Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2013, Article ID 838364, 25 pages
http://dx.doi.org/10.1155/2013/838364

Review Article

Advances in Antenna Technology for Wireless Handheld Devices

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Received 24 August 2012; Accepted 27 November 2012

Academic Editor: Mandeep Singh Jit Singh

The constant evolution of wireless handheld devices together with the apparition of multiple wireless communication systems fosters the antenna community to design new radiating and measurements systems capable of satisfying the market demands. It is an object of the present paper to provide an overview of the evolution that wireless handheld technology has experienced in the last years. In this sense, a description of the evolution of wireless handheld devices, regulations, challenges in today's smartphones, and handset characterization is reviewed. Finally, recent advances in antenna technology for wireless handheld or portable devices are presented.

1. Introduction

Communication between two distant points has been a constant challenge for mankind, from ancient smoke signals, to telegraph, to finally wireless communication through electromagnetic signals. This evolution represents a constant effort to improve the quality and effectiveness of distance communication with ever-evolving techniques to enhance the delivery of contents, from voice to data. Wireless handheld devices are the most representative paradigm of these efforts. In this regard, the antenna community often has an important role focused on designing low-profile, small, and multiband antennas together with multiple antenna systems capable of satisfying the strict demands of emergent multifunction wireless devices. Furthermore, the complexity of handheld antenna design is continuously increasing, not only by the pressure of the market needs but also by the duty of safety regulations which require efficient antennas capable of radiating as much power as possible in free-space conditions, while minimizing the power radiated towards the human head.

Antenna modeling in handheld devices, using electromagnetic simulation software, has improved significantly by allowing the simulation of the antenna behavior in complex environments surrounding the antenna. Thus, current electromagnetic software allows the simulation of handheld antennas regarding not only the human presence (such as human head and hand) but also the presence of nearby components (such as cameras, batteries, displays, and speakers).

At the same time, recent advances in measurement systems and methodologies have become hot topics in the antenna measurement community for capturing radiated performance in emergent LTE and MIMO antenna systems.

Finally, with the commercial success of wireless handheld devices comes the important role of good manufacturing techniques. This is not only important for reducing the cost of mass production, but also for enhancing the design performance and size in a controlled fashion.

The paper is divided into the following sections. Section 2 describes the evolution of handheld mobile telephones and generations, the apparition of new frequency bands, the industrial design influence on antennas, requirements and regulations, and finally antenna design challenges in today's smartphones. Section 3 explains the most relevant electromagnetic parameters to characterize antennas for wireless handheld devices such as radiation efficiency, impedance mismatch, signal branch correlation, diversity gain, MIMO capacity, Total Radiated Power (TRP), Specific Absorption Rate (SAR), Total Isotropic Sensitivity (TIS) or Total Radiated Sensitivity, Average Fading Sensitivity (AFS), and Data bit throughput (TPUT). In addition, Section 3 shows how these parameters can be measured in a reverberation chamber. Section 4 summarizes recent advances in the field of antennas for wireless handheld devices. In particular, Section 4 describes antenna technology for designing antennas at low frequencies such as FM, for short-range wireless applications, and finally for mobile communications. For this last section, several antenna design techniques are explained such as coupled monopoles and PIFAs combined with slots. In addition, a technique robust to human loading is presented based on an array of small monopoles. Section 4 further discloses the use of broadband matching networks to enhance the bandwidth of an antenna element in order to increase the number of operating bands. It is also focused on techniques to add intelligence in the ground plane for enhancing bandwidth and efficiency. Finally, a novel antenna technology based on small nonresonant ground plane boosters is described. The proposal is focused on exciting the ground plane radiation modes that the inherent ground plane of any handset platform performs at mobile frequencies. This technology removes the need of including large antenna elements featuring quarter-wavelength dimensions, thus enabling the integration of multiple antenna elements and multiple functionalities and services in the wireless platform.

2. Evolution of Handheld Mobile Telephones

The evolution of handheld mobile telephones throughout history has been captivating. The first telephone call using a handheld device dates back to the 1970s [1]. Since the 1980s, handheld telephone devices have become a commodity for everyone and the mobile market has not stopped expanding since then. The exponential increase in the number of subscribers pushes research and development in wireless communication to deliver technologies capable of accommodating that growth. These technologies have evolved to a great extent and have included going from analog to digital, and going from using one frequency band to multiple frequency bands, as well as many others. This constant evolution led to the recent deployment of the latest generation radios onto the consumer market: the Long-Term Evolution (LTE) technology.

Operators of consumer wireless handheld devices recently started to deploy the LTE wireless technology for the next-generation smartphones. Before going through the challenges engineers have to face in developing antennas for LTE-capable phones, it is important to look at the previous generations of mobile handheld devices to describe the general challenges in antenna design, some of which still remain in the current design challenges. The following sections talk about the challenges that exist in antenna design for wireless mobile handsets.

