode solver ................................ 71
    B.1.4 Integral equation solver ......................... 72
  B.2 Algorithms ........................................... 72
    B.2.1 Classic Powell .................................. 72
    B.2.2 Interpolated quasi-Newton ....................... 73
    B.2.3 Trust region framework ......................... 73
    B.2.4 Nelder-Mead simplex ............................. 73
    B.2.5 Genetic algorithm ................................ 73
    B.2.6 Particle swarm optimization .................... 74

C Discrete ports ........................................... 75
D  Coaxial cables  77

E  Simulated radiation patterns  79
  E.1 Simulated gains ................................................. 79
  E.2 Radiation patterns at \(0.8\,GHz\), port 3 ......................... 81
  E.3 Radiation patterns at \(1.5\,GHz\) ................................ 82
  E.4 Radiation patterns at \(1.9\,GHz\) .............................. 83
  E.5 Radiation patterns at \(2.4\,GHz\) ................................ 84
  E.6 Radiation patterns at \(5.3\,GHz\), port 3 ....................... 85

F  Photolithographic fabrication process  87
  F.1 Pre-treatment of the original material .......................... 87
  F.2 Application of layer ............................................. 87
  F.3 Drying ..................................................................... 88
  F.4 Positive original ..................................................... 88
  F.5 Exposure .................................................................. 88
  F.6 Developing .................................................................. 89
  F.7 Etching .................................................................... 89
  F.8 Clearing (removal of the coating) ................................. 89
  F.9 Durability (removal of the coating) ............................... 89

G  Experimental radiation patterns  91
  G.1 Measured gain ......................................................... 91
  G.2 Radiation patterns for \(0.8\,GHz\), port 3 ......................... 93
  G.3 Radiation patterns for \(1.5\,GHz\), port 1 ......................... 94
  G.4 Radiation patterns for \(1.5\,GHz\), port 3 ......................... 95
  G.5 Radiation patterns for \(1.9\,GHz\), port 1 ......................... 96
  G.6 Radiation patterns for \(1.9\,GHz\), port 3 ......................... 97
  G.7 Radiation patterns for \(2.4\,GHz\), port 1 ......................... 98
  G.8 Radiation patterns for \(2.4\,GHz\), port 3 ......................... 99
  G.9 Radiation patterns for \(5.3\,GHz\), port 3 ......................... 100
List of Tables

3.1 Parameters and corresponding final values of figure 3.15, (antenna's front). . . . . . . . . 37
3.2 Parameters and corresponding final values of figure 3.16, (antenna's back). . . . . . . . . 38
3.3 Simulated efficiency (%) and gain (dBi) for $5.3\,GHz$, port 3. . . . . . . . . . . . . . . . 45
3.4 SAR levels for GSM-900 and GSM-1800 on each port. . . . . . . . . . . . . . . . . . . 47
E.1 Simulated efficiency (%) and gain (dBi) for $0.8\,GHz$, port 3. . . . . . . . . . . . . . . . . 79
E.2 Simulated efficiency (%) and gain (dBi) for $1.5\,GHz$, port 1. . . . . . . . . . . . . . . . . 79
E.3 Simulated efficiency (%) and gain (dBi) for $1.5\,GHz$, port 3. . . . . . . . . . . . . . . . . 79
E.4 Simulated efficiency (%) and gain (dBi) for $1.9\,GHz$, port 1. . . . . . . . . . . . . . . . . 80
E.5 Simulated efficiency (%) and gain (dBi) for $1.9\,GHz$, port 3. . . . . . . . . . . . . . . . . 80
E.6 Simulated efficiency (%) and gain (dBi) for $2.4\,GHz$, port 1. . . . . . . . . . . . . . . . . 80
E.7 Simulated efficiency (%) and gain (dBi) for $2.4\,GHz$, port 3. . . . . . . . . . . . . . . . . 80
E.8 Simulated efficiency (%) and gain (dBi) for $5.3\,GHz$, port 3. . . . . . . . . . . . . . . . . 80
G.1 Measured gain in (dBi) for $0.8\,GHz$, port 3. . . . . . . . . . . . . . . . . . . . . . . . . . 91
G.2 Measured gain in (dBi) for $1.5\,GHz$, port 1. . . . . . . . . . . . . . . . . . . . . . . . . . 91
G.3 Measured gain in (dBi) for $1.5\,GHz$, port 3. . . . . . . . . . . . . . . . . . . . . . . . . . 91
G.4 Measured gain in (dBi) for $1.9\,GHz$, port 1. . . . . . . . . . . . . . . . . . . . . . . . . . 92
G.5 Measured gain in (dBi) for $1.9\,GHz$, port 3. . . . . . . . . . . . . . . . . . . . . . . . . . 92
G.6 Measured gain in (dBi) for $2.4\,GHz$, port 1. . . . . . . . . . . . . . . . . . . . . . . . . . 92
G.7 Measured gain in (dBi) for $2.4\,GHz$, port 3. . . . . . . . . . . . . . . . . . . . . . . . . . 92
G.8 Measured gain in (dBi) for $5.3\,GHz$, port 3. . . . . . . . . . . . . . . . . . . . . . . . . . 92
List of Figures

1.1 Frequency bands of interest. ................................................... 2
2.1 Geometry of a GSM/DCS dual-frequency printed monopole [3]. .......... 7
2.2 Example of PIFA in a mobile phone [7]. .................................. 7
2.3 PIFA complex patch example [3]. ........................................ 7
2.4 Most simple single printed planar monopole ................................ 8
2.5 Example of a dual-band branch line planar monopole for GSM/DCS [3]. 9
2.6 UWB simple planar monopole .............................................. 10
2.7 Printed planar monopole with slits [3]. ................................... 10
2.8 Spiral planar monopole [3]. ................................................ 10
2.9 Printed inverted-F monopole [3]. ......................................... 11
2.10 Example of an useful geometry for antenna engineering [10]. .......... 11
2.11 Fractal monopole, edited from [12]. ..................................... 12
2.12 Branch line monopole 3D wrapped structure [3]. ....................... 12
2.13 Folded monopole [3]. ....................................................... 13
2.14 Branch patch monopole [3]. .............................................. 13
2.15 L-shaped ground monopole [3]. ....................................... 14
2.16 Samsung Galaxy S antennas [14]. ........................................ 15
2.17 Example of a triband single feed base station antenna [3]. ............. 15
2.18 Multiband antenna for PCMCIA [13]. .................................... 16
2.19 Tunable printed monopole using reduced feeds for a variety of frequency bands [15]. 16
2.20 Popular devices in 2016 .................................................... 18
2.21 Selection of the strongest signal using spatial diversity [23]. .......... 19
2.22 Alamouti scheme [21]. .................................................... 20
2.23 Diversity multiplexing trade-off curve [21]. ............................. 21
3.1 Intended frequency spectrum (in red). .................................... 24
3.2 Multipath example, edited from [27]. ................................... 26
3.3 Smartphones released in 2016 suitable for the proposed antenna. ....... 28
3.4 Monopoles possible arrangements according to their number. .......... 28
3.5 Geometry of the antenna in [5]. Front side in black color and back side in gray color. Dimensions in mm. .......................................................... 30
3.6 Geometry of the antenna in [6]. Front side in black color and back side in gray color. Dimensions in mm. .......................................................... 30
3.7 Rotating [6]’s wideband monopole (unresized) upside down and placing it on [5]’s dual antenna. .......................................................... 31
3.8 Algorithms one can use in CST [31]. .......................................................... 32
3.9 Changing parameter $l4$. .......................................................... 33
3.10 Changing parameter $w6$. .......................................................... 33
3.11 Changing parameter $l10$. .......................................................... 34
3.12 Changing parameter $l5$. .......................................................... 34
3.13 Changing parameter $w1$. .......................................................... 35
3.14 Changing parameter $w13$. .......................................................... 35
3.15 Geometry of the antenna’s front. .......................................................... 36
3.16 Geometry of the antenna’s back. .......................................................... 37
3.17 Geometry of the antenna’s side. .......................................................... 38
3.18 Simplifying the $S$-parameter matrix. .......................................................... 39
3.19 Port Numbers. .......................................................... 39
3.20 Simulated magnitude of $S_{11}$. .......................................................... 40
3.21 Simulated magnitude of $S_{44}$. .......................................................... 40
3.22 Regions of the spectrum below $-10\, dB$ shaded for $|S_{44}|$’s plot. .......................................................... 41
3.23 Simulated magnitude of $S_{21}$, $S_{31}$ and $S_{41}$. .......................................................... 41
3.24 Simulated magnitude of $S_{34}$. .......................................................... 42
3.25 Envelope correlation coefficient $\rho_e$ for monopoles 1 and 2. .......................................................... 43
3.26 Envelope correlation coefficient $\rho_e$ for monopoles 3 and 4. .......................................................... 43
3.27 Envelope correlation coefficient $\rho_e$ for monopoles 1 and 4. .......................................................... 43
3.28 Envelope correlation coefficient $\rho_e$ for monopoles 1 and 3. .......................................................... 44
3.29 Coordinates system used. .......................................................... 44
3.30 Different cuts of the antenna and the corresponding radiation patterns for $5.3\, GHz$, port 3. .......................................................... 46

4.1 Photolithography scheme, edited from [41]. .......................................................... 49
4.2 Equipment used in the printing circuit laboratory. .......................................................... 50
4.3 Measuring S-Parameters. .......................................................... 50
4.4 Degrees for which radiation patterns couldn’t be measured properly (in grey). .......................................................... 51
4.5 Measuring radiation patterns in the anechoic chamber. .......................................................... 52
4.6 Anechoic Chamber Block Diagram. .......................................................... 53
4.7 Simulated vs measured parameter $S_{11}$. .......................................................... 54
4.8 Simulated vs measured parameter $S_{22}$. .......................................................... 54
4.9 Simulated vs measured parameter $S_{44}$. .......................................................... 55
4.10 Simulated vs measured parameter $S_{33}$. .............................................. 55
4.11 Simulated vs measured parameter $S_{21}$. .............................................. 56
4.12 Simulated vs measured parameter $S_{31}$. .............................................. 56
4.13 Simulated vs measured parameter $S_{41}$. .............................................. 56
4.14 Simulated vs measured parameter $S_{34}$. .............................................. 57
4.15 Measured envelope correlation coefficient $\rho_e$ for monopoles 1 and 2. ........... 57
4.16 Measured envelope correlation coefficient $\rho_e$ for monopoles 3 and 4. .............. 58
4.17 Measured envelope correlation coefficient $\rho_e$ for monopoles 1 and 4. .............. 58
4.18 Measured envelope correlation coefficient $\rho_e$ for monopoles 1 and 3. .............. 58

5.1 Frequency spectrum used in relation to the monopoles. ................................... 60
5.2 Decoupling technique tried. ................................................................. 61
5.3 Tweaking antenna's width. ........................................................................... 63

A.1 $5\, GHz$ Wi-Fi frequency band allocation [44]. ........................................... 69
A.2 FDD LTE frequency band allocation [45]. ............................................... 70
A.3 TDD LTE frequency band allocation [45]. ............................................... 70

B.1 Main solvers one can use in CST. ............................................................ 72
B.2 Algorithms one can use in CST [31]. ......................................................... 73

C.1 Discrete ports instead of coaxial cables in perspective. ................................... 75
C.2 Simulated magnitude of the parameter $S_{11}$ using discrete ports. ............... 76
C.3 Simulated magnitude of the parameter $S_{44}$ using discrete ports. ............... 76

D.1 Simulated $S_{11}$ using $10\, cm$, $25\, cm$ and $40\, cm$ coaxial feed cables. .......... 77

E.1 Different cuts of the antenna and the corresponding radiation patterns for $0.8\, GHz$, port 3. 81
E.2 Simulated radiation patterns for $1.5\, GHz$. ......................................... 82
E.3 Simulated radiation patterns for $1.9\, GHz$. ......................................... 83
E.4 Simulated radiation patterns for $2.4\, GHz$. ......................................... 84
E.5 Different cuts of the antenna and the corresponding radiation patterns for $5.3\, GHz$, port 3. 85

G.1 Radiation patterns for $0.8\, GHz$, port 3. ................................................... 93
G.2 Radiation patterns for $1.5\, GHz$, port 1. ................................................... 94
G.3 Radiation patterns for $1.5\, GHz$, port 3. ................................................... 95
G.4 Radiation patterns for $1.9\, GHz$, port 1. ................................................... 96
G.5 Radiation patterns for $1.9\, GHz$, port 3. ................................................... 97
G.6 Radiation patterns for $2.4\, GHz$, port 1. ................................................... 98
G.7 Radiation patterns for $2.4\, GHz$, port 3. ................................................... 99
G.8 Radiation patterns for $5.3\, GHz$, port 3. ................................................... 100
Glossary

3D  three-dimensional.
5G  Fifth Generation of Mobile Networks.
BER Bit error rate.
CST  Computer Simulation Technology.
DCS  Digital Cellular System.
ECC  Envelope correlation coefficient.
FDTD  Finite-difference time-domain.
GPS  Global positioning system.
GSM  Global System for Mobile Communications.
IEC  International Electrotechnical Commission.
IEEE Institute of Electrical and Electronics Engineers.
IP  Internet protocol.
LOS  Line-of-sight.
LTE  Long Term Evolution.
MIMO  Multiple-input and multiple-output.
MoM  Method of moments.
PCB  Printed circuit board.
PCMCIA  Personal Computer Memory Card International Association.
PCS  Personal Communications Service.
PIFA  Planar inverted-F antenna.
R&I  Research and Innovation.
SAR  Specific absorption rate.
SNR  Signal-to-noise ratio.

UHF  Ultra high frequency.

UMTS  Universal Mobile Telecommunications System.

UV  Ultraviolet.

UWB  Ultra-wideband.

VSWR  Voltage standing wave ratio.

Wi-Fi  WLAN (Wireless Local Area Network) technology.

WiMAX  Worldwide Interoperability for Microwave Access.
Chapter 1

Introduction

1.1 Motivation

The amount of devices connected to IP networks will be more than three times the global population by 2020. Putting in annual global IP traffic terms, it will pass the zettabyte threshold by the end of 2016. That number will nearly threefold over the next 5 years, with smartphones being responsible for 30% of it, even exceeding computers’ traffic [1]. These staggering numbers can only be met with huge investment in R&I in all constituting parts of communication systems.

Smartphones, in particular, have to be able to process, transmit and receive a great amount of data, seamlessly to the user. Adding to that, these devices are becoming increasingly more personal with the years. This tendency will result in a greater amount of data being transferred wirelessly with considerable bandwidth usage.

In order to support very high data rates, MIMO systems have proven to be very efficient. Placing several antennas at both the transmitter and the receiver enhances both reliability and the data link capacity [2]. However, the closer the antennas are to each other the more they can interact with one another. And that is particularly difficult to overcome in small sized terminals such as smartphones. For this reason, planar antennas, such as printed monopoles, have deserved some attention for their attractive features of low profile, small size, operability at the frequencies of interest and being capable of satisfying bandwidth specifications [3]. Thus, designing good printed monopoles MIMO systems has been a challenge in recent years.

Different countries vary on the wireless services they adopt, but the use of the frequency spectrum is roughly the same. Most are concentrated in $1.5\,GHz$ to $2.5\,GHz$, including GSM 1800/1900, UMTS, Wi-Fi $2.4\,GHz$ and Bluetooth, with some others services around $900\,MHz$ as well, like GSM 850/900. More recent services, like LTE and $5\,GHz$ Wi-Fi, have expanded these intervals. LTE, for instance, sits at very different frequencies across the spectrum (see appendix A). It operates at higher frequencies than $2.4\,GHz$ (Wi-Fi) and lower frequencies than $850\,MHz$ (GSM). The latter constitutes the biggest
challenge when designing antennas for small devices, since the lower the frequency the bigger an-
tenna’s dimensions have to be. An antenna does not need to cover all LTE bands, of course, but these
are important since lower frequencies have the capability to provide better coverage and signal wall-
penetration.

