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Abstract

The present document is a review of the state of the art in antennas for mobile communications terminals. This includes an overview of the specific problems encountered in the design of this kind of antennas. The main requirements regarding their implementation and operation characteristics are also considered. Different state of the art solutions are presented, along with dedicated measurement setups and standards. Some new trends are also investigated. As annex, an overview of the capabilities of the partners has been added.

Keyword List

Mobile communications terminals, antennas

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1. EXECUTIVE SUMMARY

The growth in the number of wireless standards over the past decade has been coupled with the ever-decreasing size of the mobile terminal. Consequently, a modern mobile terminal is not only physically small but also required to operate well across a large number of wireless standards. This places a number of implications on the device that connects the terminal to free-space; namely the antenna. No longer can large, single-band, externally mounted antennas be considered. The future, therefore, lies in small, internally mounted, antennas that are able to work well across a large bandwidth.

It stands to reason, therefore, that the design of any such antenna will have to take into account a variety of factors, which include: small physical size, mechanical robustness, operation on a small ground plane, input bandwidth, radiation patterns, efficiency and cost. As well as these considerations, the effect of the antenna on the user is a figure-of-merit (SAR) that has gained great importance of late, and which must be measured. The first section of this report explains these factors together with providing fundamental limits on antenna design, such as bandwidth and efficiency limitations.

Evolution has occurred in the design of terminal antennas over the years, from the electrically-large wire whip to the current compact, conformal, multi-band printed elements. Future trends may lie in reducing the size of the antenna further, which will reduce instantaneous bandwidth, whilst at the same time offering some kind of electronic tuning so that the antenna may be reconfigured to operate at different frequencies. These changes are explained in the next sections of the report.

Based on the previous sections of the report a brief description of requirements for terminal antennas (such as bandwidth, efficiency and so on) is developed. This section will be useful as a performance table for the design of terminal antennas. As well as assessing the current state-of-the-art structures, thought is given to future techniques that will influence terminal antenna design, for example the use of multiple antennas at the transmitter and receiver (MIMO). The work carried out in other funded EU projects (namely COST) on these future standards is also briefly explained, before the report rounds off with some closing remarks.

2. INTRODUCTION

With the emergence of the third generation of mobile communication standards, mobile terminals must be designed to carry higher data rates and cover more frequency bands, which supposes a challenging task for antenna designers. Nevertheless, the antenna research that goes on in this area shouldn't be performed without taking into account the system background and the important connection to the market. In an ever-evolving environment, it is vital to detect the newest trends in terminal technology, as they will set the requirements for antenna technology and design. Standardisation issues shouldn't be forgotten either, and should include specific test methods for terminals.

Nowadays, 'Personal communications devices' include not only mobile phones, but also many other devices like computers, Personal Data Assistants (PDA), that belong to everyday live and can be interconnected to different networks, without using cables. As new standards appear for wireless connectivity, terminals are required to be compatible with different platforms, and to be compatible with more than one wireless and/or cellular standard.

Emerging system aspects will also set the trend for terminal antennas, and should thus be taken into account in the design stage. These include, but are not limited to:

- operating frequency bands, limited by the channel allocation,
- bandwidth, which determines the capacity of the system,
- multiband and multi-standard devices, that cope with the mobility challenges,
- the use of diversity or even MIMO (Multiple Input Multiple Output) schemes to adapt to the ever-changing mobile channel and its multipath characteristics.

Signal processing will also influence the design of the antennas for mobile terminal applications. Thus, an optimisation of the system performance could be achieved, for instance, by flexibly allocating of the available resources, through the use of smart antennas systems.

But to be able to foresee new trends, it is important to understand the starting point and the evolution of the technologies up to now. With this objective, this document aims at drawing a realistic panorama of the state of the art in Europe, concerning small terminal antennas: requirements, design and measurements.

3. STANDARDS: FREQUENCY ALLOCATIONS

Many different mobile communication standards are currently in operation throughout Europe and around the world. The coexistence of mobile communication standards, Table 1, coupled with the mobility of users has resulted in the need for multi-band, multi-standard devices. Consequently any antenna element used in such a device is required to cover a number of standards. This multi-standard coverage represents a considerable challenge for antenna engineers, and ways that this demand has been met will be explained in Section 6.

Table 1: Frequency allocations in MHz for some cellular, wireless and navigation standards.

Standard		TX	RX
AMPS/D-AMPS		824-849	869-894
GT 800		806-821	851-866
GSM 400		450.4-457.6	460.4-467.6
GSM 850		824-849	488.8-496
E-GSM (GSM 900)		880-915	925-960
DCS (GSM 1800)		1710-1785	1805-1880
PCS (GSM 1900)		1850-1910	1930-1990
UMTS FDD		1920-1980	2110-2170
UMTS TDD		1900-1920	2010-2025
Bluetooth		2400-2483.5	
WLAN		2400-2500	
GPS			1575.42
HIPERLAN/1 - /2		5150-5350 (Indoor) 5470-5725 (Outdoor)	
UWB (IEEE 802.15.3a)		3.1-10.6 GHz	
Wi-Fi	IEEE 8002.11a/h	5150-5250 (Indoor) 5250-5350 (Outdoor) 5725-5825 (CSMA/CA ¹)	
	IEEE 8002.11b/g	2400-2483.5	

¹ CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance

4. CONSIDERATIONS

Due to the ever-decreasing size of the mobile terminal, coupled with the desire for efficient operation across a number of standards (as highlighted in Section 3) and the modern requirement for conformance to various emission standards, the design of antennas for such platforms has become very demanding. In this section these factors, which influence mobile terminal antenna design will be explained.

4.1. *Physical Size and Mechanical Robustness*

Although the progresses in the field of the microelectronics have resulted in marked reductions in the size of the terminal (Figure 1) the antenna has not benefited from such reductions since its size is not determined by technological, but by physical factors. Consequently there is much impetus to research ways of reducing the size of resonant antennas so that they will fit within a given volume, and thus be aesthetically pleasing [1]. This means that either the antenna needs to be electrically small or have been conformed to a certain shape adapted to a small volume. However, this gives rise to restrictions regarding polarisation, radiation efficiency and bandwidth, and furthermore increases the required manufacturing tolerances.



Figure 1: Evolution of mobile communications handsets.

4.2. *Effect of the Finite Groundplane*

Any groundplane with a mobile terminal will be of limited size; typically its dimensions are usually of the same order of magnitude as the wavelength at the operating frequency. This has an influence upon the matching characteristics, the impedance bandwidth, the radiation patterns and the interaction with the user

Antennas are generally measured and analysed in an electromagnetically well-defined environment, with infinite or large (with respect to the wavelength) groundplanes. However, in reality antennas must operate on an electrically small device (the terminal), which will distort its radiation characteristics. Therefore an antenna cannot be considered as an isolated element, but as part of a

whole system. To this end it is important to determine how the fact of integrating an antenna in a terminal will affect its actual behaviour regarding both input and radiation characteristics [2].

The ElectroMagnetic (EM) fields generated by an antenna will induce currents that flow on different components of the terminal, in particular its Printed Circuit Board (PCB) as depicted in Figure 2. It has been demonstrated that the most visible effects of the integration of an antenna onto a metallic box are that its frequency of operation detunes, the cross-polarisation component in the radiation pattern increases due to the currents induced on the surface of the terminal [3], [4]. Recent work has considered utilising the ground plane of the terminal as a means to optimise the available radiated power, with the antenna element merely acting as a coupling element to the wave modes of the metallic parts of the terminal [5], [6].

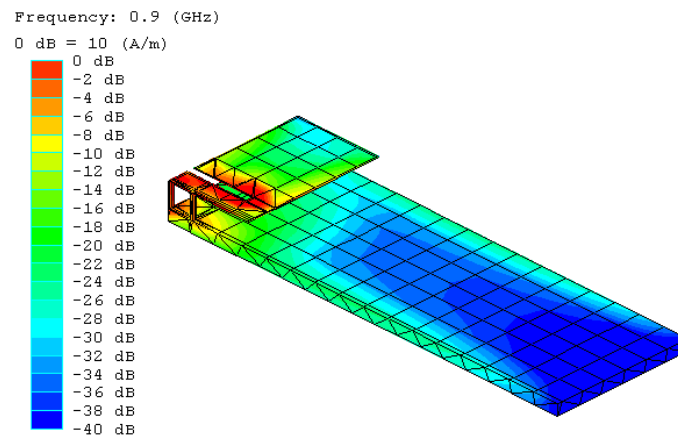


Figure 2: Simulated surface currents on the PCB groundplane induced by a patch antenna at 900 MHz

4.3. *Effect of device components*

1. *Effect of the battery*

One of the most significant distortions for the antenna behaviour is caused by the coupling to the battery casing. Recently a study on the battery effects on a small handset PIFA has been presented [7]. It concentrates on the influence on gain and bandwidth in the frequency bands of GSM1800, UMTS, and WLAN/WPAN standards IEEE 802.11b/Bluetooth. For the study, a 40mm x 100mm ground plane was chosen. The PIFA element consisted of a probe fed square patch with two shorting pins, centred on the top edge of the ground plane.

As in [8], the battery was modelled as a metal box, as rectangular metallic patch with a large number of shorting pins around its edges. The size of the battery is 37mm x 54 mm, which is consistent with typical sizes of mobile phone batteries. The antenna configuration, including ground plane and battery, is shown in Figure 3.

The effect of the battery on the antenna gain and impedance bandwidth were studied for different distances battery-PIFA. The different gaps have been achieved by moving the battery model. The antenna was matched for a resonant frequency of 2035 MHz (centre of the UMTS band) and with the largest possible bandwidth. The simulation results are shown in Figure 4 and Figure 5, respectively.

It can be concluded that the position of the battery significantly affects both the impedance bandwidth and the gain of the antenna, and should therefore be taken into account when designing a the antenna.

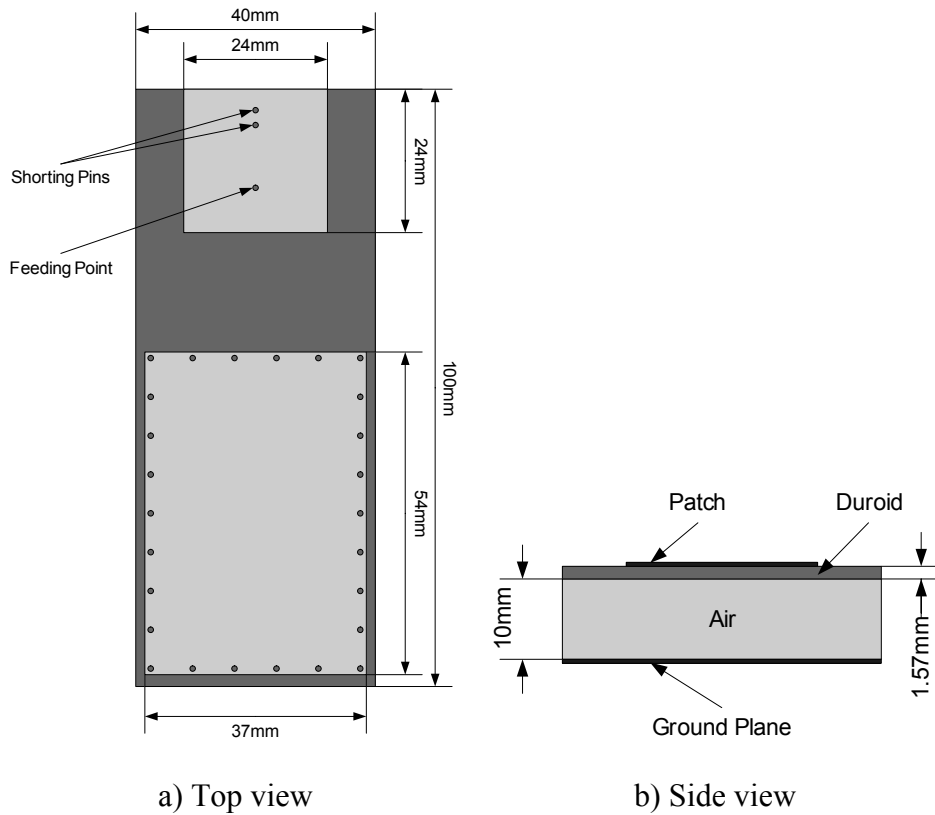


Figure 3: PIFA with battery

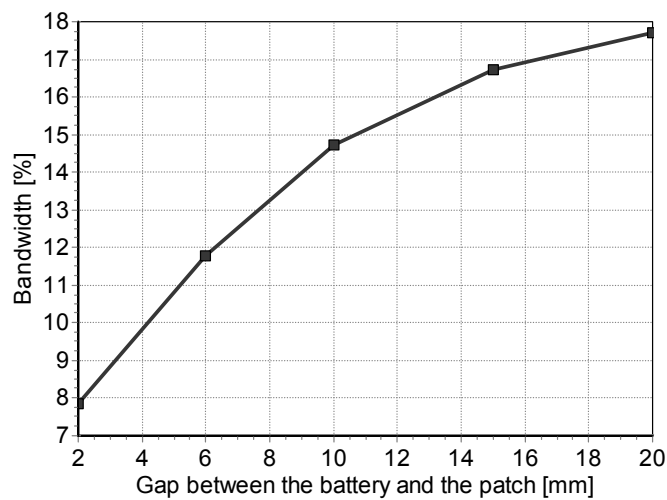


Figure 4: Bandwidth ($VSWR \leq 2$) as a function of the gap between the battery and the patch.

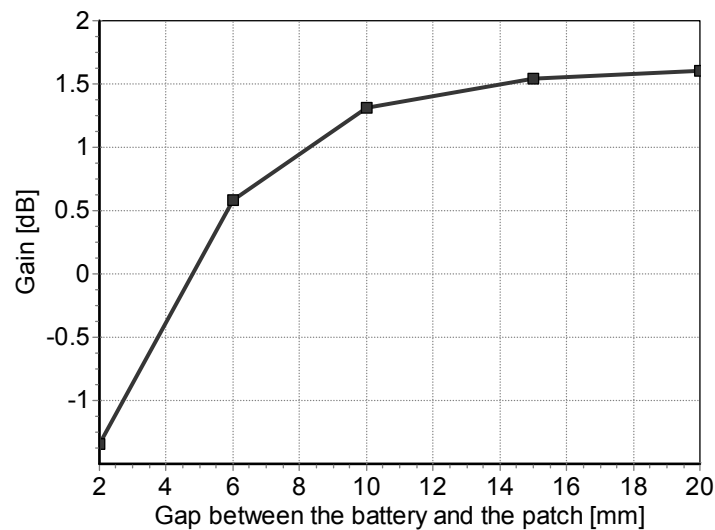


Figure 5: Gain as a function of the gap between the battery and the patch.

2. Other components

Other metallic and dielectric components of mobile terminal have also a significant influence on the antenna performance, and should also be taken into account in the design. Some elements, such as the vibration motor or the acoustic elements (loudspeakers) can even be mounted under the antenna itself, and modify its performance.

Some examples of these components are:

- ☞ The acoustic components, which include magnetic parts. They are not easy to take into account, as a same handset manufacturer can have different providers, and the fabrication tolerances can be relatively high. Their connection to the ground introduces a capacitive effect that distorts the performance of the antenna.
- ☞ The vibration motor
- ☞ The display: the currents induced onto this component can contribute to an increase of the Specific Absorption Rate (SAR), (see section 4.8)
- ☞ The casing: it is made of plastic material, and will increase the losses and detune the resonant frequency of the antenna.
- ☞ The battery connector
- ☞ The RF shielding of the circuits in the terminal.

4.4. Matching and Tuning

In order to optimise power transfer between the RF front-end and the antenna, these two parts need to be well matched to one another. Unfortunately there is a general demarcation between antenna and RF front-end design with each optimising their stage for a 50Ω (purely resistive) impedance. If the RF front-end and antenna were designed as a single integrated unit then the antenna would be optimised to the impedance of the RF front-end; which is seldom 50Ω [9].

During the manufacturing process of the antenna, mechanical tolerances may influence the resonant frequency of the antenna. It is therefore desirable that the antenna either has a sufficiently wide bandwidth that any marginal detuning will not affect performance (see Section 4.5) or has some means of tuning incorporated; be that mechanical or electrical (as in Section 6.6).

To improve the matching of a terminal antenna, different methods have been suggested, like the use of matching networks. This could help improve the performance of the antenna, without having to modify the radiating structure [10]. This technique allows enlarging the impedance bandwidth, or shifting the operating band to cover the frequencies of interest.

Other possibilities include the use of MEMs (Micro Electro Mechanic Systems) to implement reconfigurable antennas, in which the current distribution could be dynamically modified by switching on and off different parts of the structure, and thus cover different frequency bands. This solution is still in its experimental phase [11]-[13]. MEMs technology can also be applied to implement diversity schemes [14].

4.5. Bandwidth

The input bandwidth of the antenna should be sufficient to cover at least one channel of operation if the antenna is frequency-tuneable, or all the relevant parts of the spectrum if the antenna is a passive structure. It is necessary to be able to match the antenna in a proper way, as it will contribute to the total efficiency of the device.

In the case of mobile communications standards, it is necessary to obtain an impedance bandwidth of about 10%, which in some cases is quite difficult to obtain, due to many different factors, as the size of the structure (see section 5). This problem will only be increased with the future implementation of Ultra Wide Band (UWB) systems, which are characterized by multi-octave to multi-decade frequency bandwidths, and are expected to transmit and receive baseband pulse waveforms with minimum loss and distortion. In this case, both transmit and receive antennas can affect the faithful transmission of UWB signal waveforms because of the effects of impedance mismatch over the operating bandwidth, pulse distortion effects, and the dispersive effects of frequency dependent antenna gains and spreading factors [15].

4.6. Radiation Characteristics

1. Radiation pattern

Any antenna used within a mobile terminal needs not only to be efficient [16], but also able to radiate well on a small groundplane (the terminal) and in the presence of a user – that is it needs to be able to direct radiation in a useful direction away from the terminal and the user. That does not mean that the terminal should display a directional pattern, as in a multipath environment, it is desirable to obtain the signal arriving from any direction.

Often when radiation patterns of an antenna are measured only simple 2-D cuts along principal axis are shown. Although this may seem a succinct way of representing the radiation it disregards much of it about the structure. Therefore the only way of truly measuring an antenna's radiation characteristics is to measure its full 3-D patterns in a representative environment (i.e. on small groundplanes and with phantoms). Only from these measurements can true figures for Gain, Directivity and Efficiency be determined.

Figure 6 and Figure 7 show typical setups used to measure 3-D patterns. Figure 8 Shows an example 2-D cut about an antenna whilst Figure 9 shows the respective 3-D co- and cross-polar patterns. As can be seen the maximum cross-polar levels occur off-axis, Figure 9, which are not shown in the 2-D cuts, Figure 8.

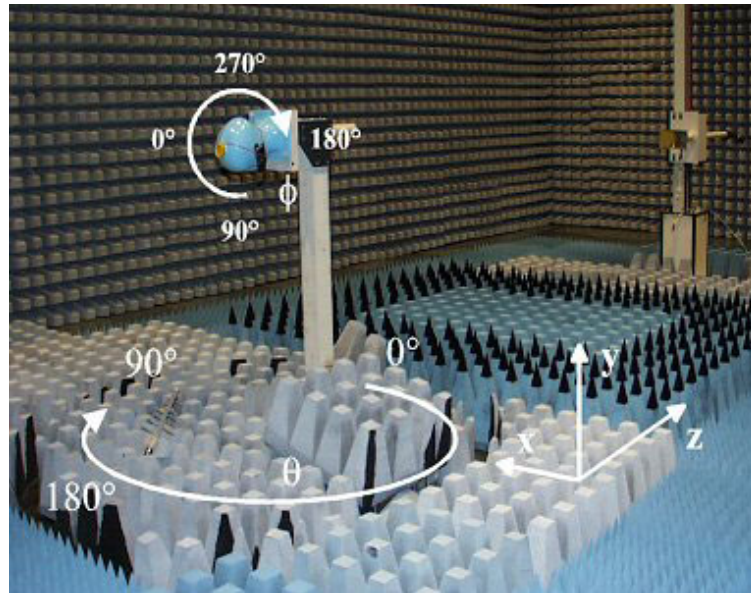


Figure 6: 3-D Far Field measurements setup including a phantom modelling a user's head.

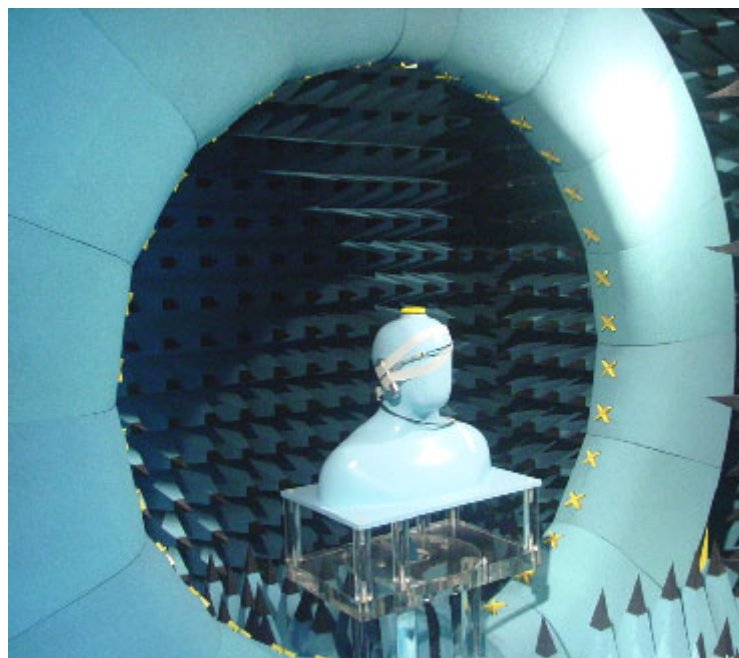


Figure 7: 3-D Near Field spherical measurements setup including a phantom modelling a user's head.

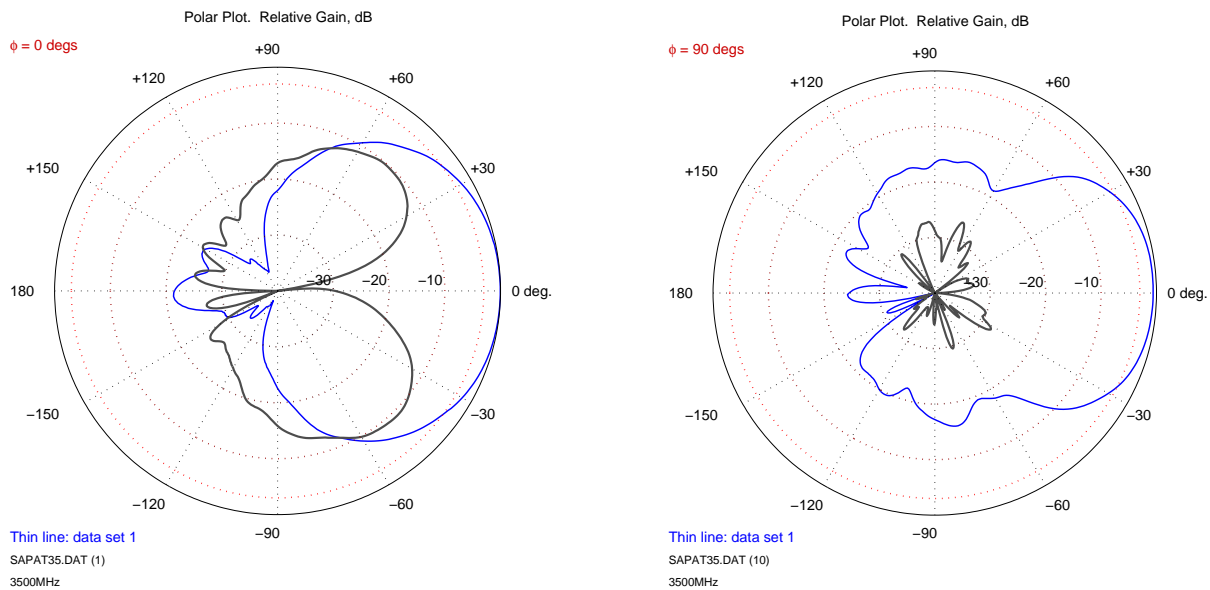


Figure 8: Example 2-D Cuts along Principal Axis

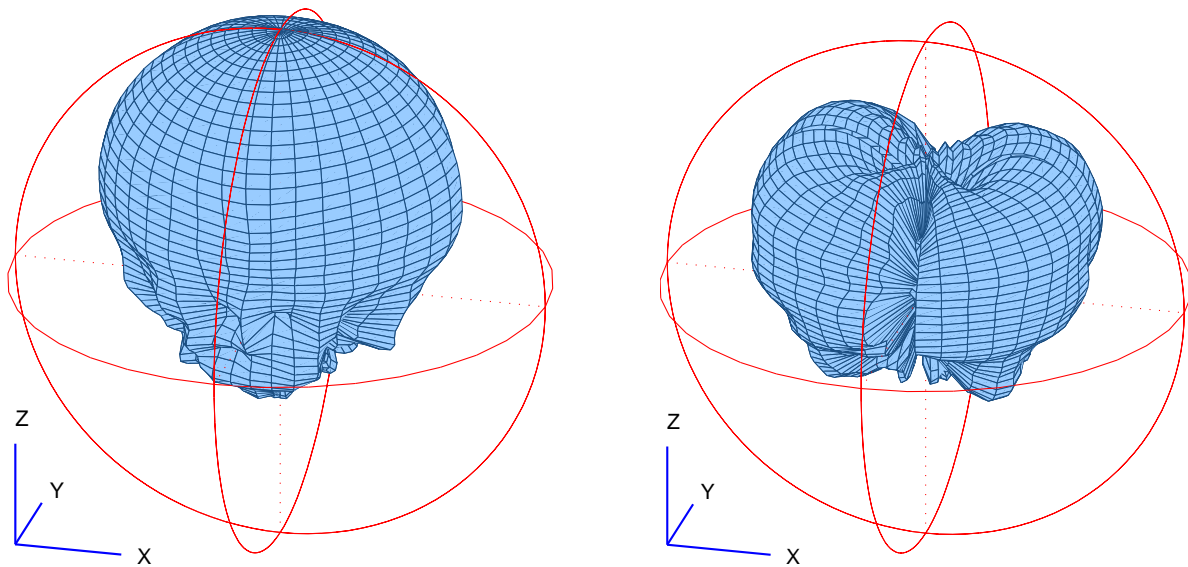


Figure 9: Example 3-D Co- and Cross-Polar Radiation Patterns

All plots are on a dB scale, -40dB at centre

2. Efficiency

In the case of mobile communications, the spatial orientation of a terminal is totally random, and radiation patterns may not fully characterise the quality of the system. Efficiency represents thus an important parameter when determining the radiation performance of a mobile handset, as it gives the ratio between the power delivered to the antenna and the power that is actually radiated. Two different kinds of efficiency can be defined: the radiation efficiency and the total efficiency.

The radiation efficiency is defined as the quotient between the power actually radiated and the power delivered to the antenna. It can be written in terms of resistance as [17]:

$$\eta_r = \frac{R_r}{R_L + R_r} \quad (1)$$

Where R_r and R_L represent the radiation resistance and the loss resistance, respectively.

The total efficiency takes also into account the losses at the ports and in the antenna itself [17]. These losses are due to the mismatching between the transmission line and the antenna. The total efficiency can then be calculated from the radiation efficiency as:

$$\eta_0 = \eta_r (1 - |s_{11}|^2) \quad (2)$$

Where s_{11} denotes the input return loss at the antenna port.

Different measurement setups can be used to determine the efficiency. It can be done by integrating the results obtained from the 3D field measurements, or by measuring the device in a Wheeler-Cap [18] or a reverberation chamber [19]. Some examples of Wheeler-cap cavities are displayed in Figure 1.