2.1. Wireless Mobile Generations. The first generation (1G) wireless communication technology was introduced back in the early 1980s. It used an analog standard. A few commercially used 1G standards included NMT (Nordic Mobile Telephone) and AMPS (Advanced Mobile Phone System). NMT network first used a frequency band in the 450-MHz region, called NMT-450. Due to the subscribers' demand, it expanded its network to the 900-MHz region (NMT-900), since it could carry more channels at that frequency band than its previous band. The AMPS standard used in the United States was deployed in the 800-MHz frequency region. The subsequent generation radios, for example, 2G, 3G, and 4G, started in the 1990s. These newer generations were drastically different in the sense that they were all using digital standards. There were many advantages to replacing analog with digital standards. One of the advantages is that digital standards could accommodate more users, which was necessary.

Even though the 2G standards, such as GSM, D-AMPS, and CDMAOne, have been superseded by their newer generations, they still remain widely used networks in all the parts of the world. The third generation (3G) network appeared on the market in early 2000, and the latest LTE network was offered in 2010. These later standards were tailored to improve data services. The following sections describe what influences antenna design and what challenges antenna engineers have to face in the development of mobile handset devices.

2.2. Increase in the Number of Frequency Bands. Wireless communication standards sometimes come with a new set of frequency bands. Fortunately, some bands of newer generations overlap previous generations, which releases some of the burden on the antenna design when a new generation standard comes into the picture. Looking back from the first generation to the current generation, the number of frequency bands kept increasing. Antennas for the first generation handheld devices were designed back in the 1980s to work in one frequency band. As the number of frequency bands increased with newer generations, the need for multiband antenna designs became necessary. Furthermore, as the mobile market became more and more popular and global travel became more accessible to the general population, there was a need for making devices with roaming capability. This was necessary in order for subscribers of one market region to be able to use the same device in other regions with similar standards but different operating frequency bands. As an example of today's US mobile devices, a phone operating in North America has the main bands operating from 824 MHz to 894 MHz and from 1850 MHz to 1990 MHz for both GSM (2G) and UMTS (3G) standards. Furthermore, an additional band is now needed for the LTE standards in the 700-MHz band. The phone would generally have roaming capability at operating bands used in the rest of the world, precisely, GSM 900, GSM 1800,

Figure 1: Mobile handheld phone examples through all the generations.

UMTS B I, and B VIII. The frequency band of coverage of these roaming bands are from 880 MHz to 960 MHz (GSM 900 and UMTS B VIII), 1710 MHz to 1880 MHz (GSM 1800), and 1920 MHz to 2170 MHz. Therefore, there is a need for designing multiband antennas that can operate in these bands with good performance.

2.3. Industrial Design Influence on Antennas. For some people, a mobile telephone handset is a device that serves only as a way of communication and they do not care whether it is big or small, thin or thick, shiny or mat. For some other people, industrial design is an important factor when it comes to using consumer electronics devices. The look and feel of their phones are important factors in making their purchasing decision.

Prior to the early 2000s, antennas in mobile handsets were designed externally. They were mostly monopole-type, retractable or not, or helical stub antennas protruding from the top of the phones (Figure 1). Industrial design did not have much influence or impose great limitations for antenna design. In the early 2000s, antenna design for mobile handsets completely changed its course and internal design became the next design evolution, as it was very appealing in terms of industrial design. However, new design challenges started to haunt engineers from many disciplines, including RF, audio, and of course antenna engineers. As expected, the integration of antennas inside the phone created interference and noise problems that had to be controlled. Furthermore, antenna design was now limited within the shape of the phone. Nonetheless, these challenges were surpassed with the help of new technologies and the fantastic creative mind of antenna engineers.

2.4. Requirements and Regulations. Requirements are an important part of mobile handset designs. Operators rely on their sets of specifications to make sure that the phones they sell work well in their network. Phone manufacturers have to make sure that they meet operator's requirements. Up to the 3rd generation wireless standards, antenna performance only was measured by two quantities: TRP and TIS. TRP is a measure of how much power is radiated by the antenna when it is connected to a transmitter. TIS is defined as a measure of the smallest power that can be input to the receiver so that the receiver can still maintain a reliable communication link. For example, the communication link reliability for the GSM standard is defined using a bit-error-rate (BER) level at 2.4%.

Figure 2: A model of the specific anthropomorphic mannequin (SAM) head.

Operator's requirements have evolved over the years. There are several reasons why this evolution occurred. Ultimately, operators, as well as phone manufacturers, know that the phones need to perform well under the real environment condition of the user holding the phone against his or her head. However, it is not possible for operators to rely on performance measurement from phone manufacturers using a human head and hand grip of a real person as each person's head and hold would differ from one to another. A focus group was needed to investigate on how to come up with a standardized model of a human head and hand. One such organization is the CTIA—The Wireless Association [2]. A subgroup in this organization was created to come up with a set of a standardized head and hand for the purpose of obtaining consistent and reliable performance measurement in a controlled lab environment. While this work was under study, operators had to rely on measured TRP and TIS in a free-space condition.

The phantom head model, called SAM (Specific Anthropomorphic Mannequin), was first introduced in 2002 (Figure 2). The material inside the plastic shell has specific electrical properties, that is, dielectric constant and conductivity that are modeled closely to the real human head. Modeling the hand was more difficult and it took longer to get to the final set of phantom hands (Figure 3).

Operators from around the world had different requirements and, when they decided to adopt new measurement conditions for their requirements, it was not at the same time. Antenna designers had to face the challenge of designing antennas with performance that had to meet various operators' requirements with different environment conditions.