To sum things up, wanting good performance and high data rates at multiple wireless services is
incredibly difficult to achieve, even using innovative MIMO systems. And this challenge is growing harder
every year. Considering that 5G will extend the range of frequencies used for mobile communications
(below 6 GHz and higher frequency bands up to 100 GHz) [4], good antenna designs will be needed as
never before.

1.2 Objectives

This thesis’s main goal is to design, fabricate and test an antenna for integration into small terminals
being capable of meeting today’s tough requirements. This antenna must be suitable for current tablets
and smartphones, which call for a great amount of different wireless services with considerable different
frequencies.

Printed monopoles have grabbed the author’s attention for their low-profile, cheap manufacturing and
ease of integration into smartphones. In fact, their physical shape is usually the same of smartphones’s,
very thin and of modest area size, not being prone to break. Moreover, these are usually of low directivity
(close to ideally isotropic), extremely adequate for phone use where electromagnetic waves arrive at the
receiver from all different directions.

These must include GSM, UMTS, GPS, Bluetooth, Wi-Fi 2.4 GHz considerations and, more recently,
both LTE and Wi-Fi 5 GHz. It will cover, therefore, several frequency bands in the 0.7 GHz to 5.3 GHz
range. If one looks at the frequency spectrum and intersects it with the wireless services just mentioned,
one concludes that the antenna will have to operate at a tri-band region. So either a UWB or a multi-
band antenna is going to meet the goal set.

![Frequency bands of interest.](image)

It is not hard to make a single ultra wide band antenna covering all those frequencies and more.
And of reasonable small size too. The difficulty comes when answering the need of the multitasking
capabilities any smartphone is capable of doing. Searching the web, with GPS on, while one receives a
call have all to be done simultaneously at very different frequencies. A single antenna cannot just work at all those different frequencies at the same time. The hallmark of this antenna will be trying to do all the above mentioned but with as many monopoles as possible.

A MIMO printed monopole antenna system suitable to fit into a smartphone is, therefore, the main goal of this thesis.

1.3 Contributions

This thesis proposes to contribute with a 4-monopoles antenna MIMO system with reasonable small dimensions so it can fit into a modern large screen smartphone. It combines two types of monopoles in order to cover a wide range of the mobile frequency spectrum and satisfy all common wireless services. Moreover, it yields low directivity across the frequency spectrum and weak interaction among monopoles. This antenna can be used in many applications and devices, whether there is a greater concern in reliability or data rate.

It is quite innovative to include so many wireless services in a 4-antennas MIMO system in such a limited space. It covers GSM (850, 900, 1800, 1900), GPS, DCS, PCS, UMTS, LTE (Bands 1-2, 23-30, 33-41 and 44), Bluetooth, Wi-Fi 2.4GHz and Wi-Fi 5GHz. More specifically, it works at 1.5GHz to 2.7GHz with 4 active monopoles and 0.7GHz to 1GHz and 5GHz to 6GHz with 2 active monopoles. The antenna achieves this under hard requirements, namely −10dB-impedance bandwidth, low correlation and smartphone size constraints.

The monopoles have been designed to meet the specific multi-frequency bands mentioned above but they can be adapted to other frequency bands as well. Moreover, loosing the return loss, be it 7.3dB or even 6dB, can make the antenna bandwidth even larger or obtain smaller dimensions. And last, if needed for tablets or computers for example, one could loosen up the dimensions restrictions. In general terms, the two types of monopoles used in this work were proposed recently in [5] and [6]. However, the following developed features are, to the author’s knowledge, new and original:
- combination of the two types of monopoles in a single small ground plane;
- use of a pair of symmetrical monopoles of each type;
- design optimization of the monopoles for the specific frequency bands of interest;
- good return loss, interaction and radiation pattern performance of the fabricated multi-antenna monopole system.

1.4 Thesis structure

This thesis is organized into five chapters. Chapter 1, this chapter, presents the motivation, the objectives, the original contributions and the structure of the thesis. Initially, to stress the importance of the
thesis topic, an overview of where global traffic is heading and to what extent smartphones play their part in it is included. It gives a sense of the importance of small antennas, with special emphasis on printed monopoles. It highlights the importance of MIMO to meet today’s wireless systems requirements, the difficulty underlying small dimensions and the trade-off that is ultimately achieved.

In chapter 2, which contains the state of the art, some of today’s current antennas for integration into small terminals are provided, exploring printed monopoles in more detail. It delves into multiband printed monopoles, analyzing the advantages and application in small terminals. Finally, it succinctly explains the main important MIMO aspects, giving a context to most of what was done throughout the thesis.

Chapter 3 starts by analyzing, in full detail, what are the requirements to be met, and describe possible configurations taking MIMO aspects into account. It then presents the design outcome based on two very recent types of monopoles, indicating the optimization procedures used. The outcome precedes the analysis of all $S$-parameters, with their symmetries explained, respective radiation patterns and other simulated contents.

Chapter 4 explores the fabrication and testing processes in detail in order to endorse the simulated results. The fabrication technique is fully explained followed by the analysis of $S$-parameters’ testing procedure and the radiation patterns measurements that took place in the anechoic chamber. It concludes by comparing simulated results with experimental ones as to validate the proposed concept.

Finally, chapter 5 is devoted to conclude on the whole project. It explains why the subject lured the author in the first place, what was effectively made and in what way that is new in the context of what already exists (some examples are provided). It wraps up by recognizing several details where there is room for improvement and someone can take off from there and use that knowledge to create a better antenna.
Chapter 2

State-of-the-art

2.1 Introduction

The number of devices connected to different networks worldwide has been soaring up in the last few years. With these devices becoming more personal and doing wirelessly what would otherwise be done offline, this tendency becomes ever more challenging for antenna engineering. Antenna design will have to keep up with the times, specially now with the arrival of 5G in the upcoming years. The frequency spectrum is expected to broaden even wider, (below $6\,GHz$ and up to $100\,GHz$ [4]).

The first challenge to consider is the size of the devices in which the antennas should fit into. Antennas for small terminals are too size constrained to easily come up with design geometries that can resonate at low frequencies. Frequency and wavelength are inversely proportional and that implies great efforts to include all frequency bands necessary. Furthermore, not only are these devices small (e.g. smartphones), but also these are usually very thin and lightweight, as well. Besides, each of the components has a cost carefully taken into consideration to not make the equipment too expensive overall. New state-of-the-art smartphones every year, with unique geometries and processing capabilities, call for new designs and/or the adaption of old ones.

Printed monopoles are very promising and it may be that the future of small terminals will be influenced by these type of antennas. These are physically lightweight, of low-profile and extremely thin, with the possibility of going thinner using the phone structure as the ground plane of the monopole itself. Moreover, they present good SAR levels for most cases, in order to avoid too much backward radiation to the user’s head, and radiation patterns essentially constant across the operating bands.\footnote{Approximately omnidirectional radiation patterns that respect SAR levels concerns, that is.} These are some of the mandatory requirements these antennas excel at without much design effort.

The wireless services currently asked for small devices span over a wide frequency spectrum. These frequency bands, which antennas have to operate at, are of very different nature. Intensive research has been carried out, in the field of multiband printed monopoles, to efficiently solve this problem, specifically at these particular small dimensions.

Yet another issue must be dealt with. The performance level of these antennas is required to suit
tough specifications to meet nowadays demands. Some of the more important are: high data rates, wide bandwidth, lower latency and diversity. In addition, traffic is not uniformly distributed throughout the day, for obvious reasons. Actually, busy-hour internet traffic is growing more rapidly than average internet traffic [1], which asks for good performance at the peak-hours of the day.

MIMO systems have shown to yield very good performances and boost the link capacity. The more monopoles added together, the more potentially powerful these antennas can be. Link capacity, for instance, increases linearly with the number of antennas at the channel end with the lowest amount, and maximum diversity is given by the multiplication of the number of antennas involved. Boosting this amount is no easy task due to the potential strong interaction among them. Considering one is talking about constricted spaces in the first place, the more utopian this idea seams. It is with great effort that all the above mentioned can be achieved and so paramount in these days.

### 2.2 Antennas for small terminals

Typical wireless services frequencies and mobile terminals size place quite a constraint on making antennas for these devices. Although the miniaturization requirement has soften over the last years, with mobile terminals size becoming bigger every year, low frequencies requirements are still present. These call for bigger antennas since wavelength increases inversely proportional to frequency. MIMO systems are often employed to meet high data rates and reliability requirements. The addition of more than one feeding port leads to interference between each antenna, which, considering the size of the terminals, is not easy to overcome without losing performance. Bigger antennas, therefore, leave less room to include as many as one would like.

Reducing antennas in size has its implications. There is a trade-off one has to consider, be it in performance, bandwidth, efficiency, etc. Considering conventional monopole antennas, for instance, these are usually operated at one-quarter of the wavelength. This means that, for LTE frequencies around $\sim 750\, MHz$, using a printed monopole, it requires a length of about $\sim 100\, mm$. Not using a monopole, in this case, could imply using half-wavelength cellular antennas and that would be pushing dimensions way more than it is possible for a smartphone [3].

One way to mitigate this problem is to shape antennas into a coil or a meandered strip. See figure 2.1 where one can see the latter. But this is just one of possible designs, as one will see in section 2.3, which explores different geometries for printed monopoles.

Before delving into typical designs for these antennas in the next sections, an essential example to include is PIFA, a widely adopted antenna for mobile phones. PIFA stands for printed inverted-F antenna and is widely used in smartphones. Not only have they typically reduced backward radiation, an important concern in smartphones, but they are easily concealable within the phone structure. It consists of an L-shaped patch, shorted to the ground plane, giving the inverted-F’s geometry. The patch dimensions can be adjusted to obtain a resonance at specific frequencies. Figure 2.2 shows a practical implementation of one of these antennas.

But the patch shape and geometry can be significantly modified, depending on the frequency bands
of operation. A more complex structure than just a rectangle is given in figure 2.3, yielding a multiband behavior. Including several of these antennas on a phone ends up covering all the wireless services people are used to. It is often the case to find a common ground at the back of the mobile phone so to include several PIFA systems resonating at different frequencies.

![Figure 2.1: Geometry of a GSM/DCS dual-frequency printed monopole [3].](image)

![Figure 2.2: Example of PIFA in a mobile phone [7].](image)

![Figure 2.3: PIFA complex patch example [3].](image)

### 2.3 Types of printed monopoles

Planar antennas have gotten much attention since the first modern phones came out, precisely for their low profile and small size. These are usually quite thin, lightweight and inexpensive to make. These antennas have a wide range of applications, including in vehicles and aircrafts, but that will not be the
focus of this thesis [3]. Some examples of very-low-profile types of printed monopoles will be provided, so one can see the different designs possibilities of this type of antennas.

2.3.1 Simple planar monopole

All possible printed monopole designs are based on the most simple one possible. It consists of a single strip and ground plane separated by a dielectric layer, the substrate, as seen if figure 2.4. The monopole can take different sizes and shapes, some incredibly complex as one will see in the following sections. Besides, it doesn’t need to be a planar structure and can be wrapped to form 3D antennas with very good performances (see figure 2.12, for instance). This is often the case when wants to reduce its length.

The feed is normally provided by a coplanar waveguide such as 50Ω microstrip lines. The first resonance occurs at \( l = \frac{\lambda_{eff}}{4} \), and higher resonances at \( l = \frac{n \times \lambda_{eff}}{4} \) for integers \( n \geq 2 \) [8]. To have an idea, \( l = 75mm \) resonates at 1 GHz. Lower frequencies correspond to bigger lengths, requiring therefore some design strategies. Planar monopoles often use densely meandered strips for achieving compact configurations, whereas 3D monopoles, as the name implies, use wrapped meandered structures. In the following sections, different aspects related to printed monopoles will be analyzed, such as, geometry and frequency.

![Figure 2.4: Most simple single printed planar monopole](image)

2.3.2 Multi-branch planar monopoles

Multi-branch planar monopoles are very common when one wants to develop a discrete antenna resonating at two or more frequency bands. It combines and merges distinct resonant components and optimizes them together. Figure 2.5 is an example of a branch line monopole, which combines two different strips. Strips are just one possibility, as one will see in section 2.3.5, where patches can be used or even slits. Both monopoles in figure 2.5 are printed on a FR4 substrate of thickness \( 0.8mm \) and present a densely meandered geometry so to achieve a more compact configuration. To have an idea, the total lengths of branch 1 and branch 2 are 212mm and 167mm, respectively. One disadvantage though is the strong coupling between adjacent meandered sections that may happen if one is not careful [3].
2.3.3 3D monopoles

3D monopoles can be easily obtained by wrapping planar monopoles so to reduce the length of the structure. Planar monopoles tend to do this by meandering strips, whereas 3D monopoles explore, in addition, volume dimensions to do the same. However, small terminals are becoming more thinner and wider nowadays, making 3D monopoles structures less popular than they once were.

Even so, the examples included in section 2.3.6 show the versatility of these antennas and some features that are still used today, such as, shaping the ground to reduce backward radiation and reduce SAR levels. Besides, base stations and other less volume constricted terminals can easily prefer these types of structures.

2.3.4 UWB monopoles

One former limitation of UWB monopoles was microstrip line’s limited bandwidth, which wasn’t more than 50% of the radiating monopole bandwidth. That limitation no longer exists and the line’s bandwidth may reach 90% nowadays. One example is the antenna shown in figure 2.6, which optimizes the radius of the circular shape to maximize the bandwidth it can cover. This particular antenna is reasonably omnidirectional throughout the frequency band it can cover [9]. Other interesting examples include frequency independent antennas, such as fractal monopoles. An example is provided in section 2.3.5. Both very small and very large elements in these type of antennas enables them to radiate over high and low frequencies.

2.3.5 Examples of planar monopoles

2.3.5.1 Monopoles with slits

Instead of using branch line structures, another way of achieving the same result is by cutting slits out of a singular rectangular patch in order to get subpatches. It is a different form of design, with no need of optimization for individual structures first. Figure 2.7 shows an example where this was the case [3]. This type of design can end up being equivalent to different resonating patches being put together.

Figure 2.5: Example of a dual-band branch line planar monopole for GSM/DCS [3].
A 3D approach is often used depending on the patches length. An example is given in section 2.3.6.

**2.3.5.2 Rectangular spiral monopole**

The examples provided so far have been a combination of separate resonant lines or patches of different lengths and widths being put together to form the whole structure. A very acknowledged design method is to use a single resonant path and fine-tune its own resonant frequencies to the ones desired. Figure 2.8 shows an example of this design method. Common designs aim dualband operations at GSM900, GSM1800 and DCS frequencies [3].

**2.3.5.3 Inverted F-monopole**

An inverted-F strip monopole follows a different logic from what was previously seen, where one of the branches of the monopole is connected to the ground plane. Ground plane is on top of the substrate, alongside with the monopole strip. There is no via-hole required to shorting the inverted-F strip to the ground plane since the center strip of the monopole is connected to the signal strip (coplanar...
line feeding), as one can see in figure 2.9. In this particular example, the design is fit to resonate at UMTS frequency bands [3].

Figure 2.9: Printed inverted-F monopole [3].

2.3.5.4 Fractal monopoles

This last type is commonly used in frequency-independent antennas. Fractal antennas are based on the fractal geometry, hence its name. It has been demonstrated that this approach, if implemented properly, can lead to efficient miniaturized designs [10]. The idea consists of allowing for many electric current modes due its natural complex structure, radiating over a very large bandwidth, only limited theoretically by the manufacturing process capabilities. Very small portions of the antenna define the high frequency limit and large scale portions define the lowest.