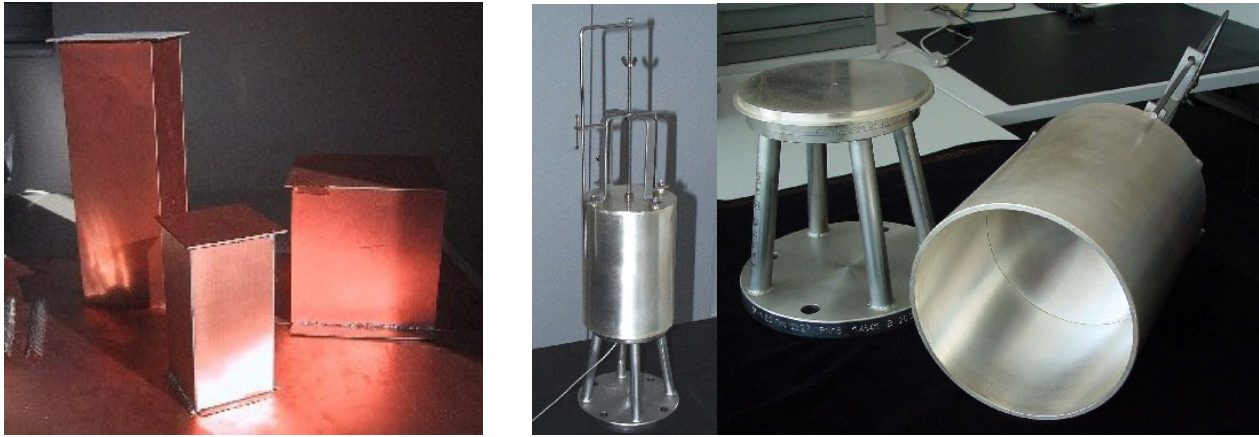


Figure 10: Wheeler-cap measurement setups.

4.7. Effect of the Environment on the Antenna

Under normal operating conditions, any mobile terminal will be subject to a certain amount of interaction with the human body and its immediate surroundings. These interactions will effectively load the antenna, causing its input characteristics to detune and its radiation characteristics to be deformed [20]. The location of these objects in relation to the antenna is usually given little thought by the user, but, since all these objects load the antenna, its performance, and consequently that of the terminal, is dependent upon these objects.

The power radiated into the far-field region, for a terminal under normal operating conditions can be written as:

$$P_{\text{rad}} = P_{\text{in}} - P_{\text{a}} - P_{\text{L}} - P_{\text{abs}} \quad (3)$$

where P_{rad} represents the power actually radiated in the far field, P_{in} the delivered power, P_{a} the losses due to the mismatching of the antenna in different user positions, P_{L} the losses in the antenna itself and P_{abs} the power absorbed by the user.

In [21] some reasons of the discrepancies in the results obtained for different users are identified, regarding P_{abs} . Among them, we could list:

- ☞ The position of the hand on the device.
- ☞ The distance between the head and the device.
- ☞ The tilting angle.
- ☞ The shape and size of the head and the hand.
- ☞ The size of the person.
- ☞ Other parameters: age, use of glasses, hearing aids, implants...

The two parts of the user's body that have the greatest influence upon the operation of the mobile due to their proximity, are the head and the hand. In the case of the head, its effect can be assessed quite easily, using a phantom with tissue simulating liquid, as shown in Figure 11.



Figure 11: Head model used in the measurements.

The effect of the hand is more difficult to quantify, since every user holds the terminal differently. This problem is especially important in case of internal antennas, since in certain cases the antenna may be totally masked, which imposes a significant degradation of the link. In [21] the correlation between the way in which the user holds the terminal and its losses is described. The conclusion of this study is that, in most cases, the losses due to absorption in the hand are much larger than those due to the relative position of the head and the terminal. The effect of the user on the radiation patterns can also be assessed using the head model in Figure 11, and the 3-D measurements setup presented in Figure 6 [22].

Reverberation chambers can also be used to measure the effect of user interaction on the radiation efficiency and radiated power, see the setup in Figure 12 and [23]-[24]. The former reference shows head loss data for 20 different phones measured in a reverberation chamber, and the latter losses due to a hand phantom.

Another solution to measure human interaction is to characterize the full 3D pattern of the antenna in presence of the environment. This environment can be a phantom head or directly a human person wearing glasses or holding the phone in a given position for instance, as shown in Figure 13. The measured power radiated in all directions is integrated, and thus the efficiency of the antenna in presence of the environment can be derived. The advantage of this method consists in having the

knowledge of the angular radiation characteristics. An example of measured results is given in Figure 14 for the radiation pattern of a transmitting phone measured without phantom (right) and with phantom (left). The far field radiated power presents a minimum that shows clearly how energy has been absorbed in the direction of the phantom.

Although there exist phantoms that allow characterising the influence of the user on the antenna, there are too many potential objects within an environment that may load an antenna and consequently no 'standard objects' can be defined. Antennas that are less susceptible to detuning due to the user should be useful too when objects are located nearby. An alternative approach to a passive antenna that is immune to detuning is to add some degree of reconfigurability to the structure so that once detuned (either by the environment or a user) it will automatically reconfigure itself to minimise any degradation in performance [25]-[26].



Figure 12: Measurement of user interaction in reverberation chamber

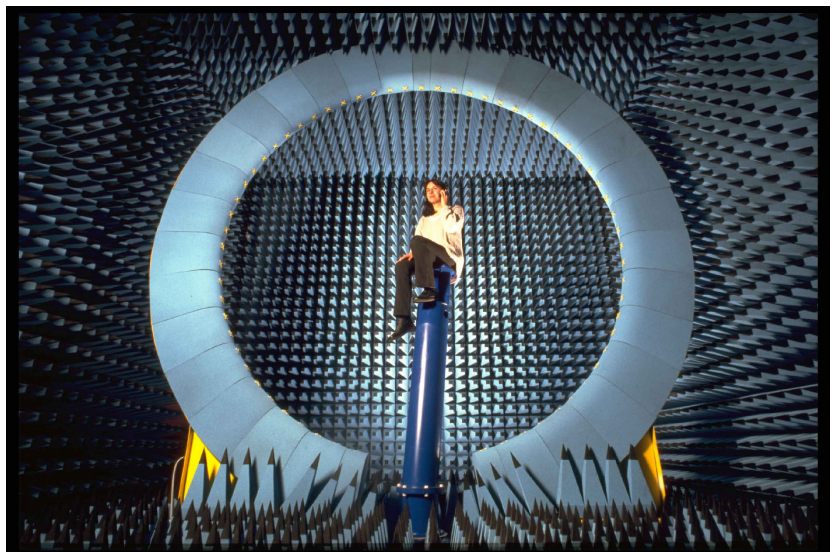
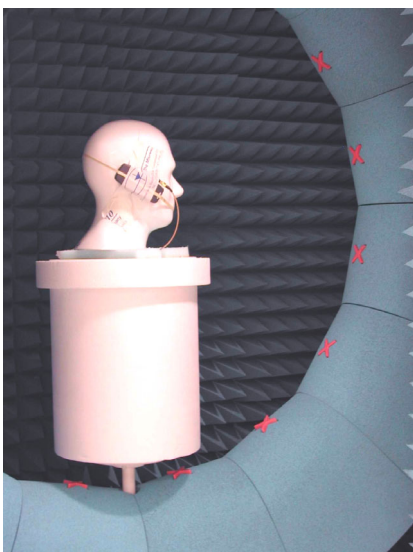


Figure 13: Measurement of user interaction in Near Field spherical test range: with head phantom (left) or with human body (right).

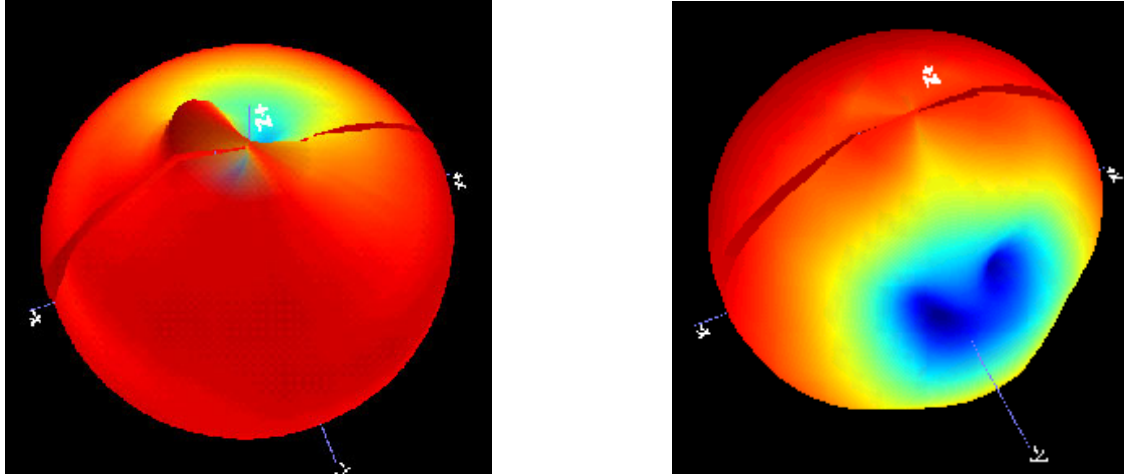


Figure 14: Measured 3D Tx radiation pattern at 895 MHz (left: without phantom ; right: with phantom)

4.8. Effect on the Antenna on the User (SAR)

Since most mobile terminals operate in close vicinity of the user it is a legal requirement of all terminal manufacturers to quantify the amount of radiation which will be absorbed by the human body; most notably the hand and head [27]. This is characterised by measuring the Specific Absorption Rate (SAR) [28], [29] and the trend amongst terminal manufacturers is to limit this as much as possible.

The power absorbed by the human tissue is given by the following expression:

$$P_{abs} = \frac{1}{2} \int_V \sigma |E|^2 dV \quad (4)$$

where E represents the peak value of the electric field, σ the conductivity of the medium, in this case the tissue, and V the volume of the considered tissue. P_{abs} is the percentage of power delivered to the antenna that is absorbed by the user's body.

This absorption takes place locally, and its distribution is inhomogeneous. Its effect translates in a local increase of the temperature of the tissue, which can be expressed in terms of the Specific Absorption Rate, SAR. The SAR, expressed in mW/g/W, reflects the speed at which the human tissue absorbs the microwave energy per unit of weight and of transmitted power:

$$SAR = c \frac{dT}{dt} \quad (5)$$

In the expression (2), c represents the specific heat, and $\frac{dT}{dt}$ the temperature increase in the tissue with the time. This expression can also be written in function of the parameters of the material and of the of the electric field values as:

$$\text{SAR} = \frac{\sigma}{2\rho} |E|^2 = \frac{\sigma}{\rho} E_{\text{eff}}^2 \quad (6)$$

Where ρ denotes the density of the material, σ its conductivity and E_{eff} the effective value of the electric field. The latter will depend on the considered frequency.

The values used for the characterization of the human tissue in the GSM and DCS frequency bands are summarised in Table 2 [30].

Table 2: Material properties used for simulating human brain tissue.

	ϵ_r	σ (S/m)	ρ (kg/m ³)
900 MHz (GSM)	42,5	0,86	1040
1800 MHz (DCS)	41	1,69	

The exposure limits are also different depending on the region and the standard considered. In Europe, the measurements are carried out according to the 1999/519/EC recommendation, in agreement with CENELEC, which takes the values given by the ICNIRP [27]. In The United States, the regulatory organisation FCC establishes that the measurements have to follow the ANSI C95.1 norm [31]. In both cases the absolute local maximum must not be considered, but its value averaged over a certain cubic volume. The established limits of local SAR, as well as the values used for the average, are presented in Table 3.

Table 3: Limits of local SAR in the head of the user.

	Maximum local SAR (W/kg)	Averaging volume (g)
Europe	2	10
USA	1.6	1

Figure 15 shows the DASY (Dosimetric Assessment System) system and Figure 16 shows the SARA2 system, both used for SAR measurements. In both cases an articulated arm allows placing the measurement probe inside the basin or phantom that contains the tissue-simulating liquid.



Figure 15: DASY3 measurement system.

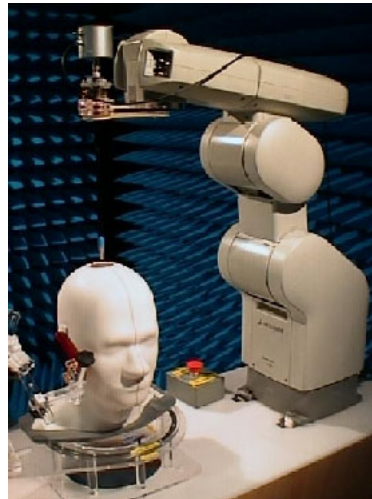


Figure 16: SARA2 measurement system.

4.9. Cost

As well as the factors mentioned in the previous subsections, manufacturers require low-cost antennas that are easy to manufacture and assemble. The final price of the antenna depends on different factors, for example, the number of units to be produced, the technology employed or if it is combined with other components, such as a matching network. Nowadays, the world production of mobile phones, and thus of such antennas, has increased to around 600 Million units per year.

5. SMALL ANTENNAS. FUNDAMENTAL LIMITS

5.1. Geometries

One of the most critical questions to consider at the first stages of any antenna design process is the type of geometry to implement. Generally speaking, antennas can be classified into three basic types, depending on their geometry: dipoles, slots and cavities. From these fundamental types, more complex geometries have been developed.

The simplest non directional antennas are basic dipoles. Such structures are designed from conductive wires or lines excited by electrical currents, which are directly responsible of the generated radiating fields. Slots antennas, also called magnetic dipoles, can be seen as a long, narrow opening on a metallic surface. The radiated field can be seen as generated from a field distribution that is held on the slot itself. A cavity antenna in its simplest configuration consists of a radiating patch on one side of a dielectric substrate ($\epsilon_r \leq 10$), which has a ground plane on the other side [32].

5.2. Downsizing Design

Generally, all the geometries get optimal behavior with resonant lengths that are around $\lambda/2$ ($\lambda/4$ in some cases where metallic planes are used). When we look for small devices, the initial resonant size $\lambda/2$ ($\lambda/4$) uses to be prohibitive for the size restriction imposed by the compactness of our devices.

A large number of downsizing solutions for small antennas can be found in literature. Some of the techniques applied to reduce antenna size are folding configurations, surface etching, shorting walls or pins, or utilizing high dielectric constant materials. However, there is always difficulty in obtaining good electrical performances (bandwidth, efficiency, gain) when reducing size (see 5.3).

In [11] the existing downsizing techniques for planar antennas have been classified. In Table 4, each technique has been evaluated by its contribution to the size reduction, to the impedance and bandwidth, and to the radiation pattern.

Table 4: Comparison of the main planar antenna size reduction techniques [11].

Performances \Rightarrow Downsizing Technique \Downarrow	Geometrical: Size Reduction with respect to Resonant Size	Circuital: Impedance Bandwidth	Radiation Pattern: Symmetry vs Low Cross Polarization
Multilayered: fold, bend, stack, etc	60 %	10 %	High
Patch Etching: slits, slots, notch, etc	50 %	7 %	Medium
Shorting Planes: walls, pins, etc	50 %	5 %	Low
Material: high dielectric, slow-wave, etc	70 %	2 %	High

From such analysis, in the same paper [11], the following basic design guidelines have been derived:

- A multilayered structure to obtain a double resonant behaviour
- Slit etching as a way of increasing the electrical path while maintaining physical size.
- Short-circuiting walls to utilize the half-size reduction factor.
- Dielectric loading, especially in packaged applications, for further size reduction at the cost of lower efficiency.

5.3. Bandwidth and efficiency. Fundamental limits

The performance of electromagnetic passive devices is sensitive to its electrical size compared to the wavelength, i.e. given an operating wavelength and certain performance, classical antennas can not be made arbitrarily small, while keeping at the same time certain operative parameters. As a matter of fact, bandwidth, losses and dimensions of the antenna are closely interrelated in small antennas, as we will see further in this chapter.

Losses in the antenna can be characterized by the radiation efficiency, η , which is defined as the ratio of total radiated power to the net power accepted by the antenna from the connected feed line [33]. This is to say that, due to the existence of losses in the antenna, only a part of the power sent by the transmitter is radiated to open air. With an efficiency of 100%, all the power delivered to the antenna would be radiated; if the efficiency is 50%, half of the power will be dissipated by ohmic losses in the antenna or dielectric losses in the substrate, and the other half would be radiated.

$$\eta = \frac{P_{\text{radiated}}}{P_{\text{input}}} \quad (7)$$

A second parameter, called quality factor (Q), related to the bandwidth, can be defined, and, for lossless antennas, can be expressed by [34]:

$$Q \approx \frac{1}{BW} = \frac{f_{\text{center}}}{f_{\text{upper}} - f_{\text{lower}}} \quad (8)$$

where BW is the fractional bandwidth.

The quality factor Q is defined as the ratio of time-average, non-propagating energy to radiated power of an antenna [35]. This parameter is a quantity of enormous interest when designing small antennas because of its lower bound, which provides knowledge of how small an antenna can be constructed, for a given fractional bandwidth.

The evaluation of antenna Q can be traced back to Chu's classical work, which derived the theoretical value of for an ideal antenna enclosed in the smallest circumscribing sphere [35]. Chu's approximate result was subsequently quoted by others in related works over the following years [36]-[39]. In 1996 McLean [40] improved on the work of Chu by deriving an exact result for the radiation Q using the fields for the TM_{01} mode directly. McLean's result is nearly the same as Chu's for very small antennas and predicts a slightly higher lower bound on for antennas approaching a length of about 1/3 wavelength.

For linearly polarized antennas constrained to fit within a bounding sphere of radius a (the smallest sphere that encloses the antenna), the minimum attainable Q is given by [40]:

$$Q = \frac{1}{ka} + \frac{1}{(ka)^3} \quad (9)$$

Where k is the wave number at the operating wavelength λ ($k = 2\pi/\lambda$).

The lower bounds provided by Chu and McLean have been found to be elusive to achieve in practice (i.e., the Q is always higher and the bandwidth less than expected). To obtain a Q approaching the limit given in equation (9), an antenna must effectively use the entire volume within the bounding sphere. Many antennas are constrained by their intended application to fit within smaller area; in particular, many whip-like antennas to be mounted on masts, handhelds, etc are required to fit within an elongated volume, therefore, one would suspect that the minimum attainable Q for such antennas is significantly higher.

In fact, in the general case, known solutions of radiation Q calculation for a given antenna do not take into account the energy stored inside the sphere. Foltz & Mc Lean [41] used an oblong spheroid that more closely represents the volume constraints in these situations. This allows obtaining a more realisable (higher) limit of the Q factor for antennas having a “main” dimension.

The Chu limit for linear polarization is obtained, in particular, for an infinitesimal electric dipole, with a uniform current distribution. Real current distributions are closer to a sinusoidal form. Thiele et al. [42] have used the far-field approach to obtain a more realisable bound taking those current distributions into account. The main idea of Thiele et al. is to relate the Q factor with the superdirectivity ratio R_{sd} of the antenna, which is a well-known hypothesis: $R_{sd} \approx 1+Q$ (R_{sd} is a far-field quantity). From this, a more realizable limit of Q for a linearly polarized antenna can be determined. This paper provides a more realistic lower bound for the fundamental limit on the radiation Q . This prediction is based on the assumption of a sinusoidal current distribution along an electrically small antenna, in contrast with the classical approach, where a Hertzian dipole with a uniform current distribution was considered. An evaluation of the different methods can be found in [43]. A comparison between the different limits is displayed in Figure 17.

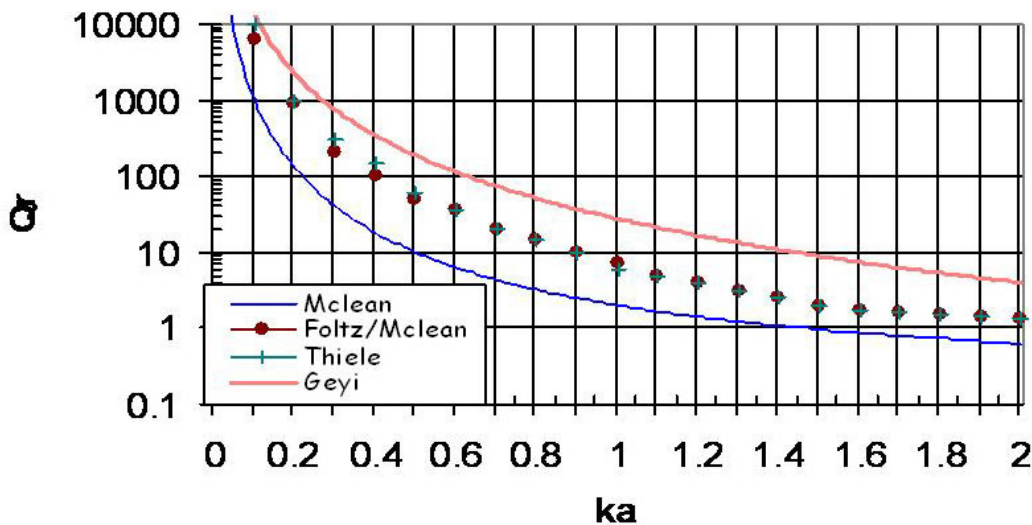


Figure 17: Fundamental Limit and Realistic Limit of quality factor Q

The former expressions of the limit Q have been formulated considering lossless antennas. Taking into account losses (characterized by η), another fundamental relationship [11] between the radius a of an electrically small antenna, its maximum fractional bandwidth BW, and its radiation efficiency, can be written:

$$BW \cdot \eta \cong (ka)^3 \quad (10)$$

The former expression, which is valid only if $ka \ll 1$, implies that a larger bandwidth can be gained at the price of radiation efficiency, once the size of antenna is constrained [33].

Regarding return loss, it would be desirable that the antenna was matched at the input port. Therefore, the input impedance should be as close as possible to the output impedance of the transmitter.

5.4. Terminal antennas

The fundamental limits describes above implied that the antenna is radiating in free space, as in Figure 18 (a). Yet, this is not the case when considering antennas for mobile communications terminals [45]. Indeed, to take into account the effect of the ground plane, the radius a of the considered sphere should include the whole terminal, as displayed in Figure 18 (a) and (b), for external and integrated antennas, respectively.

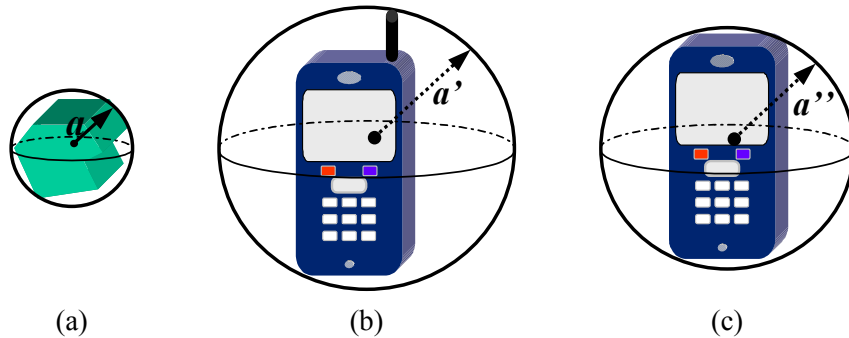


Figure 18: Graphic representation of McLean's sphere.

- (a) Antenna in free space.
- (b) Terminal with external antenna.
- (c) Terminal with internal antenna.

6. **HANDSET ANTENNAS**

In meeting the evolving demands placed on antenna design for mobile terminals, Section 4, there has been a marked change in the elements utilized on the handset over the years. In this section the ways that the antenna types have changed will be explained, with specific reference to current compact internal antennas and also some indication of future trends.

6.1. *Monopoles.*

The monopole was the first element considered for mobile terminals. Due to it being a simple structure that was easy and cheap to manufacture it was in use for many years. An example of a monopole is shown in Figure 19.



Figure 19: Terminals with $\lambda/4$ monopole antenna.

Although the monopole is a simple element, the fact that it protruded quite considerably from the handset (around 8cm for terminals that operate in the GSM band) resulted in much work being undertaken to make it more compact, both from an aesthetic perspective and also to improve rigidity.

6.2. *Helices*

Helices, as shown in Figure 20, were proposed to overcome some of the problems inherent with monopoles. By using a helix antenna, terminals have a more compact aspect, and become more resistant to impacts. Some examples of terminals with helix antennas are presented in Figure 21.



Figure 20: Helix antennas.



Figure 21: Terminals with helix antennas.

A further success of helix antenna is in part due to the fact that it is relatively simple to develop dual band elements. A way of doing so is using two imbricated helices, or combining the helix with a monopole, [46]. However, the use of several combined elements can nevertheless be costly, in terms of price and manufacturing complexity. Therefore, it is more common to design multiband antennas by changing the step and the diameter of the helix in order to obtain multiple resonances [47].

A special case of the helix is the meander line antenna, presented in Figure 22. It consists of a metallic line printed on a thin dielectric support, which can be flexible. This line acts as a monopole, but its length is shortened by bending it a certain number of times.



Figure 22: Meander line antenna.

Here, the resonant frequencies and the input impedance can be adjusted by changing the number of meanders, or their width. Multi-band operation can be achieved by using more than one line, and/or adjusting the width of the line width and the distance between the meanders [48], [49].

This type of antennas can be found in a great number of terminals, and even in PCMCIA cards, (Figure 23). In some cases it can be also used as internal antenna, though its efficiency is then considerably diminished.



Figure 23: Some devices with meander line antenna.

6.3. *Internal Antennas*

The growing importance of aesthetics in terminal design together with a desire for increased ruggedness has led to much emphasis being placed on internally mounted antennas that are located out of sight inside the terminal. Consequently the majority of terminals on the market today utilize internally mounted antennas, such as those shown in Figure 24.



Figure 24: Mobile terminals with internal antenna.

The design of internally-mounted antennas is, however, no trivial task due not only to the extensive requirements of modern antennas (as highlighted in Section 4) but also to plethora of physical factors that impinge on its performance inside the terminal, such as the close proximity of electronic components, Figure 25.

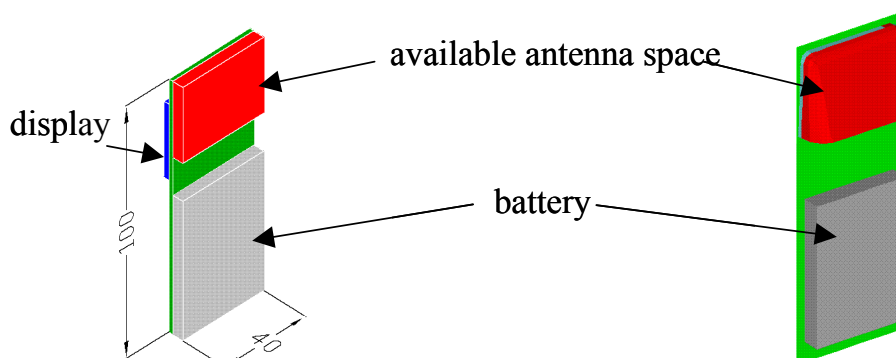


Figure 25: Description of the typical problem.

In this section a variety of antenna types that are commonly used as internally-mounted antennas are briefly explained.

3. Patch Antennas

Patch antennas are popular in mobile terminals, due to their flexibility, low cost and manufacturing ease. A patch consists of a simple metallic sheet that is usually flat (though can, to some degree, be conformed to a surface) which serves as a radiating element raised some distance above a ground plane. The patch can be fed in a number of ways: directly using a probe, capacitively coupled using a printed feed line or parasitically using another element. In terminals it is common to use a direct feed. Two examples of patch antennas in mobile terminals are show in Figure 26.

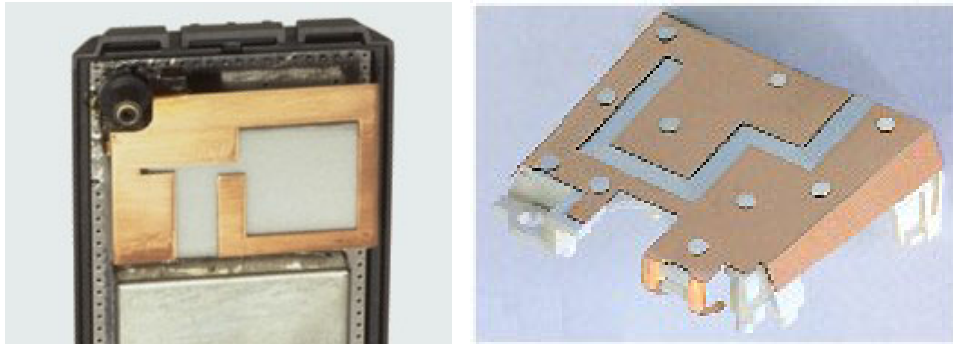


Figure 26: Patch Antennas.

In research environments the medium between the antenna and its groundplane, the dielectric, is usually a high-quality low-loss microwave substrate; this also provides a surface for the patch and the groundplane to adhere to. These high-quality materials are expensive, way in excess of what is deemed acceptable in a commercial company and consequently alternatives must be sought.

A popular alternative is to use air as the dielectric, though it has the problem that a mechanism to support the patch is required. Several solutions exist: fixing the antenna to the case or onto a printed carrier, Figure 27, or printing the antenna onto a flexible surface [50] such as in Figure 28 and Figure 29.

However, the use of materials in the dielectric region will inevitably result in an increase in losses (hence a decrease in efficiency) and, due to the complexity of the manufacturing costs will rise.



(a)

(b)

Figure 27: Terminals with integrated antenna: (a) with plastic carrier or (b) fixed to the back cover.