Figure 3: Examples of phantom hand models.

Figure 4: SAR measurement system. The wireless handheld device radiating RF power is attached to a phantom cheek. A probe measures the electrical field generated by the device inside a phantom filled with liquids emulating the human tissue at the frequencies of interest.

In certain phone designs where the antenna is external or when there is enough antenna volume for the internal antenna design, it is not a problem to meet all operators' requirements. When the design is limited due to industrial or mechanical designs, then antenna variants for different markets are needed, each one of them meeting the operator's requirements of their market while the over-the-air (OTA) performance in the roaming market can be relaxed a little bit.

A good example of antenna design change due to a requirement modification is when the operator AT&T changed the cellular antenna requirements from free-space to talk position (with the phone placed against the phantom head). In order to come up with an attractive handset design and still meet operator's OTA performance requirements and other regulations, Motorola came out with a thin phone with the cellular antenna in the bottom of the phone. Placement of the antenna in the bottom of the phone allowed them to design a thin form-factor handset and still meet the operator's requirement with great performance in the low band (824–894 MHz). That year marked the change in antenna location in antenna design.

Requirements are specific to operators. Handset manufacturers must also meet the broadcasting and RF emission regulations that are specific to countries. For example, the Federal Communication Commission (FCC) [3] has duties of regulating RF emissions in the United States. A few regulations pertaining to mobile phone radiated emission and antennas include SAR (Specific Absorption Rate) compliancy, HAC (Hearing Aid compliancy), and GPS E911 requirements.

SAR relates to the near E-field effects of the antennas (Figure 4). FCC regulations mandate that all phones used in the United States must meet a SAR limit of 1.6 W/Kg averaged over a volume of 1 gram of tissue [4]. In some other countries, the SAR limit is 2 W/kg averaged over a volume of 10 grams of tissue [4]. The SAR requirement can be a show stopper for phone manufacturers. They must meet the regulations or else the phones cannot be released to the market. Antenna designers have to make sure that such regulations are met. One way to reduce the SAR value is to decrease radiated power. This is done by reducing the transmit power or detuning the antenna impedance so that antenna performance is degraded. However, this technique of SAR reduction would impact the OTA performance and may cause a failure to meet the operators' OTA requirements. Fortunately, there are other techniques. The general idea is to reduce the E-field towards the head. One example that helps reduce SAR in the low band (850 MHz band) is moving the antenna located on the top of the phone to the bottom. A phone with good OTA performance and a thin form factor design would have a very difficult time to meet the SAR limit if the cellular antenna was placed on the top of the phone. This is another important factor of the antenna location.

Regulations in the United States for interference with hearing aid devices due to wireless mobile handsets were imposed on phone manufacturers and operators around 2006 [5]. There are two kinds of interference related to HAC: T-Coil and RF emission. Interference due to T-coil is taken care of by acoustics engineers and relates to the coupling effect between the coil in the handset earspeaker and that of the hearing aid. Antenna engineers have to deal with the RF emission interference, precisely the near E- and H-fields emanating from the cellular antenna around the earspeaker of the phone. These fields are measured within a 5 cm by 5 cm squared area centered 15 mm above the phone earspeaker [6]. They are required to be below a certain strength level in order to be compliant. Just like the SAR problem, antenna engineers have to find ways to reduce the near fields around the earspeaker without affecting the OTA performance of the phones.

Another antenna challenge relating to regulations pertains to the Enhanced 911, or E911. This mandate from the FCC organization was created to assure that, when calling 911 for an emergency, the user can be geographically located with a certain amount of accuracy within 30 seconds after dialing 911 in the United States. In order to locate a user this fast, a standalone GPS system is not enough. The system needs some assistance from the network to acquire the required location accuracy within a small amount of time. This system is called assisted-GPS (aGPS). Regardless of whether the system is standalone or assisted, the most important parameter in the system is antenna performance. The GPS antenna has to be designed in such a way that, under the use-case condition, its radiation pattern has a good coverage of the sky, where the GPS satellites are. Even though the aGPS system generally works with ease under the open-sky environment, that is, no obstruction between the sky and the system, the difference between good and bad antenna design can be seen when it comes to testing it in the urban and indoor environments.

There are other requirements and regulations specific to operators and countries, but the ones just previously described are the challenging ones that antenna engineers have to deal with during the concept design phase and development of antenna systems in wireless mobile handsets.

2.5. Antenna Design Challenges in Today's Smartphones. The previous sections highlighted some challenges that antenna engineers have had to face in antenna design for phones. These challenges are not getting easier in today's mobile handheld devices. Smartphones are becoming a universal device that subscribers want to have. These devices are packed with a great amount of applications. They are no longer just a simple phone. Examples of such applications include data communications such as internet browsing, movie streaming, email access, navigation system, remote control, geotagging in photoshooting, and a payment system. All these applications need the use of an antenna built in the smartphone, whether it is a cellular, Bluetooth, WiFi, GPS, NFC, or FM antenna. The obvious challenge is to design all the necessary antennas inside a compact device. Placement of these antennas is crucial to the design as coupling between antennas needs to be minimized. Another design challenge in compact devices is the additional NFC antenna needed for near-field communication such as the payment system, FeliCa, in Japan. This NFC antenna is conventionally made of a coil resonating at 13.56 MHz. The coil is generally designed on a ferrite sheet to minimize Eddie current created by the coil on any metal surface underneath the NFC antenna. Big coils and ferrite materials can often cause performance degradation in other antennas located nearby, which can complicate other antenna designs as space can become more limited.