In multiband applications, it has been demonstrated that the position of the multibands may be controlled by proper adjustment of the scale factor (see figure 2.10). It has proven its utility in some UWB applications. However, there is some controversy around these antennas with some authors claiming the concept is more attractive than its performance per se [11]. Figure 2.10 depicts a typical example.

Figure 2.10: Example of an useful geometry for antenna engineering [10].
2.3.6 Examples of 3D monopoles

2.3.6.1 Wrapped monopoles

Branch line monopoles get often too big for small terminals. These printed monopoles can be wrapped and form a 3D structure as shown in figure 2.12. This can be done to most printed monopoles actually. One should be careful with the distance from the ground plate, though, since these antennas will be used in smartphones, most likely. It can sometimes be preferable to have such geometries in some device applications. These can yield good results as well [3].

2.3.6.2 Folded monopole

A famous design consists of folding a monopole of rectangular shape, greatly reducing its length. See figure 2.13, where the protruding monopole has a volume of about $10 \times 17.5 \times 5 \, \text{mm}^3$. This type of monopoles are suitable for DCS, PCS, UMTS and Wi-Fi $2.4 \, \text{GHz}$, yielding quite a wide bandwidth, from $1.7 \, \text{GHz}$ to $2.6 \, \text{GHz}$. The total monopole height from the ground plane in fig. 2.13 is about $1.3 \, \text{cm}$ though, which does not make it applicable in today’s smartphones. But base stations and other communications terminals can use them of course, since these remain very low-profile nevertheless [3].
2.3.6.3 Branched patch monopoles

Rather than branch line structures, singular patches can be used instead and added together, ending up in the design of monopoles comprising two subpatches resonating at different frequencies. It is the same principle as before, but with a different type of structure. The length of these sub-patches is commonly too big for smartphones and a 3D approach is often used. Figure 2.14 is an example of this. Here too, the monopoles are wrapped to reduce its length. The decision depends on the device they are destined to [3].

2.3.6.4 L-shaped ground

The previous inverted-F monopole, in section 2.3.5, already shows the possibility of changing ground plane shape and place. That is notorious in this next example, commonly used to reduce backward radiation. In small terminals like smartphones, SAR levels are an important concern and there is the
need to limit radiation towards the user’s head. Yet, one worries when volume starts to increase, since these devices are usually very thin. Figure 2.15 shows an example suitable for GSM-1800 [3].

![Figure 2.15: L-shaped ground monopole [3].](image)

### 2.4 Multiband printed monopoles

The different wireless services spanning across a wide frequency spectrum require antennas that must be able to work at multiple bands at once. Indeed, a multiband antenna solution is usually smaller and less costly than a solution with a distinct antenna for each frequency band [13]. See figure 2.16, where this is the case for Samsung Galaxy S, having 6 antennas overall. Actually, since they all share the same ground, it is technically one single antenna system, but the point gets across.

As discussed in previous sections, the multi-band return loss behavior can be obtained using configuration and feeding options.

#### 2.4.1 Single feed

To obtain dual-band or multiband operation, one can use single feed antennas. These are absent of mutual coupling problems and in some applications that is essential, although the signal belonging to different services has to be properly discriminated at the front end. Considering two or three very distinct frequencies, it is often not feasible or possible to use a UWB antenna. A common design procedure is to combine and merge distinct resonant components and optimize them overall. Figure 2.1 is a good example.

It is essential to combine an accurate analysis technique (for instance IE-MoM or FDTD) with a fast optimizer (genetic algorithm, for example, detailed in appendix B) [13].

Dual or tri-band resonances are the most common cases for multiband operation with single feed. It gets logically more difficult when trying to increase the number of different bands. Yet, up to four or five
different frequency bands is feasible with proper tuning without sacrificing volume and performance too much [13].

Figure 2.17 shows an example of a triband base station antenna with a single feed port. The rectangular patch has dimensions of $55 \times 90 \text{ mm}^2$ and the whole structure has $170 \times 200 \text{ mm}^2$.

2.4.2 Multiple feed

On a different perspective, multiple feed ports can be used for each operating frequency band. Naturally, mutual coupling problems arise, although each service is decoupled already at the antenna stage. It makes sense for frequency bands which are far apart, as long one is careful with mutual coupling effects degrading the overall performance [13].
Figure 2.18 is a good example. It covers both the GSM family (namely, GSM 900, GSM 1800 and GSM 1900) and $2.4\,GHz$ Wi-Fi, using two feeding ports. A PIFA was chosen to cover the GSM bands and an IFA was added to ensure the access to Wi-Fi.

![Multiband antenna for PCMCIA](image)

Figure 2.18: Multiband antenna for PCMCIA [13].

### 2.4.3 Reduced feeds

Sometimes less feeding ports than bands are used. Using a feeding port to GSM, $2.4\,GHz$ Wi-Fi and GPS and a separate one for low LTE frequencies is a possible solution.

Figure 2.19 shows four antennas out of which #1 and #2 work at lower LTE frequencies and antennas #3 and #4 work at the upper band $1.7\,GHz$ to $5.75\,GHz$. Monopoles #1 and #2 work at a single band using a feeding port each, and #3 and #4 work at several using a single feeding port each as well.

![Tunable printed monopole using reduced feeds for a variety of frequency bands](image)

Figure 2.19: Tunable printed monopole using reduced feeds for a variety of frequency bands [15].
2.5 Multiband printed monopoles for small terminals

Getting printed monopoles into small terminals does not ask for miniaturization alone. Devices like smartphones require a lot more challenges to be overcome. Small dimensions, low weight and low manufacturing costs are easily achieved when considering printed monopoles.

SAR, the power absorbed per mass of tissue, becomes a concern as well. There are European and American standards, among others, that establish acceptable levels of radiation for these devices. One way to prevent high SAR levels is to increase the size of the ground so it reduces backward radiation to a person’s head.

There is also a wide range of wireless services that cannot be dismissed. Building an antenna for small terminals, like smartphones, cannot exclude emergent services, like LTE or WiFi. It would not be of practical purpose even if good performances could be achieved. Not only new emergent wireless services have to be included, but competition for the available frequency spectrum has led to a broader degree of requirements and specifications than before. Higher efficiency, capability to handle multiple frequency bands, robust to changes in the environment for efficiency and optimized use of the available channel capacity are some of new traits these antennas ought to accommodate [13].

Typical wireless services for mobile handsets are: GSM 850/900, GSM 1800/1900, GPS, UMTS, Bluetooth, Wi-Fi 2.4 GHz. More emergent services, that have been widely adopted, include: Wi-Fi 5 GHz and LTE. Some others depend more on the regions of the globe, like WiMAX. LTE bands span over a wide frequency spectrum. Due to size constraints, it may not be possible to work at every single one, but the more the better. It is important to work at lower frequencies as well, since these penetrate buildings more efficiently and provide for a better coverage.

MIMO considerations are compulsory in most cases, since it is one of the best ways to both meet high data rates and/or information reliability. This brings mutual coupling to the table and requires a clever design to allow for negligible independence between different monopoles. In such reduced small terminals, adding to the specifications already mentioned, it sets the bar quite high in order to fulfill them all. Typical mutual coupling values are $-15\,\text{dB}$, but one ought to look at the envelope correlation coefficient to have a better feeling for how independent antennas are and make an effort to obtain values smaller than 0.1. Lastly, operable bandwidth corresponds to a return loss coefficient above $10\,\text{dB}$, but considering the power commonly involved in these devices, it can go down to $6\,\text{dB}$ if it must.

There are several smartphones on the market and their dimensions differ significantly, but they all fit reasonably in the palm of the hand. Moreover, their geometry is typically a rectangle, with horizontal width about half the height. Some research indicate that the average size should stabilize around 5-5 inches ($\sim$14cm) by the end of 2016 [16]. Popular smartphones with bigger screens, called phablets often enough, are much bigger with screens up to 7 inches. An average area size is then $145 \times 73\,\text{mm}^2$, and it is more or less what one can work with when designing an antenna from the ground up. Figure 2.20 shows two widely popular smartphones and a phablet.

Finally, radiation patterns should be as little directive as possible. Ideally isotropic in fact, since these devices transmit and receive data in all directions. Directivity of 0 dB is therefore very desirable.
It is now clear the sheer amount of specifications and requirements these antennas are put through and how difficult designing a good antenna can be.

### 2.6 Diversity and MIMO antenna systems

The channel in which electromagnetic waves go through is the part of the communications system that cannot be engineered. Weather conditions, propagation loss, reflections, interference and other factors set limits on the technologies that are used [20].

Even when one assumes good propagation conditions and sets aside the weather hindering electromagnetic waves (that actually depends on the frequency used) and propagation loss, the transmitted signal goes through many different paths. It arrives at the receiver through differing angles and/or different time delays and/or different frequency shifts (i.e., Doppler) depending on the path it took. Consequently, the received signal power fluctuates in time, space and frequency. This is phenomenon is known as fading [21].

The use of multiple antennas at the transmitter and receiver in wireless systems, known as MIMO, is a neat way to circumvent many of the obstacles mentioned above. The technology helps meeting not only the challenges posed by the impairments in the wireless channel but many of the resource constraints as well.

For the purpose of this thesis, some of the benefits of MIMO are not worth being discussed, mainly dealing with signal processing at the receiver (combining all the different signals) or taking advantage of multiple users sharing time and frequency resources. Spatial diversity and spatial multiplexing though, which make MIMO much of what it is famous for, are very worth being discussed.
2.6.1 Spatial diversity

Space diversity can be used to improve the reliability of the link and it consists of sending multiple independent replicas of the same information to the receiver, as to increase the probability of at least one of the copies not experience a deep fade. For a channel with $N_T$ transmit antennas and $N_R$ receive antennas, MIMO systems can potentially yield a spatial diversity of $N_T \times N_R$ [22, 21]. There are other forms of diversity, but in the context of this thesis, diversity is explored by spatially separated antennas. In short, diversity, is summed up in the phrase 'do not put your all your eggs in one basket' and is key to guarantee reliability across plenty of systems these days.

Most sophisticated forms of spatial diversity work with space-time codes, maximal ratio combining, antenna arrays, etc. Nevertheless, figure 2.21 shows a simple case where spatial diversity is used. It depicts the situation where the strongest of two received signals is selected. As long the two antennas are sufficiently far from one another, the two received signals shall undergo through uncorrelated fading. It is not efficient discarding ‘half’ of the signal comparing to other forms of this technology mentioned above, but it shows a case where most of the deep fades are avoided and average SNR actually increases\(^2\).

![Graph of fading envelope over time](image)

Figure 2.21: Selection of the strongest signal using spatial diversity [23].

2.6.2 MIMO antennas

Spacial multiplexing is the benefit of MIMO that is often considered the most significant considering it is the main one responsible for the linear increase in link capacity. It consists of transmitting multiple

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\(^2\)SNR increases logarithmically with respect to the number of antennas using spatial diversity
different independent data streams to increase data rate. Since each data stream experiences at least the same channel quality that would be experienced by a single-input single-output system, the capacity gets multiplied by a factor equal to the number of streams. In a 3x2 MIMO system, for example, the capacity would be equal to the minimum number of streams, 2 in this case. It is the \( \min N_T, N_R \) that yields the gain in capacity [21].

The performance benefits of the MIMO channel, usually characterized in terms of diversity and multiplexing, are not mutually exclusive, as one shall see in subsection 2.6.3. In fact, these can work together to achieve an optimal trade-off.

### 2.6.3 Diversity-MIMO trade-off

Considering a 2x2 MIMO system, one has two antennas electrically far enough from one another, at both the transmitter and the receiver. On the one hand, it is possible to make use of spatial multiplexing and send two pieces of different information in one time slot. On the other hand, one can send the same piece of information twice in the same time slot so as to guarantee greater reliability. It is possible to do both, however. A very simple but powerful scheme is worth mentioning here, since it is capable of achieving what is called rate-1\(^3\), taking two time slots to transmit two different symbols.

The Alamouti scheme, as depicted in figure 2.22, consists of transmitting the two symbols and their conjugates in two consecutive time-slots. The improvement can be seen in figure 2.22 as well.

\( \text{Rate-1 designates a space-time block-code that achieves full diversity without sacrificing data rate.} \)

The Alamouti scheme does not require any previous knowledge of the channel and that can be an advantage. But in cases where the channel does not change very rapidly, the transmitter and receiver can test the channel first as to know how signals are going to be affected and compensate accordingly. In those cases, using transmit-MRC for example, the performance is better.

It is clear at this point that the full benefits of diversity and multiplexing cannot be realized simultaneously. Notice that in a 2x2 MIMO system, as seen just now, the potential maximum diversity is actually 4 if one sacrifices data rate.

![Figure 2.22: Alamouti scheme [21].](image)
On the one hand, *diversity* assumes data rate is held constant as BER decreases and SNR increases, while on the other hand *multiplexing* assumes a constant BER for an increasing data rate. An optimum trade-off can be achieved, as proven in fact possible by [22], trading one benefit against the other, providing transmission schemes where data rate increases with BER decreasing with SNR even if not as fast as in pure diversity or pure multiplexing schemes [20]. Figure 2.23 shows the general case of one benefit vs the other and a particular example. One conclusion jumps out as it is clear the more antennas one has, the better a performance can potentially be achieved.

![Figure 2.23: Diversity multiplexing trade-off curve [21].](image)
Chapter 3

Design and optimization

3.1 Introduction

In a world where demand is increasing for small terminals to provide fast and reliable wireless services, low-profile small antennas call for new and better designs. Out of today’s and future’s necessity, very good performance is key when allocating an ever increasing number of communication systems within such small volumes, be it LTE, bluetooth, Wi-Fi, GSM, UMTS, WiMax, and others. Many are needed to be supported simultaneously [24].

Mobile terminal antennas have to meet many tough specifications. Frequency bands that vary significantly, low VSWR (< 3, sometimes just 2), low directivity (ideally 0 dB), obviously high efficiency, and enough bandwidth to cover people’s needs, in a very constricted space.

The frequency bands depend on the wireless services one wants to include logically, but these remain pretty constant across any mobile terminal. Some systems are of considerable low frequency, for instance, hardening the task of miniaturization. The low gain specification is due to the need for a very low directivity pattern to minimize signal variations as handset position is varied [24]. This is because electromagnetic waves get reflected in various objects and reach the antenna from several different paths.

Printed monopoles may be the way to go to meet future’s demands. These are very thin, of small volume and with typical good radiation patterns.

The hard specifications challenge can be met if one considers MIMO systems. These systems are vital to answer high capacity demands and support the fourth-generation mobile communication system [5]. They have rapidly gained popularity due to its powerful performance-enhancing capabilities, constituting a breakthrough in wireless communication system design [21]. It is an obvious choice therefore, to have such intention from early on.

In order to achieve good performance then, one must integrate multiple antennas with good impedance match and low mutual coupling [5]. That notably shapes the antenna possible configurations, since there is not much room to arrange monopoles as one would want. Although the more monopoles added the better, it may worsen the antenna overall when trying to meet all the specifications mentioned above. A
standard screen size for a large screen smartphone is $160 \times 80 \text{ mm}^2$ and the design should not deviate much from that.

Finally, given the myriad of parameters than can shape the antenna, fast algorithms should be used since they compensate for the lack of computational power in typical personal computers. Different solving algorithms must be explored, since these operate with different mathematical functions.