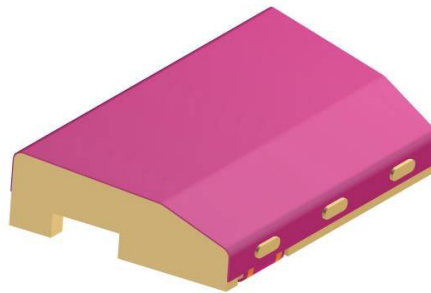


Figure 28: Antenna printed on flexible substrate with plastic carrier.



Figure 29: Typical structure of a 3D-MID antenna.

Another limitation with patch antennas is that they are inherently high Q [51]. Section 3 highlighted the wealth of standards that a terminal may be required to work across, and as such there has been much research interest in developing methods of broadening the bandwidth of patch antennas [51], [52].

There are essentially two ways that a patch antenna can be modified so that it covers a wide number of standards: by making it multi-band (that is it covers many bands all at once), or adding some kind of electronic tuning so that only a single mode of operation is ever covered at once. One drawback with the approach of the former is that the volume required for the antenna increases – something which is of a premium in handsets. Although the latter adds additional filtering to the RF front-end [25] it requires the use of electronic circuitry; something that at present, terminal manufacturers are unwilling to invest in. Consequently most of this research has focused on developing passive wide- or multi-band antennas.

A straight-forward method of increasing the bandwidth of a patch is to introduce another resonant section. Figure 30 shows an example of a commercial antenna where this was done to achieve dual-band GSM/DCS operation; the metallic section on the left-hand edge is for DCS (1800MHz) operation, whilst the larger area in the middle is for GSM (900MHz).

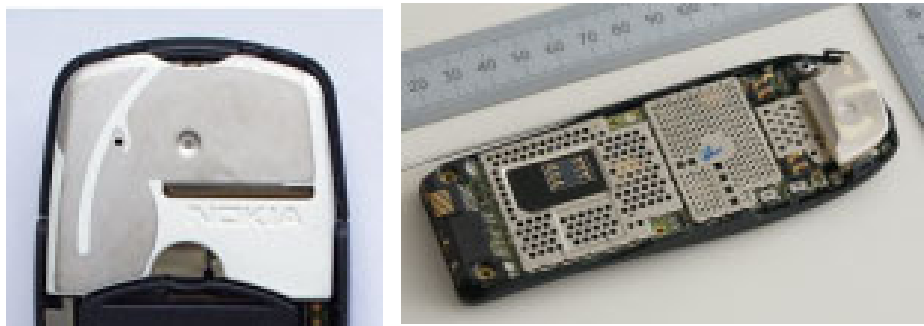


Figure 30: Terminals with integrated 3D-MID antenna .

Another way of increasing the bandwidth is to utilise multiple patches (each one for a different frequency range) with a dual-feed approach; this also allows for a dual-polarised antenna arrangement [54], [55] and [63].

4. Slot Antennas

Slot antennas are a type of aperture antenna, which are commonly used at microwave frequencies. Characteristics of aperture antennas are lightweight, cheap to manufacture, and lend themselves to being flush-mounted against a surface [17]. Typical shapes of slots are linear (a straight line), or annular. Figure 31 and Figure 32 show the layouts of a linear and annular slot respectively.

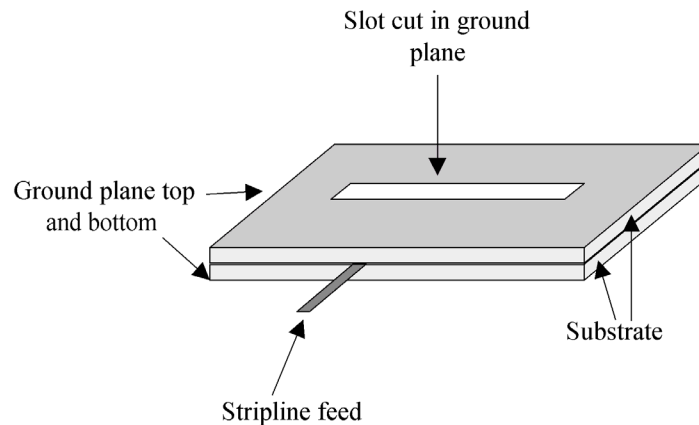


Figure 31: Layout of a Linear Slot

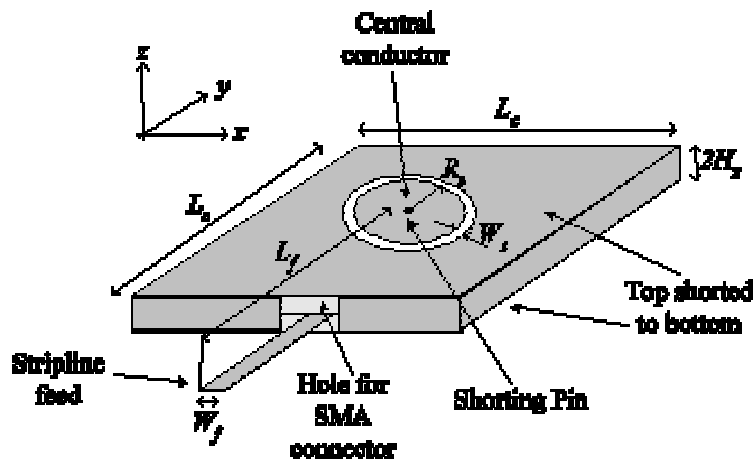


Figure 32: Layout of an Annular Slot

In terms of mobile terminals where a slot would be flush-mounted on a surface, one of the major drawbacks with slots is that their radiation is bi-direction about their surface [51]. One way of overcoming this is by introducing a cavity backing, as in Figure 33 and Figure 34. This cavity backing has the effect of increasing the loaded Q of the structure and thus narrowing its input bandwidth; though this may not necessarily be a problem provided some kind of electronic tuning can be used (see Section 6.6).

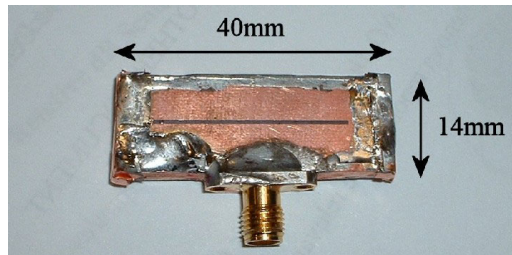


Figure 33: Cavity backed linear slot



Figure 34: Cavity backed annular slot with a shorting pin

5. *Dielectric Loaded Antennas*

One method of reducing the size of an antenna that has gained considerable amount of research interest over the past decade is the use of dielectric loading. Here a piece of high permittivity dielectric (usually, but not necessarily, ceramic) is used to surround a radiating element, resulting in a Dielectric Resonant Antenna (DRA). Since the physical size of an antenna is dependent upon the permittivity of the surrounding medium (the higher the permittivity the smaller the antenna) an increase in this dielectric will result in a decrease in antenna size. Figure 35 shows some DRAs.



Figure 35: Ceramic antennas

Relative permittivities between 10 and 100 have been used in DRAs [66], which have allowed large size reductions to be achieved. However, the reduction in size comes at the expense of bandwidth, which will narrow. Furthermore, the use of dielectric to reduce size has had quite an impact on antenna efficiency; published efficiency values can be as high as 95% [67], through to 45% [68] and even as low as 25% [69]. Also due to the cost of the dielectric and the associated manufacturing process, DRAs are a rather expensive antenna to use in mobile terminals.

Instead of using a single DRA antenna, an alternative would be a number of thin ceramic layers, onto which the metallic structure of the antenna is printed, using LTCC (Low Temperature Co-fired

Ceramics) technology². The advantage of this technology is that both the antenna and, for example, the RF circuits can be integrated on a single substrate. This is the case of the Bluetooth module presented in Figure 36 [70].

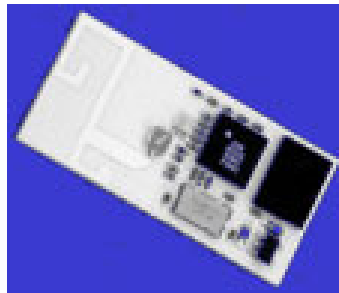


Figure 36: Bluetooth module on LTCC with integrated antenna.

When it comes to antennas this technology is still in its experimental phase. Its cost is relatively high for small volumes of production, the final structure is quite fragile, and its integration into mobile terminals still requires further research.

6.4. *Multiband terminal antennas*

The advent of the 2nd and 3rd generations of mobile phones, as well as new mobile services (high speed data transfer, WLAN, etc.) has added a new requirement to the specifications of terminal antennas, namely the ability to handle multiple frequency bands, in order to accommodate all required services in the same terminal.

Multiband antennas can be divided into three different categories, according to the way the different bands are obtained: single-feed single-resonator antennas, single-feed multi-resonator antennas and multi-feed antennas, the second category being the most common in terminal antennas.

1. *Single feed multiband antenna*

Within single-feed multiband antennas, two different categories can be established. The first one includes antennas on which different modes will be excited to operate in different frequency bands. The second category includes radiating structures consisting of different resonators, with some kind of connection between them.

a) *Single resonator antenna*

The simplest design for multiband antennas is based on the microstrip patch antenna depicted in Figure 37. Two different resonant frequencies appear when the first two resonant modes of the patch, determined by its length and width respectively, are excited. This can be obtained by properly selecting the position of the feeding probe.

² LTCC technology can be defined as a way to produce multilayer circuits with the help of single tapes, on which conductive, dielectric and / or resistive pastes can be applied. These single sheets have to be laminated together and fired in one step at relatively low temperatures, (850°C-875°C), so that it is possible to use low resistivity materials such as silver and gold.

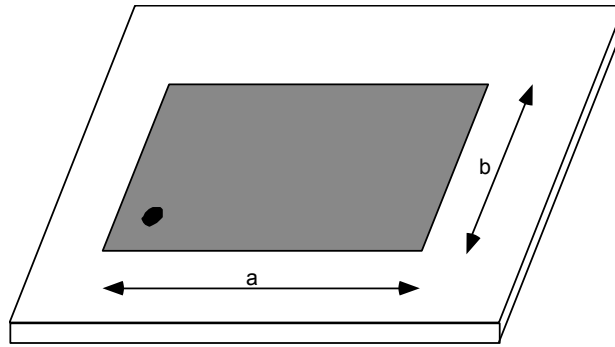


Figure 37: Microstrip patch antenna

If the frequency bands are close to another, or if more bands are needed, the center frequencies of which are not multiple of those of the first modes, more intricate shapes must be chosen for the resonator. Moreover, the use of microstrip technology allows obtaining only limited bandwidth. To enlarge it, the same principle can be applied to other kind of antennas.

With the use of single feed, single resonator antennas, multiband operation can be obtained with a structure that is small in size, and makes an optimum use of the available volume. But, on the other hand, it is extremely difficult to cover more than two bands. Moreover, the bandwidth of the two bands is always related and cannot be controlled by the designer, as the same volume is used for both. That means that the lower band will always have a narrower bandwidth than the upper band. This is clearly illustrated in Figure 38, which shows a dual band PIFA, for the GSM and DCS bands [71]. However, the compactness of this antenna makes it suitable for mobile communication applications.

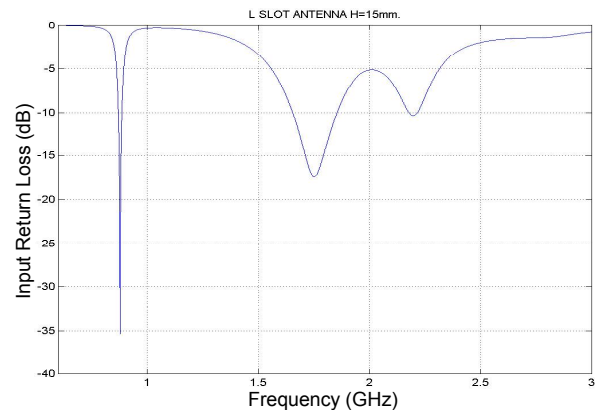
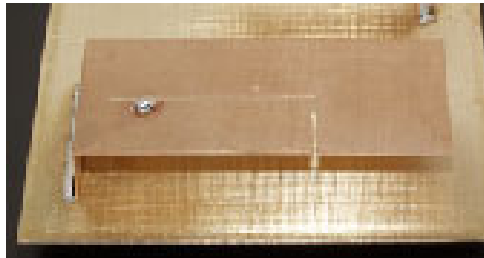


Figure 38: Example of a dual band PIFA and its Input Reflection Coefficient

b) Multi resonator antenna.

In this case, different parts of the antenna are resonating, depending on the frequency. These resonators are connected either galvanically through a conducting strip or a filter, or through electromagnetic coupling. Two possible designs are presented in Figure 39: a dual-band dipole and an electromagnetically coupled dual-band patch antenna.

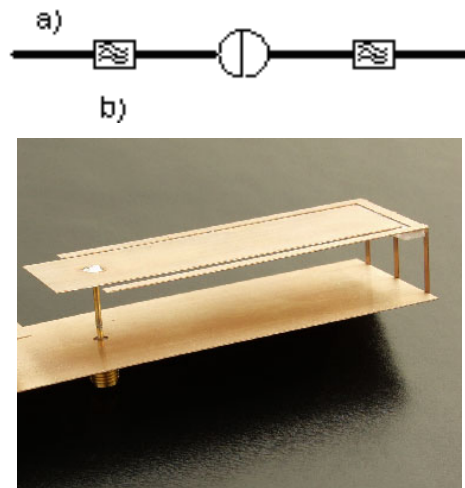


Figure 39: Two designs of dual-band antennas

- a) dual-band dipole: the two resonators are separated by a band-stop filter. At the lower frequency, the the entire structure is resonating. At the higher frequency, the filter blocks the signal and only the smaller dipole is resonating.
- b) Electromagnetically coupled resonators: The inner patch resonates at the higher frequency of operation. The second band is obtained through the electromagnetic coupling between the two parts of the structure, that act them as a PIFA.

The antennas designed using these techniques are still reasonably small in size, and the production cost can be kept low. An advantage with respect to single-feed, single-resonator antennas is that, now, the centre frequency and the bandwidth of each band, although not entirely independent from each other, can be controlled to some extent. Yet, the bandwidth obtained for the lower bands is still limited. Moreover, these antennas may be difficult to design, and require experienced engineers and reliable CAD tools.

Another example of such antennas is illustrated in Figure 40 [72]. Figure 41 shows the current distribution on the structure at the centre frequency of each band. In the lower frequency band, the current distribution on the ground plane shows a resonant behaviour. The ground plane acts then as a counterpole to the antenna, and contributes to the radiation, as mentioned in section 4.2 [5].

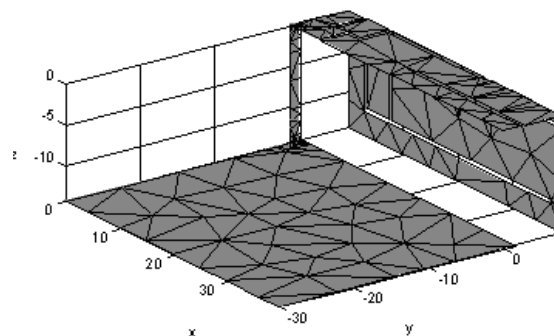


Figure 40: Dual-band antenna with defined the mesh used for the simulation. At the upper frequency, the vertical part acts as the resonator and determines the operating frequency. The horizontal part acts as the ground plane.

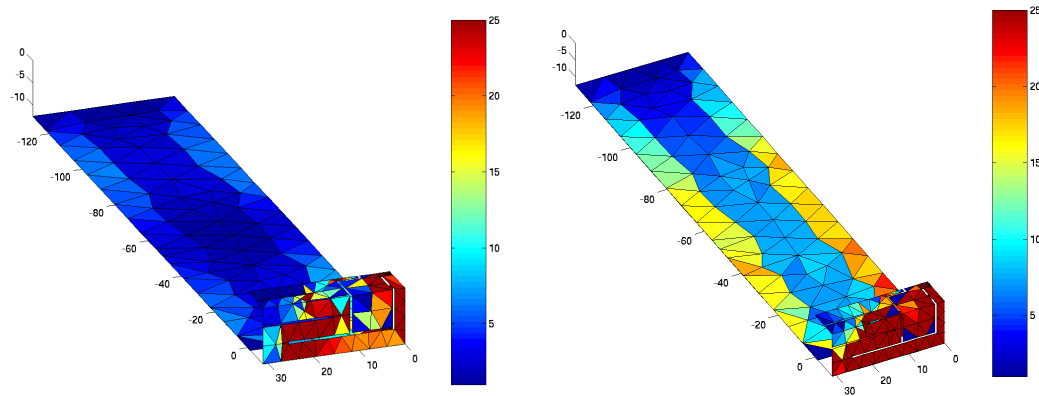


Figure 41: Current distribution for the upper (left) and the lower (right) frequency bands.

If additional frequency bands are required, it is possible to etch a $\lambda/2$ -radiating slot in the structures described above, to add a new resonance in a higher frequency band without increasing the overall size of the structure, as depicted in Figure 42 [73]. In this case, the range of frequencies that can be covered with the slot is limited by the size of the patch.

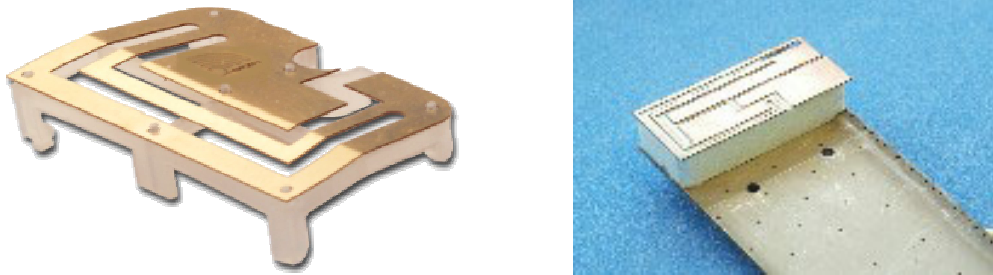


Figure 42: Triple-band (left) and quad-band (right) single-feed, multi-resonator handset antennas with radiating slot.

Several multiband designs with a main resonator and additional superimposed [74]-[76] or uniplanar resonators [52]-[53] are shown below on Figures 37, 38 and 39.

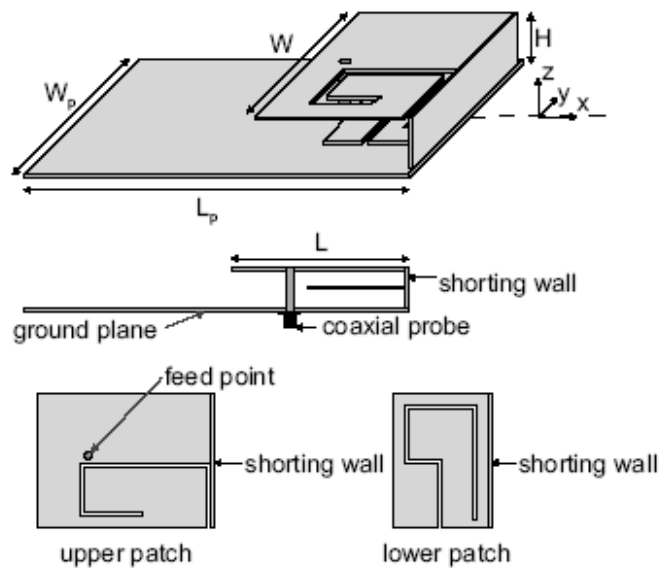


Figure 43: Dual-wideband antenna (GSM-DCS/PCS/UMTS) from [74]. Antenna geometry: $L_p = 100$ mm, $W_p = 40$ mm, $W = 35$ mm, $L = 46.2$ mm, $H = 11.6$ mm

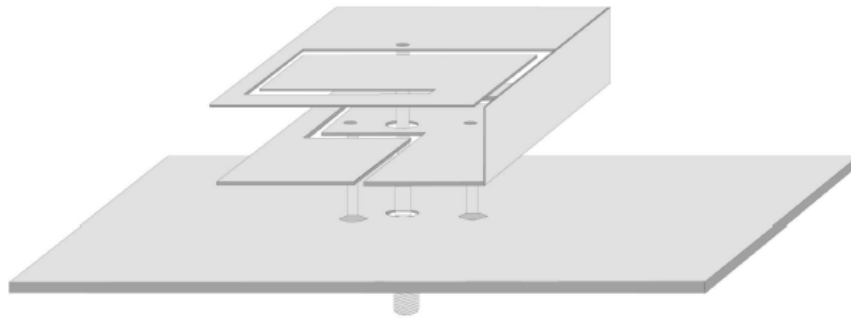


Figure 44: Dualband antenna (GSM- UMTS) from [75] and [76]

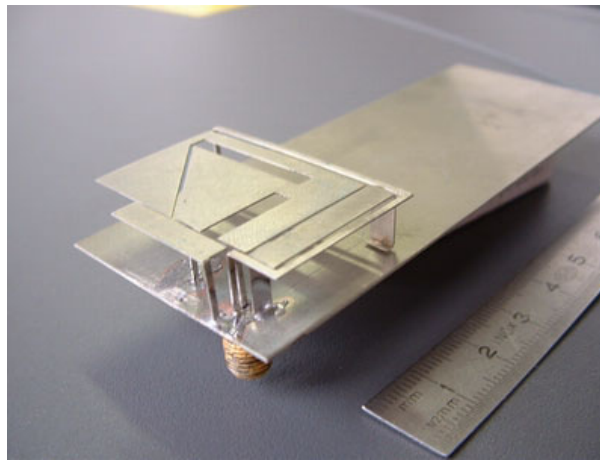


Figure 45: Multiband handset antenna (GSM-DCS-PCS-UMTS-WLAN) from [52] and [53]

2. Multiple feed multiband antenna

To avoid the drawbacks of single-feed antennas, it is possible to use two different radiators, with separate feeds, placed close to each other. In this way, the design is more flexible, as both elements can be tuned almost independently. An example of this is shown in Figure 46 [54], in which each frequency and each polarisation have a separate feeding point.

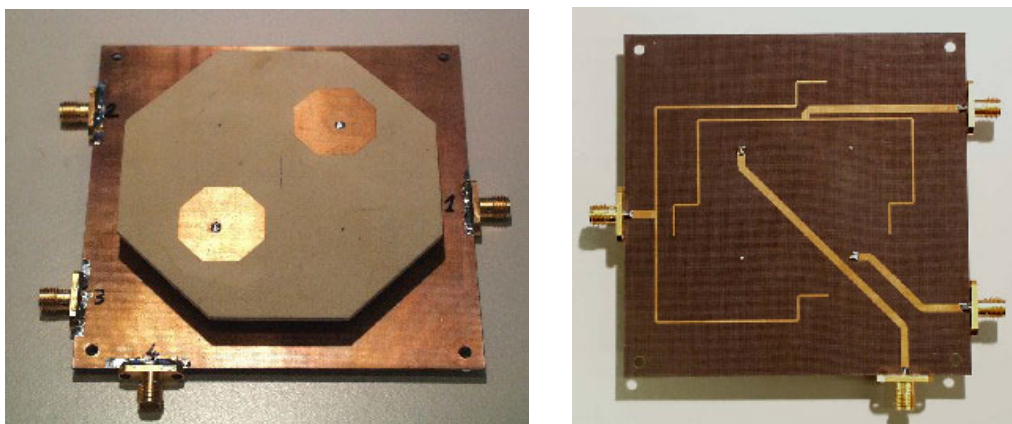


Figure 46: Dual band dual polarized antenna (from [54]): an octagonal aperture coupled patch radiates at the lower frequency and acts as a ground plane for the two patches antennas that cover the higher frequency band.

The main problem for this type of multiband antenna is to control the mutual coupling between the ports. This can be done either by using different polarizations for the different bands [55], if the polarisations of each band can be chosen freely, either by using parasitic elements to compensate the mutual coupling, as in the multi-band handset antenna presented in [63], or by placing selecting each feeding point in a relatively cold zone for the other frequency band, as in [54].

This multiport solution can also be used to design antennas for devices such as multi-standard PCMCIA cards used in laptop computers, as shown in Figure 47. In Figure 48, a structure with two antennas is depicted [56]. A dual-band Planar Inverted-F Antenna (PIFA) was chosen to cover the GSM 900, 1800 and 1900 bands, whereas an Inverted-F Antenna adds the WLAN capability. A prototype of the structure is presented in Figure 49.

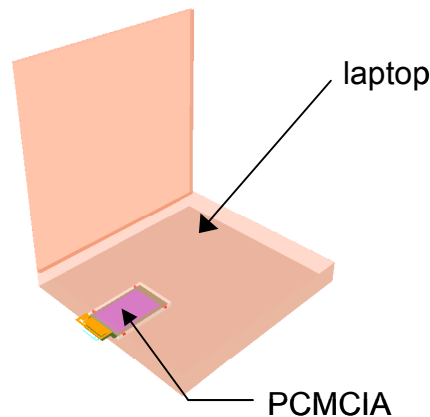


Figure 47: Model of a PCMCIA inserted in a laptop computer.

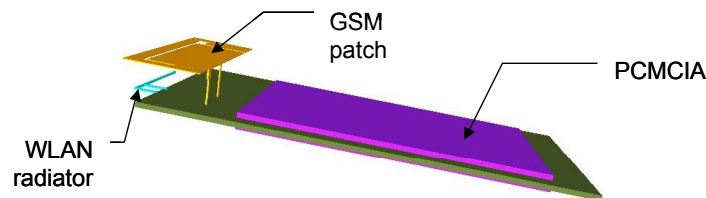


Figure 48: Multi-standard PCMCIA with integrated antennas for GSM 900, 1800, 1900 and WLAN operation.

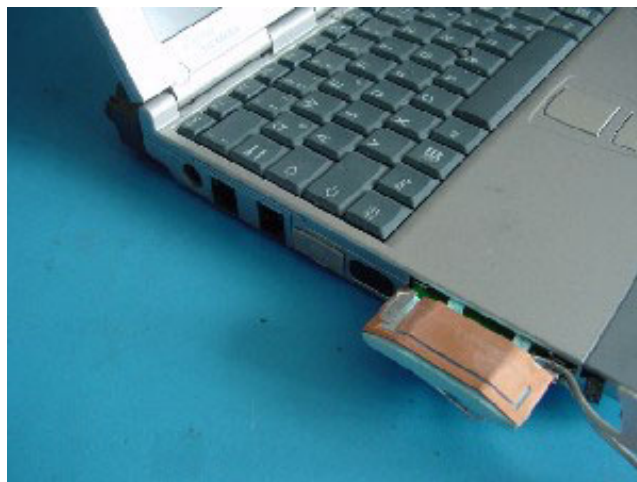


Figure 49: Prototype of the multi-standard PCMCIA.

6.5. Pre-fractal antennas

1. Pre-fractal structures: design considerations

As stated in section 5, the quality factor is related with the impedance bandwidth of the antenna. It is supposed that the bandwidth of an antenna could be improved when the antenna efficiently uses the available volume of the radiansphere that surrounds it. In this sense, the space-filling properties of fractal geometries were expected to help when trying to design useful antennas that might improve some features of common Euclidean ones [57].

Space-filling fractal curves are potential candidates to build miniature antennas thanks to their capability of compressing large wires into small areas. In [57] a Koch curve was analyzed in a monopole configuration and presented as a first example of fractal curve with improved characteristics. This first experience was extended to fractal dipole configurations using bidimensional and three dimensional fractal trees [58].

A lot of effort is concentrated on demonstrating how fractals of higher fractal dimension are more efficient at lowering resonant frequencies than any other geometry [59] and, conversely, that fractals are not more effective than other geometries with the same wire diameter, total wire length and occupied area [60], [61]. Figure 50 shows the realisation of different pre-fractal monopoles, while Figure 51 and Figure 52 display their computed quality factor and radiation efficiency, respectively.

Yet, a recent work [62] definitively demonstrated that space-filling prefractal antennas are not suitable to design efficient miniature antennas. Though suitable for reaching higher miniaturisation ratios compared with a conventional $\lambda/4$ monopole, they store a lot of energy in the near-fields of the antenna and have higher ohmic losses. Both inconveniences result in high values of quality factors and low values of radiation efficiencies.