As mentioned in the previous section, creating a controlled environment for testing over-the-air performance in labs needs to be close to the real use-case environment. Operators are now starting to adopt and create requirements for OTA phone performance testing in the talk position, including the phantom hand (Figure 5). Even though one hand-grip testing does not represent the entire spectrum of hand grips from real users, it is still one step closer to capturing performance effects of a real use-case condition. This new requirement forces antenna engineers to pay attention to the effect of the hand on the antenna performance so that a system can be designed to satisfy the requirement.

The next-generation smartphones that are LTE-capable further increase the level of challenge involved in antenna design. For an LTE system in phones, a second antenna, for receive diversity, is needed, along with a primary cellular antenna. Both antennas are operating in the same frequency band. That is an additional antenna to design in a small device that is already populated with multiple antennas. For MIMO design, antenna efficiency, antenna isolation, gain imbalance, and correlation between the two antennas are important parameters in designing antennas for the LTE systems. In MIMO systems, optimal system gain is obtained if the two antennas are totally uncorrelated, have similar gain performance, and are uncoupled. Increasing the antenna space can help reach optimal performance. However, in phone design, space is limited. Fortunately, operator requirements can tolerate the secondary receive antenna having an antenna efficiency level of about 3 to 6 dB below that of the primary. This is helpful for the secondary antenna design as its efficiency does not have to be as good as that of the primary antenna. However, isolation and correlation remain the challenging tasks to work on.

Figure 5: Over-the-air phone testing in the talk position, including the phantom hand.

Correlation is mostly dependent upon the far-field antenna pattern. Radiation pattern characteristics at frequencies of 1500 MHz and higher are generally dependent upon the antenna location. This means that, at higher frequency, the radiation patterns of the two antennas can be very different with enough distance separation between them and therefore it is generally not an issue in meeting the operators' requirements at LTE bands higher than 1500 MHz. The challenge still remains for LTE bands at frequencies below 1000 MHz. This is because the radiation patterns at these frequencies have somewhat similar characteristics, no matter where the antennas are placed within the real estate of the phone design. The reason to this similarity in characteristics is because the PCB, or ground of the antenna, is the main radiating element at frequency below 1000 MHz for a typical phone length. Operators target an envelope correlation coefficient (ECC) of 0.5 as their requirement.

Isolation is also a challenge in smartphones at frequencies below 1000 MHz due to antenna small electrical distance separation. If not designed well, the overall efficiency of both antennas can degrade dramatically and instead of designing a system that gives additional processing diversity gain performance, one can end up with a system that has a similar or worse performance to a conventional system with one antenna.

LTE systems are data centric. At this stage, voice is not supported on the LTE network. Voice-over-LTE (VoLTE) is still in the test phase and is not yet deployed. Therefore, there is no simultaneous data communication over LTE and voice communication. For a 3G UMTS smartphone that has additional LTE bands, simultaneous data and voice can only be done in 3G. So, if a phone call is received and a user answers during a data connection over the LTE network, then data connection has to fall back to a slower speed in the 3G UMTS network. One operator, that is, Verizon Wireless in the United States, takes it one step further to have a design that is capable of having simultaneous voice in the CDMA network and data communication over their LTE network. The reason for this design is that their CDMA network does not allow simultaneous voice and data communication. One antenna is designed for voice in the 850- and 1900-MHz bands, and for the receive diversity for the LTE band at 750 MHz. The other antenna is designed to be the primary transmit/receive antenna for data communication at the LTE band and EVDO CDMA bands. This is a complex and challenging system to design for a smartphone and to meet not only all the operators' OTA requirements but also the SAR limit for simultaneous transmission, which is still at 1.6 W/kg average over 1 gram of tissue.

An overview of the challenges and issues antenna engineers have to face during the concept and development phases of wireless mobile handsets was discussed. From the beginning of the history of mobile phones, the challenge level for designing antennas has never decreased. There has always been a constant increase in the number of challenges from one generation to the next. In the midst of all this, the extraordinary creativity of the antenna designers has helped them overcome all the challenges that have led from the design of a wireless mobile device with a large external single-band antenna design to a small and slim device with multiband and multiantenna systems.

3. Verifying Designed Performance: Handset Antenna Characterization

Antenna characterization has experienced a rapid development through the last couple of decades, and a large part of antenna measurement development has been caused by the introduction of handset antennas. For traditional antennas, such as those used for radars, point-to-point links, or macrocell base stations, the radiation pattern is of great importance. Those types of antennas are specifically designed to direct energy in a certain direction and avoid spilling energy in other directions.

Handset types of antennas are by nature electrically small, which means that they exhibit more or less omnidirectional radiation patterns due to the small size of the radiating element. This is not necessarily a bad thing; handset antennas are used in an arbitrary orientation with signals arriving to the device from arbitrary directions, and there is a benefit in collecting as much of this energy as possible. Therefore, designing handset antennas towards a specific radiation pattern is of less interest. Hence the parameters used to characterize handset antennas have somewhat different focus than those used for the traditional types of antennas mentioned above.