### 3.2 Antenna specifications

#### 3.2.1 Frequency bands

Being an antenna aimed to integrate smartphone/tablet-like terminals, the usual UHF frequencies are a requisite. It has to cover GSM-900/1800, UMTS, GPS, $2.4 \text{ GHz}$ Wi-Fi and several LTE bands so as to meet the minimum requirements any good smartphone does nowadays. Moreover, it is part of the initial intention to include $5 \text{ GHz}$ Wi-Fi as well, so it could comply with IEEE 802.11ac 2014’s wireless networking standard.

Figure 3.1 shows the intended spectrum (in red) so one can have an idea where the resonances are wished to occur.

![Figure 3.1: Intended frequency spectrum (in red).](image)

#### 3.2.2 Number of monopoles

Requiring LTE from the start is a specification *per se*, since LTE requires at least 2 antennas at the receiver\(^1\). As mentioned in chapter 2, being diversity indispensable for reliability in wireless systems, the more antennas one can bring to this project the better. *Spatial diversity*, in particular, is mandatory to consider as it is specially promising for small mobile units since it requires no additional bandwidth or power. It uses two or more antennas, which are separated by enough distance, so that the fading is approximately decorrelated between them. And although the cost associated with additional antennas and signal processing may not be negligible, for a small number of antennas it usually is ([23, chap. 5](#)).

Adding more antennas leads, therefore, to MIMO considerations. In a more stricter definition, in fact, MIMO refers specifically to *spatial multiplexing*, as a way to increase throughput, where the transmission of multiple data streams occurs simultaneously over the same bandwidth and hence one has multiple...

\(^1\)Receive diversity places no particular requirements on the transmitter therefore these techniques are not specified in the LTE standard. Nevertheless, they will most certainly be used in all LTE handsets and base stations ([23, chap. 5](#)).
inputs and outputs. And indeed, the benefit of MIMO that is, in many respects, most significant is the increase in link capacity that it can provide [20, chap. 3].

Therefore, one of the goals was to make a MIMO antenna with as many monopoles as possible, taking advantage of both spatial diversity and spatial multiplexing, analyzed in chapter 2, so to get both better reliability and throughput. Besides, in general, the number of data streams that can be reliably supported by a MIMO channel equals the minimum of the number of transmit antennas and the number of receive antennas [21, chap. 1]. Since the limitation on the number of antennas resides on the mobile station for most cases, it follows one should increase the latter.

3.2.3 Return loss

When the transmission line and the system mismatch, some of the energy in the signal incident on the load will be reflected back along the line forming a standing wave. Here, along the line, energy traveling in the forward direction and energy traveling in the reverse direction act to form field maxima (nodes) and field minima (antinodes) at specific positions along the line. The ratio of antinode to node voltage defines what is called VSWR, and can be defined in terms of return loss as well, also called, reflection coefficient (usually expressed in decibels). Antennas bandwidth, for example, can be quoted in terms of return loss (or VSWR), as the range of frequencies over which the antenna’s return loss is above a certain reference value. Thus, this is one other parameter to have in mind.

VSWR of 2 (conversely return loss of $9.54 \text{ dB}$), for example, implies that 89% of the available power reaches the load, that is, only 11% of the incident power is reflected. Thus the lowest possible VSWR is highly desirable for maximization of power transfer to the load.

A serious problem arises in some high-power transmission applications when too high a VSWR may result in transmission line dielectric over-voltage breakdown as a large-amplitude standing wave is formed [25, chap. 6]. Consequently, a stricter definition of the antenna bandwidth is recommended in these cases thus, more than 15 dB or 20 dB return loss bandwidth is used [8, chap. 16], implying a limit on VSWR.

However, this is not the case for printed monopoles for integration into small terminals. The power involved allows to cut some slack on this parameter. The reader will often encounter a VSWR of 2.5 (about 7.3 dB return loss) in some of the literature regarding this subject. See [3] for example, which includes several examples yielding quite a wide bandwidth because of this. And indeed, it can suffice for a great deal of applications. Nonetheless, a more rigorous criterion will be adopted in this thesis, often endorsed in the literature as well. Whatever the value suitable for each specific application, 10 dB will be considered as the return loss reference goal for simulations hereafter.

3.2.4 Directivity and gain

Equally important, low directivity is mandatory. Besides the unwelcome propagation loss and noise, rays get reflected as well, taking several paths from the transmitter to the receiver [26, chap. 3]. Most phones and tablets experience this phenomenon, commonly called multipath, rather than receiving elec-
tromagnetic waves in LOS. Seldom is not the case, even in LOS situations (see figure 3.2). All the mobile incoming rays can add together in different ways, constructively or destructively, but the point here is the sheer amount of different directions they take. Moreover, in mobile terminal applications one usually does not know the direction of the base station and the orientation of the (mobile terminal) antenna. So, even in a LOS situation, low directivity is a must. For those reasons, ideally, the antenna should be isotropic. Not being the case, the least directive the antenna is, the better. Luckily, it is typical of small antennas to get radiation patterns with those characteristics. Hence, this will not be a top concern.

![Figure 3.2: Multipath example, edited from [27].](image)

3.2.5 Antenna size

One last concern is antenna’s size. Last to be analyzed but perhaps the most important. If size was not a constraint then this project would be of much less importance. Antennas could just be taken apart as much as needed until their interaction was negligible, leaving aside being considered a MIMO system or not. It is the small size of these type of antennas that forces the close proximity between elements and undesired interaction between them. The outcome of this project is, ultimately, a trade-off between size and good performance.

3.3 Antenna configuration

Although smartphones’ screen size is getting bigger, it is still technologically difficult to come up with good printed antennas, given the spare room left when adding more and more monopoles. Smartphones still have to fit in the hand and that is quite a size restriction per se, given the wireless services nowadays. Low LTE frequencies aggravate this problem, setting the bar even higher. Not only it requires two antennas at least, but the lower the frequency required, the more difficult it becomes to build an antenna for such small devices, since wavelength increases inversely proportional to frequency.

As seen in section 3.2, one of the goals set is to add as many monopoles as feasible. On the one hand, one should indeed explore how many monopoles it is viable to put into the same area without jeopardizing the whole system, adding as many as possible. Additionally, the less monopoles one adds,
the more limited a performance can be achieved for the antenna. On the other hand, an extra monopole is enough to worsen it all. This idea is somewhat summed up in the phrase 'a bird in the hand is worth two in the bush'.

More complex issues can format a printed antenna's shape, namely, the substrate, feeding ports and device's shape and materials. The device the antenna gets into dictates many of its characteristics. Not only the way the device's materials can get in the way of antenna's performance, by means of their dielectric properties for example, but the way it is going to be dealt by the user acts on the antenna's behavior as well (hands and other body parts absorb radiation). Likewise, the substrate and feeding ports, like coaxial cables or discrete ports make a difference when simulating $S$-parameters. Even coaxial cables's length, due to the relative small size of the ground plane on these type of antennas, matters. Details like these should be known beforehand, as they are in the case of these thesis. Both substrate and coaxial cables length are known and the antenna was simulated for free space situations, the same way it is going to be tested.

### 3.3.1 Area and volume of the small terminal

There is a need to impose limits to the maximum area the antenna can reach. Being able to fit into a regular tablet is less of a challenge, although not trivial, when compared to a smartphone. So the goal to build an antenna for a modern smartphone is set. Even so, the sheer amount of phone sizes does not make clear what size one ought to consider. Popular devices like the iPhone 7 Plus, with an area of $160 \times 80 \text{ mm}^2$, will settle the maximum area to bear in mind, with an excuse for slight variations in size ($\sim 5\%$), if really needed.

The height is typically so small in these antennas that it does not even get to be $1 \text{ mm}$ thick, ideal for smartphones nowadays. This has been the tendency observed in the last years: getting the screen bigger and its side thinner. That alone can be a game changer when manufacturers choose what antenna(s) they want. Getting the maximum room on these devices is paramount as recently seen with the removal of the headphone jack in some more recent phones, sparking some controversy nonetheless. Room is undoubtedly very crucial and it is one of the printed monopoles' greatest advantages when compared to other type of antennas. As a side note, increasing the height of the substrate can be done so to extend the efficiency (up to 90 percent) and bandwidth (if careful with surface waves) in some particular cases [8, chap. 14]. This will not be the case in this thesis, but even when such cases are considered, they are still of reasonably small height sizes.

In short, only the area constitutes a concern when it comes to these type of antennas. And that is where the optimization effort will be concentrated: getting it big enough to include as many monopoles as possible, and thus strive for a more complex MIMO system, but not so big to the point it does not make sense to call it a smartphone's antenna anymore.

---

2 Defining the area as length $\times$ width, one gets volume by multiplying it by height, so to be clear what dimensions one refers to.
3.3.2 Current devices on the market

So one can have a feeling for what kind of devices the antenna ought to fit into, some examples of current devices on the market are included.

Important note to have in mind: any device on the market is a specific piece of technology well thought through. The antenna is no exception and each device needs its specific customized antenna to meet the requirements/goals its own manufacturer intends to. Therefore, it is expected this antenna would suffer some customization/improvement for each specific gadget. That being sad, assuming the antenna would be of the area and volume indicated, here are a couple of examples of recent smartphones into which the antenna could be used (see figure 3.3). In the case of tablets, any would be fit to include the antenna given the usual dimensions of such devices.

Figure 3.3: Smartphones released in 2016 suitable for the proposed antenna.

3.3.3 Number and place of the monopoles

The arrangement of the monopoles on the substrate depends strongly on the surface’s shape. A square or circular surface is obviously different from a rectangular one. And the latter is the one to consider: a rectangle vertically two times longer than it is wide, approximately, as commonly seen in smartphones. Intuitively, to get monopoles to be as further apart as possible, one should put them along the bigger axis as to take advantage of the physical distance. But that depends on the number of monopoles to consider. Dividing the surface as in figure 3.4 gives a rough idea of where to put monopoles as their number increases.

Figure 3.4: Monopoles possibile arrangements according to their number.

It might not be possible to have 4, 6 or even 8 monopoles if their interference gets to big to dismiss.
This has to be accounted for *a posteriori*. First, 2 or 4 monopoles will be added. Then, after running some simulations, a larger number can be considered. It is clear from figure 3.4 that the more monopoles the less room is left between them, and interference has to be looked out. Besides, as mentioned in previous sections, the goal is to maximize the number of monopoles indeed, but the frequency bands they work at are equally important. Getting 6 or 8 monopoles would be easier if one could just consider very high frequencies. That would allow for smaller monopole sizes and therefore more freedom to move them around. But some of the intended wireless services, such as LTE and GSM-900 (see figure 3.1), ask for resonances at around $700 \text{ GHz}$ to $900 \text{ GHz}$, thus a big challenge resides here alone.

### 3.3.4 Specific geometry of the monopoles

Here are presented the pillars of this thesis, that one has considered at the design early stages.

The idea at first was not to build such an antenna from scratch but optimize an existing one. The printed dual-antenna in [5] kicked off the whole project, as depicted in figure 3.5. It struck as very promising since not only covered most of the spectrum mentioned in section 3.2, but it was smaller than the average phone size nowadays. Simulations confirmed the antenna would yield a return loss above $10 \text{ dB}$ from $1.61 \text{ GHz}$ to $2.75 \text{ GHz}$ with a mutual coupling lower than $-15 \text{ dB}$ within that interval.

Following the logic in section 3.2 regarding the intended spectrum, GPS frequencies around $1.5 \text{ GHz}$, low LTE frequencies and $5 \text{ GHz}$ Wi-Fi were still missing. One could try reshaping these monopoles to get a much wider frequency spectrum, but that would fail to bring more than two antennas, ending up failing to strive for a more ambitious MIMO system, even if such difficult solution was found. Even so, tweaking the two antennas dimensions was not a bad idea. Noticing $1.5 \text{ GHz}$ was close to the lowest frequency covered of $1.61 \text{ GHz}$, one could try to wide the spectrum a little bit. Moreover, succeeding in bringing two or four more monopoles to the antenna, one would have a greater number of active monopoles in the same part of the spectrum.

At this point another antenna caught one’s attention [6]. Such antenna, shown in figure 3.6, put forward a wideband monopole arranged along an edge of a ground plane. The spectrum covered was not the one intended, since it was from $0.22 \text{ GHz}$ to $0.60 \text{ GHz}$, but its dimensions could be adjusted accordingly. The interest came with the idea of interfering the least with the antenna in figure 3.5, introducing two more monopoles to meet the frequency spectrum specifications indicated in section 3.2. Notice in figure 3.6 that the ground plane could be taken as the ground plane used in figure 3.5 if inverted $180^\circ$. Something along the lines of figure 3.7

With that in mind, the possibility of including more monopoles was not excluded. But one needed to optimize for these 4 monopoles (or even discard this attempt) first, before jumping to further ideas. If, *a posteriori*, the prospect of adding a new monopole seemed reasonable, one would consider it. One should predict a strong interaction between monopoles so closely together, constituting the major challenge to overcome but, nevertheless, one ought to remain open to that idea.

---

2Figure 3.7 is just for explaining how one antenna is going to be put on top the other. The dimensions are completely off what they really look like. But for the sake of the rotation, it does not matter. Nevertheless, as one shall see, [6]’s wideband monopole will become 5 times smaller in height, approximately.
3.4 Optimization procedure

The final design ended up being a combination of two very recent antennas ([5], from 2014 and [6], from 2015). Hundreds of simulations took place in order to optimize both antennas when put together.

There were a lot of variables to consider, starting by the materials used for the substrate, since both
antennas used different materials among themselves and different from the ones available at IT/IST\textsuperscript{4} printed circuits laboratory, as well. First, both papers were individually validated through CST\textsuperscript{5} software tool by recreating their 3D models and respective simulations. After that, the materials of both antennas were changed and their dimensions tweaked so to re-validate the two antennas at the frequencies of interest. Finally, both antennas were put together and further optimization was carried out.

As an important note, at this optimization stage, one only cares for both $|S_{ii}|$ and $|S_{ij}|$ to meet the specifications. There is no concern for what radiation patterns or respective gains might be. These should be typical of these type of antennas, as one can verify by looking at the most important references this thesis is based on ([5] and [6]).

### 3.4.1 Algorithms and solvers used

CST allows the selection of several different solvers, depending on the device one wants to test. The transient solver was chosen since it was indicated for studying the field propagating through a component or along the traces of a PCB [30].

There are several algorithms at one's disposal when working with CST. Classic Powell, Interpolated Quasi-Newton, Trust Region Framework, Nelder-Mead Simplex, Genetic Algorithm and Particle Swarm Optimization. The order by which these algorithms were mentioned was not randomly peaked. The first should be used in cases where initial parameters already give a good estimate of the optimum, and

---

\textsuperscript{4}Instituto Superior Técnico, Lisbon, where this project took place.

\textsuperscript{5}Software tool for the 3D EM simulation.
parameter ranges are small. The latter, when initial parameters give a poor estimate of the optimum, and parameter ranges are large [31]. The Nelder-Mead Simplex Algorithm sits in the middle and that is why it was used most of the times, often interchanging with the Trust Region Framework in the final stage of the optimization process, that should be used when one thinks the model is good around a certain ’trust region’. Figure 3.8 gives a visual perspective of what was mentioned.

![Algorithms](image)

Figure 3.8: Algorithms one can use in CST [31].

Once the algorithm is chosen, an arbitrary number of goals can be defined. The optimizer will try to satisfy either the sum of all goals or the maximum of them [31]. The maximum of goals was not a good choice to peak since every single goal had to be achieved. As an example, obtaining $10\,\text{dB}$ return loss for the frequency bands of interest could maximize the number of goals achieved. That would be useless if one had extremely high mutual coupling still, even if only for a single pair of monopoles.

And last in the process, one can set the weight for each goal and let the optimizer know which one has greater priority. $|S_{ii}|$ was naturally set with higher priority than $|S_{ij}|$, given its superior importance. A high $|S_{ij}|$ value does not necessarily mean a bad interaction performance. The envelope correlation coefficient must also be evaluated.