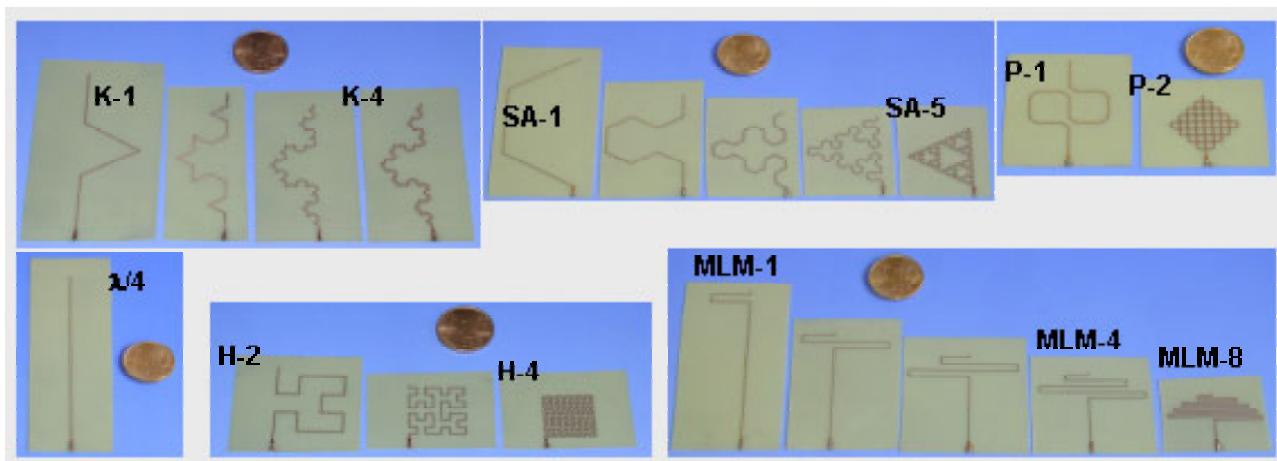


Figure 50: Fabricated monopoles compared with a 10 eurocents coin: Hilbert monopoles, Peano monopoles, $\lambda/4$ monopole and rhomb monopole, Peano variant 2 monopoles, Peano variant 3 monopoles and Meander line Loaded Monopoles

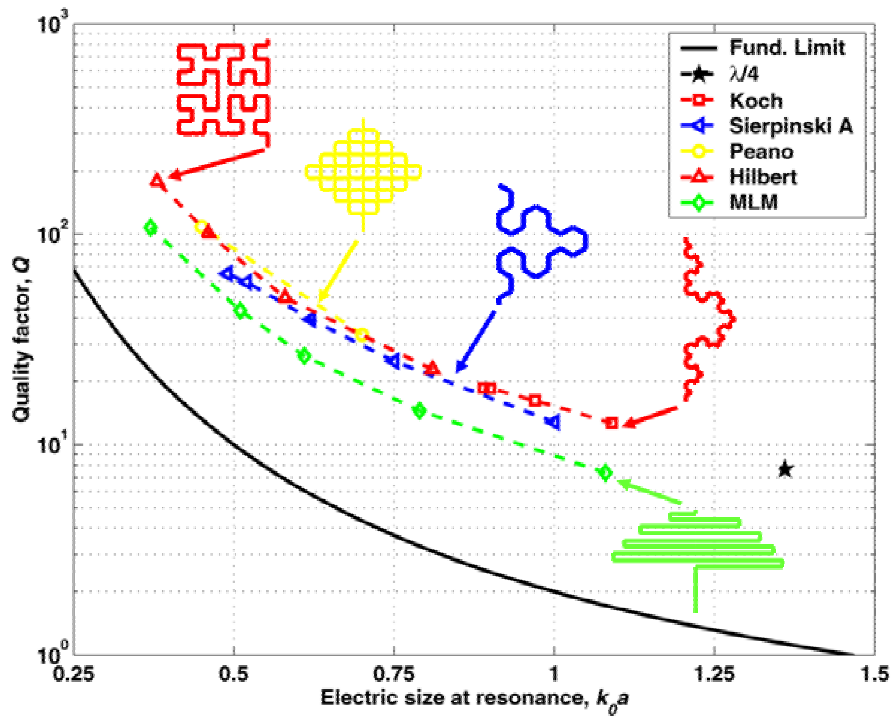


Figure 51: Computed quality factor at resonance versus electrical size of the antenna. Dashed lines join families of prefractions

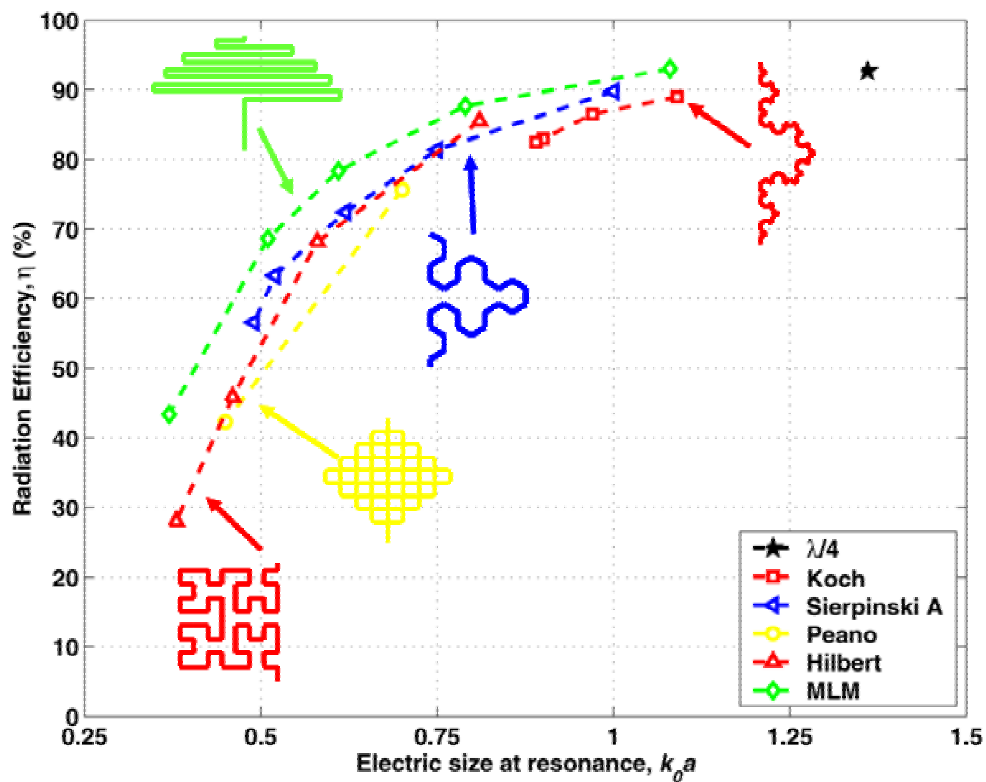


Figure 52: Computed radiation efficiency at resonance versus electrical size of the antenna. Dashed lines join families of prefractions

2. Example

A novel microstrip patch antenna with a Koch pre-fractal edge and a U-shaped slot proposed for multi-standard use in GSM1800, UMTS and HiperLAN2 has been proposed [64]. Making use of a Planar Inverted-F Antenna (PIFA) structure an interesting size reduction is achieved. The multi-band behavior has been obtained by broadening the lower frequency resonance of the fractal patch to cover GSM1800 and UMTS, and inserting an U-slot dimensioned for the HiperLAN2 band. The effect of small ground plane has been taken into account. Experimental results have validated the design procedure and confirm the fulfillment of the requirements for multi-standard mobile terminal applications.

The antenna has been implemented in microstrip planar technology. A finite ground plane, of dimensions 100 mm×45 mm, has been chosen to represent a common handset size. The patch element has been printed on a Duroid 5880TM substrate ($\epsilon_r = 2.2$, $h = 1.57$ mm). To meet the bandwidth requirements a 10 mm thick air gap has been introduced between the substrate and the ground plane. The antenna structure is shown in Figure 53.

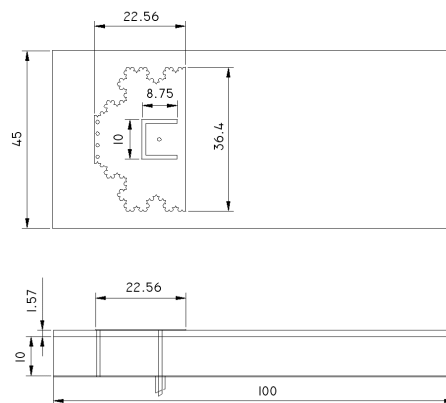


Figure 53: Structure of the fractal PIFA with a U-slot (dimensions in mm).

The patch element has been designed based on a simple rectangular shape where the longitudinal resonant edges have been substituted by the fourth iteration of the Koch fractal curve. To obtain the additional miniaturization effect, the Koch-edge patch has been implemented in a PIFA configuration. By doing so, the patch element length has been reduced by 62% in comparison with the simple rectangular patch.

The desired upper band (HiperLAN2) antenna behavior has been achieved using a U-shaped slot [65]. The U-shaped slot has been cut inside the patch element around the feeding point Figure 54.

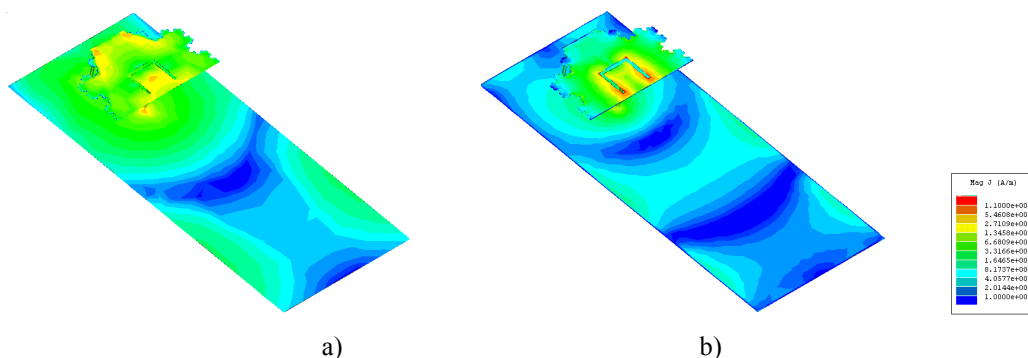


Figure 54: Current distribution on the patch surface (simulation results):
 a) $f = 2.035$ GHz, b) $f = 5.25$ GHz.

For the lower frequency bands (GSM1800 and UMTS), the dimensions of the slot are much smaller than the wavelength, so the cut does not influence the antenna behavior. In this case, the active region covers the entire patch shape, as shown in Figure 54 a). For the HiperLAN2 band the effectively excited area is limited to the interior of the U-shaped slot in Figure 54 b). In the upper frequency band the antenna works as a simple rectangular patch. It is not necessary to miniaturize the inner rectangular patch because it fits inside the fractal element.

An antenna prototype has been fabricated with the use of photolithographic printing circuit technology. The resulting structure is displayed in Figure 55, whereas the input return loss and radiation patterns are shown in Figure 56 and Figure 57, respectively.

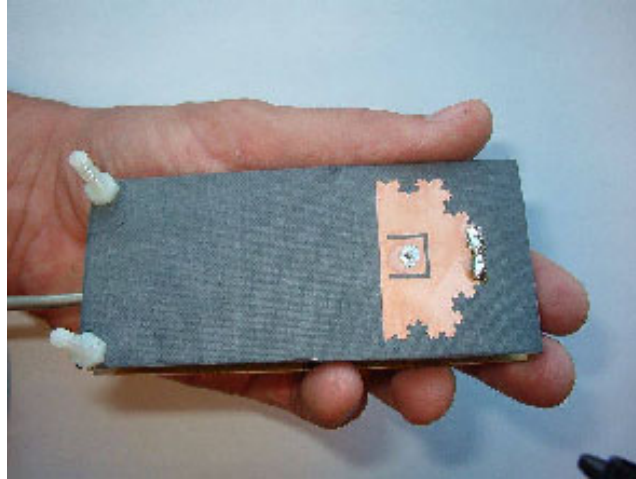


Figure 55: Fractal antenna prototype

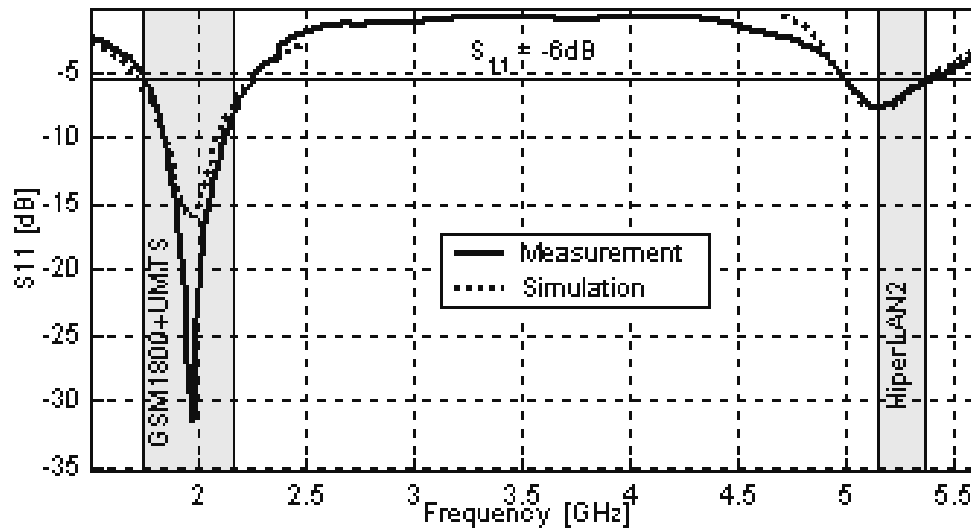


Figure 56: Comparison of computed and experimental S_{11} results.

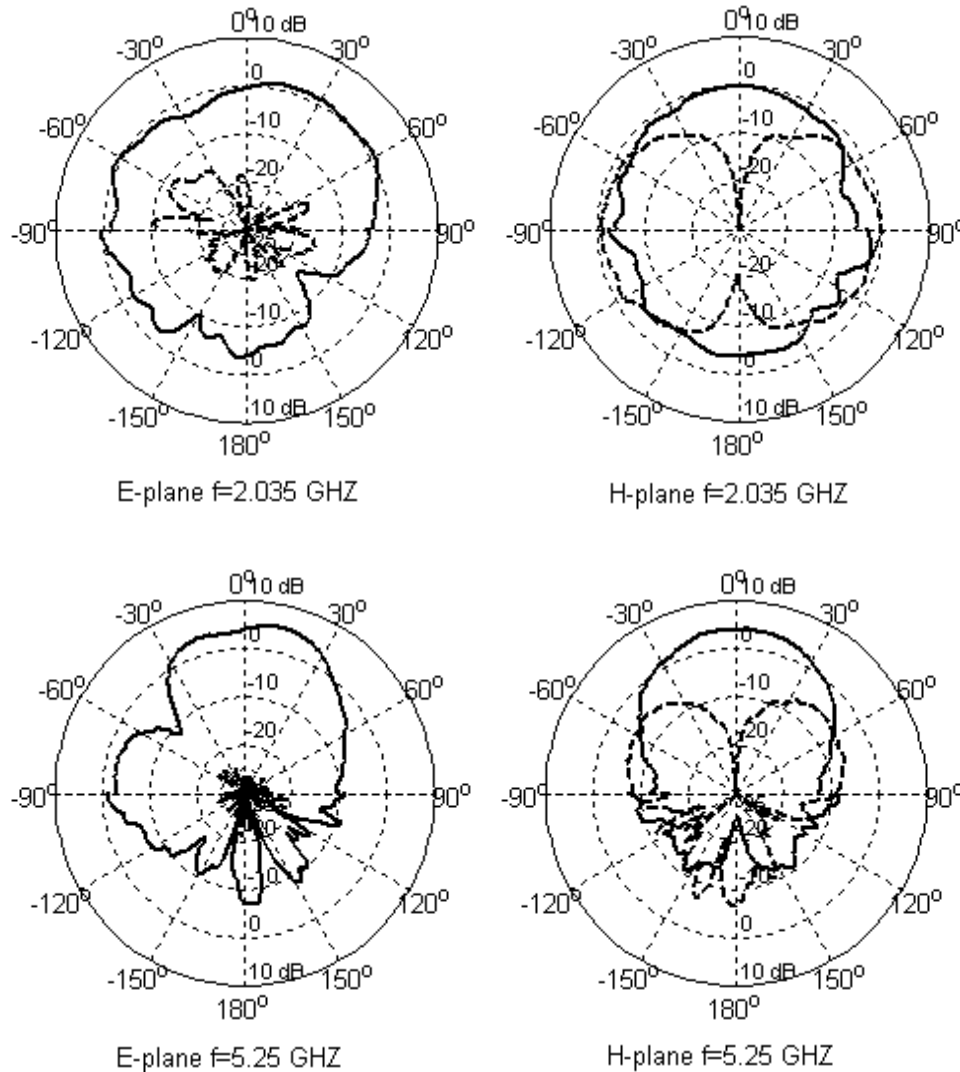


Figure 57 :Measured radiation pattern – gain scale
 (— co-polarization, - - - cross-polarization).

6.6. Electrically-Small Frequency-Tuneable Antennas

One of the drawbacks with designing an antenna so that it covers a variety of frequency ranges/standard instantaneously is that its physical volume will increase relative to an antenna, which only covers a small range. This approach goes against the trend of size reduction at the terminal. Furthermore, from a transmission perspective a passive antenna that is wideband is likely to excite a number of modes across its operating range, each with different radiation characteristics; polarisation and pattern.

If, on the other hand, an antenna was made electrically-small, such that it could be fitted into a given space without the need for it to be conformed, then its instantaneous bandwidth would reduce. However, provided that the instantaneous bandwidth was sufficient to operate on a single channel of a given standard then the deployment of such an antenna is not limited provided there is some means to tune the mode.

Recent work has suggested that by utilising an electrically-small mode in an annular slot antenna, pure transmission characteristics may be obtained, yet at the expense of a narrow input bandwidth (10MHz) [77]. However, incorporation of a tuning network as in Figure 58 allowed this mode to be tuned across a 630MHz range whilst still maintaining very similar radiation characteristics. Figure 59 shows the input response as a function of tuning voltage for this system and shows example 3-D radiation patterns at the lower, middle and upper parts of the tuning range with the antenna located flat in the x-y plane [78].

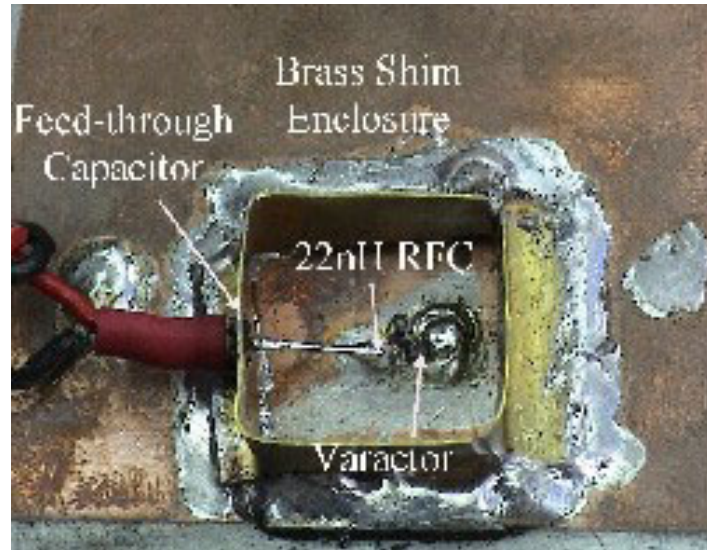


Figure 58: Rear of a cavity-backed annular slot showing the tuning mechanism (the varactor)

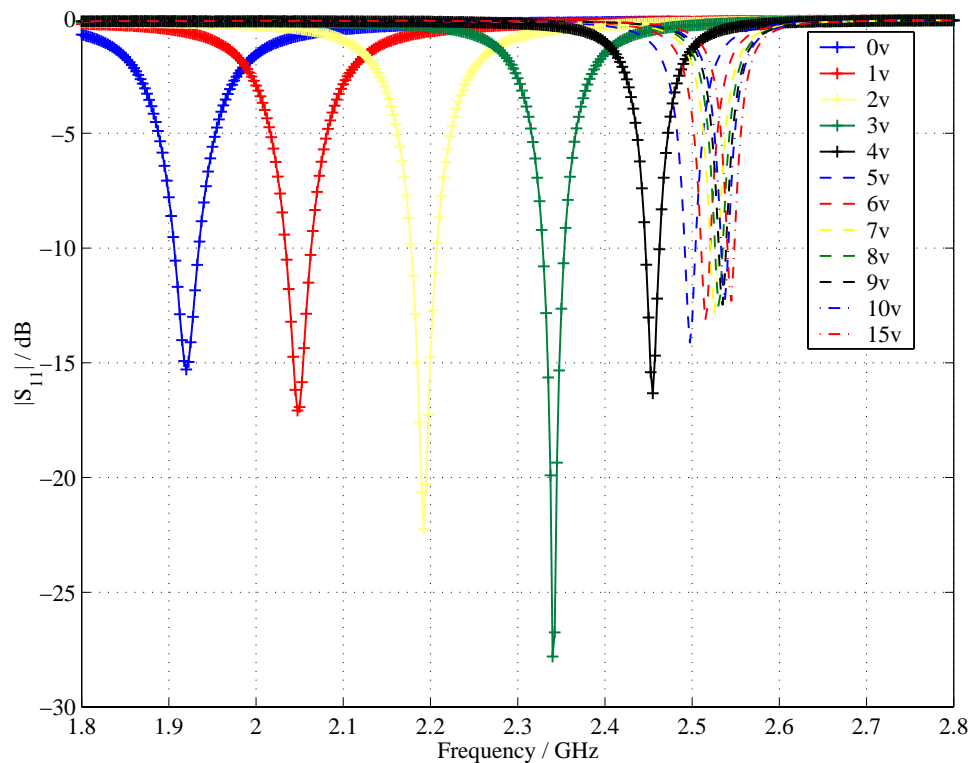


Figure 59: Variation of Input Response with Bias Voltage

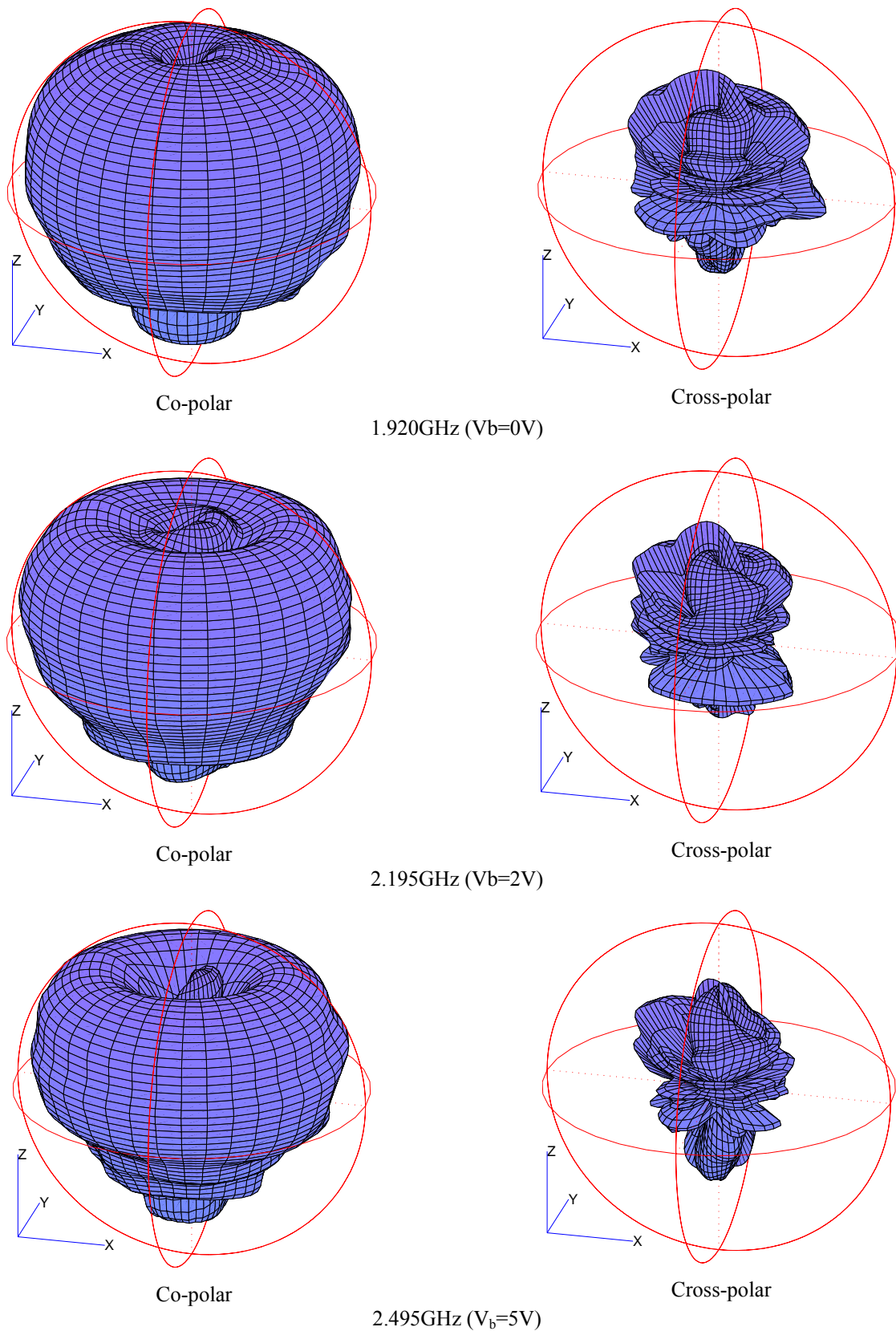


Figure 60: Variation in Radiation Pattern with Bias Voltage. All plots are on a relative dB Scale, -40dB at centre

Another benefit of tuneable electrically-small antennas is that, due to their narrow input bandwidth they offer additional filtering to the RF front-end. This can be of great benefit in an environment that is rich in interfering signals [78].

6.7. Antenna miniaturisation.

Miniaturization is one of the major goals, especially in small handset devices. In a wireless system the antenna has to be, in addition, robust, lightweight, easy to fabricate and low cost. Yet, it is commonly known that size reduction decreases both the antenna bandwidth and the input impedance [39]. The difficulty resides then in finding a trade-off between size, function range, impedance, and bandwidth for a specific device and antenna.

1. Example: IFA antennas

For a given resonant structure, the overall size can be decreased by using either inductive or capacitive loading. To illustrate this method, the single band Inverted F Antenna (IFA) presented in Figure 61 will be considered.

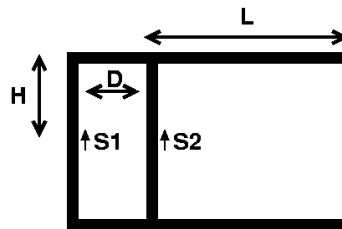


Figure 61: Symmetrical realisation of an IFA for higher input impedance and symmetrical feeding to adapt to state of the art front end amplifiers

The symmetric implementation is chosen to allow the integration into a hand-held device with a resonant frequency of 2.44 GHz or 5.2 GHz, thus avoiding the use of a ground plane. Symmetrical fed antennas are more insensitive to their environment, and their input impedance is twice that of the conventional IFA. Moreover, modern front-end amplifiers use a symmetrical structure; hence by using a symmetrical feed the matching network can be eliminated.

The antenna can be fed either in the middle of the left vertical line (S1) or in the middle of the right vertical line (S2). As the current flows mainly on the inner vertical arm of the IFA, if the source is placed in S1 the input impedance is up to three times higher than in the case of a source placed in S2, as displayed in Figure 62.

In Figure 61 the main parameters of the IFA are indicated. For a given resonant frequency, the total size of the antenna is determined by the sum of its length L and its height H as:

$$T = H + L \approx \frac{\lambda}{4} \quad (11)$$

where λ represents the wavelength at the frequency of interest.

For small values of H , a capacitive coupling between the upper and lower part of the antenna occurs, hence the total length T of the antenna can be shortened. The distance D between the vertical parts of the antenna allows controlling the input impedance, but has no effect on the resonant frequency.

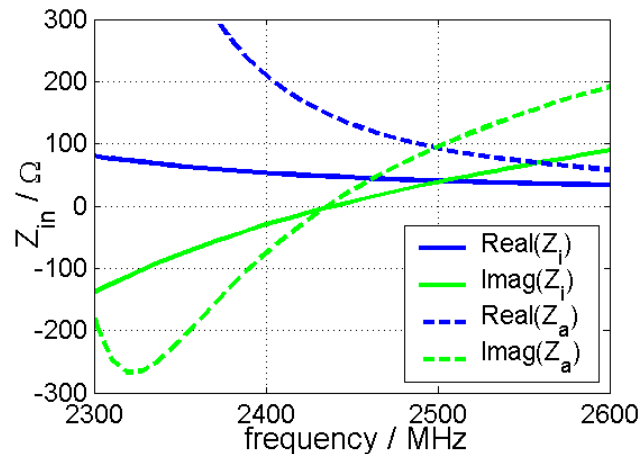


Figure 62: Simulated input impedance of the symmetrical IFA. Source placed on S1 (dotted line) vs. source placed on S2 (full line)

a) Capacitive Loading

A way of miniaturising the IFA is connecting capacity between the ends of the two horizontal arms, as shown in Figure 63. Both the input impedance and the resonant frequency are thus decreased.