Another shift in antenna characterization is ongoing right now. This shift is caused by the introduction of multielement antennas, which are used to facilitate antenna diversity or MIMO communication. Still, the same basic characteristics as for single-element handset antennas are important, but these are complemented with additional parameters to validate the antennas functionality in the modern communication system.

3.1. *Figure-of-Merits for Wireless Handheld Devices.*

There are several figure-of-merits (FOMs) which are interesting for characterization of wireless handheld devices.

The FOMs can be divided into passive and active parameters, where the former are antenna only parameters, and the latter include radio circuitry. This division reflects another fundamental difference between the two groups of FOMs, which is that the passive antenna parameters are component values, whereas the active parameters are composite values combining performance of several components into a single value.

3.1.1. *Passive Antenna Parameters.*

Commonly used passive antenna parameters are

(a) radiation efficiency [7],

(b) impedance mismatch [7],

(c) signal branch correlation [8],

(d) diversity gain [8],

(e) MIMO capacity [8].

The first two are traditional antenna parameters applicable to all types of small antennas, whereas the latter three are relevant for multielement antennas (MEAs). This does not mean that the two former parameters are less important for MEAs. On the contrary, radiation efficiency is still the most important design parameter for electrically small antennas.

Radiation efficiency of an antenna is basically the ratio of power radiated from the antenna to the delivered power to the antenna feed, which means that it is a description of the internal losses of the antenna element. This means that the radiation efficiency goes directly into the link budget of the communication system and therefore has a direct impact on the performance of the system.

Radiation efficiency is often paired with impedance mismatch as the most useful design parameters for antennas in wireless handheld devices. Total radiation efficiency (sometimes also called antenna efficiency) is a combination of these two, defined as the product of the radiation efficiency and the efficiency due to mismatch.

It is applicable to talk about radiation efficiency also in the case of MEAs. The most proper way to characterize the efficiency of each element of an MEA is to look at its performance when the other elements are present, in order to fully account for loss due to mutual coupling between elements. Such radiation efficiency that accounts for mutual coupling can be referred to as Embedded Element Efficiency, where the embedded prefix denotes the presence of other nearby antenna elements.

Signal branch correlation is applicable to antennas with two or more branches and is a measure of how uncoupled the antenna elements are. It is calculated as the cross correlation between the signals received on two separate antenna ports. The signal branch correlation, as well as radiation efficiency and impedance mismatch, is example of component parameters, that is, parameters directly showing the performance of a certain part of the communication system.

Diversity gain and MIMO capacity, the two latter passive parameters in the list above, are actually composite parameters determined by the first three passive antenna parameters just mentioned: radiation efficiency, mismatch, and correlation. In the literature, there are a few definitions of diversity gain to be found, and it is important to apply these definitions in a correct way in order to draw justified conclusions from a set of data. The basic difference between different diversity gain definitions is how the radiation efficiency is embedded in the parameter. The three basic definitions of diversity gain are Apparent Diversity Gain, Effective Diversity Gain, and Actual Diversity Gain, where the difference is the reference from which the diversity gain is calculated [8]. The reference can either be one of the diversity branches (Apparent Diversity Gain), an ideal single reference antenna (Effective Diversity Gain), or any practical antenna to be replaced (Actual Diversity Gain).

Note that the passive parameters discussed here are integral quantities, based on the assumption of a statistically isotropic multipath environment surrounding the antenna. This type of environment is especially useful for handset antenna characterization, not only due to the similarity to the environment where most handsets are used, but also due to that a handset is arbitrarily oriented due to individual preferences of the users. This environment can be referred to as Rich Isotropic MultiPath environment (RIMP) [9].

In some cases, there is interest in creating the integrated parameters over other types of spatial distributions. An example of this is the Mean Effective Gain parameter which can be described as radiation efficiency weighted with respect to a certain angular distribution of incoming waves to the antenna under test [10].

An extreme in the sense of spatial distributions is the pure Line-of-Sight environment, where there is a single signal component arriving at the antenna under test. This is the direct opposite of the RIMP environment mentioned above, meaning that these two environments complement each other. The difference between these two environments is how they impact a multiantenna system such as diversity or MIMO. An example of a LOS parameter is the LOS diversity gain [11].

3.1.2. Active Antenna Parameters. Commonly used active antenna parameters are

(f) Total Radiated Power (TRP) [7],

(g) Specific Absorption Rate (SAR),

(h) Total Isotropic Sensitivity (TIS) or Total Radiated Sensitivity (TRS),

(i) Average Fading Sensitivity (AFS) [12],

(j) Data bit throughput (TPUT) [13].

Figure 6: Anechoic chamber having a gate with 31 probes to electrically measure the radiation in one plane radiated by the device under test. The device under test is rotated so as to have the full 3D data.

The three first parameters of active antenna parameters listed above can at this point all be considered traditional characterization parameters for wireless devices. Both TRP and TIS can be directly related to the total radiation efficiency of the device antenna and are therefore commonly used parameters to characterize the radiation efficiency of devices without a direct external cable connection to its antenna. SAR is a bit different from other antenna parameters described in this section of the paper, since it is not a pure over-the-air parameter but a measure of the absorption rate of power in simulated human brain tissue.