Considering the large amount of parameters, the algorithms mentioned above dictate if an optimum is found. But the antenna designer can sweep individual parameters to get a feeling for the way they influence the antennas performance. Along the process, sometimes this is more suitable. Notice that, given the plethora of parameters, not all vary what they should when running the optimizer. Moreover, the Trust Region Framework for instance, assumes an already good model. It may only find a near local optimum, instead of a better local one, let alone the global best.

### 3.4.2 Sensitivity analysis

So one can have a feeling for which parameters shape the antenna’s behavior the most, a few examples are included here. Their values were swept around their optimum to find out the influence they have on the antenna’s behavior.

As an important note, the antenna went through a couple of thousand simulations. Not only by
changing individual parameters countless times, but by using the algorithm indicated in section 3.4.1 as well. For each time the algorithm was run, more than 100 simulations took place (sometimes three times that). And whenever it was run, dozens of parameters were changed. Therefore, showing the plethora of simulations done during optimization is absurd and it is only with hindsight one is capable of choosing the right parameters to illustrate important variations leading to the final outcome in section 3.4.3.

3.4.2.1 Parameters which don’t affect S-plots

Figure 3.9 is representative of one of those dimensions in the antenna where the S-plots barely ever change. Such details in the geometry are important when they can influence the size of the overall antenna, for example, and adjusting them does not harm performance in any way. It was not the case here though, and there was no advantage in shaping the F-geometry in a particular way. In fact, having the fabrication process in mind, less edges one would have by keeping this shape. Figure 3.10 is another good example. Another parameter that doesn’t affect antenna’s behavior is $w_4$.

![Figure 3.9: Changing parameter $l_4$.](image)

![Figure 3.10: Changing parameter $w_6$.](image)
3.4.2.2 Changing S11 parameters

On another note, a critical parameter is shown in figure 3.11. The minus and plus sinus in the figure denote the way the parameter affects the geometry. As the value of \( l_{10} \) increments, a big lump starts emerging around \( 1.8 \text{GHz} \), barely widening the bandwidth in the upper part of the frequency spectrum. On the other hand, as this parameter decrements, the plot shrinks horizontally, drastically changing its performance.

Another parameter affecting the optimum \(|S_{11}|\) is \( l_5 \), as seen in figure 3.12. Other examples include: \( l_6, w_5, d_1, h_1, w_{10}, l_{12}, l_{11}, w_{11}, w_{12} \) and \( d_4 \).

![Figure 3.11: Changing paramater \( l_{10} \).]

![Figure 3.12: Changing paramater \( l_5 \).]

3.4.2.3 Changing S44 parameters

Moving on to parameters affecting \(|S_{44}|\), increasing \( w_1 \) on the left, which denotes the width on the left side of the upper big monopole (see figure 3.13), one loses all possibilities of having \( 5 \text{GHz} \) Wi-Fi, let alone the middle frequencies \( w_1 \) when one increments more than \( 1 \text{mm} \). For negative values, the big monopoles almost lose all their performance in the spectrum of interest, by drastically going above \(-10 \text{dB}\).
Other examples include: \( w_2, l_{14}, w_{14}, h_2, d_2, d_3, w_{15}, w_{11}, w_{12} \) and \( d_4 \).

### 3.4.2.4 Changing overall parameters

Lastly, there are parameters that affect both \(|S_{11}|\) and \(|S_{44}|\). That is the case of \( w_{13} \), as seen in figure 3.14, and \( w_3, l_1, l_3 \) as well. Changing the position of the feed, if that were a parameter, has a huge impact as well. The sheer amount of other parameters one could add is enormous and for that reason only the parameters in figures 3.15 and 3.16 were analyzed.

### 3.4.3 Outcome

From the substrates available, the Rogers RT/Duroid 5880 with thickness 0.787 mm was chosen. It is a good quality substrate with low permittivity (2.20), low losses and good homogeneity.
3.4.3.1 Front

Figure 3.15 is an approximate 2D life-size picture of the antenna's front with black being the usual copper and white being the substrate RT Duroid 5880.

The connection points for each of the 4 coaxial cables, where the copper cores protrude, are located next to \( w_4 \) and \( w_3 \) and their symmetrical points, where one finds semicircles in the copper.

![Figure 3.15: Geometry of the antenna's front.](image)

3.4.3.2 Back

Figure 3.16 is an approximate 2D life-size picture of the antenna's back, with the 4 monopoles of the front included (but greyed out) so one can have an idea of the relative position to ground (coloured black).

The coaxial cables positions are easy to spot either due to the circular shapes extracted from the ground copper or the greyed out front of the antenna present in the figure 3.16 as well.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>l0</td>
<td>length of the substrate</td>
<td>143.1</td>
</tr>
<tr>
<td>w0</td>
<td>width of the substrate</td>
<td>85.2</td>
</tr>
<tr>
<td>w1</td>
<td>top width of the biggest monopole</td>
<td>16.1</td>
</tr>
<tr>
<td>w2</td>
<td>bottom width of the biggest monopole</td>
<td>15.5</td>
</tr>
<tr>
<td>w3</td>
<td>width of the bottom feed line</td>
<td>3.8</td>
</tr>
<tr>
<td>w4</td>
<td>F: width of the vertical bar</td>
<td>1.4</td>
</tr>
<tr>
<td>w5</td>
<td>F: width of the top horizontal bar</td>
<td>16.5</td>
</tr>
<tr>
<td>w6</td>
<td>F: width of the bottom horizontal bar</td>
<td>9.9</td>
</tr>
<tr>
<td>l1</td>
<td>height of the upper part of the biggest monopole</td>
<td>33.7</td>
</tr>
<tr>
<td>l2</td>
<td>height of the bottom part of biggest monopole</td>
<td>61.8</td>
</tr>
<tr>
<td>l3</td>
<td>height of the bottom feed line</td>
<td>1.8</td>
</tr>
<tr>
<td>l4</td>
<td>F: height of the vertical bar</td>
<td>11.9</td>
</tr>
<tr>
<td>l5</td>
<td>F: height of the top horizontal bar</td>
<td>3.1</td>
</tr>
<tr>
<td>l6</td>
<td>F: height of the bottom horizontal bar</td>
<td>2.2</td>
</tr>
<tr>
<td>l7</td>
<td>F: height of the bottom part below the bottom horizontal bar</td>
<td>4.3</td>
</tr>
<tr>
<td>d1</td>
<td>F’s distance to the axis of symmetry</td>
<td>11.9</td>
</tr>
<tr>
<td>d2</td>
<td>upper part of the biggest monopole’s distance to the axis of symmetry</td>
<td>21.0</td>
</tr>
<tr>
<td>d3</td>
<td>bottom part of the biggest monopole’s distance to the axis of symmetry</td>
<td>27.1</td>
</tr>
<tr>
<td>h1</td>
<td>F’s distance to the bottom of the substrate</td>
<td>113.5</td>
</tr>
</tbody>
</table>

Table 3.1: Parameters and corresponding final values of figure 3.15, (antenna’s front).

Figure 3.16: Geometry of the antenna’s back.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w10</td>
<td>top width</td>
<td>28</td>
</tr>
<tr>
<td>w11</td>
<td>top narrow vertical bar width</td>
<td>7.6</td>
</tr>
<tr>
<td>w12</td>
<td>top far right width of vertical bar</td>
<td>3.2</td>
</tr>
<tr>
<td>w13</td>
<td>width in the middle of the ground</td>
<td>34</td>
</tr>
<tr>
<td>w14</td>
<td>width of the middle non-copper bar</td>
<td>18.8</td>
</tr>
<tr>
<td>w15</td>
<td>bottom width</td>
<td>20.8</td>
</tr>
<tr>
<td>l10</td>
<td>height of the middle upper part</td>
<td>16.2</td>
</tr>
<tr>
<td>l11</td>
<td>height of the upper vertical bar</td>
<td>27.1</td>
</tr>
<tr>
<td>l12</td>
<td>height of the middle</td>
<td>19.9</td>
</tr>
<tr>
<td>l13</td>
<td>height of the vertical bar</td>
<td>18.6</td>
</tr>
<tr>
<td>l14</td>
<td>height of the middle non-copper bar</td>
<td>2.5</td>
</tr>
<tr>
<td>l15</td>
<td>height of the bottom part</td>
<td>47.3</td>
</tr>
<tr>
<td>d4</td>
<td>distance separating the two part at the top</td>
<td>4.1</td>
</tr>
<tr>
<td>h2</td>
<td>Bottom part’s height</td>
<td>50.1</td>
</tr>
</tbody>
</table>

Table 3.2: Parameters and corresponding final values of figure 3.16, (antenna’s back).

### 3.4.3.3 Side

Figure 3.17 depicts the antenna thin side of less than 1 mm. Notice that the materials used will match the ones used in the laboratory. This may sound obvious but both [5, 6] used two different substrates from the one used here, and this had to be taken into account since it strongly influences results and cannot be overlooked.

![Figure 3.17: Geometry of the antenna’s side.](image)

- **copper**
  - thickness 0.035 mm
- **Annealed copper (lossy)**
- **substrate**
  - thickness 0.787 mm
  - Rogers RT5880 (lossy)
  - $\epsilon_r = 2.2$
  - $\mu_r = 1$
  - $\tan\delta = 0.0009$ @ 10GHz

### 3.5 Simulation results

#### 3.5.1 S-Parameters

##### 3.5.1.1 Symmetries

Before going through the $S$-parameters, one should take into consideration some mathematical properties that will ease up the analysis process. Looking at the scattering matrix, one is dealing with a 4x4 matrix. There is no need to present all 16 plots. Some $S$-parameters are redundant due to the physical
symmetry and reciprocal properties of the antenna.

Being reciprocal (made of reciprocal elements) for example, leads to a $S$-parameter matrix equal to its transpose. Physically symmetrical on the other hand, leads to equal elements both in its diagonal and outside of it. That was, in fact, an important reason to keep it symmetrical. Taking this into account, there are only 6 different $S$-parameters needing to be looked at, namely $S_{11}$, $S_{21}$, $S_{31}$, $S_{41}$, $S_{34}$ and $S_{44}$, as shown in figure 3.18.

$$
\begin{pmatrix}
S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\
S_{2,1} & S_{2,2} & S_{2,3} & S_{2,4} \\
S_{3,1} & S_{3,2} & S_{3,3} & S_{3,4} \\
S_{4,1} & S_{4,2} & S_{4,3} & S_{4,4}
\end{pmatrix}
\quad \text{becomes} \quad
\begin{pmatrix}
S_{1,1} & S_{2,1} & S_{3,1} & S_{4,1} \\
S_{2,1} & S_{1,1} & S_{4,1} & S_{3,1} \\
S_{3,1} & S_{4,1} & S_{3,1} & S_{4,1} \\
S_{4,1} & S_{3,1} & S_{4,1} & S_{3,1}
\end{pmatrix}
$$

Figure 3.18: Simplifying the $S$-parameter matrix.

The monopoles’ ports were numbered as shown in figure 3.19. It is easy to see that $S_{11}$ is equal to $S_{22}$, 1 interacts with 4 the same way 2 does with 3 ($S_{23}$ equals $S_{14}$), etc. Consequently, one only has to analyze monopole 1 and its interactions with the remaining monopoles without the need to repeat the process to monopole 2.

### 3.5.1.2 Input reflection coefficient results

It is important to make some considerations regarding the $S$-parameters obtained through CST. The antenna was simulated using 4 coaxial cables since it was known that the prototype would be fed like this. A great deal of time and effort was spent optimizing the antenna in these conditions. Using any other kind of ports (or even substrate) would require new optimization effort. Even so, some testing
using discrete ports was done as well and its results are present in the appendix C. Using coaxial cables or discrete ports depends on the type of devices one intends to use these antennas into.

Figure 3.20: Simulated magnitude of $S_{11}$.

Figure 3.20 shows the magnitude of $S_{11}$ in $dB$ across the frequency spectrum in which the antenna operates. Notice one has $|S_{11}| < -10 dB$ from $1.46 GHz$ to $2.7 GHz$ with a lump in between at $2.25 GHz$. This lump, getting the maximum value of $-8.9 dB$ at the peek is not desirable but it does not really represent a problem. Not only because $-10 dB$ is a more rigourous reference, not always considered as such for this type of antennas (see [15] for example, where -6dB is used as a criterion for frequencies greater than $1.5 GHz$), but also because, although CST is a great tool for simulating a great variety of antennas, the simulation results do not model reality in such a strict sense. One will see this in chapter 4, where measured results show no problem regarding this case.

Figure 3.21: Simulated magnitude of $S_{44}$.

Figures 3.21 and 3.22, which refer to monopole 4, show tri-band resonance considering all the regions in the spectrum that $|S_{44}|$ goes below $-10 dB$: $0.73 GHz$ to $0.96 GHz$, $1.64 GHz$ to $3.1 GHz$ and $3.86 GHz$ to $6.16 GHz$.

As mentioned before, CST is a good simulation software tool but acknowledges some error margin. The results will be slighly better as one shall see in chapter 4, where $S_{44}$ gets to be below $-10 dB$ for GPS frequencies around $1.5 GHz$. In addition, any of those peaks present in figure 3.21 do not go above
−7.35 dB which can suffice for many applications. For those cases, the monopoles can work actively at any frequency from 0.7 GHz to 6.4 GHz yielding quite a wide bandwidth.

3.5.1.3 Mutual coupling

Figure 3.23 shows mutual coupling between monopole 1 and monopoles 2, 3 and 4. Results are considered good when below −15 dB, being in this case below −11.3 dB for all these monopoles pairs.

One is comfortable with these results and can assume these monopoles are approximately independent. But magnitude does not say it all. Whenever magnitude is below −15 dB, one can be sure there is low mutual interaction, with the opposite not being true if it gets above such value. Phase plays a role here and that is why the envelope correlation coefficient (ECC), usually represented by $\rho_e$, is calculated. Section 3.5.2 explores this in more detail.

The remaining pair, monopoles 3 a 4 (see figure 3.24), raised the most concern due to $|S_{34}|$’s high value at the frequencies of interest at which $|S_{44}|$ is below −10 dB, specially from 0.7 GHz to 1 GHz and 1.5 GHz to 2 GHz. These concerns, in light of one not having come up with a way to get those peaks down by any means, were finally mitigated when evaluating ECC (see section 3.5.2), which considers both module and phase when assessing the interaction between antennas.
3.5.2 Envelope correlation coefficient

Envelope correlation coefficient (ECC) is a parameter commonly evaluated when working with an antenna in a MIMO configuration. It is based on a fundamental equation that requires 3-dimensional radiation pattern considerations but admits a simple closed-form equation, see 3.1, that only relates the scattering parameters.

Equation 3.1 is usually preferred over the 3-D radiation pattern method since it requires little computational power and yields sufficiently accurate results in many experimental environments such as in-door environments with rich multipath propagation performance, [32].

\[
\rho_e = \frac{|S_{ii}S_{ji} + S_{ij}S_{jj}|^2}{|(1 - |S_{ii}|^2 - |S_{ji}|^2)(1 - |S_{jj}|^2 - |S_{ij}|^2)|} \tag{3.1}
\]

One infers from equation 3.1 that if two antennas are completely independent from one another then \( \rho_e = 0 \). \( \rho_e \) can vary from 0 to 1 and the lowest it gets the better for the MIMO antenna system overall. Some authors consider 0.3 as the maximum a system’s ecc should achieve in order to still be considered a good one [33]. Others even 0.5 [see 34, 35, 36]. However, 0.1 is widely accepted as the best reference value to meet any rigorous demands regarding MIMO systems.