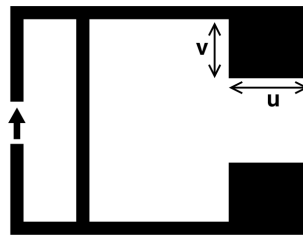


Figure 63: Capacitive loaded planar IFA. By incrementing v and u the capacity is increased.

b) Inductive Loading

The total size of the structure can also be reduced by inserting an inductance in the S2, as depicted in Figure 64. As the inductance is augmented, the resonant frequency decreases. Simultaneously, the input impedance gets smaller and the bandwidth of the antenna is reduced. By the use of the inductive loading, the size can be reduced between 20 % and 30 % compared to an unloaded IFA.

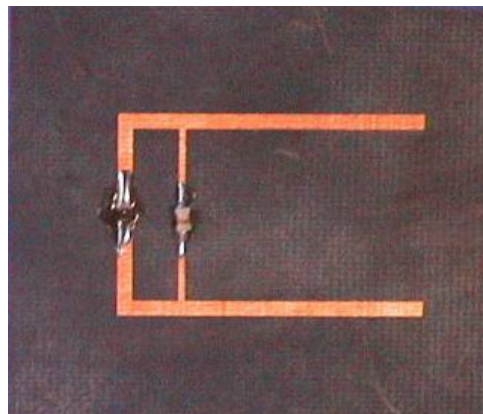


Figure 64: Inductively loaded inverted F antenna

2. Example: Coupling structures

Especially at the lower frequencies of the GSM900 band the small-size and bandwidth requirements are difficult to meet simultaneously when using self-resonant antenna structures. As mentioned earlier, it was noticed that at 900 MHz a large part of the power is actually radiated by surface currents on the chassis ground plane [5]. Therefore, small non-resonant (and thus non-radiating) structures that efficiently couple power into the characteristic wavemodes of the chassis have been developed [6]. The necessary resonances for these antenna structures are created by matching circuits.

The volume of the antenna design shown in Figure 65 is only 1.3 cm³. The design meets bandwidth and SAR requirements of the E-GSM900 and also the GSM1800 systems. Radiation efficiency is high and the radiation patterns are suitable for use in mobile handsets. This antenna structure can be easily extended to multiband antennas by replacing the matching circuit with a multiresonant matching circuit.

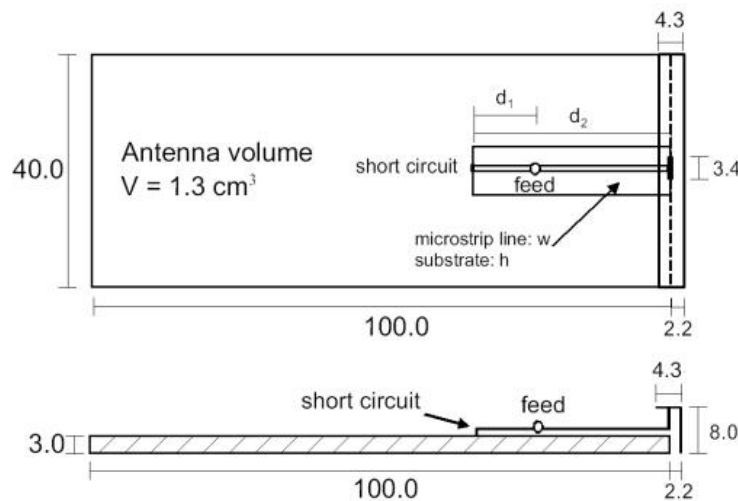


Figure 65: Layout of ground plane with coupling element and matching circuit

6.8. Example: Effects of the User on a Triple-Band Handset PIFA

Recently a new triple-band PIFA antenna for small handsets has been presented [79]. It is intended to be used in future multi-standard handsets supporting both mobile communication (GSM1800 and UMTS) and WLAN systems (HiperLAN2). A photo of the antenna prototype is shown in Figure 66.



Figure 66: Photo of the handset PIFA prototype.

In order to evaluate the effects of the user on the antenna performance, measurements were performed at the University of York. The measurement setup is shown in Figure 67.

The PIFA has been placed in the standard 'tilt' position where the phone is tilted 15° away from the mouth. As there is no standard hand available, and no standard position for the hand, an improvised hand has been used. It consists of a rubber glove filled with the same liquid used in the head. The hand has been used in a realistic position.



Figure 67: Photo of the measurement system.

The input reflection coefficient of the PIFA was measured in the following situations:

1. in free space (**freespace**);
2. in the plastic holder (**holder**);
3. in the plastic holder near the head (**holder+head**);
4. in the plastic holder near the head with the hand holding the handset away from the PIFA (**holder+head+hand**)(**away**);
5. in the plastic holder near the head with the hand holding the handset and partially covering the PIFA (**partial covering**);
6. in the plastic holder near the head with the hand holding the handset and completely covering the PIFA (**complete covering**).

The corresponding results are shown in Figure 68 and Figure 69.

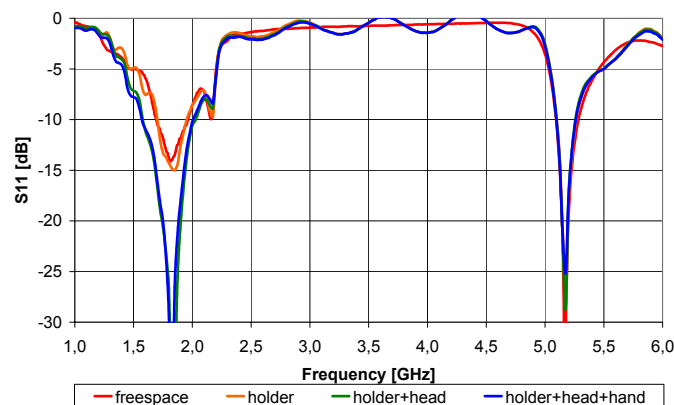


Figure 68: Effect of the plastic holder, head and hand on the input return loss.

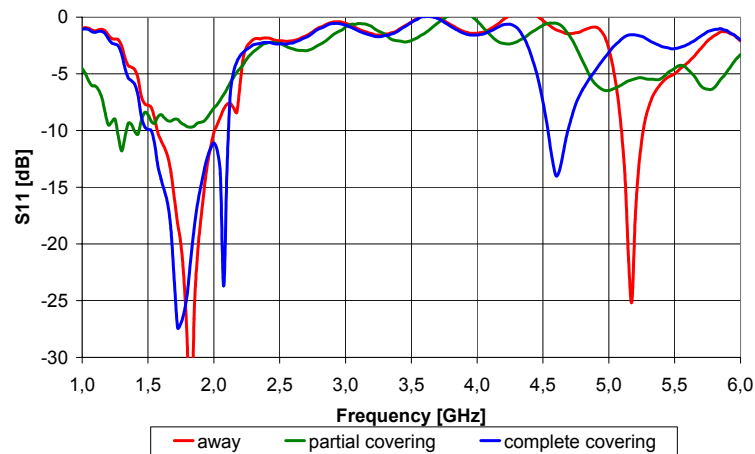


Figure 69: Effect of the position of the hand on the input return loss.

As it can be seen in Figure 68 the effect of the holder, the head and the hand, when holding the handset away from the PIFA, are almost negligible. Only the matching in the lower bands (GSM1800 and UMTS) is affected. However, as the hand moves closer to the PIFA (Figure 69) the mismatch and detuning increases reaching a maximum when the hand completely covers the PIFA. In a real handset this proximity effect is less critical because the antenna is covered by a plastic case.

7. EXAMPLES OF REQUIREMENTS FOR SMALL TERMINAL ANTENNAS

Here is a short review of typical specifications for mobile phone antennas. Note that these are only examples, as they may change depending on the manufacturer.

7.1. Operating frequencies in MHz

The most usual operation frequencies correspond to the standards listed in section 3, Table 1. Due to the diversity of standards that coexist nowadays, almost any combination of frequency bands is possible, ranging from 100 MHz to 10 GHz.

7.2. Input power

Conducted power at the antenna's input from a 50Ω load must comply the specifications of each standard (normally around 29 to 33 dBm for 2G cellular). In the case of UMTS, the required level is 24dBm. But other standards, some other aspects must be taken into account, as the very short pulses used for UWB communications, with only a few μW per MHz, or continuous power. In April 2002, after extensive inputs from industry, the FCC issued its First Report and Order on UWB technology [80] to support deployment of UWB systems. The FCC regulations classify UWB applications into several categories. Maximum emissions in the prescribed bands are at an effective isotropic radiated power (EIRP) of -41.3 dBm per MHz, and the -10 dB level of the emissions must fall within the prescribed band.

7.3. Matching

In both receive and transmit mode, the VSWR value in the operating bands is required to be (typically):

- $VSWR < 2$ ($S_{11} < -10\text{dB}$)
- $VSWR < 2.5$ ($S_{11} < -7.5\text{dB}$)
- $VSWR < 3$ ($S_{11} < -6\text{dB}$)

These requirements vary depending on the type of terminal and the kind of antenna used.

7.4. Radiated Power

In free space, the TRP (Total Radiated Power) > 27-30 dBm (depending on the frequency bands). Typically, 3-D measurements are required to determine the TRP. Both TRP and radiation efficiency can be calculated by 3-D pattern integration from measured 3-D radiation patterns, but it can also be directly measured in a reverberation chamber.

7.5. Receiver Sensitivity and Bit Error Rate

The quality of a mobile terminal on reception is characterised by its receiver sensitivity. This is often given as a total isotropic sensitivity (TIS) at a certain Bit Error Rate (BER) level, e.g. 2%. TIS is obtained by measuring the level at which the BER = 2% for many angles of incidence of a plane wave uniformly distributed over the unit sphere, and averaging these levels. In [81] it is described how to measure TIS in an anechoic chamber, and in [82] how to measure it in a reverberation chamber. The reverberation chamber can also be used to measure Average Fading Sensitivity [82], which is a more realistic performance parameter of a mobile terminal operating in a fading environment. This can be measured very fast in the reverberation chamber.

7.6. Radiation Efficiency

The radiation efficiency describes the ratio of power made available to the antenna and the total radiated power³. The contributions to total antenna efficiency are impedance mismatch and absorption. The latter includes both losses in the antenna itself and in its near environment, such as a hand or head phantom. Some manufacturers specify a minimum radiation efficiency in the antenna's bands of operation.

7.7. Gain in Free-Space

Typically the realised gain of terminal antennas is around 0 dBi. However, the gain is representative for the radiation level in one chosen direction, so it is not an appropriate performance parameter for a mobile terminal that operates in a multipath environment. Therefore, a difference must be made between *peak gain*, given by the maximum of the radiation pattern, and the *average gain*. The latter reflects the ratio between the TRP and the input power, and is thus linked to the efficiency.

7.8. SAR

The handset shall comply with the recommendations detailed in Table 5.

Table 5: SAR recommendations according to CENELEC, ICNRP and FCC.

Recommendations	CENELEC & FCC on the whole body	CENELEC & ICNRP over 10g of tissue	FCC over 1g of tissue
Continuous exposure Average over 6mn	0.008 W/kg	2 W/kg	1.6 W/kg

³ This is NOT the same as antenna efficiency, which considers the losses of the antenna itself (N.B. antenna mismatch is nothing to do with antenna efficiency; it merely shows the inability of the designer to match the antenna to the RF front-end).

8. FUTURE ANTENNA REQUIREMENTS

As well as the current issues facing antenna design (Section 4), there are emerging techniques, which will affect antenna design in the future. In this section some of these issues are discussed.

8.1. Diversity

Diversity is a phenomenon whereby two or more independent paths exist between a transmitter and receiver. These independent paths are useful for a number of reasons, for example: to provide link robustness by mitigating against fading or to enhance channel capacity by allowing frequency re-use. Diversity is already used in Japanese and Korean systems, as well as in WLAN terminals, and UMTS is prepared for it.

There are a number of ways in which diversity may be realised: spatial diversity where multiple antennas are physically separated from one another, polarisation diversity where a variety of polarisations are used and frequency diversity where different frequencies. Due to poor spectral efficiency, the latter is seldom used, and hence the two former options are most popular.

A host of characterisation methods exist to quantify the performance of diversity antenna, [83], [84], [85] and [86], the most useful being actual diversity gain. Practically a reverberation chamber lends itself well to these measurements. Figure 70 shows a typical reverberation chamber together with the diversity gain results of DECT handset measured on transmit.

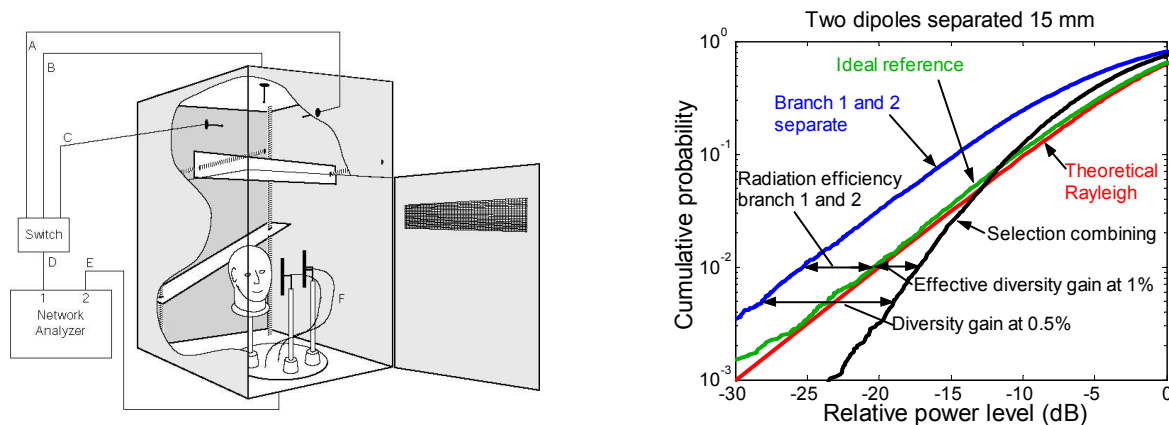


Figure 70: Set-up for measuring diversity gain of an example dual dipole diversity antenna in a reverberation chamber (left), and resulting cumulative probability distribution function of signal amplitudes (right). The apparent and effective diversity gains are marked as 1% and 0.5% cumulative probability levels, respectively. The diversity algorithm is selection combining.

In the design of these kind of antennas, system aspects must be taken into account, as some aspects, like the decision algorithm will have a strong influence on the behaviour of the structure. Another aspect that has to be considered is how to characterise the performance of such a device. Nowadays, there are still no definite rules, and few recommendations, as those presented in section 9.

8.2. *MIMO*

Compared to single antenna architectures, the use of multiple antenna elements at the transmitter (TX) and receiver (RX) of a communications link allows the system to: beam-steer, beam-null or fully exploit the scattering characteristics of the channel. This can result in a marked increase in channel capacity for the same utilisation of bandwidth resources and transmitter power [78].

Such a scheme that makes use of multiple antennas at the input and output is called a Multiple-Input Multiple-Output (MIMO) scheme, and is a major driving force in implementing antenna arrays in small mobile terminals. Consequently, it may therefore dictate the size, number, input-match, polarisation and pattern requirements of the antennas for a given system. A brief description of its underlying principles is given here.

Fundamental to a MIMO scheme is the ability to achieve separate decorrelated paths between each of the TX and RX antennas. In order for the paths to be decorrelated the environment has to be sufficiently rich in scattering so that independent fading will be exhibited in each of the paths between transmit and receive antennas [87]. One way of achieving this is to separate the receive elements. For the case of a two-element receiver, this will introduce a relative phase-shift between the two elements. Due to this phase-shift, the same signals received at each antenna will be decorrelated from one another [78].

As well as providing decorrelation by spacing the elements apart, using antenna elements that are able to provide some degree of diversity; be that through having different radiation patterns and polarisations, will also enable the paths between TX and RX to be decorrelated

The system is designed in such a way that the information is distributed in an optimum way between the channels, in such a way that the strong channels get larger capacity than the weak channels. This is continuously adapted to the changing environment and channels. The maximum available capacity of a MIMO system can be measured in the simulated fading environment of a reverberation chamber, as described in [88]-[90], or by constructing the appropriate arrays and measuring the performance through channel sounding as described in [91] Furthermore, due to the lack of available space on the mobile terminal and the desire to use multiple elements, the antennas will have to be electrically-small [78].

MIMO systems will be discussed in more detail in the final WP report to be written next year.

8.3. *Antenna quality measures for multi-antenna terminals*

Classical characteristics do not sufficiently describe the performance of MIMO systems. Indeed, it is difficult to relate the capacity of a MIMO system directly to characteristics like the gain and or the radiation pattern of an array. For example, the efficiency of an array depends on its excitation, which makes a characterisation of a MIMO array difficult, as the excitation is not constant.

Usually, when dealing with MIMO systems, only the capacity and the correlation properties are considered. But for the development of multi-antenna terminals the behaviour in terms of power has also to be taken into account. Thus, the power transmission gain of the system and the effective gain of the antennas are used as quality measures.

The task of an antenna array in a MIMO system is to allow for the exploitation of the multipath nature of the propagation channel, using sophisticated signal processing. Thus, the array and the propagation channel have to be adapted to each other, and it is then reasonable to treat them as a whole, and to describe them statistically to take into account the many channel possibilities of a

propagation environment. Therefore, the quality measures used to characterise the antennas for specific propagation channels must also have a statistical nature.

1. Capacity

The main interest of MIMO systems, compared to conventional communications systems, is their increased capacity,. Capacity is therefore the ultimate quality measure for these systems. It depends on the correlation properties between the channel coefficients h_{ij} and the signal-to-noise-ratio (SNR). For the sake of simplicity, but without consequences for the quality measures, only MIMO systems without channel state information at the transmitter will be considered here. With this assumption, the transmit power is equally (and not optimally) spread among the transmit antennas. For such MIMO systems the capacity can be given in two ways:

$$C = \log_2 \det \left(I + \frac{P_T}{m\sigma^2} HH^* \right) \quad (12)$$

$$C = \log_2 \det \left(I + \frac{SNR}{m} H_F H_F^* \right) \quad (13)$$

Where I denotes the identity matrix, P_T the total transmit power, m and n the number of transmit and receive antennas, σ^2 the noise power, and $*$ the conjugate complex transpose. In equation (11) the capacity is expressed as a function of the transmit power P_T .

The attenuation of the transmission link, caused by the antennas and the radio channel, is also taken into account. To investigate the influence of the correlation properties on the capacity of the system, the matrix H_F representing the behaviour channel is often normalized, so that it is independent of the attenuation of the channel. Thus, the capacity becomes a function of the SNR at the receiver, as shown in equation (12). The channel matrix H_F is normalized using the Frobenius Norm, so that the mean attenuation of each channel matrix trace $(HH^*)/nm$ is equal to one. The channel attenuation, which is included in the channel matrix, has to be expressed in the SNR when normalizing the channel matrix.

2. Correlation

The correlation properties of H have a strong influence upon the capacity. The number of correlation coefficients between all elements h_{ij} in H is n^2m^2 , thus it is difficult to assess the correlation properties. A simple way to find whether the correlation is high or low is to consider only the transmit and receive correlation, in which only the correlation among signals transmitted or received from different antennas is considered. The complex transmit and receive correlation coefficients of two zero-mean elements h are defined as:

$$\rho_{Tx} = \frac{E[h_{ki}h_{kj}^*]}{\sqrt{E[|h_{ki}|^2]E[|h_{kj}|^2]}} \quad (14)$$

$$\rho_{Rx} = \frac{E[h_{ik}h_{jk}^*]}{\sqrt{E[|h_{ik}|^2]E[|h_{jk}|^2]}} \quad (15)$$

The power correlation coefficient is given by $\rho_P = |\rho_{com}|^2$.

3. *Power Considerations*

Since most mobile terminals are battery driven, the efficiency of the antennas is an important topic. Mutual coupling among closely spaced antennas does not only influence the signal flow and the correlation properties, it can also strongly reduce the efficiency of an array.

Yet, as the efficiency of an array depends on its excitation, it is not the best quality measure for arrays in MIMO systems. The system model, given in [92] allows considering the power transmission gain of the whole MIMO link, including the antennas. The power transmission gain is given by the ratio of the power received at the signal drain to the power fed into the transmit antennas. The latter is equal to the power radiated from the transmit antennas only if the efficiency of the transmit array is 100%. By comparing the power gain of MIMO systems with different arrays in the same channel, conclusions on the performance of the arrays in terms of power can be easily drawn.

To assess the behaviour of single antennas in an array the Mean Effective Gain (MEG) can be used. The MEG is the ratio of the mean receive power of an antenna under test to the mean receive power of a reference antenna, when both antennas are used in the same channel with the same transmit antenna. This definition can be extended to characterise complete arrays. The Mean Effective Array Gain (MEAG) is the ratio of the mean received power of an array to the mean received power of a reference antenna.

4. *Characterisation of the radio channel*

MIMO systems exploit the spatial domain of the propagation channel. The smart antennas system is adapted to the multipath structure of the channel by using sophisticated signal processing. In environments where MIMO systems can be applied, the propagation situation changes rapidly. Hence, it is not sufficient to investigate the performance of MIMO antennas at one specific moment, and using only one realisation of the propagation channel. The performance of a MIMO array is determined by the ability of the array to adapt to the changing channel conditions. Both the antenna arrays and the propagation channel should be treated together, with a statistical description, to take into account different channel realisations of a given propagation environment.

MIMO systems take advantage of the spatial properties of the propagation channel. Therefore, in the evaluation of MIMO antenna arrays, it is necessary to use a proper characterisation of the spatial channel properties. Parameters like the angular spread of the waves impinging at the receiver have a significant influence on the MIMO system performance. A meaningful conclusion from a comparison of MIMO antenna arrays can only be drawn if the spatial properties of a realistic propagation channel have been taken into account.

There are many studies addressing the properties of the MIMO propagation channel. These efforts have resulted in realistic characterizations of the propagation channel for different environments, e.g. indoor or outdoor.

8.4. *Evaluation methods for multi-antenna terminals*

In order to reach the desired high data rates in next-generation mobile systems, the use of multi-antenna configurations at both ends of the radio link is needed. The multi-path radio link in such a scenario is highly stochastic, and its evaluation not possible in a simple manner. To obtain statistically relevant performance data when comparing multi-antenna configurations, several hundred meters of measurement routes in the several types of propagation environments would be

needed for each prototype antenna. This is almost impossible in practice due to the large amount of measurements needed, but also due to restrictions imposed by the authorities on the usage of the frequency bands in which commercial communications networks are already operating.

Instead, it would be useful to evaluate the performance of new multi-antenna mobile terminals in real signal-propagation environments already in an early phase of the design process. For this purpose, a method has been developed that enables the virtual placement of a computer-simulated antenna design in a realistic propagation-environment model. The environment model is based on channel-sounder measurements performed with a spherical antenna array, with help of which the spatial and directional properties of the signal-propagation environment along rural and urban routes were characterised. Sets of simulated (or measured) 3-D radiation patterns of new multi-antenna designs can now be virtually driven through this database of measured routes and the antenna performance (e.g. correlation, diversity, or MIMO capacity) of several designs compared in a representative, repeatable manner [93]-[95].

8.5. Example of multi-antenna terminals

The following example illustrates the analysis of compact arrays for MIMO systems in mobile communications terminals. In this case, three Inverted-F Antennas were used in the terminal. The aim of the antenna configuration was to combine different diversity techniques such as pattern, polarization and spatial diversity to reduce the correlation among transmit or receive signals. The simulation model of the multi-antenna terminal consists of a metallic block, representing the battery and the display of the device, and a PVC housing with a wall thickness of 2 mm, as displayed in Figure 71. As stated previously, the metallic block used as ground plane acts as part of the antenna system and will have a strong influence on the radiation patterns and the mutual coupling impedances. The whole device was simulated with a standard EM code based on method of moments. It allows calculating the pattern of the coupled antenna system as well as the mutual coupling and self impedances of the antennas, which serve as an input for the model of the MIMO transmission link given in [92].

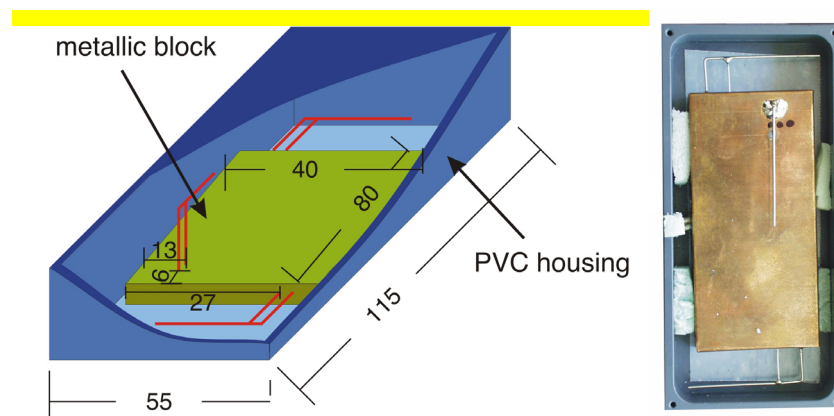


Figure 71: Multi-antenna terminal @2GHz. All measures are given in millimetres.

Figure 72 shows the antenna array used on the other side of the MIMO communications link. It consists of three $\lambda/2$ dipoles arranged along the sides of a triangle. A stochastic, full polarimetric, three dimensional and path-based indoor channel model was used for the simulations.

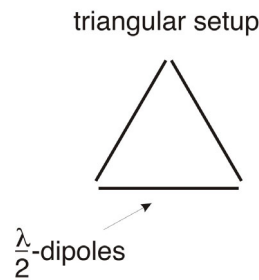


Figure 72: Antenna used on the opposite end of the link.

A larger reference MIMO system was used as reference. It was equipped with three vertical $\lambda/2$ -dipoles with $\lambda/2$ spacing between them on each side of the link. The array structure is presented in Figure 73.

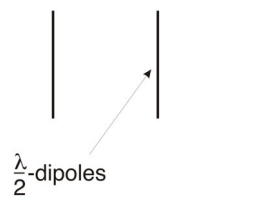


Figure 73: Antenna array used as reference.

Table 6 summarised the quality measures for the multi-antenna MIMO terminal described above and the reference system. Since the correlation is very low for both cases, the capacity for a constant SNR is equal. Yet, the capacity for a constant transmit power is different, due to the fact that the MEG and the transmission gain are worse for in the case of the terminal with the three Inverted F-antennas. This is due to mutual coupling and polarization mismatching effects. A detailed analysis of the MEGs of the single antennas has allowed optimising the small array.

Table 6: Quality measures for the antenna array in the multi-antenna terminal compared to three half-wavelength dipoles with $\lambda/2$ spacing

	10% outage capacity (SNR=10dB)	10% outage capacity ($P_1=const.$)	Max. power correlation at terminal	MEG for each antenna	50% transmission gain
Reference (3 dipoles)	7.5 bit/s/Hz	11.2 bit/s/Hz	0.1	-0.6 dB -0.6 dB -0.6 dB	-116.4 dB
Multi-antenna terminal (3 IFAs)	7.5 bit/s/Hz	10.6 bit/s/Hz	0.1	-2.4 dB -2.4 dB -2.5 dB	-121.2 dB

For the optimization of antenna arrays, which can be integrated into small handsets it is essential to take the propagation channel into account, as stated in section 8.3. This can be done by realistic channel models or by using data obtained by channel measurements processed in a way that it can be used in a field test. The performance of a MIMO array cannot be determined without treating it together with the propagation channel.

9. MEASUREMENTS OF SMALL TERMINAL ANTENNAS: STANDARDISATION ISSUES

A lot of effort is being devoted to the definition of accurate measurement setups and procedures, to fully characterise the radiation behaviour of user terminals for mobile communications. Although there is still no real standard, some recommendations have been issued by different institutions, and may be applied for the measurements. Here, two of them are presented.

9.1. CTIA measurements

CTIA-The Wireless Association™ is a US based international organization that serves the interests of the wireless industry by lobbying government agencies and assist with regulations [96]. CTIA has established a certification program for mobile phones, which includes radiated performance testing. A working group including operators, mobile phone manufacturers, and test equipment vendors, are evolving a detailed test plan. The most recent release of this is reference below is [97].

According to the test plan, the total transmit power (TRP) and total integrated sensitivity (TIS) are obtained by full sphere radiated measurements in an anechoic chamber. The test setup includes a base station emulator which is used to establish a call to the mobile phone inside the anechoic environment. For transmit, the mobile's effective isotropic radiated power (EIRP) can be recorded as a function of the direction of radiation using an narrow band power measurement device. For receive, the base station emulator is used to record the receiver sensitivity as a function of angle of arrival. Integration of the EIRP and the Sensitivity over the full sphere yields the TRP and TIS, respectively.