TIS is originally a single antenna parameter but it is possible, when measuring TIS in a multipath scattering environment as the reverberation chamber, to extend the measurement to include multielement antenna performance. That is, exactly the same measurement procedure as used for single element TIS will include the performance improvement offered by the multielement implementation, as long as the measurement is performed in a multipath scattering and with the multiple signal combination activated in the device.

The last parameter, data bit throughput, has attracted considerable interest in MIMO-OTA discussions in the antenna community over the past few years, mainly because of its close link to end-user experience. The basic principle behind this type of throughput measurement is to create a scattering environment in which the unit experiences fading and sample the data throughput over time to get a statistical value of what data bit rate the unit can support given a certain average available power. The measurement chamber needs in this case to work as a spatial channel emulator, and there are several ways of achieving this either with existing measurement setup (like reverberation chambers), or modifications of existing chambers (like anechoic chambers).

Data bit throughput is essentially equal to an error rate measurement taken over a fading sequence, whether it is bit

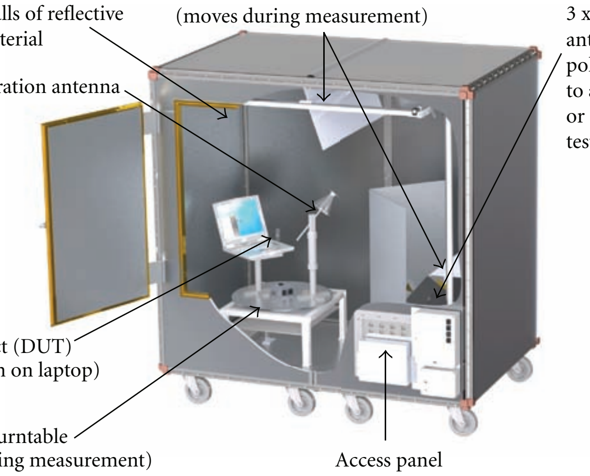


Figure 7: Reverberation chamber configured for measurements of antennas for wireless handheld devices.

error rate (BER), packet error rate (PER), frame error rate (FER), or block error rate (BLER). The process of sampling the error rate specifically during a fading sequence has been referred to as Average Fading Sensitivity (AFS) and is then very similar to how data throughput measurements are performed today. It is interesting to note that there is a relationship between the AFS and TIS value of a device.

3.2. Measurement Methods of Antennas for Wireless Handheld Devices. There are two dominating range types for small antenna measurements; anechoic chambers and reverberation chambers. Although many of the parameters accessible through measurements in these two chamber types are identical, the methods themselves work in diametrically opposite ways.

In an anechoic chamber, everything but the direct signal from the measurement antenna to the antenna under test is removed, hence the name of anechoic chamber; no echoes exist in the measurement setup. To measure any integral parameter, the antenna under test is rotated to cover all different angles of arrival at the antenna. The integral parameters described above are then calculated from the information given in each angular direction (Figure 6).

The reverberation chamber on the other hand is fully reflective and creates a field with many angles of arrival present at the same time, that is, a lot of echoes but no direct signal path. As the so-called mode stirrers are moved, signals will combine in different ways, and over a full stirring sequence all angles of arrival will be equally probable. Hence the integral parameters described above can be extracted as a direct result of a measurement sequence. Figure 7 shows an example of how a reverberation chamber looks like.

Figure 8 shows the schematic setup for anechoic and reverberation chamber measurements, respectively. Note that the instrumentation is similar between the two methods.

With the current trend of creating fading channels to test handset antennas, there is much work ongoing to modify the anechoic chamber to facilitate multipath fading in the originally pure LOS environment. The proposed method means placing a ring or sphere of probes in the anechoic chamber and feed signals through these antennas so that a specific fading profile is created in the center of the test volume. The drawback with this modification is that the chamber has to be converted back to a normal anechoic chamber, that is, removing the additional probes, before traditional antenna parameters can be measured, so most of MIMO-enabled anechoic chambers are likely to be dedicated to MIMO testing only.

Reverberation chambers have an inherent multipath fading due to its reflective nature, and therefore MIMO OTA measurements can be performed without any other modifications than adding fixed measurement antennas to facilitate the MIMO signaling.

Figure 9 shows the schematic setups for MIMO OTA measurements in reverberation and modified anechoic chambers. Note that both measurement setups are equipped with channel emulator to control the fading. In modified anechoic chamber, the channel emulator is essential in order to create the fading, and it is done by feeding prefaded signals on each of the probes in the chamber. In the reverberation chamber the channel emulator is optional due to its inherent fading, but the channel emulator gives a wider range of possible power delay profiles in the measurement setup.

Table 1 shows a compilation of the different measurement methods and which figures of merit used for design of small antennas are applicable for each method.