The ECC evaluated for monopoles 1 and 2 is no greater than 0.025, as one can see in figure 3.25, but that lump is outside of the interval the monopoles operate. 0.025 per se would meet the requirement of less than 0.1, but that lump only goes from 1 GHz to 1.3 GHz. In fact, considering any pair between monopoles, low ecc is always the case as one will see.

The one case one should be worried the most is the mutual coupling between monopoles 3 and 4 (see section 4.4.1.2). Figure 3.26 alleviates this concern since \( \rho_e \) is less than 0.0025 at its maximum peak.

As expected, figures 3.27 and figure 3.28 show envelope correlation coefficients between monopoles 1 and 4 and 1 and 3 respectively, lower at the peak than any of the previous pairs considered. Noticing once more, these are the pairs with monopoles the furthest apart.
3.5.3 Radiation patterns

3.5.3.1 System of coordinates

Figure 3.29 shows how theta and phi are defined relative to the antenna since in this section all radiation patterns will use these coordinates system.
3.5.3.2 Polar plots

To study the antenna’s radiation patterns, five discrete frequency values were chosen for the following reasons:

0.8 GHz, made sense being both the middle frequency of the low spectrum region of this antenna (<1 GHz), where low-LTE frequencies are located, and GSM-800.

1.5 GHz, since GPS works in a very narrow band around this frequency it was a natural choice to make. That leads to radiation patterns very representative of what the antenna is like when being used for GPS applications.

1.9 GHz, one of the GSM frequencies.

2.4 GHz, since it is used for WiFi and bluetooth.

5.3 GHz, being one of the frequencies 5GHz-Wi-Fi works at, which is being adopted in new routers alongside 2.4GHz-Wi-Fi.
These five distinct frequencies correspond to a vast number of polar plots. Although this antenna is symmetrical and manages to narrow down the amount of necessary plots to present, for three of the above frequencies there are two monopoles operating at each one. Therefore, in total, there are 8 sets of polar plots to present. For that reason, they were all included in appendix E.

So the reader gets a feeling for what they look like, 5.3GHz’s radiation patterns, obviously relative to monopole 3, the one able to operate at that frequency, was put here along with the correspondent values.

Having figure 3.29 in mind, figure 3.30 has on the left the corresponding plane cuts for easier understanding.

Ideally one has low directivity, since either a phone or a tablet make use of multipath propagation rather than em waves in line of sight. 5.3GHz’s radiation patterns are considered good results precisely because directivity is low (see table 3.3) for the majority of the plane cuts (ideally would be isotropic).

<table>
<thead>
<tr>
<th></th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\phi$</td>
<td>4.3</td>
<td>-1.38</td>
<td>-8.63</td>
</tr>
<tr>
<td>$G_\theta$</td>
<td>2.95</td>
<td>0.257</td>
<td>4.41</td>
</tr>
<tr>
<td>$G_{\text{total}}$</td>
<td>6.69</td>
<td>2.53</td>
<td>4.62</td>
</tr>
<tr>
<td>$\text{Rad}_{\text{effic.}}$</td>
<td>96.0395</td>
<td>$\text{Tot}_{\text{effic.}}$</td>
<td>89.2463</td>
</tr>
</tbody>
</table>

Table 3.3: Simulated efficiency (%) and gain (dBi) for 5.3GHz, port 3.
Figure 3.30: Different cuts of the antenna and the corresponding radiation patterns for 5.3 GHz, port 3.
3.5.4 SAR levels

Despite it has never been a goal to optimize the antenna having SAR levels into account, it is important to mention these. The power absorbed per mass of tissue (W/kg) - SAR (Specific Absorption Rate) - has to be, according to US/Australian standards, less than \(1.6\, W/\text{kg}\) (averaging over \(1\, \text{g}\)) and less than \(2\, W/\text{kg}\) (averaging over \(10\, \text{g}\)) according to European standards\(^6\) [37, 38].

CST software tool was used in order to evaluate the values in table 3.4. The antenna meets all the requirements\(^7\) for GSM frequencies (hence \(0.9\, \text{GHz}\) and \(1.8\, \text{GHz}\)), the ones at which the antenna is closest to a person’s head. But one should know that SAR does not take into account power peaks, microwave hearing effect or time of exposure. But leaving that aside, it is a level many agree it is well below any adverse health effects could occur.

<table>
<thead>
<tr>
<th>Port</th>
<th>Port 1</th>
<th>Port 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0.9, \text{GHz})</td>
<td>0.23</td>
<td>0.10</td>
</tr>
<tr>
<td>(1.8, \text{GHz})</td>
<td>0.53</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Table 3.4: SAR levels for GSM-900 and GSM-1800 on each port.

These tests were solely ran in CST. No experimental measures occurred. Additional data from CST: Stimulated power: \(0.5\, W\); Averaging method: IEEE/IEC 62704-1.

\(^6\)Both cannot be compared, since are based on different estimation methods.

\(^7\)Given antenna’s mass < \(10\, \text{g}\), CST only allowed for the evaluation averaging over \(1\, \text{g}\), thus nothing but american/australian SAR levels are presented.
Chapter 4

Antenna fabrication and test

4.1 Introduction

Obtaining the freedom to trust the results, and any future simulations regarding them, was this chapter’s main objective. Any presumptions made about the antenna’s behavior were validated or discredited this way.

The antenna prototype was fabricated in the IT/IST laboratory of printed circuits using the photolithographic process described in the appendix F. The process consists of, to put it briefly, getting a PCB board under UV light with the intended geometric shape protected by a photoresist solution. A corrosive solution then removes the burnt copper leaving behind the desired antenna’s configuration. Once clean, coaxial cables are introduced and welded on its back.

The antenna was then tested for the S-parameters using a vector network analyzer. Radiation patterns and respective gains were finally measured in the anechoic chamber. Again IT/IST laboratories were used. Errors are naturally introduced during the process of course, but a great deal of effort was put into minimizing these. The materials and cables dimensions were accounted for in all simulations, including coaxial cables length and dielectric properties. Besides, the equipment used was carefully calibrated and an anechoic chamber\(^1\) was used, providing for good isolation from the environment.

In most sections throughout this chapter, measured results are put against simulated ones so the reader can have a feeling for how accurate theoretical simulations are. It is worth saying that the final antenna’s design presented in chapter 3, and tested here, went through many steps following the author’s logic. Any other reasoning would naturally lead to different outcomes. Once obtained good agreement between simulation and experimental results, alternative designs should be realistic as well.

\(^1\)isolated room designed to absorb reflections of electromagnetic waves and test antennas as if they were in open space without interference of exterior influences, [39].
4.2 Fabrication process

One of the advantages of printed antennas is the fabrication processes available. These antennas are often cited for their low profile characteristics but they are extremely competitive when it comes to their manufacturing process. The easiness and speed of several inexpensive fabrication processes available leads to overall lower prices on the devices these antennas are inserted into. Moreover, they are mechanically robust when mounted on rigid surfaces.

The fabrication process used to make the antenna is the photolithographic process which consists of using an etching chemical process radiation to shape the PCB’s copper to the desired geometry. It first involves getting the surface absolutely grease free. To achieve that, a rag can be used with some detergent (carefully chosen) to also remove any oxides. Naturally, extreme caution to avoid fingerprints is needed at this stage.

A photoresist solution is then applied to the whole surface. This must be done in a subdued light room, with no sunshine or of similar brightness, or better yet, a dark room. This is followed by a 24-hour period to let the PCB board dry or, if one wants to speed up the process, a drying chamber can be used as well.

The photoresist solution used, in this case, was *Positiv 20*, sensitive to ultraviolet rays. The idea is to expose the unwanted copper areas to UV light. In order to do so, a positive original master film of the circuit drawing is prepared and placed on top of the board surface\(^2\). A sheet of glass is clamped together so that no light leaks underneath the drawing.

The photoresist solution is resistant to the developer (caustic soda and water, usually) except where it was exposed to UV light. After developing for a couple of minutes, the intended detailed copper pattern can be seen. The removing of the photoresist coating can then finally be done by means of acetone or another proper solvent [40].

This processed if fully detailed in appendix F. Figure 4.1 depicts the photolitography process and figure 4.2 shows the equipment used in the IT/IST printing circuit laboratory.

![Photolitography scheme](image.png)

**Figure 4.1:** Photolitography scheme, edited from [41].

\(^2\)A positive photolithographic process is described. Negative photoresist solutions could also be used.
4.3 Measurement techniques

All the measurements took place at IT/IST laboratories.

4.3.1 S-parameters

The S-parameters were measured using an Agilent’s vector network analyzer (see figure 4.3). The errors within the instrument were compensated with electronic calibration and the ports not involved in the measurements were terminated with 50Ω loads [42].
4.3.2 Radiation patterns

To measure the radiation patterns, an anechoic chamber was used in farfield configuration. Figure 4.5 shows the receive horn antenna for the frequency bands of interest and how the tested antenna was set and positioned as well. It does not matter which antenna is the transmitting one, since the tested antenna could be used as a receive antenna too, leading to the exact same radiation patterns. For measuring the radiation patterns in the 3 different plane cuts, the tested antenna was mounted on a platform capable of turning 360°.

Standard antennas used:
- Log-periodic for 0.8 GHz and 1.5 GHz measurements
- FMI 08240-10 1.72 GHz to 2.61 GHz for 1.9 GHz and 2.4 GHz measurements
- FMI 12240-15 3.94 GHz to 5.99 GHz for 5.3 GHz measurements

And FMI (Flann Microwave) 06240-10 to evaluate the gain (operates from 1.14 GHz to 1.73 GHz)

Two important aspects have to be mentioned. The anechoic chamber is indicated to operate at frequencies greater than 1.5 GHz, but nevertheless, 0.8 GHz was measured as well. If, for this frequency, the radiation patterns don’t match the simulated ones, that is understandable.

It is also important to mention that, for two of the plane cuts (φ = 90° and φ = 0°), the platform turns its back on the receiving antenna. For about 60° (150° - 210°) the platform is in between both antennas, obstructing the measurements. Figure 4.4 shows, in grey, the degrees for which measurements are not expected to agree with simulation. Other than that, all radiation patterns were measured as expected.

Figure 4.4: Degrees for which radiation patterns couldn’t be measured properly (in grey).
Figure 4.5: Measuring radiation patterns in the anechoic chamber.
Figure 4.6: IT Microwave Anechoic Chamber Block Diagram

N5183A: Agilent MXG Microwave Analog Signal Generator, 100 kHz to 20 GHz
N5264A: Agilent PNA-X Measurement Receiver for Antenna Test
N5280A, Agilent Frequency Down Converter
AL-4906: Orbit/FR Positioner Control
AL-4146-2: Orbit/FR Local Control Unit
AL760: Orbit/FR Azimuth Positioner
AL560: Orbit/FR DUT Polarization Positioner
AL360: Orbit/FR Probe Positioner
4.4 Comparison of simulation and experimental results

4.4.1 S-Parameters

4.4.1.1 Input reflection coefficient

Figure 4.7 contains $S_{11}$ simulation and measured results displaying two curves almost coincident except for $1.6\,GHz$ to $2.5\,GHz$ interval. Nothing to worry about here since lab’s curve is below that of which is below $-10\,dB$ for most of the intended frequency interval. Even the lump one can see in the simulated curve reaching at its peek $-8.9\,dB$ (mentioned in chapter 3 in section 3.5.1.2) does not exist when measured. What is not desirable though is the red curve going above the blue one at $2.5\,GHz$ transgressing the ideal $-10\,dB$ reference from $2.5\,GHz$ to $2.7\,GHz$. Even so, the measured result is $-8.3\,dB$ at its maximum within the interval of interest, which is not a very high value.

$S_{22}$ measured results confirm the symmetries analyzed in chapter 3 and yield even better results concerning the frequency regions for which the lab curve is above $-10\,dB$. Since the simulated results are completely achieved in a different port, these differences are probably due to very small fabrication asymmetries.

As in the case of $S_{11}$ and $S_{22}$, the measured curve for $S_{44}$, shown in figure 4.9, is almost coincident for
the whole studied spectrum. The discrepancies found are actually good ones. Apart from the spectrum regions the red curve goes above the blue one, there is no reason for concern. When the lab curve goes over the simulation curve one has to look if it has crossed the $-10 \, dB$ reference. That is the case for $3.15 \, GHz$ to $3.85 \, GHz$ which is fine, supposed to be that way from the start, and then $1 \, GHz$ to $1.46 \, GHz$ which was the initial intention despite the fact one did not manage to get such result. This way it is possible to work at GPS frequencies for monopoles 3 and 4 as well, around $1.5 \, GHz$. Summing up, the test results show results are below the reference value for $0.74 \, GHz$ to $1 \, GHz$, $1.46 \, GHz$ to $3.15 \, GHz$ and $3.85 \, GHz$ to $6 \, GHz$.

Figure 4.9: Simulated vs measured parameter $S_{44}$.

Figure 4.10, accounting for $S_{33}$ measured curve, does not yield good results for high frequencies. In the author’s opinion, this is due to the way the antenna was cut at the fabrication process. It is clearly visible the asymmetry between these two monopoles in the fabricated prototype. $S_{44}$ measured curve, therefore, should be the results in which to trust the most.

Figure 4.10: Simulated vs measured parameter $S_{33}$.

4.4.1.2 Mutual coupling

Figures 4.11, 4.12, 4.13 and 4.14 are fully consistent with the simulation results and therefore there is no reason to address any detail that has been commented already in chapter 3. But the consistency
is, per se, something deserving to be commented on: despite natural erraticism in all the lab curves, they follow all CST curves pretty accurately. Moreover, discrepancies below $-20 \, dB$ are not worth worrying about.

Figure 4.11: Simulated vs measured parameter $S_{21}$.

Figure 4.12: Simulated vs measured parameter $S_{31}$.

Figure 4.13: Simulated vs measured parameter $S_{41}$.
4.4.2 Envelope correlation coefficient

This topic was introduced in chapter 3 where it was stated that 0.1 was a good maximum value for this parameter. Indeed, one will find the same to be true here. Not only $S$-parameters’s measured magnitude is very coincident but phase is almost coincident as well.

4.4.3 Radiation patterns

As in chapter 3, too many radiation pattern plots led the author to include them in a separate appendix, appendix G in this case. Experimental results are very consistent with the simulated ones, as one will see. It was also included the measured gains for each plane cut and each frequency.
Figure 4.16: Measured envelope correlation coefficient $\rho_e$ for monopoles 3 and 4.

Figure 4.17: Measured envelope correlation coefficient $\rho_e$ for monopoles 1 and 4.

Figure 4.18: Measured envelope correlation coefficient $\rho_e$ for monopoles 1 and 3.
Chapter 5

Conclusions

Through technology, distance no longer hinders communication. Any two points on earth can communicate as if they were next to each other and that is astounding per se, when one thinks about it. But humankind as gone beyond that, in fact, moving plenty more wireless services into smartphones.

People have been used to take photos, videos, call or text someone and access the web or email through their phones for quite a while. But in the last two years alone, a bountiful of new different services came up and it is now possible, using only your smartphone, make electronic payments at a local store, use it as a subway card or airline boarding pass, control one’s vehicle or even weigh objects. The point being that more and more services are moving on to mobile terminals and the more personal these are becoming. Smartphones have already substituted computers in many daily tasks and that will keep happening, with traffic from wireless and mobile devices accounting for two-thirds of total IP traffic by 2020, [1].

This technological shift will be accompanied by heavy research and investment in the field so it can keep up with demand. It is this tendency that lured the author to this subject. That motivated to create a good antenna with the best performance possible for thin small terminals (143.1 × 85.2 mm²).