An important contribution of this test plan is the level of detail dedicated to the evaluation of measurement uncertainty. For example, the test plan presents a required procedure to accurately characterize the chamber quiet zone by ripple testing with dipoles and loop antennas. Also guidelines are given to establish a comprehensive measurement uncertainty budget for the laboratory.

The current version test plan focuses on the standards and frequency bands that are currently in use in the US. However, the method and procedures are equally applicable to other standards and frequency bands. A summary of some of the measurement parameters are shown in Table 7.

Table 7: Measurement parameters according to CTIA standard.

	Measurement Parameters	Angular Sample Spacing	Test Configurations
Mobile Station Transmit	EIRP, TRP, NHRP	15° in θ and ϕ	Free Space, Phantom Head (Left + Right Ear)
Mobile Station Receive	Sensitivity, TIS	30° in θ and ϕ	Free Space, Phantom Head (Left + Right Ear)

9.2. *COST273/SWG2.2 activities*

In the frame of the COST 273 (COoperation européenne dans le domaine de la recherche Scientifique et Technique) [98]-[99], there is a Sub-Working Group 2.2 (SWG) dealing with “Antenna performance of Small Mobile terminals”.

The aim of this SWG 2.2 is to establish measuring techniques for antennas on small mobile terminals as well as establishing performance relations by including information from the propagation environment where the terminals are used. The groups are investigating how to make reliable measurements of mobile phones including the transmitter and the receiver as well as the influence from the user. Methods for including the influence of the propagation channel are based on the Mean Effective Gain (MEG) and special focus is on UMTS terminals.

One of the main achievements is a document that describes the methods to be used in order to assess the radio performances of the 3G user equipment/mobile stations (UE/MS) in active mode in both the up- and the downlink. The test procedure is based on the test method developed as a result of COST 273 SWG 2.2 members’ contributions. Background work has also been made in the former COST259 project.

This measurement procedure applies only to UE/MS used under the “speech mode” conditions that correspond to predefined positions for voice application when the handset is held close to the user’s head. This method is also applicable to free space measurements.

The testing methodology applies to any 3G handset, with internal or external antenna, that supports the speech mode. It is also applicable to the testing of dual-mode (GSM / UMTS) terminals.

The radio tests considered here are:

1. The measurement of the radiated output power
2. The measurement of the radiated sensitivity

The purpose of this work is to serve as a standard test procedure for radio performance testing of mobile terminals. It is the intention that this procedure is going to be used by test houses, network operators, mobile terminal and antenna manufacturers, research institutes etc. The motivation for the development of this document is the lack of standards in this area in 3GPP. COST 273 SWG2.2 has reported the progress of the pre-standardization in several 3GPP RAN4 meetings.

The major parts of this test procedure are based on the 3-D pattern measurement method. It has been considered necessary to define some items and components in the test procedure in detail, such as test channels and phantom set-ups, in order to make the testing in different laboratories harmonized. The procedure is, however, not limited to some specific antenna chambers or positioners, but just gives examples of systems that are presently available. Moreover, the pre-standard is open for the use of some alternative to the 3-D pattern measurement method, provided that the specified performance parameters and the total measurement uncertainty can be achieved with the test method. In the first phase the pre-standard uses TRP (Total Radiated Power) and TRS (Total Radiated Sensitivity) as the performance parameters but it is also prepared for the use of Mean Effective Gain (MEG) or Mean Effective Radiated Power (MERP) and its corresponding parameter Mean Effective Radiated Sensitivity (MERS) for the receiver performance as the preferred performance parameter in a later stage.

10. CONCLUSIONS

In this document, a review of the state of the art of small terminal antenna design was carried out. This included an overview of the frequency bands considered, and the requirements for this kind of devices, regarding antenna behaviour. The main problems and factors that influence the design have also been analysed. These include the effect of the geometry of the terminal, its different elements, the environment and the user himself.

A review was also made of the different technologies that can be used for implementing terminal antennas. Different examples were also displayed, as well as the current and future requirements for their performance in real life. Finally, some aspects regarding the measurement of such antennas were also analysed.

This report will be used as basis to explore new possibilities in the design of small terminal antennas, which should lead to a better understanding of future trends for mobile terminals.

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ANNEX: PROFICIENCY OF THE PARTNERS

In this annex, a summary of the questionnaires filled by the partners is displayed. The aim was to gain an insight on their proficiency in the area of small terminal antennas and their current research activities. All the partners involved in WP2.2-1 and WP2.2-2 participated in this inventory, which also reviews the existing measurement facilities available for the benchmarking activities of WP 2.2-2.

1. CHALMERS UNIVERSITY OF TECHNOLOGY (CHALMERS)

1. Institution

Chalmers University of Technology
Department of Electromagnetics - Antenna Group
SE - 412 96 Gothenburg, Sweden
WEB site <http://www.elmagn.chalmers.se/elmagn/antenna/>

2. Technical proficiency

1. Standards

Mobile standards:

- GSM family (GSM/DCS/PCS)
- UMTS
- DECT
- CDMA

Wireless standards

- WLAN
- Bluetooth

Other applications

- Satellite positioning
- Satellite communication
- UWB

2. Simulation tools:

Commercial packages

- WIPL-D
- FemLab
- HFSS
- QuickWave 3D

Self-developed

- PCB-MoM (MoM program for printed circuit boards)
- Wire-MoM (MoM program for thin wire structures)
- G1DMULT (for modeling reverberation chamber)
- G3DCavity (for modeling reverberation chamber)

3. Prototyping

Technology

Anything that can be made by a workshop

Capacity/Volume/Cost

Single prototypes only

4. Measurements facilities

Matching:	Network analyzer up to 20 GHz
Gain and Directivity:	Indoor test range 4 m down to about 1 GHz, and outdoor test rang 24 m.
Efficiency :	Reverberation chamber from 800 MHz and up.
Human interaction:	Head and hand phantoms.
SAR:	No

3. Research

1. Staff

Number of persons involved:

12

Number of post-graduate students involved

7

Number of PhDs:

5

2. List of PhDs:

Prof Kildal, Prof Carlsson, Dr Yang, Dr Sipus, Dr Skobelev

3. List of publications:

The following publications related to measurements in reverberation chamber:

1. K. Rosengren, P-S. Kildal, "Characterization of antennas for mobile and wireless terminals in reverberation chambers : Improved accuracy by platform stirring", Microwave and Optical Technology Letters, 20 September 2001 (K. Rosengren is with Flextronics Design, Kalmar)
2. K. Rosengren, P-S. Kildal, "Study of distributions of modes and plane waves in reverberation chambers for characterization of antennas in multipath environment", Microwave and Optical Technology Letters, 20 September 2001 (K. Rosengren is with Flextronics Design, Kalmar)
3. P-S. Kildal, C. Carlsson, J. Yang, "Measurement of free space impedances of small antennas in reverberation chambers", Microwave and Optical Technology Letters, Vol 32, No 2, pp112-115, January 2002 (C. Carlsson is with Bluetest AB)
4. P-S. Kildal, K. Rosengren, J. Byun, J. Lee, "Definition of effective diversity gain and how to measure it in a reverberation chamber", Microwave and Optical Technology Letters, Vol. 34, No 1, pp. 56-59, July 5, 2002. (J. Byun and J. Lee is with Samsung, South Korea)
5. P-S. Kildal, C. Carlsson, "Detection of a polarization imbalance in reverberation chambers and how to remove it by polarization stirring when measuring antenna efficiencies", Microwave and Optical Technology Letters, Vol. 32, No 2, pp. 145-149, July 20, 2002 (C. Carlsson is with Bluetest AB)
6. M. Bäckström, O. Lundén, P-S. Kildal, "Reverberation chambers for EMC susceptibility and emission analyses", Review of Radio Science 1999-2002, pp. 429-452. (Bäckström and Lundén are with Swedish Defense Research Center, FOI, Linköping)
7. P-S. Kildal, K. Rosengren, "Electromagnetic analysis of effective and apparent diversity gain of two parallel dipoles", IEEE Antennas and Wireless Propagation Letters, Vol. 2, No. 1, pp 9-13, 2003 (K. Rosengren is with Flextronics Design, Kalmar)

8. U. Carlberg, P.-S. Kildal, A. Wolfgang, O. Sotoudeh, C. Orlenius, "Calculated and measured absorption cross sections of lossy objects in reverberation chamber", to appear in IEEE Transactions on Electromagnetic Compatibility, May 2004.

Plus a number of conference papers on similar topics. The following are not covered by the articles above:

IEEE AP-S International Symposium, Columbus, Ohio, June 2003

1. A. Wolfgang, C. Orlenius and P.-S. Kildal, "Measuring output power of Bluetooth devices in a reverberation chamber" (Orlenius is with Bluetest AB).
2. A. Wolfgang, J. Carlsson, C. Orlenius and P.-S. Kildal, "Improved procedure for measuring efficiency of small antennas in reverberation chambers" (Orlenius is with Bluetest AB).
3. C. Orlenius, N. Serafimov and P.-S. Kildal, "Procedure for measuring radiation efficiency in downlink band for active mobile phones in a reverberation chamber" (Orlenius is with Bluetest AB).

IEEE AP-S International Symposium, Monterey, California, June 2004

1. K. Rosengren, P. Bohlin and P.-S. Kildal, "Multipath characterization of antennas for MIMO systems in reverberation chamber including effects of coupling and efficiency" (P. Bohlin is with the Dept. of Signals and Systems, Chalmers Univ. of Technol.).
2. M. Lundmark, R. Serrano Calvo, P.-S. Kildal and C. Orlenius, "A solid hand phantom for mobile phones and results of measurements in reverberation chamber" (M. Lundmark and C. Orlenius are with Bluetest AB).
3. R. Bourhis, C. Orlenius, G. Nilsson, S. Jinstrand and P.-S. Kildal, "Measurements of realized diversity gain of active DECT phones and base-stations in a reverberation chamber" (Nilsson and Jinstrand are with Ascom Tateco AB).
4. P.-S. Kildal and K. Rosengren, "Electromagnetic characterization of MIMO antennas including coupling using classical embedded element pattern and radiation efficiency".
5. R. Olsson, P.-S. Kildal and S. Weinreb, "A novel low-profile log-periodic ultra wideband feed for the dual-reflector antenna of US-SKA" (Weinreb is with California Inst. of Technol.).

4. List of patents:

1. P.-S. Kildal, "A method and an apparatus for measuring the performance of antennas, mobile phones and other wireless terminals", International Patent Application No. PCT/SE01/00422, 31 March 2000.
2. P.-S. Kildal, "Broadband multi-dipole antenna with frequency-independent radiation characteristics", Swedish Patent Application No. 0302175-5, 7 August 2003.

5. List of research projects:

1. Characterization of antennas for mobile terminals
2. UWB antenna feed for US SKA project.

4. Products

Participation in industrial products: Cooperation with Bluetest AB in connection with commercialization of method for measuring antennas and mobile terminals in reverberation chamber.

2. HELSINKI UNIVERSITY OF TECHNOLOGY (HUT)

1. Institution:

Helsinki University of Technology
IDC SMARAD/Radio Laboratory
Otakaari 5A, FI-02150 Espoo,
PO Box 3000, FI-02015 HUT
Finland
WEB site: www.hut.fi/Units/Radio

2. Technical proficiency

1. Standards

Mobile standards:

- | | |
|----------------------------|-----|
| - GSM family (GSM/DCS/PCS) | yes |
| - UMTS | yes |
| - DVB-T | yes |

Wireless standards

- | | |
|-------------|-----|
| - WLAN | yes |
| - Bluetooth | yes |

Other applications

- | | |
|----------|-----|
| - UWB | yes |
| - 60-GHz | yes |

2. Simulation tools:

Commercial packages

- XFDTD (Remcom Inc)
- IE3D (Zeland Inc)
- HFSS (Agilent Inc)
- SEMCAD (SPEAG)
- FEKO (EM Software&Systems)

3. Prototyping

Technology

PCB, manual assembly

Capacity/Volume/Cost

very small capacity, high cost

4. Measurements facilities

Matching:	4 Agilent Vector Network Analyzers
Gain and Directivity:	<ul style="list-style-type: none">- large anechoic chamber for 2 - 200 GHz- small anechoic chamber for 0.8 - 5 GHz
Efficiency (& radiated power)	<ul style="list-style-type: none">- several Wheeler Caps- same 2 anechoic chambers as above- 64-channel multi-probe antenna measurement system- Measurement-Based Antenna Test System (MEBAT)- Spectrum analyzers, Test receivers
Human interaction:	Planar phantom and SAM-head phantom with brain tissue simulating liquids (900/1800 MHz ranges)
SAR:	In-house SAR and 3-D near-field-scan setup DASY4 SAR and 3-D near-field-scan setup

3. Research

1. Staff

Number of persons involved: 7

Number of post-graduate students involved: 3

Number of PhDs: 2

2. *List of PhDs:*

- Clemens Icheln
- Pertti Vainikainen

3. *List of publications:*

1. O. Kivekäs, J. Ollikainen, P. Vainikainen: Wideband dielectric resonator antenna for mobile phones, *Microwave and Optical Technology Letters*, Vol. 36, No. 1, January 2003, pp. 25-26.
2. K. Sulonen, P. Suvikunnas, L. Vuokko, J. Kivinen, P. Vainikainen: Comparison of MIMO antenna configurations in picocell and microcell environments, *Journal on Selected Areas in Communications*, Vol. 21, No. 5, 2003, pp. 703-712.
3. O. Kivekäs, J. Ollikainen, T. Lehtiniemi, P. Vainikainen: Effect of the chassis length on the bandwidth, SAR, and efficiency of internal mobile phone antennas, *Microwave and Optical Technology Letters*, Vol. 36, No. 6, 2003, pp. 457-462
4. K. Sulonen, P. Vainikainen: Performance of mobile phone antennas including effect of environment using two methods. *IEEE Transactions on Instrumentation and Measurement*, Vol. 52, No. 6, December 2003, pp.1859-1864.
5. C. Icheln, J. Krogerus, P. Vainikainen: Use of baluns in small-antenna radiation measurements, *IEEE Transactions on Instrumentation and Measurement*, Vol. 53, No. 2, April 2004.
6. P. Vainikainen, "Antennas for Terrestrial Mobile Communications", Sec. 21-25 in J.D.Kraus, R. Marhefka (ed.), *Antennas for All Applications*, 3rd ed., McGraw-Hill, 2002, 6/928 p.
7. O. Kivekäs, J. Ollikainen, T. Lehtiniemi, P. Vainikainen: Bandwidth, SAR, and efficiency of internal mobile phone antennas, accepted for publication in *IEEE Transactions on Electromagnetic Compatibility*

... and many publications in high level international conferences

4. *List of patents:*

1. J. Ollikainen, P. Vainikainen, *Broadband antenna realized with shorted microstrips*, United States Patent, No. 6,008,764, Dec. 28, 1999.
2. J. Ollikainen, O. Kivekäs, P. Vainikainen: *Tunable patch antenna for wireless communication terminals*, US Patent 6650295, November 18, 2003.
3. J. Ollikainen, P. Vainikainen: *Oikosuljetuilla mikroliuskoilla toteutettu laajakaista-antenni* (Broadband antenna realized with shorted microstrips), Pat. FI110395 B, Appl. 971235, 25.03.1997, (15.1.2003), 22 p.
4. J. Ollikainen, O. Kivekäs, I. Kelder, P. Vainikainen: *Radiolaitteen modulaarinen kytkentärakenne ja kannettava radiolaitte* (Modular coupling structure for portable radio devices and portable radio device), accepted Finnish Pat., Appl. 20002529, 17.11.2000, (2004), 13 p. + 8 drawings.

5. *List of research projects:*

Several projects in the field of terminal-antenna development and evaluation

4. *Products*

Participation in industrial products: N/A

3. IHE UNIVERSITÄT KARLSRUHE (UKARL)

1. Institution

Institut für Höchstfrequenztechnik und Elektronik
Kaiserstrasse 12
76128 Karlsruhe
WEB site <http://www.ihe.uni-karlsruhe.de/>

2. Technical proficiency

1. Standards

Mobile standards:

GSM family (GSM/DCS/PCS)
UMTS
UWB

Wireless standards

WLAN
Bluetooth

Other applications

MIMO
ACC
SRR
radar sensing

2. Simulation tools:

Commercial packages

ADS (Agilent)
Ansoft Designer
Momentum (ADS)
HFSS (Ansoft)
FEKO

Microwave Studio

Self-developed

ARRAY

MPATCH 6.0

3. Prototyping

Technology

Etching and illumination

Capacity/Volume/Cost

Not on focus of the institute

4. Measurements facilities

Matching:	Network analyzers HP8510C, HP8530A, HP8722D and Agilent E8357A
Gain and Directivity:	Anechoic Chamber (EMC-Measurements)
Efficiency :	
Human interaction:	Only with the use of the anechoic chamber
SAR:	

3. Research

1. Staff

Number of persons involved:

10 Persons

Number of post-graduate students involved

9 Persons

Number of PhDs:

9 Persons

2. List of PhDs:

List of participants in A2.1, Small Terminal, only:

Christiane Kuhnert, Karin Schuler, Stephan Schulteis, Christian Waldschmidt

3. List of publications:

(only publications from 2003 and the participants in A2.1)

1. C. Waldschmidt, C. Kuhnert, S. Schulteis and W. Wiesbeck, "Compact MIMO-arrays based on Polarisation Diversity", *IEEE International Symposium on Antennas and Propagation*, pp. 499-502, Columbus, USA, 2003
2. C. Waldschmidt, W. Sörgel, F. Pivit and W. Wiesbeck, "Broadband Multimode Antennas for MIMO Applications", *IEEE International Symposium on Antennas and Propagation*, volume 2, pp. 511-514, Columbus, USA, 2003
3. C. Waldschmidt, C. Kuhnert, W. Sörgel and W. Wiesbeck, "MIMO Antennas in Small Handheld Devices?", *Internationales Wissenschaftliches Kolloquium Ilmenau*, CD-ROM, ISSN 0943-7207, Ilmenau, 2003
4. C. Kuhnert, C. Waldschmidt, S. Schulteis, W. Wiesbeck, "Simulation and Measurements of MIMO Systems with Pattern and Polarization Diversity," *Internationales Wissenschaftliches Kolloquium Ilmenau*, CD-ROM, ISSN 0943-7207, Ilmenau, 2003
5. C. Waldschmidt, C. Kuhnert, W. Sörgel and W. Wiesbeck, "Options for the Integration of Arrays for MIMO into Handhelds", *Proceedings of the International Conference on Electromagnetics in Advanced Applications*, pp. 767-770, Torino, Italy, 2003
6. C. Kuhnert, C. Waldschmidt, S. Schulteis, W. Wiesbeck, "Animations and Movies in Antenna Lectures," *Proceedings of the International Conference on Electromagnetics in Advanced Application*, pp. 767-770, Torino, Italy, September 2003
7. W. Sörgel, S. Schulteis, W. Wiesbeck, "Transient Radiation of Ultra Wideband Antennas for Radio Links", *International Conference on Electromagnetics in Advanced Applications*, pp. 257-258, Torino, Italy, Sept. 2003
8. Y. Venot, K. Schuler, W. Wiesbeck, Tapered Slot Antenna for LTCC Multilayer Substrate Integration in mm-Wave Applications, *INICA-2003, Proceedings ITG-Conference on Antennas*, Berlin, Germany, September 17-19, 2003
9. S. Schulteis, C. Waldschmidt, C. Kuhnert und W. Wiesbeck, "Design of a Capacitively Loaded Inverted F Antenna for Wireless-LAN Applications", *Proceedings International ITG-Conference on Antennas*, no. 178, pp. 187-190, Berlin, Germany, September, 2003
10. C. Waldschmidt, C. Kuhnert, T. Fügen and W. Wiesbeck, "Realistic Antenna Modelling for MIMO Systems in Microcell Scenarios", *Kleinheubacher Berichte*, Miltenberg, 2003
11. C. Waldschmidt and W. Wiesbeck, "MIMO Antennas for Small Handheld Devices", *PIERS*,

- p. 250, Honolulu, Hawaii, USA, 2003
12. C. Waldschmidt, C. Kuhnert, T. Fügen and W. Wiesbeck, "Measurements and Simulations of compact MIMO systems based on Polarization Diversity", *IEEE Topical Conference on Wireless Communications*, Honolulu, Hawaii, USA, 2003
 13. C. Waldschmidt, C. Kuhnert, S. Schulteis and W. Wiesbeck, "Analysis of compact Arrays for MIMO based on a complete RF system model", *IEEE Topical Conference on Wireless Communications*, Honolulu, Hawaii, USA, 2003
 14. K. Schuler, Y. Venot, W. Wiesbeck, „Innovative Material Modulation for Multilayer LTCC Antenna Design at 76.5 GHz in Radar and Communication Applications", *Proceedings of the Conference Proceedings European Microwave Conference*, München, Germany, Oktober, 2003

4. List of patents:

None

5. List of research projects:

Mostly industry projects

4. Products

Participation in industrial products:

Volume:

None

- <5 000 units
- >5 000 units
- >50 000 units
- >500 000 units

4. IMST GMBH (IMST)

1. Institution

IMST GmbH
Department of Antennas & EM Modelling
Carl-Friedrich-Gauss-Str. 2
D-47475 Kamp-Lintfort
Germany
WEB site: www.imst.com

2. Technical proficiency

1. Standards

Mobile standards:

- GSM family (GSM/DCS/PCS) yes
- UMTS yes

Wireless standards

- WLAN yes
- Bluetooth yes

Other applications

- UWB yes
- GPS

2. Simulation tools:

Commercial packages

- Empire (IMST)
- Ansoft Designer
- Concept (U. Hamburg)

3. Prototyping

Technology

- NdYAG-Laser with conversion software (input as DXF files)
- Etching: Metallic patches on PCB antennas. Hard and flexible substrates, including PTFE.

- LTCC prototyping: multilayer ceramic structures

Capacity/Volume/Cost

- Laser cut antennas:
 - o Initial work: ≈ 0.5 -1h
 - o Per antenna: ≈ 0.2 -0.5h (depends on complexity)
 - o Up to ≈ 30 units. Over 30, outsourced.
- Etching (metallic patches and PCB antennas)
 - o 10 units: ≈ 2 h
 - o 100 units: ≈ 8 h
 - o Processing time must include film preparation (normally, external)
 - o Outsourcing for large amounts (over 100), or special necessities: vias, surface processing or varnish.

4. Measurements facilities

Matching:	2 Vector Network Analyzers (HP8719, R&S)
Gain and Directivity:	- large anechoic chamber for 400MHz - 100 GHz (6x8x12) - small anechoic chamber for 0.8 - 5 GHz
Efficiency (& radiated power):	- Wheeler Caps - same 2 anechoic chambers as above
Human interaction:	SAM-head phantom with brain-tissue simulating liquids (900/1800 MHz ranges)
SAR:	- In-house SAR and 3-D near-field-scan setup - DASY4 SAR and 3-D near-field-scan setup

3. Research

1. Staff

Number of persons involved: 6

Number of post-graduate students involved: 1

Number of PhDs: 3

2. List of PhDs:

1. Dirk Manteuffel: "Analyse und Synthese von integrierten Antennen für Mobiltelefone unter besonderer Berücksichtigung des Benutzereinflusses" (Analysis and synthesis of antennas for mobile telephones, taking into account the effect of the user), gerhard Mercator-Universität, Duisburg, Germany, 2002, ISBN 3-8322-0976-X.
2. Matthias Geissler: "Neue Modelle und verbesserte Methoden für Entwurf und Charakterisierung von Antennen für Mobiltelefone" (new models and improved methods for the design and characterisation of antennas for mobile telephones), Universität Duisburg-Essen, Germany, July 2003, ISBN 3-8322-2571-4.
3. Marta Martínez-Vázquez: "Antenas integradas para terminals móviles de tercera generación" (Integrated antennas for 3G mobile terminals), Universidad Politécnica de Valencia, Spain, July 2003, ISBN 8468840475.

3. List of publications:

1. D. Manteuffel, H. Rösmann, 'Entwicklung einer Inverted-F-Antenne für Transponderanwendungen mit dem FDTD-Verfahren', *1. Öffentliches Statusseminar „Energieautarke Mikrosysteme“ AUTARK*, Kamp-Lintfort, 1997.
2. M. Geissler, "Neue Entwicklungen bei Handyantennen", *Funkschau* 15/97, München, Germany, 1997.
3. S. González García, L. Baggen, D. Manteuffel, D. Heberling, 'Study of coplanar waveguide-fed antennas using the FDTD method', *Microwave Opt. Tech. Lett.*, vol.19, no. 3, pp. 173-176, 1998
4. M. Geissler, D. Heberling, "An Optimised Antenna for Mobile Phones", *IEEE Antennas and Propagation Society Symposium*, Atlanta, USA, 1998.
5. L. Baggen, D. Manteuffel, S. González García, D. Heberling, 'Antennendesign und FDTD-Simulationen: Theorie und Messung', *ITG Fachtagung Antennen*, pp. 123-128, Munich (Germany), 1998.
6. M. Geissler, D. Heberling, "Eine optimierte Antenne für Handys", *ITG Fachtagung Antennen*, pp.317-322, Munich (Germany), 1998.
7. S. González, L. Baggen, D. Manteuffel, D. Heberling, 'Study of coplanar fed antennas using the FDTD method', *Proc. PIERS*, p. 45, Nantes, 1998.
8. D. Heberling, M. Geissler "Trends on Handset Antennas, *European Microwave Week*, Munich, Germany, 1999.
9. M. Martínez-Vázquez and D. Sánchez-Hernández, 'Integrated Antennas for Mobile Communication Handsets', *COST 259 Meeting on Wireless Flexible Personalized Communications*, Valencia (Spain), 2000.