4. Antenna Technology for Wireless Handheld Devices

The massive incorporation of wireless handheld devices such as mobile phones in our lives has changed their functionality conception. Nowadays, mobile phones are not only used to communicate, but they also offer a big range of services such as digital camera, video player, internet connectivity, geolocalization, TV services, or FM radio. In this regard,

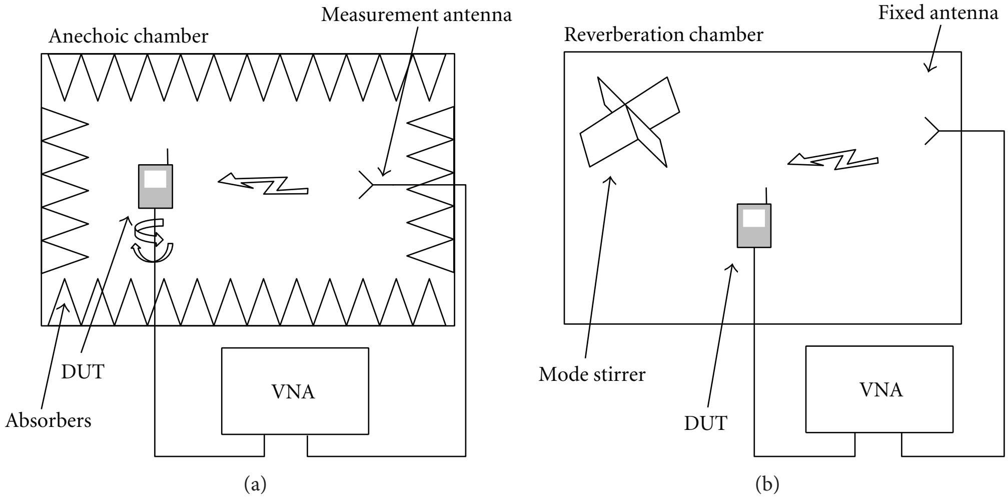


Figure 8: Example measurement setups for passive (cable-fed) testing of antennas for wireless handheld devices. For active device testing the DUT is replaced by a functional handset, and the vector network analyzer (VNA) is replaced by a base station simulator.

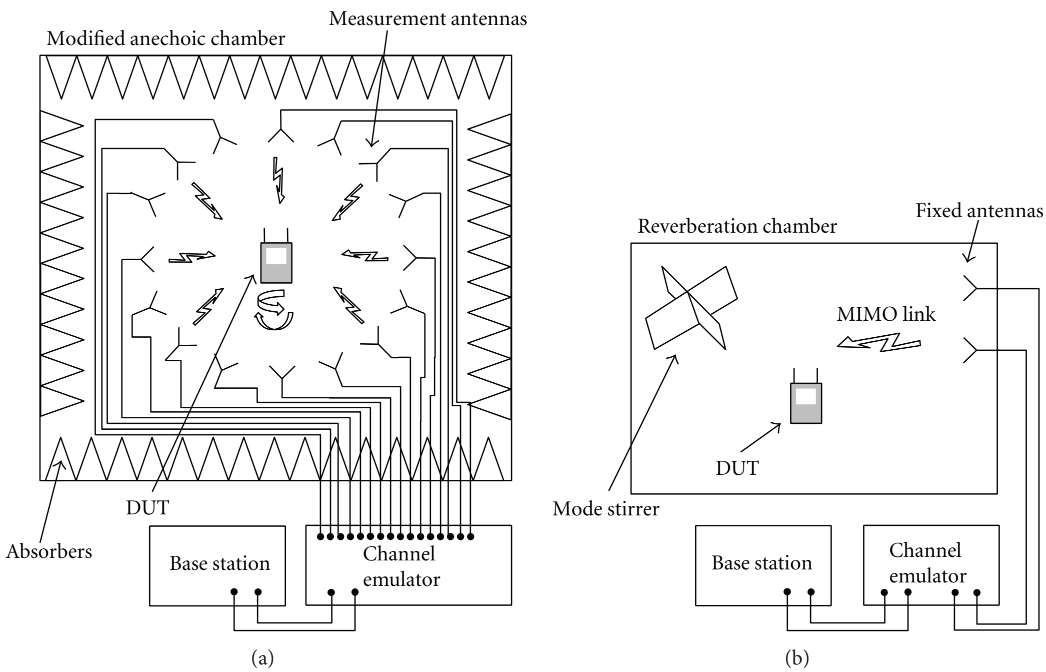


Figure 9: Example measurement setups for active MIMO testing of antennas for wireless handheld devices.

antenna industry as well as academic areas are being forced to evolve constantly to obtain small and multiband antennas capable of radiating efficiently in such a hostile environment. On one hand, the volume constraints in wireless handheld devices produced by the reduction of the available space due to the existence of multiple components (such as displays, batteries, speakers, and shieldings) must be considered for optimizing the antenna performance. On the other hand, user interaction also needs to be taken into account from two perspectives. Firstly, the amount of power absorbed by the human body, especially the head and hand, has to be minimized. Secondly, the antenna needs to be robust to such human interaction which causes power absorption and/or detuning effects. Minimizing power losses is an important aspect since they produce higher battery consumption and eventually call drops.

With the objective of reviewing several antenna applications that can be found in current or emergent wireless handheld devices, this section is divided into three main parts. Firstly, antennas for reception applications are discussed, in particular for FM reception (88–108 MHz). Secondly, a brief discussion on antennas for short-range wireless applications is presented, and finally a summary of some advances in the field of handset antennas is disclosed.