The antenna’s configuration was chosen based on two recent papers [5] and [6], from 2014 and 2015 respectively. These cover very interesting frequency bands and, combined, seemed very promising. The simulation software used was CST, a well-known antennas software simulation tool, and it allowed to test both monopoles together on the same ground plane as well as running several optimization algorithms (see appendix B). In addition, a sensitivity analysis was carried out using the parameters sweeper. The design achieved was taken into the laboratory and a prototype was fabricated and tested. There is a good agreement between simulation and experimental results, which validates the design procedure and enhances the proof of concept.

In more detail, to meet today’s requirements, a 4-antennas MIMO system has been designed, covering three distinct frequency bands in the mobile frequency spectrum. It covers all common wireless systems, or better put, several frequencies that can be used for whatever the wireless services needed. UMTS (band 5) and LTE (band 5) operate at exactly the same frequencies, for instance. Possible services this antenna works at are, therefore, GSM (850, 900, 1800, 1900), GPS, DCS, PCS, UMTS, LTE
(Bands 1-2, 23-30, 33-41 and 44), Bluetooth, Wi-Fi 2.4 GHz and Wi-Fi 5 GHz.

The antenna does it so by using 4 different monopoles on the same PCB carefully put together so they behave as independently as possible. For some LTE bands (5-6, 8, 12-14, 17-20, 26-28 and 44), only two monopoles can operate. These bands are situated at relatively low frequencies in the mobile spectrum and require, for that reason, bigger monopoles.

It was possible, however, to make these monopoles resonate at frequencies around $\sim 5.2 \text{ GHz}$ as well, allowing for the recent Wi-Fi standards to be met. For the majority of the wireless services mentioned above, it is possible to have all 4 monopoles actively working (see figure 5.1). This is a very good way to meet diversity and data rate demands nowadays. One can have one monopole working exclusively at GPS frequencies, two others for Wi-Fi, and another tuned for GSM/UMTS, for instance. It is up to the programmer to decide which ones to use to best fit the user needs.

As seen in chapter 2, there is a trade-off between reliability and data rate possible for every MIMO system and the more antennas at both the transmitter and receiver the better. This limitation is generally on the receiver side and the proposed antenna system meets that challenge elegantly. Besides, MIMO systems have been widely appreciated for their increase in link capacity, rather than reliability. That is another good reason for increasing the minimum number of antennas at one of the communication channel sides, since $\min(N_T, N_R)^1$ yields the gain in the capacity link.

![Figure 5.1: Frequency spectrum used in relation to the monopoles.](image)

The antenna has low gain in almost every plane considered. The less directive these antennas are, the better for these devices (see appendix G). Besides, mutual coupling is low, essential in MIMO systems. That was confirmed by the evaluation of $ecc$ for all monopoles pairs, never exceeding 0.025,

---

$^1 N_T, N_R$ - number of antennas at the transmitter and receiver, respectively.
way below 0.1, showing how poorly they interact with each other.

To the best of author's knowledge, no four-elements antenna has been created covering such a wide part of the mobile frequency spectrum. [15] and [36] are good 2014 examples of four-elements antennas. Yet, the first considers $6\,dB$ as the return loss reference, yielding an uninteresting bandwidth when considering $10\,dB$ return loss. The second however, albeit not having such wide bandwidth as this thesis's antenna is able to attain, when considering $-10\,dB$, is able to achieve good measured results (not simulated ones). But this is achieved with a much bigger substrate area, $230 \times 176\,mm^2$, only suitable for tablets therefore.

It is not to say the antenna does not need improvement. Its size only fits into bigger than average smartphones, even if this is the tendency one observes today. Ideally, the antenna would fit into any phone on the market. And that is the trade-off considered in this whole project. In short, the more powerful a performance, the more loose the constraints had to be, including size dimensions. A good trade-off has been achieved in the author's opinion.

5.1 Future work

For a practical implementation of this 4-monopoles antenna, one has to consider specific dimensions and materials, along with other constraints unique to each device and/or application. In that regard, every optimization process is very unique and not much can be said other than that one should look out for mutual coupling interference and not disregard it in favor of impedance bandwidth. The optimization should include testing with the specific device’s materials surrounding the antenna and with a person’s body if that is the case. As an example, it is common enough to find smartphones made of metal and cleverly use its back as the antenna’s ground. Changes like these must be obviously accounted for.

There is a lot of room for improvement considering the created antenna in free space alone. Two major points are to be considered: mutual coupling and its size. Mutual coupling is not less than $-15\,dB$ across all monopoles pairs considered. Some techniques were tried but to no avail as depicted in figure 5.2. They consist in using slits in the ground plane [43]. Further work could be done in this topic.

![Figure 5.2: Decoupling technique tried.](image)

Changing the substrate material can be an option to take, since RT/duroid 5880 was the only one
used in this project (FR4 is commonly used, for example). The dielectric properties can notably influence results to one’s advantage. Another possible approach is to change the feeding ports. Discrete ports and coaxial cables length have huge impact on the antennas performance. This can be seen in appendixes C and D. One should notice that all simulations and testing considered an open space situation only. The device the antenna is integrated into will influence the antenna’s performance as well, along with the user’s body.

Tweaking antenna’s dimensions should not be excluded from consideration. The optimization algorithms used may not have discovered the best optimum possible, see appendix B to see which algorithms one can use using CST. The computational effort required was too big to ask for to guarantee the best solution was found. If one eliminates redundant parameters, there are about 60 parameters in the project to consider. Moreover, one could always add new structures to try reducing mutual coupling and improve performance. Running two or three different optimization algorithms, and get these parameters to vary sufficiently, is extremely demanding and requires much more computational processing power than the one the author had access to. Besides, some algorithms used suppose the parameters already sit in a place not far from the optimum. The author advise trying to get access to powerful computers in order to test for possible better solutions.

One was very strict when setting up $10\,\text{dB}$ as the reference value for the return loss. The intention was to meet the requirements of any application or device on the market. As explained in chapter 3, often one can find $7.3\,\text{dB}$ or even $6\,\text{dB}$ enough, since the power involved is commonly low ($\sim 0.5\,\text{W}$).

Since the biggest constraint in modern smartphones is its size, the author suggests loosening up the reflection coefficient constraints by $\sim 1\,\text{dB}$ as a way to shrink the antenna width to a more reasonable dimension compatible with most smartphones on the market. Looking at the parameter $w_2$, that ultimately sets the width of the antenna, one can try reducing it by $\sim 5\,\text{cm}$, for example. That would lead to an area of $140 \times 79\,\text{mm}^2$, capable of fitting in a more considerable number of phones. The results are shown in figure 5.3.

One can always think of different ways to improve this antenna of course. Other type of printed antennas, as PIFAs for example, could be tried out. But that would be to a different logic from the start. As said before, if it is to be applied to a specific device, it does not matter being very rigorous at this stage until all proper testing conditions can be put together and properly considered.

\footnote{Two computers were used to run CST. One had an i3 processor of $2.13\,\text{GHz}$ and the other an $2.4\,\text{GHz}$ Intel Core i5.}
Figure 5.3: Tweaking antenna’s width.
References


[38] European Telecommunications Standards Institute, “SAR European levels, European specification ES 59005 (1998),” 2016. [Online; accessed September 8, 2016], http://www.etsi.org/deliver/etsi_tr/134900_134999/134925/03.00.00_60/tr_134925v030000p.pdf.


Appendix A

LTE and $5\,GHz$ Wi-Fi bands

This thesis is focused on an antenna to be used in LTE and $5\,GHz$ Wi-Fi wireless services, among others. These frequency allocations are quite sparse along the spectrum. Figures A.1, A.2 and A.3, show these frequency bands in detail.

<table>
<thead>
<tr>
<th>CHANNEL NUMBER</th>
<th>FREQUENCY MHz</th>
<th>EUROPE (ETSI)</th>
<th>NORTH AMERICA (FCC)</th>
<th>JAPAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>5180</td>
<td>Indoors</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>40</td>
<td>5200</td>
<td>Indoors</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>44</td>
<td>5220</td>
<td>Indoors</td>
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<td>✓</td>
</tr>
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<td>5240</td>
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<td>✓</td>
<td>✓</td>
</tr>
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<td>5260</td>
<td>Indoors / DFS / TPC</td>
<td>DFS</td>
<td>DFS / TPC</td>
</tr>
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<td>5280</td>
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<td>DFS</td>
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</tr>
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<td>DFS</td>
<td>DFS / TPC</td>
</tr>
<tr>
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Figure A.1: $5\,GHz$ Wi-Fi frequency band allocation [44].
### FDD LTE Bands & Frequencies

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**Figure A.2:** FDD LTE frequency band allocation [45].

### TDD LTE Bands & Frequencies

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<td>44</td>
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**Figure A.3:** TDD LTE frequency band allocation [45].
Appendix B

Solvers and algorithms

Chapter 3, section 3.4.1, mentioned the solver and algorithms used but did not specify the suitability of each one. Here is a more detailed explanation on the solvers and algorithms available in CST.

### B.1 Solvers

#### B.1.1 Transient solver

The transient solver is a general purpose 3D EM simulator. Real time domain simulation is useful for studying the field propagating through a component or along the traces of a PCB, and can be used in a huge range of EM applications.

Besides the specific capabilities in time domain, the transient solver also delivers broadband frequency domain results like S-parameters. These simulations can be performed with an arbitrarily fine frequency resolution without extra computational cost, thus avoid missing single resonances inside the spectrum. Field results for many frequencies (for example 100 farfield samples) can be derived from one single simulation run [46].

#### B.1.2 Frequency domain solver

The frequency domain solver is, like the transient solver, a general purpose tool. It delivers electromagnetic near and farfields as well as S-Parameters. Although the line cannot be drawn easily and there are always exceptions, the Frequency Domain Solver is the better choice, if you are looking at electrically small structures, or devices with a high Q-value. It achieves results with higher accuracy for very detailed structures compared to the transient solver [47].

#### B.1.3 Eigenmode solver

The eigenmode solver is dedicated to the simulation of closed resonant structures. Primary results are, besides the field distribution of the modes, the eigenfrequencies of the structures. The eigenmode
solver also takes advantage of CST’s proprietary PERFECT BOUNDARY APPROXIMATION (PBA), which delivers fast convergence in short time.

Typical application areas are the determination of the poles of a highly resonant filter structure, Q-value (also external) calculation, and the design of slow wave structures (like Travelling Wave Tube (TWT) or accelerating cavities) [48].

B.1.4 Integral equation solver

CST’s integral equation solver is again a specialized solver. It is dedicated to electrically large structures, which are governed by metal; dielectrics, lossy and lossless, however, can be taken into consideration.

CST MWS’s integral equation solver uses a Method of Moments (MoM) discretization with a surface integral formulation of the electric and magnetic field. In order to reduce the numerical complexity a Multilevel Fast Multipole Method (MLFMM) approach is used. This makes it much more efficient than full volume methods and particularly applicable to full wave simulations of objects in the range from approximately 10 to a couple of hundreds of wavelengths [49].

![Figure B.1: Main solvers one can use in CST.](image)

B.2 Algorithms

Figure B.2, already shown in chapter 3, section 3.4.1, is worth visualizing once again so one can see how the algorithms can be ordered relatively to parameters.

B.2.1 Classic Powell

Algorithm suitable for one-variable problems that robustly finds an optimum within the given parameter bounds. Sometimes, many iterations are necessary it gets to the optimum. Optimization terminates if two consecutive goal values yield less than the defined accuracy. It can be extremely accurate when compared to other algorithms, although much slower in comparison [31].
B.2.2 Interpolated quasi-Newton

A much faster local optimizer (compared to Classic Powell) which uses interpolation to approximate the gradient of the parameter space. The Interpolated Quasi Newton method is considered to have fast convergence. In short, the parameter space is sampled in each variable direction and simulations are only performed for these discrete parameter space points. Suitable for computationally demanding models [50, 31].

B.2.3 Trust region framework

A powerful local optimizer which builds a linear model on primary data in a "trust" region around the starting point. The modeled solution will be used as new starting point until it converges to an accurate model of the data. The Trust Region Framework can take advantage of S-parameter sensitivity information to reduce the number of simulations needed and speed up the optimization process, and is the most robust of the optimization algorithms. It is suitable for general optimization, especially on models with sensitivity information [50, sic].

B.2.4 Nelder-Mead simplex

A local optimization technique which uses multiple points distributed across the parameter space to find the optimum. Nelder Mead simplex algorithm is less dependent on the starting point than most local optimizers and is suitable for complex problem domains with relatively few parameters and/or systems without a good initial model [50]. It uses relatively few evaluations if the problem has a low number of parameters (i.e., less than 5) [31].

B.2.5 Genetic algorithm

A global optimizer that uses a higher number of evaluations to explore the search space and then refines them through multiple generations, with random parameter mutation. By selecting the “fittest”
sets of parameters at each generation, the algorithm converges to a global optimum. Suited for larger numbers of parameters (recommended the use of distributed computing) [50, 31].

B.2.6 Particle swarm optimization

This algorithm treats points in parameter space as moving particles. At each iteration, the position of the particles changes, according not only to the best known position of each particle, but the best position of the entire swarm as well. Particle swarm optimization works well for models with many parameters [50].
Appendix C

Discrete ports

Depending on the device or application, different feeding ports can be used. Coaxial cables were chosen so simulations would match the conditions of the prototype. If theoretical results indeed match the experimental ones, they would be more reliable this way. Having verified in chapter 4 that that was true, one can extrapolate that simulating in the same conditions will allow a fair comparison with experimental results.

Discrete ports make much more sense for several applications and that is why simulations using these are included here. Note: coaxial cables strongly influence some of the results. Even their length has to be accounted for. Therefore, the discrete ports’ results were re-optimized by tweaking some of the dimensions in the antenna’s geometry, so one could get similar results for either port types.

Figure C.1: Discrete ports instead of coaxial cables in perspective.

All mutual coupling plots are very similar and not worth including here.
Figure C.2: Simulated magnitude of the parameter $S_{11}$ using discrete ports.

Figure C.3: Simulated magnitude of the parameter $S_{44}$ using discrete ports.
Appendix D

Coaxial cables

Figure D.1 shows the effect of the cables on the F-shaped monopole. $cx$ denotes the cables length. Just by shortening the cables to 10 mm and 25 mm, the antenna’s $S_{11}$’s magnitude changes significantly. Same is true for any other plot considered. Good results have been achieved with discrete ports, see appendix C. Also good results would be achieved with other cable lengths, but details like these should be known from the start. In fact, it is well known that the feeding coaxial cable is important if a small ground is used [3]

![Parametric Plot: Magnitude in dB](image)

Figure D.1: Simulated $S_{11}$ using 10 cm, 25 cm and 40 cm coaxial feed cables.
Appendix E

Simulated radiation patterns

E.1 Simulated gains

<table>
<thead>
<tr>
<th></th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
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| $\text{Rad}_{\text{effic.}}$ | 91.7846 | $\text{Tot}_{\text{effic.}}$ | 70.5342 |

Table E.1: Simulated efficiency (%) and gain (dBi) for 0.8 GHz, port 3.

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<td>0.89</td>
<td>-3.04</td>
<td>0.84</td>
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| $\text{Rad}_{\text{effic.}}$ | 40.4297 | $\text{Tot}_{\text{effic.}}$ | 38.0890 |

Table E.2: Simulated efficiency (%) and gain (dBi) for 1.5 GHz, port 1.

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<td>2.79</td>
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| $\text{Rad}_{\text{effic.}}$ | 95.2555 | $\text{Tot}_{\text{effic.}}$ | 58.5868 |

Table E.3: Simulated efficiency (%) and gain (dBi) for 1.5 GHz, port 3.
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$\text{Rad}_{effic.}$ 94.4974  $\text{Tot}_{effic.}$ 76.9308

Table E.4: Simulated efficiency (%) and gain (dBi) for 1.9 $GHz$, port 1.