10. D. Manteuffel, A. Bahr, I. Wolff, 'Investigation on integrated antennas for GSM mobile phones', *AP2000 – Conference on Antennas and Propagation*, Davos (Switzerland), 2000.
11. A. Bahr, M. Schneider, D. Manteuffel, D. Heberling, 'Recent trends for mobile phone antennas with special emphasis to interaction with the user', *AP2000 – Conference on Antennas and Propagation*, Davos (Switzerland), 2000.
12. M. Geissler, D. Heberling, I. Wolff, "Properties of integrated handset antennas", *AP2000 – Conference on Antennas and Propagation*, Davos (Switzerland), 2000.
13. M. Geissler, D. Heberling, I. Wolff, "Bandwidth and radiation properties of internal handset antennas", *IEEE Antennas and Propagation Society Symposium*, Salt Lake City, USA, 2000
14. M. Martínez-Vázquez, M. Geissler, D. Heberling and D. Sánchez-Hernández, 'Recent Developments in Antenna Design for Personal Communications Handsets at the IMST', *COST 260 Meeting on Smart Antennas*, Rennes (France), 2000.
15. M. Martínez-Vázquez, M. Geissler, D. Heberling and D. Sánchez-Hernández, 'Dualband Spurline-Antenne für Handys', *ITG Diskussionssitzung: Antennen für mobile Systeme*, Starnberg (Germany), 2000.
16. M. Geissler, M. Martínez-Vázquez, D. Manteuffel, D. Heberling e I. Wolf, 'Bandbreitenuntersuchungen an integrierten Handyantennen', *ITG Diskussionssitzung: Antennen für mobile Systeme*, Starnberg (Germany), 2000.
17. D. Manteuffel, A. Bahr, D. Heberling, I. Wolff, 'Wirkung der Gehäuseabmessungen auf integrierte Antennen in kleinen Mobilfunktelefonen', *ITG Diskussionssitzung: Antennen für Mobile Systeme*, Starnberg (Germany), 2000.
18. A. Martínez-González, M.A. Sánchez-Aguilar, M. Martínez-Vázquez and D. Sánchez-Hernández, 'A Comparison of Dual-Band Spur-Line Printed Antennas for Hand-Held Handsets', *Microwave and Optical Technology Letters*, 2001, vol. 30, n° 3, pp. 205-207.
19. D. Manteuffel, A. Bahr, D. Heberling, I. Wolff, 'Design considerations for integrated mobile phone antennas', *ICAP – International Conference on Antennas and Propagation*, pp. 252-256, Manchester (UK), 2001
20. M. Martínez-Vázquez, M. Geissler and D. Heberling, 'Advanced Antenna Concepts for PCS Handsets', *COST 260 Meeting on Smart Antennas*, Gothenburg (Sweden), 2001.
21. D. Manteuffel, A. Bahr, P. Waldow, I. Wolff, 'Numerical analysis of absorption mechanisms for mobile phones with integrated multiband antennas', *IEEE Antennas and Propagation Society Symposium*, Boston (Massachusetts, USA), July 2001.
22. M. Martínez-Vázquez, M. Geissler and D. Heberling, 'Volume Considerations in the Design of Dual-Band Handset Antennas', *IEEE Antennas and Propagation Society Symposium*, Boston (Massachusetts, USA), July 2001.
23. M. Geissler, M. Gehrt, D. Heberling, P. Waldow, I. Wolff, „Investigations on radiation Q of integrated handset antennas”, *IEEE Antennas and Propagation Society Symposium*, Boston (Massachusetts, USA), July 2001.
24. M. Martínez-Vázquez, M. Geissler and D. Heberling, 'Volume Reduction of Integrated Handset Antennas', *16th International Conference on Applied Electromagnetics and Communications*, Dubrovnik (Croatia), October 2001.
25. M. Martínez-Vázquez, M. Geissler, D. Heberling and D. Sánchez-Hernández, 'Compact

- Dual-Band Antenna for Mobile Handsets', 2002, *Microwave and Optical Technology Letters*, vol. 32, n° 2, pp. 87-88.
26. D. Manteuffel, A. Bahr, Chr. Bornkessel, F. Gustrau, I. Wolff, 'Fundamental aspects for the design of low-SAR mobile phones', *IEE AMS-2002 – Technical Seminar on Antenna Measurement and SAR*, pp. 25/1-25/5, Loughborough (UK), 2002
 27. M. Martínez-Vázquez and O. Litschke, 'Novel Triple-Band Antennas for Personal Communications Handsets', *IEEE Antennas and Propagation Society Symposium*, San Antonio (Texas, USA), June 2002.
 28. E. Suárez-Pejenaute, R. Baggen and M. Martínez-Vázquez, 'Antenas Integradas para Aplicaciones Bluetooth sobre Substrato LTCC', *Simposium Nacional de la URSI*, Alcalá de Henares (Spain), September 2002.
 29. M. Martínez-Vázquez and O. Litschke, 'Design Considerations for Quad-Band Antennas Integrated in Personal Communications Devices', *Journées Internationales de Nice sur les Antennes*, Nice (France), November 2002.
 30. E. Suárez-Pejenaute, R. Baggen and M. Martínez-Vázquez, 'Integrated Antennas on LTCC Substrate for Bluetooth Applications', *Journées Internationales de Nice sur les Antennes*, Nice (France), November 2002.
 31. M. Martínez-Vázquez, O. Litschke and D. Heberling, 'Design of Integrated Multiband Antennas for Personal Communications Handsets', *COST 284 Meeting on Innovative Antennas for Emerging Terrestrial & Space-based Applications*, Budapest (Hungary), 2003.
 32. D. Manteuffel, D. Heberling, 'Innovationen in der Antennenentwicklung für Mobiltelefone unter Berücksichtigung des Benutzereinflusses', *8. ITG Fachtagung „Mobilfunk – Stand der Technik und Zukunftsperspektiven*, pp. 131-136, Osnabrück, 2003.
 33. D. Manteuffel, 'Design of Multiband Antennas for the Integration in Mobile Phones with Optimized SAR', *IEEE Antennas and Propagation Society Symposium*, Columbus (Ohio, USA), June 2003.
 34. Geissler, M., Litschke, O., Heberling, D., Waldow, P., Wolff, I., 'An improved method for measuring the radiation efficiency of mobile devices', *Antennas and Propagation Society International Symposium*, 2003 IEEE, Volume: 4, 22-27 June 2003.
 35. M. Martínez-Vázquez and O. Litschke, 'Quadband Antenna for Handheld Personal Communications Devices', *IEEE Antennas and Propagation Society Symposium*, Columbus (Ohio, USA), June 2003.
 36. M. Geissler, O. Litschke, D. Heberling, P. Waldow, I. Wolff, 'An Improved Method for Measuring the Radiation Efficiency of Mobile Devices', *IEEE Antennas and Propagation Society Symposium*, Columbus (Ohio, USA), June 2003.
 37. M. Martínez-Vázquez and O. Litschke and D. Heberling, 'Design of a Quadband Antenna System for PCMCIA', *International ITG Conference on Antennas*, Berlin (Germany), September 2003.
 38. D. Manteuffel, D. Heberling, I. Wolff, 'EM User Interaction – Consideration for the Design of Mobile Phones', *International ITG Conference on Antennas*, Berlin (Germany), September 2003.
 39. M. Geissler, O. Litschke, A. Winkelmann, D. Heberling, P. Waldow, 'Accurate

- Measurement characterisation of mobile terminal antennas”, *International ITG Conference on Antennas*, Berlin (Germany), September 2003.
40. O. Litschke, M. Geissler, D. Heberling, P. Waldow, “Adaption of the Wheeler Cap Method for Measuring the efficiency of mobile handset antennas”, *International ITG Conference on Antennas*, Berlin (Germany), September 2003.
 41. D. Heberling, M. Geissler, O. Litschke and M. Martínez-Vázquez, ‘Improved Radiation Efficiency of Mobile Systems and Application to a Novel Multiband Antenna’, *International Microwave and Optoelectronics Conference*, Iguazú (Brasil), September 2003.
 42. D. Manteuffel and M. Martínez Vázquez, ‘Conception d’antennes et simulation électromagnétique à l’IMST’, *Reunion du GDR "Ondes" du CNRS, "Antennes miniatures multistandards"*, Paris (France), 2003.
 43. M. Martínez-Vázquez and O. Litschke, ‘Small Multiband Antenna for Personal Communications Devices’, *17th International Conference on Applied Electromagnetics and Communications*, Dubrovnik (Croatia), October 2003.
 44. D. Manteuffel, ‘A concept to minimize the user interaction of mobile phones’, *IEE AMS-2004 – Technical Seminar on Antenna Measurement and SAR*, Loughborough (UK), May 2004.
 45. M. Martinez-Vazquez, D. Manteuffel and O. Litschke, ‘Performance of multiband handset antennas in the presence of a human user’ (invited paper), *2004 URSI International Symposium on Electromagnetic Theory*, Pisa (Italy), May 2004.
 46. M. Martínez-Vázquez and O. Litschke, ‘PCMCIA Multi-Standard Antenna for Laptops’, *Joint COST 273/284 Workshop on Antennas and Related System Aspects in Wireless Communications*, Gothenburg (Sweden), June 2004.
 47. M. Martínez-Vázquez and O. Litschke, ‘Design of a Multi-Standard Antenna System for PCMCIA’, *IEEE Antennas and Propagation Society Symposium*, Monterey (California, USA), June 2004.
 48. M. Martínez-Vázquez, O. Litschke, D. Heberling and D. Sánchez-Hernández, ‘On the Design of Integrated Multiband Antennas for Personal Communications Handsets’, *Submitted to IEE Proceedings*.

4. List of patents:

1. D. Manteuffel, A. Bahr, J. Baro, "Integrierte Antenne für Mobilfunktelefone" (Integrated antenna for mobile telephones), publication N°. DE100 22 107.6, Deutschen Patent- und Markenamt, 2000.
2. A. Bahr, D. Manteuffel, J. Baro, "Antennenanordnung für Mobiltelefone", (Antenna arrangement for mobile telephones), publication N° DE100 50 902.9, Deutschen Patent- und Markenamt, 2000.
3. A. Bahr, D. Manteuffel, J. Baro, "Antennenanordnung für Mobilfunktelefone", (Antenna arrangement for mobile telephones), publication N° DE100 29 733.1, Deutschen Patent- und Markenamt, 2000.
4. M. Geissler, A. Winkelmann, M. Böttcher, “Verfahren zum Messen einer Funkeinheit und Funkeinheit”, publication N° DE100 55 266.8, Deutschen Patent- und Markenamt, 2000.

5. D. Manteuffel, "Integrierte Dreiband-Antenne", (Integrated triple band antenna). publication N° DE10137946.3, Deutschen Patent- und Markenamt, 2001
6. M. Martinez-Vazquez and M. Geissler, 'Planare Mobilfunkantenne' (Planar antenna for mobile communications), publication N° DE 100 54 192, Deutschen Patent- und Markenamt, Germany, 2002.
7. A. Bahr, D. Manteuffel, J. Baro, "Integrated antenna for mobile telephones", publication N° US 6,473,044, United States Patent, Assignee: Alcatel; 2002.
8. M. Geissler and M. Martinez-Vazquez, 'Mehrbandantenne mit parasitären Strahlern' (Multiband antenna with parasitic radiator), publication N° DE 10204079 A, Deutschen Patent- und Markenamt, Germany, 2003.
9. M. Geissler, M. Martinez-Vazquez and A. Winkelmann, 'Antenne mit geneigter Strahlerfläche' (Antenna with inclined radiating surface), publication N° DE10331281, Deutschen Patent- und Markenamt, 2004
10. A. Bahr, D. Manteuffel, J. Baro, "Antenna arrangement for mobile radiotelephones", publication N° US 6,542,126, United States Patent; Assignee: Alcatel; 2003.

5. *List of research projects:*

- Several projects in the field of terminal-antenna development and evaluation.
- Cooperation with IMS Connector-Systems for the design and fabrication on antennas for mobile applications

4. *Products*

Participation in industrial products: Yes

Volume:

- | | |
|------------------|-----|
| - <5 000 units | Yes |
| - >5 000 units | Yes |
| - >50 000 units | Yes |
| - >500 000 units | Yes |

5. INSTITUTO SUPERIOR TÉCNICO (IST)

1. Institution

IT/DEEC – Instituto Superior Técnico

Av. Rovisco Pais, 1049-001 Lisboa, Portugal

WEB site <http://www.it.pt>

2. Technical proficiency

1. Standards

Mobile standards:

- GSM family (GSM/DCS/PCS)
- UMTS

Wireless standards

- WLAN (IEEE 802.11b, HyperLAN2)
- Bluetooth

Other applications

- Satellite positioning

2. Simulation tools:

Commercial packages

ENSEMBLE

IE3D

WIPL-D

3. Prototyping

Technology

Photolithography printing

Dielectric lenses

Wires

Capacity/Volume/Cost

Only prototypes

4. *Measurements facilities*

Matching:	Vector Network Analysers (up to 75 GHz)
Gain and Directivity:	Far-field anechoic chamber (1 to 18 GHz, 40 GHz, 60 GHz)
Efficiency :	No
Human interaction:	No
SAR:	No

3. *Research*

1. *Staff*

Number of persons involved:

5

Number of post-graduate students involved

0

Number of PhDs:

2

2. *List of PhDs:*

- Custódio Peixeiro
- António Moreira

3. *List of publications:*

(2003-2004)

1. Jorge Brissos and Custódio Peixeiro, "Triple-Band Microstrip Patch Antenna Element for

- Cellular-WLAN Integration”, *Proc. of 12th IST Mobile & Wireless Communications Summit*, pp. 807-811, Aveiro, Portugal, June 2003.
2. Tiago Gandara and Custódio Peixeiro, “Dual Band Dual Polarised Stacked Microstrip Patch Antenna Element for UMTS and Bluetooth/IEEE 802.11b Applications” *Proc. of 4th Conference on Telecommunications*, pp. 107-110, Aveiro, Portugal, June 2003.
 3. Jorge Brissos and Custódio Peixeiro, “Triple-Band Microstrip Patch Antenna Element with an Input/Output Port for Each Band” *Proc. of 4th Conference on Telecommunications*, pp. 165-168, Aveiro, Portugal, June 2003.
 4. A. A. Moreira, "Antenna Arrays for Multiple Standard MIMO Systems", *Proc. of 4th Conference on Telecommunications*, pp. 555 - 558, Aveiro, Portugal, June 2003.
 5. Jorge Brissos and Custódio Peixeiro, “Triple-Band Microstrip Patch Antenna Element for GSM1800, UMTS and HiperLAN2”, *Proc. of IEEE Antennas and Propagation International Symposium*, vol. 4, pp. 130-133, Columbus, Ohio, E. U. A., June 2003.
 6. Jorge Brissos and Custódio Peixeiro, “Compact Triple-Band Microstrip Patch Antenna Element for Cellular and WLAN Systems” *Proc. of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, pp.916-920, Beijing, China, September 2003.
 7. J. Guterman, A. A. Moreira and C. Peixeiro; “Dual-Band Miniaturized Microstrip Fractal Antenna or a Small GSM1800 + UMTS Mobile Handset”, accepted to *The 12th IEEE Mediterranean Electrotechnical Conference (MELECON 2004)*, Dubrovnik, Croatia, May 2004.
 8. J. Guterman, A.A. Moreira and C. Peixeiro; “Triple-Band Miniaturized Fractal Planar Inverted-F Antenna for a Small Mobile Terminal”, accepted to *15th Conference on Microwaves, Radar and Wireless Communications (MIKON 2004)*, Warsaw, Poland, May 2004.
 9. R. Urban and C. Peixeiro, “Ground Plane Size Effects on a Microstrip Patch Antenna for Small Handsets”, accepted to *15th Conference on Microwaves, Radar and Wireless Communications (MIKON 2004)*, Warsaw, Poland, May 2004.
 10. L. Fregoli and C. Peixeiro, “Small Multi-Band Planar Inverted-F Antenna for Mobile Communication Systems and WLAN/WPAN Applications”, accepted to *2004 URSI International Symposium on Electromagnetic Theory*, Pisa, Italy, May 2004.

4. **List of patents:**

None

5. **List of research projects:**

EU IST program FLOWS

COST 284

4. **Products**

Participation in industrial products:

Volume:

- <5 000 units
- >5 000 units
- >50 000 units
- >500 000 units

No

6. CNRS-LEAT

1. *Institution*

CNRS-LEAT (CNRS stands for National Center for Scientific Research and LEAT stands for Electronics, Antennas and Télécommunications Laboratory)

250 Rue A. Einstein, Bat. 4 Les Lucioles, 06560 Valbonne, France

WEB site: <http://www.elec.unice.fr/>

2. *Technical proficiency*

1. *Standards*

Mobile standards:

- GSM family (GSM/DCS/PCS)
- UMTS
- GSM850

Wireless standards

- WLAN
- Bluetooth
- Hiperlan/2
- IEEE 802.11

Other applications

- GPS
- Satellite telecommunications (circular polarization patches for L and X bands)

2. *Simulation tools*

Commercial packages:

- IE3D always used
- HFSS
- ADS-Momentum.

Self-developed:

TLM code

3. *Prototyping*

Technology:

Foldable metal sheets

Capacity/Volume/Cost:

Only prototyping

4. Measurements facilities

Matching:	(Several) Vector Network Analyzers
Gain and Directivity:	One Anechoic chamber starting at 800 MHz with a measurement configuration more dedicated to antennas having a big ground plane.
Efficiency :	We are currently designing different Wheeler caps and testing different processing methods to obtain the efficiency.
Human interaction:	No
SAR:	No

3. Research

1. Staff

Number of persons involved:

2 full professors (Robert Staraj, Georges Kossiavas)

1 Assistant professor (C. Luxey)

Number of post-graduate students involved:

1 PhD (Philippe Letuc)

Number of PhDs:

1 PhD (Pascal Ciais)

2. **List of PhDs:**

L. Zaid, "Antennes compactes pour communications avec les mobiles et les liaisons de proximités", Dec. 10th 1998.

J.-M. Carrere, "Antennes multinorme pour systèmes de communications mobiles", Sept. 21th 2001.

P. Lethuc, "Antennes imprimées miniatures pour systèmes de télécommunications. Applications aux communications mobiles", June 16th 2003

3. **List of publications:**

1. G. Kossiavas, A. Papiernik, J.P. Boisset, M. Sauvan, "The C-patch : a small microstrip element", *Electronics Letters*, vol. 25, n°4, 16th February 1989, pp. 253-254.
2. G. Kossiavas, A. Papiernik, P. Brachat, P. Ratajczak, " A quarter-wavelength antenna with superposed square patches", *Microwave Journal*, June 1998, pp. 82-89.
3. L. Zaid, G. Kossiavas, J.-Y. Dauvignac, J. Cazajous, A. Papiernik, "Dual-frequency and broad-band antennas with stacked quarter wavelength elements", *IEEE Trans. On Antennas and Propagation*, vol. 47, n°4, April 1999, pp. 654-660.
4. L. Zaid, G. Kossiavas, J.-Y. Dauvignac, A. Papiernik, "Very compact double C-patch antenna", *Electronics Letters*, vol. 34, n°10, 14th May 1998, pp. 933-934
5. J.-M. Carrere, R. Staraj, G. Kossiavas, H. Legay, G. Caille, C. Luxey, J. Baro. "Conception d'une antenne bibande à large bande pour la téléphonie mobile." *Annales des Télécommunications* 57.11-12 (2002): 1019-1035.
6. S. Villeger, P. Le Thuc, R. Staraj, G. Kossiavas, "Dual-Band Planar Inverted-F Antenna", *Microwave and optical Technology Letters*, Vol. 38, N° 1, 5th July 2003, pp. 40-42.
7. P. Le Thuc, R. Staraj, G. Kossiavas, "Dual-Band Wideband Radiating Element For Mobile Handsets", *Microwave And Optical Technology Letters*, Vol. 39, N° 4, 20th November 2003, pp. 288-290.
8. P. Ciais, R. Staraj, G. Kossiavas, C. Luxey, "Design Of An Internal Quad-Band Antenna For Mobile Phones", *IEEE Microwave And Wireless Components Letters*, March. 2004.

4. **List of patents:**

1. G. Kossiavas, A. Papiernik, P. Brachat, J. Cazajous, P. Ratajczak, "Planar Printed-Circuit Antenna with Short-Circuited Superimposed Elements", US Patent No. US5986606, Nov. 16, 1999.
2. J.M. Carrere, G. Kossiavas, R. Staraj, H. Legay, "Compact Multiband Antenna", World Patent No. WO02101874, December 19, 2002.

5. **List of research projects:**

PhD students working on small antennas.

4. **Products**

Participation in industrial products: No

7. ECOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE (LEMA EPFL)

1. Institution

Ecole Polytechnique Fédérale de Lausanne

LEMA (Laboratoire d'Electromagnétisme et d'Acoustique)CH-1015 Lausanne

Switzerland

WEB site: <http://itop.epfl.ch/LEMA/>

2. Technical proficiency

1. Standards

Mobile standards:

- GSM family (GSM/DCS/PCS) : GSM/DCS
- Others (specify) : UMTS

Wireless standards

- Bluetooth

Other applications

- Satellite positioning GPS,
- ...

2. Simulation tools:

Commercial packages

- Agilent ADS/Momentum
- Ensemble

Self-developed

3-D metallization on multilayered dielectrics (MoM)

MoM for very large structures

3. Prototyping

Technology

- In house workshop with standart tools
- Multilayered PCB with metallized holes

Capacity/Volume/Cost

- one to ten ptototypes depending on complexity. No figures on cost are available for the moment, as we are in the course of changing the organization of the workshops

4. *Measurements facilities*

Matching:	- Agilent VNA HP8510 X (50 MHz – 110 GHz) - Agilent VNA HP8720
Gain and Directivity:	- Anechoic chamber (500 MHz-20 GHz) - 3 axe positioner - Measurement setup dedicated to small antennas (Gain and efficiency)
Efficiency :	Measurement setup dedicated to small antennas (Gain and efficiency)
Human interaction:	none
SAR:	none

3. *Research*

1. *Staff*

Number of persons involved:

16 persons

Number of post-graduate students involved

3 persons

Number of PhDs:

9

2. *List of PhDs:*

1. Lionel BARLATEY, "Structures rayonnantes en milieu stratifié isotrope", Thèse EPFL No. 923, 1991. Directeur de Thèse: Prof. F. Gardiol
2. John SANFORD, "Spherically Stratified Lenses", Thèse EPFL No. 1065, 1992. Directeur de Thèse: Prof. J. Mosig
3. Yan BRAND, "Antennes imprimées SSFIP: de l'élément isolé au réseau planaire", Thèse EPFL No. 1568, 1996. Directeur de Thèse: Prof. J. Mosig
4. Philippe GAY-BALMAZ, "Structures 3-D planaires en milieux stratifiés: fonctions de

- Green et application à des antennes incluant des parois verticales", Thèse EPFL No. 1569, 1996. Directeur de Thèse: Prof. J. Mosig
5. Karim RIZK, "Propagation in microcellular and small-cell urban environment", Thèse EPFL No. 1710, 1997. Directeur de Thèse: Prof. F. Gardiol
 6. Giorgio GHERI, "CAD systems for planar antennas: joining new numerical techniques with Java and Web computing", Thèse EPFL No. 1835, 1998. Directeur de Thèse: Prof. J. Mosig
 7. Eric SUTER, "Efficient and accurate acceleration schemes for large scale planar antenna computations", Thèse EPFL No. 2286, 2000. Directeur de Thèse: Prof. J. Mosig
 8. Olivier STAUB, "Electrically small antennas", Thèse EPFL No. 2311, 2000. Directrice de Thèse: Prof. A. Skrivervik
 9. Ferdinando TIEZZI, "Planar antennas with inhomogeneities: numerical techniques and software engineering", Thèse EPFL No 2706, 2003. Directeur de Thèse: Prof. J. Mosig

3. *List of publications:*

1. J.-F. Zürcher, "The SSFIP - A global concept for high performance broadband planar antennas", *Electronics Letters.*, vol. 24, No. 23, pp. 1433-1435, November 1988.
2. J.-F. Zürcher, "On some thermal properties of microstrip antennas", *MOTL*, Volume 10, Nr.5, December 1995, pp. 261-263
3. J.-F. Zürcher, Y. Brand, "An active Strip-Slot-Foam Inverted Patch antenna", *MOTL*, vol. 13, no. 3, October 20, 1996, pp. 114-119.
4. S.A. Bokhari, J-F. Zürcher, J.R. Mosig, F.E. Gardioli, "A small microstrip patch antenna with a convenient tuning option", *IEEE Transactions on Antennas and Propagation*, vol. 44, no. 11, November 1996, pp. 1521-1528.
5. O. Staub, J-F. Zürcher, A. Skrivervik, "Some considerations on the correct measurement of the gain and bandwidth of electrically small antennas", *MOTL*, vol. 17, no. 3, February 1998, pp. 156-160.
6. J-F. Zürcher, A. Skrivervik, O. Staub, S. Vaccaro, "A compact dual port, dual frequency printed antenna with high decoupling", *MOTL*, vol. 19, no.2, October 5, 1998, pp. 131-137.
7. J-F. Zürcher, D. Marty, O. Staub, A. Skrivervik, "A compact dual-port, dual-frequency SSFIP/PIFA antenna with high decoupling", *MOTL*, vol. 22, no. 6, September 20, 1999, pp. 373-378.
8. J-F. Zürcher, Qin Xu, A.K. Skrivervik, J.R. Mosig, "Dual-frequency, dual-polarization four-port printed planar antenna", *MOTL*, vol. 23, no. 2, October 20, 1999, pp. 75-78.
9. J-F. Zürcher, O. Staub, A.K. Skrivervik, M. Hermanjat, "Accurate measurement of the maximum gain of electrically small antennas", *MOTL*, vol. 23, no. 6, December 20, 1999, pp. 328-331.
10. J-F. Zürcher, J.R. Mosig, A.K. Skrivervik, Q. Xu, S. Vaccaro, "Multi-frequency, multi-polarization N-port printed planar antennas", *Microwave Engineering Europe*, June 2000, pp. 29-33.
11. J-F. Zürcher, O. Staub, A.K. Skrivervik, "SMILA: a compact and efficient antenna for mobile communications", *MOTL*, vol. 27, no. 3, November 5, 2000, pp. 155-157.

12. J-F. Zürcher, I. Giangrandi, O. Staub, A.K. Skrivervik, "A dual-frequency printed conformable antenna for mobile communications", *MOTL*, vol. 27, no. 6, December 20, 2000, pp. 386-390.
13. A.K. Skrivervik, J-F. Zürcher, O. Staub, J.R. Mosig, "PCS antenna design: the challenge of miniaturization", *IEEE Antennas and Propagation Magazine*, vol. 43, Issue 4, August 2001, pp. 12-27.
14. A.K. Skrivervik, J-F. Zürcher, "Recent advances in PCS antenna design and measurement", *Automatika*, Zagreb, No 1-2, 2002, pp. 55-61.
15. J-F. Zürcher, "A single-port, dual-frequency SSFIP antenna integrating a lowpass filter", *MOTL*, vol. 39, no. 6, December 20, 2003, pp. 472-475.
16. V. Deillon, J-F. Zürcher, A. Skrivervik, "A compact dual-band dual-polarized antenna element for GSM/DCS/UMTS base stations", *MOTL*, vol. 40, no. 1, January 5, 2004, pp. 29-33.
17. O. Staub, J-F. Zürcher, A.K. Skrivervik and J.R. Mosig, "PCS antenna design: the challenge of miniaturization", 1999 AP-S International symposium and USNC/URSI National radio science meeting, Orlando, Florida, July 11-16, 1999, pp. 548-551.
18. J-F. Zürcher, J.R. Mosig, A.K. Skrivervik, Q. Xu, S. Vaccaro, "Multi-frequency, multi-polarization N-port printed planar antennas", *AP2000 Millenium Conference on Antennas & Propagation*, Davos, Switzerland, April 9-14, 2000, Symposium CD-ROM, session 2A4, paper No 0004, pp. 1-4.
19. O. Staub, J-F. Zürcher, A.K. Skrivervik, "Gain improvement and gain measurement for electrically small antennas", *AP2000 Millenium Conference on Antennas & Propagation*, Davos, Switzerland, April 9-14, 2000, Symposium CD-ROM, session 2A6, paper No 0442, pp. 1-4.
20. J-F. Zürcher, A. K. Skrivervik, O. Staub, "SMILA: a miniaturized antenna for PCS applications", *IEEE International Symposium on Antennas and Propagation*, Salt Lake City, USA, July 16-21, 2000, Proceedings vol. 3, pp. 1646-1649.
21. O. Staub, J-F. Zürcher, A.K. Skrivervik, J.R. Mosig, "Miniaturizing antennas for personal communication systems (PCSs)", *30th European Microwave Conference*, Paris, France, October 3-5, 2000, Proc. vol. I, pp. 348-353 (Invited paper).
22. J-F. Zürcher, A.K. Skrivervik, O. Staub, "Multi frequency antennas for PCS applications", *Diskussionssitzung "Antennen für mobile Systeme 2000"*, *Fachausschuss "Antennen" der ITG im VDE*, Starnberg, Germany, October 12-13, 2000, pp. 49-52.
23. A.K. Skrivervik, J-F. Zürcher, O. Staub, "On small antennas", invited presentation at the *SSF (Swedish Strategic Research Foundation) Workshop on Antenna Technology*, Tammsvik, Sweden, January 22-24, 2001.
24. A.K. Skrivervik, J-F. Zürcher, "Measurement of gain and efficiency of electrically small antennas", *Proceedings of the 9th COST 260 meeting and workshop*, Gothenburg, Sweden, May 2-5, 2001, pp. 81-84.
25. A.K. Skrivervik, J-F. Zürcher, "Recent advances in PCS antenna design and measurement", *16th International Conference on Applied Electromagnetics and Communications (ICECom 2001)*, Dubrovnik, Croatia, October 1-3, 2001, pp. 163-168 (Invited Communication).