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$\text{Rad}_{effic.}$ 98.2766  $\text{Tot}_{effic.}$ 66.8652

Table E.5: Simulated efficiency (%) and gain (dBi) for 1.9 $GHz$, port 3.

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$\text{Rad}_{effic.}$ 98.2560  $\text{Tot}_{effic.}$ 80.1291

Table E.6: Simulated efficiency (%) and gain (dBi) for 2.4 $GHz$, port 1.

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$\text{Rad}_{effic.}$ 98.0194  $\text{Tot}_{effic.}$ 79.0861

Table E.7: Simulated efficiency (%) and gain (dBi) for 2.4 $GHz$, port 3.

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$\text{Rad}_{effic.}$ 96.0395  $\text{Tot}_{effic.}$ 89.2463

Table E.8: Simulated efficiency (%) and gain (dBi) for 5.3 $GHz$, port 3.
E.2 Radiation patterns at 0.8 GHz, port 3

Figure E.1: Different cuts of the antenna and the corresponding radiation patterns for 0.8 GHz, port 3.
E.3 Radiation patterns at 1.5 GHz

(a) \( \Phi=90^\circ \), port 1

(b) \( \Phi=90^\circ \), port 3

(c) \( \Phi=0^\circ \), port 1

(d) \( \Phi=0^\circ \), port 3

(e) \( \Theta=90^\circ \), port 1

(f) \( \Theta=90^\circ \), port 3

\( E_{\Theta} \) \hspace{1cm} \( E_{\Phi} \)

Figure E.2: Simulated radiation patterns for 1.5 GHz.
E.4 Radiation patterns at 1.9 GHz

Figure E.3: Simulated radiation patterns for 1.9 GHz.
E.5 Radiation patterns at 2.4 GHz

Figure E.4: Simulated radiation patterns for 2.4 GHz.
E.6 Radiation patterns at $5.3 \text{ GHz}$, port 3

(a) Constant $\Phi$, $\Phi=90^\circ$

(b)

(c) Constant $\Phi$, $\Phi=0^\circ$

(d)

(e) Constant $\Theta$, $\Theta=90^\circ$

(f)

$\mathbf{E_{THETA}}$  $\mathbf{E_{PHI}}$

Figure E.5: Different cuts of the antenna and the corresponding radiation patterns for $5.3 \text{ GHz}$, port 3.
Appendix F

Photolithographic fabrication process

This topic has already been addressed in section 4.2. However, a more detailed explanation of the fabrication process used is presented here taken from [40].

F.1 Pre-treatment of the original material

The surface to be sprayed must be absolutely grease free. To ensure this, clean with a good detergent (Vim, ATA or other powdered cleaner). Rub in the detergent with a moist rag so that it brightens the copper surface, removes any oxides and makes the copper layer completely wettable. This can be checked by running the surface under a tap to make sure that there are no water repellent areas left. After rinsing the plate thoroughly, dry it between sheets of absorbent paper taking extreme care to avoid any fingerprints on the board surface. Abrasive pads or solvents other than good detergents should not be used for cleaning the surface.

F.2 Application of layer

A dark room is not required for the application of the photoresist. This must be done however in a subdued light i.e. without sunshine or similar brightness and it is also very important that the work is carried out in a dust-free atmosphere. The board should be placed in a horizontal position and the spray applied from a distance of approximately 20 cm (8") from the board. One should apply a uniform coverage. Please note that application of too much spray will result in undesirable edges and coats of varying thicknesses requiring a longer exposure time (see paragraph 5). Whilst spraying, the spray can should be held in a vertical or slightly inclined position and after applications of the spray coating the boards should not be exposed to daylight.
F.3 Drying

After application of the sprayed-on coating, boards must be dried immediately in the dark. If necessary, the varnish can be dried at room temperature which will take at least 24 hours. It is safer to accelerate drying in a drying chamber of thermostatically controlled oven. If using for example an electric grill, make sure that all opening are covered and any source of light is shut off. Raise the temperature slowly to 70° maximum and dry at this temperature for about 20 minutes. Caution: Any drying temperature exceeding 70° is liable to damage the board!

F.4 Positive original

The original circuit drawing should be carefully prepared as it will be used as a master (positive) and will be copied onto the board surface. If the circuit is drawn with Indian ink, it is advisable to use transparent paper (tracing paper) of 90g/m2. For the production of high quality printed circuits, use originals on highly transparent film material only. Today print-outs on tracing paper or transparencies can be used. Be aware that the original drawing must be entirely impermeable to light and that the film of the original must allow ultraviolet rays to pass through. Originals showing extremely narrow sections of the circuit can be placed upside-down, so that direct copying onto the coating can be done. This will eliminate any side lighting effect with the resulting loss of width. Some trade journals publish circuit diagrams with a scale of 1: 1 on one side. By means of a transparency spray with brand TRANSPARENT 21, developed by KONTAKT CHEMIE, you can make such sides transparent and permeable for ultraviolet light. So, the direct copying out of circuit diagrams from trade journals on plates coated with Positiv 20 is possible. Transparent 21 makes tedious repro works unnecessary. If quality is not so important, you can also make photocopies onto transparencies. Place the original on top of the board surface. Put a sheet of glass on top of this and clamp them together, so that no light leaks underneath your drawing original.

F.5 Exposure

Time required for exposure depends on both the thickness of the coating and the intensity of the light source. A wide range of exposure ensures the safety margin required. Since our photoresist varnish Positiv 20 is sensitive to ultraviolet rays, ultraviolet lamps e.g. a mercury vapour lamp Philips HPR 125W or sunlamps 300W can be used. Exposure time depends on the thickness of the coating and will take 60 - 120 seconds at a distance of up to 25 - 30cm. Start with 60 s, if the film (transparent sections) remains cloudy, a longer exposure time (not under 120 seconds) will be necessary. Check the film every 15 seconds. It is important that the plates are not exposed to the UV- light before the lamp has reached full intensity normally 2–3 minutes from being switched on. In the event that an ultraviolet lamp is not available, any other lamp can be used that emits sufficiently high amount of effective ultraviolet light, e.g. Xenon lamps or super actinic tubes. Light from punctiform lamps is preferable to light from tubular lamps. The spectral sensitivity for the photoresist Positiv 20 lies between 360 and 410 nm.
F.6 Developing

Remove the plate from under the glass. Then bring the exposed plate in the developer in a plastic tray and agitate gently. Developing may not be performed in direct light, dark conditions are preferred. To prepare the developer in the correct concentration add 7 grams of caustic soda (NaOH) to one litre of cold water. Caustic soda is normally obtainable from any chemist’s shop or pharmacy. After a maximum of 2 minutes the image of the conductor should be fully developed. If not the board is under exposed. Normally the exposed section of the photoresist coating are removed in the developer, the original copper is clearly visible. The circuits are now outlined in a different colour compared to the copper. Do not leave the plate in the developer for an overlong time, otherwise it will attack the unexposed parts of the photoresist coating. In cases of over-exposure and if the ink drawings are not completely opaque, the image of the circuits will appear for a short time but will eventually be removed by the developer. CAUTION: After developing rinse the board in running cold water. Also wash your hands thoroughly in water every time you have worked with caustic soda.

F.7 Etching

Photoresist varnish Positiv 20 is resistant to acid baths of ferric chloride, ammonium persulphate, chromic acid and hydrofluoric acid. The latter two are used for etching glass plates using the usual processing methods. For the etching of copper plates we recommend an etching bath of ferric chloride heated to approximately 45° C of a density of 35 – 40%. Using the following mixture modern etching practice allows short etching times. 200 ml hydrochloric acid (HCL 35%) 30 ml hydrogen peroxide (H2O2 30%) 770 ml water (H2O) This mixture has a pungent smell and produces light vapours. It is essential that it is used with great care. Avoid any contact with the skin, but if this should occur, the affected area must be washed immediately. When using it is essential that the eyes be protected. The mixture also attacks clothing and other materials and the extreme care required in handling cannot be over-emphasized. The solution should be stored in dark bottles – not closed by airtight stoppers, because an excess pressure will then be generated inside the bottle by the disintegration of H2O2.

F.8 Clearing (removal of the coating)

For removing the photoresist coating acetone or other ketone solvents can be used. After the clearing process we recommend the application of our protective Soldering Varnish SK 10 which effectively protects the circuit’s paths from oxidation and also assists the soldering process.

F.9 Durability (removal of the coating)

Positiv 20 has a limited shelf life until the date indicated (EXP) on the to prim of the aerosol. The product has to be stored cool (optimal between +8 and +12° C in refrigerator, not in the freezer).
20 in an aerosol not only facilitates the production of printed circuits of all sizes, but also allows the production of photoengraving and enables the precise transfer of image elements to materials of many different kinds. Once your board or foil has been printed, it is advisable to safely protect the circuit against environmental effects. This can be done with absolute safety by using Plastik 70 spray which is a transparent protective varnish of acrylic resin giving a clear transparent coating with high quality insulation. A protective film of this type will permit the soldering of metallic surfaces. Place the original on top of the board surface. The spraying agents are high quality products manufactured by Kontakt Chemie – Europe's leading manufacturer of Electronic Sprays. Europe's leading manufacturer of Electronic Sprays
Appendix G

Experimental radiation patterns

G.1 Measured gain

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>0.6507</td>
<td>-3.1317</td>
<td>-9.8918</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>0.2610</td>
<td>2.0595</td>
<td>2.4744</td>
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<tr>
<td>$G_{total}$</td>
<td>3.4705</td>
<td>3.2076</td>
<td>2.7192</td>
</tr>
<tr>
<td>Sim$G_{total}$</td>
<td>1.45</td>
<td>2.11</td>
<td>1.66</td>
</tr>
</tbody>
</table>

Table G.1: Measured gain in (dBi) for 0.8 GHz, port 3.

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>0.6757</td>
<td>-1.7040</td>
<td>-4.7580</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>0.6757</td>
<td>-0.1366</td>
<td>3.5157</td>
</tr>
<tr>
<td>$G_{total}$</td>
<td>3.6860</td>
<td>2.1603</td>
<td>4.1182</td>
</tr>
<tr>
<td>Sim$G_{total}$</td>
<td>0.89</td>
<td>-3.04</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Table G.2: Measured gain in (dBi) for 1.5 GHz, port 1.

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>0.7771</td>
<td>-3.2895</td>
<td>-3.4858</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>-5.3632</td>
<td>0.9367</td>
<td>0.8976</td>
</tr>
<tr>
<td>$G_{total}$</td>
<td>1.7225</td>
<td>2.3289</td>
<td>2.2472</td>
</tr>
<tr>
<td>Sim$G_{total}$</td>
<td>2.26</td>
<td>2.11</td>
<td>2.79</td>
</tr>
</tbody>
</table>

Table G.3: Measured gain in (dBi) for 1.5 GHz, port 3.
<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>0.2499</td>
<td>-0.0970</td>
<td>-0.5774</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>0.7792</td>
<td>-0.4652</td>
<td>1.6727</td>
</tr>
<tr>
<td>$G_{total}$</td>
<td>3.5329</td>
<td>2.7331</td>
<td>3.7021</td>
</tr>
<tr>
<td>$Sim_{G_{total}}$</td>
<td>2.61</td>
<td>2.79</td>
<td>3.87</td>
</tr>
</tbody>
</table>

Table G.4: Measured gain in (dBi) for 1.9 GHz, port 1.

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>0.8669</td>
<td>-3.3095</td>
<td>-4.2997</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>-1.1146</td>
<td>-0.4532</td>
<td>0.9427</td>
</tr>
<tr>
<td>$G_{total}$</td>
<td>2.9985</td>
<td>1.3597</td>
<td>2.0790</td>
</tr>
<tr>
<td>$Sim_{G_{total}}$</td>
<td>2.87</td>
<td>2.37</td>
<td>2.69</td>
</tr>
</tbody>
</table>

Table G.5: Measured gain in (dBi) for 1.9 GHz, port 3.

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>1.8758</td>
<td>0.1372</td>
<td>-1.8086</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>2.8895</td>
<td>-0.1801</td>
<td>1.0558</td>
</tr>
<tr>
<td>$G_{total}$</td>
<td>5.4225</td>
<td>2.9917</td>
<td>2.9917</td>
</tr>
<tr>
<td>$Sim_{G_{total}}$</td>
<td>4.11</td>
<td>1.74</td>
<td>4.91</td>
</tr>
</tbody>
</table>

Table G.6: Measured gain in (dBi) for 2.4 GHz, port 1.

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>1.0751</td>
<td>-2.5823</td>
<td>-4.8377</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>-0.0105</td>
<td>-4.1549</td>
<td>2.1732</td>
</tr>
<tr>
<td>$G_{total}$</td>
<td>3.5764</td>
<td>-0.2875</td>
<td>2.9615</td>
</tr>
<tr>
<td>$Sim_{G_{total}}$</td>
<td>3.36</td>
<td>0.68</td>
<td>3.15</td>
</tr>
</tbody>
</table>

Table G.7: Measured gain in (dBi) for 2.4 GHz, port 3.

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>$\phi = 90^\circ$</th>
<th>$\phi = 0^\circ$</th>
<th>$\theta = 90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_\theta$</td>
<td>2.3700</td>
<td>-2.5100</td>
<td>-10.5114</td>
</tr>
<tr>
<td>$G_\phi$</td>
<td>3.3565</td>
<td>0.7484</td>
<td>4.3176</td>
</tr>
<tr>
<td>$G_{total}$</td>
<td>5.9015</td>
<td>2.4282</td>
<td>4.4582</td>
</tr>
<tr>
<td>$Sim_{G_{total}}$</td>
<td>6.69</td>
<td>2.53</td>
<td>4.62</td>
</tr>
</tbody>
</table>

Table G.8: Measured gain in (dBi) for 5.3 GHz, port 3.
G.2 Radiation patterns for 0.8 GHz, port 3

Figure G.1: Radiation patterns for 0.8 GHz, port 3.
G.3 Radiation patterns for 1.5 GHz, port 1

Figure G.2: Radiation patterns for 1.5 GHz, port 1.
G.4 Radiation patterns for 1.5 GHz, port 3

Figure G.3: Radiation patterns for 1.5 GHz, port 3.
G.5 Radiation patterns for 1.9 GHz, port 1

![Diagram of radiation patterns]

(a) $E_\theta, \phi = 90^\circ$

(b) $E_\phi, \phi = 90^\circ$

(c) $E_\theta, \phi = 0^\circ$

(d) $E_\phi, \phi = 0^\circ$

(e) $E_\theta, \theta = 90^\circ$

(f) $E_\phi, \theta = 90^\circ$

Figure G.4: Radiation patterns for 1.9 GHz, port 1.
G.6 Radiation patterns for 1.9 GHz, port 3

Figure G.5: Radiation patterns for 1.9 GHz, port 3.
G.7 Radiation patterns for $2.4\,GHz$, port 1

Figure G.6: Radiation patterns for $2.4\,GHz$, port 1.
G.8 Radiation patterns for $2.4 \text{GHz}$, port 3

(a) $E_\theta$, $\phi = 90^\circ$

(b) $E_\phi$, $\phi = 90^\circ$

(c) $E_\theta$, $\phi = 0^\circ$

(d) $E_\phi$, $\phi = 0^\circ$

(e) $E_\theta$, $\theta = 90^\circ$

(f) $E_\phi$, $\theta = 90^\circ$

\[\text{LAB} \quad \text{CST}\]

Figure G.7: Radiation patterns for $2.4 \text{GHz}$, port 3.
G.9 Radiation patterns for 5.3 GHz, port 3

Figure G.8: Radiation patterns for 5.3 GHz, port 3.