26. A.K. Skrivervik, J-F. Zürcher, "PCS antenna measurement", *2002 IEEE APS International Symposium and USNC/URSI National Radio Science Meeting*, San Antonio, Texas, June 16-21, 2002, Vol. III, pp. 702-705.
27. F. Nunez, D. Llorens del Rio, J-F. Zürcher, A.K. Skrivervik, "Optimization of a tri-band mobile communication antenna using genetic algorithms", *Journées Internationales de Nice sur les antennes (JINA'02)*, Nice, 12-14 novembre 2002, vol. II, pp. 65-68.
28. A.K. Skrivervik, F. Nunez, M-E. Cabot, I. Stevanovic, J-F. Zürcher, "Terminal antennas: developments and trends", *Antenn 03, Nordic Antenna Symposium*, Kalmar, Sweden, May 13-15, 2003, pp. 13-22 (invited paper).
29. A.K. Skrivervik, J-F. Zürcher, "Multiband terminal antennas", *17th International Conference on Applied Electromagnetics and Communications (ICECom 2003)*, Dubrovnik, Croatia, October 1-3, 2003, pp. 391-394 (Invited Communication).
30. F. Nunez, A.K. Skrivervik, "GA optimization of terminal antennas by the estimation of the population density of probability using dependency trees", *17th International Conference on Applied Electromagnetics and Communications (ICECom 2003)*, Dubrovnik, Croatia, October 1-3, 2003, pp. 336-339.
31. F. Nunez, A.K. Skrivervik, "GA optimization of terminal antennas by the estimation of the population density of probability using dependency trees", *IEEE AP-S International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting*, Monterey, California, USA, June 20-26, 2004 (accepted for presentation)

4. *List of patents:*

Schlitzantenne

licence No. CH690808

date of publication: 1996-03-14

inventors: U. Dersch, J-F. Zürcher, M. Liebendörfer, M. Mattes

depositor: ASCOM TECH AG

Miniaturized antenna for converting an alternating voltage into a microwave and vice versa, notably for horological applications

brevets US5646634, AU3431495, AU695429, CA2159961, EP0708492, FR2726127, JP8213819

date of publication: 1997-07-08

inventors: S.A. Bokhari, J-F. Zürcher, J.R. Mosig, F.E. Gardiol

depositor: ASULAB SA

Horological piece comprising an antenna

licence Nos. US5699319, DE69602999D, EP0766152, FR2739200, JP9127267

date of publication: 1997-12-16

inventors: A.K. Skrivervik
depositor: ASULAB SA

Slot antenna in particular for a timepiece
licence Nos. EP0954051, CN1234629, JP2000022435
date of publication: 1999-11-03
inventors: O. Staub, A.K. Skrivervik, J-F. Zürcher
depositor: ASULAB SA

Antenna forming structure providing additionally a shielded box allowing one to include in particular all or part of the electronics of a small volume portable unit
deposit No. (Switzerland): 1999 1849/99 - request for European licence No 99120230.0
date of deposit: 1999-10-11
inventors: J-F. Zürcher, A.K. Skrivervik, O. Staub
depositor: ASULAB SA

Multifrequency antenna for small volume instrument
deposit No. (Switzerland): 2000 0488/00 - request for European licence No 00200934.8
date of deposit: 2000-03-15
international license and U.S. validation pending
inventors: J-F. Zürcher , A.K. Skrivervik, O. Staub
depositor: ASULAB SA

Structure formant une antenne PIFA et un boîtier dans un appareil électronique portable
deposit No. (Switzerland): 2001 2140/01 - request for European licence No 01204447.5-2208
date of deposit; 2001-11-21
inventors: J-F. Zürcher , A.K. Skrivervik
depositor: ASULAB SA

5. *List of research projects:*

8. LUND INSTITUTE OF TECHNOLOGY (LU)

1. Institution

Department of Electrosience
Lund Institute of Technology
P.O. Box 118
SE-221 00 Lund
Sweden
WEB site: www.es.lth.se

2. Technical proficiency

1. Standards

Mobile standards:

- GSM family (GSM/DCS/PCS)
- UMTS

Wireless standards

- WLAN
- Bluetooth
- UWB

2. Simulation tools:

Commercial packages:

- SEMCAD
- FEMLAB
- PBFDTD

3. Measurements facilities

Matching:	Network analyzer up to 20 GHz
Gain and Directivity:	Indoor anechoic chamber
Efficiency :	

Human interaction:	Head and shoulder phantom. MICS Torso simulator
SAR:	

3. Research

1. Staff

Number of persons involved:

Anders Derneryd, Gerhard Kristensson,
Mats Gustafsson, Anders J Johansson,
Anders Karlsson

Number of post-graduate students involved: 0

Number of PhDs: 2

2. List of PhDs:

Peter Waller, "Patch Antennas on Inhomogeneous Substrates for Mobile Terminals," (Licentiate Thesis), June 14, 2002.

Anders J Johansson, "Wireless Communication with Medical Implants: Antennas and Propagation.", PhD Thesis, Lund University, August 2004

3. List of publications:

Thomas Rylander and Peter Waller, "Patch antennas on in-homogeneous substrates," LUTEDX/(TEAT-7105)/1-14/(2002).

Thomas Rylander and Peter Waller, "A numerical study of patch antennas on inhomogeneous substrates," *JINA 2002*, Nice, France, November 12-14, 2002.

Anders Karlsson, "Physical limitations of antennas in a lossy medium," LUTEDX/(TEAT-7114)/1-15/(2003) *IEEE Trans. Antennas Propagat.* (Accepted for publication.)

Gerhard Kristensson, Peter Waller and Anders Derneryd, "Radiation efficiency and surface waves for patch antennas on inhomogeneous substrates," *IEE Proc. - Microwaves, Antennas and Propagation*, **150**(6), 477-483 (2003).

Anders Derneryd and Gerhard Kristensson, "Signal correlation including antenna coupling," *IEE Electronics Letters*, **40**(3), 157-159 (2004).

Anders Derneryd and Gerhard Kristensson, "Antenna signal correlation and its relation to the impedance matrix." (*IEE Electronics Letters*, to appear.)

Anders J. Johansson, "Simulation and Verification of Pacemaker Antennas," *EMBC 2003*, Cancun, Mexico, September 17-21, 2003.

Anders J Johansson, "Performance of a Radio Link Between a Base Station and a Medical Implant Utilising the MICS standard", *EMBS-04*, SF, USA, September 1-4

4. *List of research projects:*

Correlation of antenna signals

Physical limitations on information capacity

Mobile radio channel

Wireless communication with implants

Antennas for medical implants

9. UNIVERSITY OF BRISTOL (UoB)

1. Institution

University of Bristol
Wireless and Networks Research Labs
Department of Electrical and Electronic Engineering
Merchant Venturers Building
Woodland Road
Bristol
England
BS8 1UB
WEB site n.a.

2. Technical proficiency

1. Standards

Mobile standards:

- GSM family (GSM/DCS/PCS)
- UMTS

Wireless standards

- 802.11a,b,g
- Bluetooth
- HiperLAN I and II
- UWB

Other applications

- PMR Talkback for F1 racing team
- MIMO antenna arrays

2. Simulation tools:

Commercial packages:

- Agilent ADS
- Agilent Momentum

Self-developed:

- FDTD Gemma

3. Prototyping

Technology:

All artwork is produced in-house using state-of-the-art laser plotting techniques. This is then photo-etched and developed using facilities at the University onto substrate to create PCBs.

Capacity/Volume/Cost:

Facilities at the University of Bristol are aimed towards prototyping and would not lend themselves to production runs of greater than 10 antennas at a time.

4. Measurements facilities

Matching:	A number of Vector Network Analysers: Rohde and Schwarz ZVC (8GHz), HP8510 (20GHz), Agilent 8722ES (40GHz), Anritsu 37397C (65GHz)
Gain and Directivity:	Full 3-D pattern measurements are carried out in-house using bespoke software. From these patterns the Poynting Vector is integrated over full 3-D space and divided by the maximum radiation in a particular direction (which is very rarely along the principle axes that 2-D analysis would only consider) to calculate true directivity. Gain is calculated using the True Gain Technique ⁴
Efficiency :	This is calculated from the apriori knowledge of true directivity and true gain. All losses (such as cable losses) and mismatches (due to a non-perfectly matched antenna) are calculated and compensated for.
Human interaction:	This method has been shown to allow a high degree of repeatability between measurements, and since it makes use of standard antenna characterisation equipment (such as an

⁴ Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., "A practical approach for reliably determining the efficiency of an antenna," in *Technical Seminar on Antenna Measurements and SAR*, Loughborough, UK, May 2002, IEE, pp. 27/1–4.

⁵ Harrold, T.J., Hilton, "Novel Antenna Technologies for 4th Generation Handsets" Prepared for Kyocera Corporation, Yokohama R&D, Japan, 7th August 2003

⁶ Rostbakken, O., *Automatic Frequency Tuning of a Microstrip Patch Antenna*, P.hD., University of Bristol, Department of Electrical Engineering, 1997.

	<p>anechoic chamber, VNA and positioner) it lends itself to wide use amongst antenna engineers.</p> <p>As well as measuring the insitu effect that a human has on the performance of an antenna ⁵[2], methods for automatically counteracting the human detuning influence on the antenna has been researched ^{6,7}.</p> <p>Work is also currently being undertaken in applying a wide-band technique to the detection of breast cancer.</p>
SAR:	<p>There is no research currently being undertaken in the Department of Electrical and Electronic Engineering in the area of SAR measurement. However, in the University of Bristol, the Department of Biophysics is active in the both the design of human phantoms and the measurement of SAR.</p>

3. Research

1. Staff

Number of persons involved: (currently) 11

Number of post-graduate students involved: (currently) 6

Number of PhDs: (currently) 6 - as above

2. List of PhDs:

Urwin-Wright, P.R. "An Electrically-Small Tuneable Annular Slot for Future Mobile Terminals", submitted for examination February 2004

Hunt-Grubbe, H.W.W "Transmission Response Measurements with Multiple-feed Antennas", 2nd year of study

Pesik, L.J. "Beamforming Algorithms for Smart Antennas", 3rd year of study

Foo, S.E. "Characterisation of UTRA FDD Channels using Smart Antennas", writing-up

Hunukumbure, M. "MIMO Extensions to 3G UMTS", writing-up

⁷ Urwin-Wright, P.R., *An Electrically-Small Tuneable Annular Slot for Future Mobile Terminals*, P.h.D., University of Bristol, Department of Electrical Engineering, 2004

Tan, C.M. “Estimation Techniques for Channel Characterisation”, writing-up

3. **List of publications:**

(since 2000)

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., “An investigation of the ground plane dependency of the annular slot in its ‘dc’ mode,” *for submission to Electronics Letters*.

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., “A UMTS systems evaluation of the adaptively tuneable annular slot in its ‘dc’ mode,” *for submission to IEEE Transactions on Antennas and Propagation*.

Craddock, I.J., Hilton, G.S., Urwin-Wright, P.R., “An investigation of pattern correlation and mutual coupling in mimo arrays,” in *Proceedings of IEEE International Symposium on Antennas and Propagation*, Monterey, USA, June 2004, IEEE, *Invited Paper*.

Nilavalan, R., Gbedemah, A., Craddock, I.J., Li, X., Hagness, S.C. “Numerical investigation of breast tumour detection using multi-static radar”, in *Electronics Letters*, vol. 39, no. 25, December 2003, p 1787-9

Hellen, M.K., Craddock, I.J.” Calculation of the input impedance of dipoles in proximity to walls” in *IEE Proceedings: Microwaves, Antennas and Propagation*, vol. 150, no. 5, October 2003, pp 369-74

Railton, C.J., Paul, D.L. Craddock, I.J. “Analysis of a 17 element conformal array of stacked circular patch elements using an enhanced FDTD approach”, in *IEE Proceedings: Microwaves, Antennas and Propagation*, vol. 150, no. 3, June 2003, pp 153-8

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N.,, “On the pattern control of an annular slot operating in its ‘dc’ mode,” in *3rd Management Meeting of Cost 284*, Budapest, Hungary, April 2003.

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., “A Tuneable Electrically-Small Antenna Operating in the ‘DC’ Mode,” in *5th European Personal Mobile Communications Conference*, Glasgow, UK, April 2003

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., “A Reconfigurable Electrically-Small Antenna Operating in the ‘DC’ Mode,” in *57th Vehicular Technology Conference*, Jeju, Korea, April 2003.

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., “An Electrically-Small Annular Slot Operating in the ‘DC’ Mode,” in *12th International Conference on Antennas and Propagation*, Exeter, UK, March 2003, IEE, vol. 2, pp. 686–9.

Hilton, G.S., Urwin-Wright, P.R., “The Analysis of Balanced Feed Antenna Structures for use in Integrated Antenna-Transceivers,” in *12th International Conference on Antennas and Propagation*, Exeter, UK, March 2003, IEE, vol. 1, pp. 320–3.

Paul, D.L., Railton, C.J., Craddock, I.J. “Full-wave modelling of coaxial cables by FDTD technique” in *Electronics Letters*, vol. 38, no. 21, Oct 2002, pp 1261-2

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., “Comparison of an Electrically-Small Planar Antenna Array with a Conventional Monopole Array,” in *56th Vehicular Technology Conference*, Vancouver, Canada, September 2002, IEEE, pp. 596–600.

Boon-Ping, K., Craddock, I.J., Urwin-Wright, P.R., Railton, C.J., “Lumped Device Modeling with FDTD Including Packaging Effects,” in *IEEE MTT-S International Microwave Symposium Digest*, Seattle, USA, June 2002, IEEE, vol. 2, pp. 1139–42.

Urwin-Wright, P.R., Hilton, G.S., Craddock, I.J., Fletcher, P.N., “A practical approach for reliably determining the efficiency of an antenna,” in *Technical Seminar on Antenna Measurements and SAR*, Loughborough, UK, May 2002, IEE, pp. 27/1–4.

Nilavalan, R., Craddock, I.J., Railton, C.J. “Quantifying numerical dispersion in non-orthogonal FDTD meshes” in *IEE Proceedings: Microwaves, Antennas and Propagation*, Vol. 149, no. 1, February 2002, pp 23-7

Koh, B.P., Craddock, I.J., Urwin-Wright, P.R., Railton, C.J. “FDTD analysis of varactor-tuned patch antenna including device packaging effects” in *Electronics Letters*, vol. 37, no. 25, December 2001, pp 1494-5

Craddock, I.J., Paul, D.L., Railton, C.J., Ball, G., Watts, J. “Cylindrical-Cartesian FDTD model of a 17-element conformal antenna array” in *Electronics Letters*, vol. 37, no. 24, November 2001, pp 1429-31

Nilavalan, R., Craddock, I.J., Paul, D.L., Railton, C.J. “Conformal antenna array modeling using a locally nonorthogonal FDTD” in *Microwave and Optical Technology Letters*, vol. 30, no. 4, August 2001, pp 238-40

Hellen, M.K., Craddock, I.J. “On the accuracy of the complex image method” in *IEEE Antennas and Propagation Society International Symposium (Digest)*, vol. 4, July 2001, p 846-9

Nilavalan, R., Craddock, I.J., Railton, C.J. “Practical method for the determination of time step in non-orthogonal FDTD” in *Electronics Letters*, vol. 37, no. 11, May 2001, pp 679-80

Paul, D.L., Craddock, I.J., Railton, C.J., Fletcher, P.N., Dean, M. “FDTD analysis and design of probe-fed dual-polarized circular stacked patch antenna” in *Microwave and Optical Technology Letters*, vol. 29, no. 4, May 2001, pp 223-6

Hellen, M.K., Craddock, I.J., “Improving the accuracy of the complex image technique” in *Microwave and Optical Technology Letters*, vol. 28, no. 6, March 2001, pp 402-6

Navarro, E.A., Craddock, I.J., Paul, D.L., “Synthetic dielectrics for planar antenna design” in *Electronics Letters*, vol. 36, no. 6, 2000, pp 491-3

4. List of patents:

5. List of research projects:

- Ofcom Spectral Efficiency Scheme AY4776
- Kyocera Portable terminal antenna arrays for MIMO schemes

- Toshiba development of MIMO antennas
- Breast Cancer Detection
- Samsung Integrated Antenna Transceivers
- Mobile VCE, Core 3 Programme, Wireless Enablers, Characterisation of PAN Channels.

4. Products

Participation in industrial products: None

10. SATIMO

1. Institution description

SATIMO

(Société d'Applications Technologiques de l'Imagerie Micro-Onde)

22, avenue de la Baltique

Z.A. de Courtaboeuf

91953 Courtaboeuf Cedex

France

WEB site: www.satimo.fr

2. Technical proficiency

1. Standards

Active measurements of Mobile phones:

- GSM family (GSM,DCS,PCS)
- WCDMA family (WCMA1800/WCDMA1900/WCDMA2000-UMTS)
- CDMA family (US-Korea Cellular/US PCS/Korea PCS)
- TDMA

Active Measurements of Wireless devices

- PC's (WLAN)
- Bluetooth devices
- ISM devices

Measurement of antennas for positioning systems

- ARGOS 3
- GPS
- GALILEO

Antenna products:

- Reference antennas (dipoles) for commonly used wireless frequency bands
- Reference antennas (standard horns) for calibration purposes
- Near Field probes for spherical and planar near field measurement systems
- Ground Segment Reference antennas for ARGOS, GPS and GALILEO

2. Simulation tools:

Commercial packages:

- CST Microwave Studio
- EMPIRE
- IE3D

Self-developed:

- Method of Moment codes
- Mode Matching codes

3. Prototyping

Technology:

- Patch antennas
- Dipole antennas
- Horn antennas
- Helix antennas
- Array antennas

Capacity/Volume/Cost:

4. Measurements facilities

Matching:	<ul style="list-style-type: none"> - Rohde & Schwarz ZVK Vector Network analyser - Agilent HP8753 Vector Network analyser
Gain and Directivity:	<ul style="list-style-type: none"> - Satimo STARGATE 64 antenna test facility - Satimo STARLAB antenna test equipment
Efficiency :	<ul style="list-style-type: none"> - Satimo STARGATE 64 antenna test facility - Satimo STARLAB antenna test equipment
Human interaction:	<ul style="list-style-type: none"> - Satimo STARGATE 64 antenna test facility - Satimo STARLAB antenna test equipment
SAR:	<ul style="list-style-type: none"> - Satimo STARGATE 64 antenna test facility

	- Satimo STARLAB antenna test equipment
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3. Research

1. Staff

Number of persons involved:

- 9 people

Number of post-graduate students involved:

- 2 people

Number of PhDs:

- 3 people

2. List of recent publications:

Ph. Garreau, D. Bateman, A. Gandois, B.J. Cown, H. Vailong, "Intégration de code d'analyse S.A.F. sur un banc de mesure rapide de S.E.R. bistatique", SEE, October 2000, Brest, France

V. Monebhurrin, J.-Ch. Bolomey, L. Duchesne, "Non invasive statistical SAR assessment of portable phones", European BioElectromagnetics Association (EBEA), September 2001, Helsinki, Finland

L. Duchesne, M. Le Goff, P.O. Iversen, "Reference dipoles for antenna test range validation", IEEE-AP, July 2001, Boston

L. Foged, L. Duchesne, Ph. Garreau, P.O. Iversen, J.-Ch. Bolomey, "Minimization of the truncation impact on measured radiation pattern of quasi omnidirectionnal antennas in spherical near-field test ranges", IEEE-AP, July 2001, Boston

Gandois, Ph. Garreau, G. Barone, "Active measurements of wireless devices in a spherical near-field test range", IEEE-AP, July 2001, Boston

L. Foged, L. Duchesne, P.O. Iversen, J. Lemanczyk, "Design of an L-band test range validation antenna", IEEE-AP, July 2001, Boston

L. Duchesne, L. Foged, J.-Ch. Bolomey, "Microwave imaging techniques for industrial applications", September 2001, Naples, Italy

L. Duchesne, L. Durand, Ph. Garreau, "Development of a compact MS-GPR radar based on multi-sensors technology", 3rd DTIF Technical Workshop, September 2002, Ispra, Italy

M. Sabbadini, L. Foged, J.-M. Baracco, M. Bandinelli, M. Bercigli, “Wideband medium-gain radiating elements in multi-layer composite technology”, 25th ESA Antenna Workshop, September 2002, Noordwijk, The Netherlands

P. Dumon, D. Belot, Ph. Garreau, L. Duchesne, “Low frequency spherical near field measurement facility at CNES”; AMTA, November 2002, Cleveland, United States

J.-Ch. Bolomey, Ph. Garreau, L. Duchesne, “Near-field techniques for coupling cross section measurements and diagnostic of complex radiating systems”, RF & Hyper 2002 exhibition, October 2002, Paris, France

V. Monebhurrin, J.-Ch. Bolomey, L. Duchesne, M. Le Goff, Ph. Garreau, “Statistical analysis of SAR data : towards a Fast Non Invasive SAR Assessment of Mobile Phones”, RAWCON, August 2002, Boston, United States

M. Sabbadini, A. Giacomini, M. Bandinelli, M. Bercigli, D. Gabbani, J.-M. Baracco, L. Foged, “Numerical modelling and experimental validation of multiplayer antennas with complex feeding network”, 26th ESA Antenna Workshop, September 2003, Noordwijk, The Netherlands

M. Le Goff, L. Foged, L. Duchesne, J.-M. Baracco, K. Van’t Klooster, “Galileo ground segment reference antenna designed for maximum phase stability and multi-path immunity”, 26th ESA Antenna Workshop, November 2003, Noordwijk, The Netherlands

E. Di Giampaolo, F. Mioc, M. Sabbadini, F. Bardati, G. Marrocco, J. Monclard, L. Foged, “Measurement and analytical validation of astigmatic beam tracer”, 26th ESA Antenna Workshop, November 2003, Noordwijk, The Netherlands

N. Robic, L. Duchesne, Ph. Garreau, P. Bellocq, P.O. Iversen, “Measurement of directive antennas using rapid probe array within a spherical near-field test range”, AMTA, October 2003, Irvine, United States

E. Di Giampaolo, F. Mioc, R. Chovanec, F. Bardati, M. Sabbadini, L. Foged, “Validation of the ABT scattering prediction method for the analysis of complex environment.”, IEEE AP-S URSI, June 2003, Columbus, United States

L. J. Foged, L. Duchesne, P. Iversen, G. Barone, “High precision probes for Wide-band near-field measurements in dual polarization”, ISAPE, August 2003, Beijing, China

P.O. Iversen, P. Garreau, K. Englund, E. Pasalic, O. Edvardsson, G. Engblom, “Real Time Spherical Near Field Antenna Test Range for Wireless Applications”, Proceedings of AMTA 1999 – Antenna Measurement Techniques Association, pp. 363 – 368, October 4-8 1999, Monterey Bay, California

L. Foged, F. Mioc, L. Duchesne, Ph. Garreau, G. Barone, E. Di Giampaolo, “Synergy of fast antenna measurements and efficient numerical modelling techniques”, ANTEM 2004 / URSI, Ottawa 2004

E. Di Giampaolo F. Mioc, M. Sabbadini ,F. Bardati, G. Marrocco, J. Monclard , L. Foged, “Measurement and analytical validation of astigmatic beam tracer”, 26th ESA Antenna Workshop, Noordwijk 2003

L. Duchesne, Ph. Garreau, N. Robic, A. Gandois, P.O. Iversen, G. Barone, “Compact multi-probe antenna test station for rapid testing of antennas and wireless terminals”, 4th Mediterranean Microwave Symposium, Marseille 2004

Ph. Garreau, L. Duchesne, A. Gandois, J. Dréan, P.O. Iversen, “Antenna characterization solutions offered by using near field measurement techniques”, 4th Mediterranean Microwave Symposium, Marseille 2004

L. J. Foged, A. Giacomini, J.M. Baracco, L. Duchesne, Ph. Garreau, “Simplified design of wide-band dual polarized probes for high precision antenna measurements”, 26th Annual Antenna Measurement Technologies Associations, Atlanta 2004

Ph. Garreau, A. Gandois, L. Duchesne, P.O. Iversen, “Probe array concepts for fast testing of large radiating structures”, 26th Annual Antenna Measurement Technologies Associations, Atlanta 2004

J.A. Graham, P.O. Iversen, “Rapid spherical near-field antenna test system for vehicle mounted antennas”, 26th Annual Antenna Measurement Technologies Associations, Atlanta 2004

L. Duchesne, L. Foged, Marc Le Goff, J. M. Baracco, P. Dumon, K. van’t Klooster, “Ground segment reference antennas for positioning applications”, 13^{èmes} Journées Internationales de Nice sur les Antennes, Nice 2004

3. *List of patents:*

- Patents on antenna measurement techniques and technologies
- Patents on antenna designs

4. *List of research projects:*

- ESA projects
- GJU projects
- EC projects
- CNES projects
- CNRS projects

4. *Products*

Participation in industrial products:

- Antenna measurement test facilities (STARLAB family)
- Reference antennas (dipoles and standard horns)
- Reference antennas for ground segment positioning system (ARGOS, GPS, GALILEO)

Volume:

- <5 000 units

11. UNIVERSITAT POLITÈCNICA DE CATALUNYA (UPC)

1. Institution

Universitat Politècnica de Catalunya
Jordi Girona 1-3
Campus Nord, Modulo D-3
08034 Barcelona
Spain
WEB site: www.tsc.upc.es

2. Technical proficiency

1. Standards

Mobile standards:

- GSM family (GSM/DCS/PCS)
- UMTS
- Others (specify)

Wireless standards

- WLAN
- Bluetooth
- ...

Other applications

- Satellite positioning
- ...

2. Simulation tools:

Commercial packages

- HFSS
- IE3D
- NEC

Self-developed

FIESTA 3D (*Fast Integral Equation Solver for Antennas and Scatterers in 3D*)

3. *Prototyping*

Technology

Capacity/Volume/Cost

4. *Measurements facilities*

Matching:	Networks analyzers up to 50 GHz
Gain and Directivity:	Anechoic chamber (7x7x10 m) with spherical positioners system, operating from 1 to 40 GHz.
Efficiency :	Wheeler caps, different size and geometries, up to 3 GHz
Human interaction:	
SAR:	

3. *Research*

1. *Staff*

Number of persons involved:

10 (ACE) 2(WP 2.2)

Number of post-graduate students involved

2 (ACE) 1(WP 2.2)

Number of PhDs:

8 (ACE) 1(WP 2.2)

2. *List of PhDs:*

Jofre, Luis

Cardama, Angel
Romeu, Jordi
Rius, Juan Manuel
Blanch, Sebastián
Gonzalez, José María
Ubeda, Eduard
Heldring, Alex

3. **List of publications:**

(related to small-antennas)

Journals

Cetiner, B.A.; Jofre, L.; Qian, J.Y.; De Flaviis, F.; "Small-size broadband multi-element antenna for RF/wireless systems", *Antennas and Wireless Propagation Letters*, Volume: 2, Issue: 22, 2003, Pages:326 – 329

Jofre, L.; Cetiner, B.A.; De Flaviis, F.; "Miniature multi-element antenna for wireless communications", *IEEE Transactions on Antennas and Propagation*, Volume: 50, Issue: 5, May 2002, Pages:658 – 669.

Gonzalez-Arbesu, J.M.; Blanch, S.; Romeu, J.; "Are space-filling curves efficient small antennas?", *Antennas and Wireless Propagation Letters*, Volume: 2, Issue: 10, 2003, Pages:147 – 150.

Baliarda, C.P.; Romeu, J.; Cardama, A.; "The Koch monopole: a small fractal antenna", *IEEE Transactions on Antennas and Propagation*, Volume: 48, Issue: 11, Nov. 2000, Pages:1773 – 1781.

Blanch, S.; Romeu, J.; Corbella, I.; "Exact representation of antenna system diversity performance from input parameter description", *Electronics Letters*, Volume: 39, Issue: 9, 1 May 2003, Pages:705 – 707.

Gonzalez-Arbesu, J.M.; Romeu, J.; "Size-reduction of pre-fractal Sierpinski monopole antenna", *Electronics Letters*, Volume: 38, Issue: 25, 5 Dec. 2002, Pages:1628 – 1630.

Puente, C.; Romeu, J.; Pous, R.; Ramis, J.; Hijazo, A.; "Small but long Koch fractal monopole", *Electronics Letters*, Volume: 34, Issue: 1, 8 Jan. 1998, Pages:9 - 10

Conferences

Cetiner, B.A.; Qian, J.Y.; Liu, S.; Jofre, L.; Li, G.P.; De Flaviis, F.; "A compact wideband MEM switched diversity antenna for indoor mobile channels", *Microwave Symposium Digest, 2003 IEEE MTT-S International*, Volume: 3, 8-13 June 2003, Pages:1711 - 1714 vol.3

Elsadek, H.; Eldeeb, H.; DeFlaviis, F.; Jofre, L.; Abdallah, E.; "Microstrip multi-element diversity antenna array for three dimensional microwave holographic input", *IEEE Antennas and Propagation Society International Symposium*, 2002., Volume: 3, 16-21 June 2002, Pages:226.

Cetiner, B.A.; Jofre, L.; Li, G.P.; de Flaviis, F.; "Small size CPW-fed chip antenna for integration with RF/wireless communication systems", *IEEE Antennas and Propagation Society International Symposium*, 2002., Volume: 2 , 16-21 June 2002, Pages:504 - 507 vol.2

Cetiner, B.A.; Jofre, L.; Chang, C.H.; Qian, J.Y.; Bachman, M.; Li, G.P.; De Flaviis, F.; "Integrated MEM antenna system for wireless communications", *Microwave Symposium Digest, 2002 IEEE MTT-S International* , Volume: 2 , 2-7 June 2002, Pages:1333 – 1336.

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Patent number: ES2112163

Date: 19/05/1995

Sierpinsky Fractal Antennas

C. Puente, R. Pous, J. Romeu

Patent number: 97 00048

Date: December 1996

Small and Multiband Top Loaded Antenna

J.Romeu, J. Soler, S. Blanch

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5. List of research projects:

- "Fractal antennas for communication systems" (Spanish Government CICYT 2FD97/0135). 1998–2001.
- "Advanced antennas and front-ends for UMTS base stations". (Spanish Government CICYT TIC 2001–2364-C03-03). 2001-2004.
- "Exploring the limits of fractal electrodynamics for the future telecommunications technologies ("FRACTALCOMS")", (IST 2001-33055). 2001 - 2003.

4. Products

Participation in industrial products: none