Table 1: Measurement methods for characterization of antennas for wireless handheld devices and applicable figures of merit for respective method.

FOM	Table ref.	Reverberation chamber	Anechoic chamber	Multi-probe MIMO setup in anechoic chamber
Radiation efficiency	a	Yes	Yes	No
Impedance mismatch	b	Yes	Yes	No
Signal branch correlation	c	Yes, calculated direct from received signals	Yes, calculated from radiation patterns	Yes, calculated direct from received signals
Diversity gain	d	Yes, direct from received signal distributions	Yes, calculated from radiation patterns	Yes, direct from received signal distributions
MIMO capacity	e	Yes, from received signal statistics	Yes, from radiation patterns	Yes, from received signal statistics
TRP	f	Yes	Yes	No
SAR	g	No	No	No
TIS or TRS	h	Yes	Yes	No
TIS/TRS including diversity reception	h	Yes	No, no multipath fading in anechoic chamber	No
Average fading sensitivity (AFS)	i	Yes	No, no multipath fading in anechoic chamber	Yes
Data bit throughput (TPUT)	j	Yes	No, no multipath fading in anechoic chamber	Yes

4.1. Broadcast Antennas: FM. The main challenge of designing antennas for providing operation in the FM service mainly relies on size limitations. Regarding the FM service, a conventional monopole antenna ($\lambda/4$) operating at FM frequencies is 75 cm length, which is too long for being integrated in a handset phone. In order to overcome this limitation, some mobile phone manufacturers incorporate the FM antenna in the wire of the headsets, but this solution goes against having a fully integrated wireless handheld device. Other solutions found in the literature propose the use of active schemes [13], thus resulting in an undesired increment of the battery consumption. In order to solve the aforementioned shortcomings this section explains two techniques for designing internal antennas at the FM band based on

(i) nonresonant elements [14–16],

(ii) reusing a PIFA antenna operating at mobile communication services [17, 18].

4.1.1. Nonresonant Elements. The authors of [15, 16] describe the problem of designing a resonant antenna such as a spiral at the FM band taking into account the reduced space of a PCB (Printed Circuit Board). Since the available space is limited, coupling between antenna tips forces the need of increasing the total length in order to attain the desired resonance, thus resulting in a length larger than $\lambda/4$. For example, to attain resonance at 100 MHz in a 40 mm $\times$ 20 mm $\times$ 5 mm antenna volume, a length of 2262 mm is needed, which becomes larger than a quarter of a wavelength at this operating frequency ($\lambda/4$ = 750 mm) [16]. Moreover, due to the aforementioned volume constraints, the width of the antenna has to be thin. Such constraint in the design width can considerably increase ohmic losses, thus producing a poor radiation. In order to solve these limitations, the proposed idea substitutes a resonant antenna by a nonresonant antenna inspired in the Hilbert geometry with a high-Q inductive element that brings the antenna to resonance. With this approach, better efficiency is obtained (around 20 dB more). Although the efficiency for the nonresonant element is around 1%, this result is still acceptable for FM reception for two reasons. First, the transmit power for FM broadcast tower is in the order of KW. Second, the free-space loss for FM is not as critical as other telecommunication services such as cellular communications (GSM); for example, at 100 MHz, the free-space loss is approximately 20 dB less than at 900 MHz. As a result, more power is available in the air. With this condition, a small compact antenna for FM reception inspired in the fractal geometry of the Hilbert curve is proposed, which becomes suitable for being integrated in current wireless handheld devices thanks to its reduced dimensions of just 30 mm × 10 mm × 1 mm (Figure 10).

Besides the common electromagnetic parameters such as SWR (Standing Wave Ratio), radiation patterns, and efficiency, another figure of merit is proposed to evaluate the performance of antennas for FM reception. It consists of demodulating the RF signal to an audio signal. This procedure is presented in Section 4.1.2 where the performance of the proposed Hilbert antenna is compared to the performance of a $\lambda/4$ monopole concluding that the Hilbert solution offers a similar audio quality of the received signal with the advantage of its reduced size and its integration capabilities.

4.1.2. Reusing a Mobile Antenna. This section introduces a solution for integrating an FM receiver antenna in a wireless

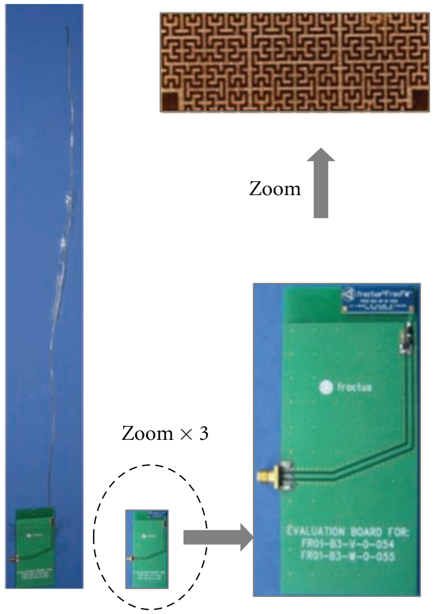


FIGURE 10: External wire (75 cm length) and internal FM Chip Hilbert antennas (30 mm × 10 mm) integrated within a typical smartphone platform [19–21].

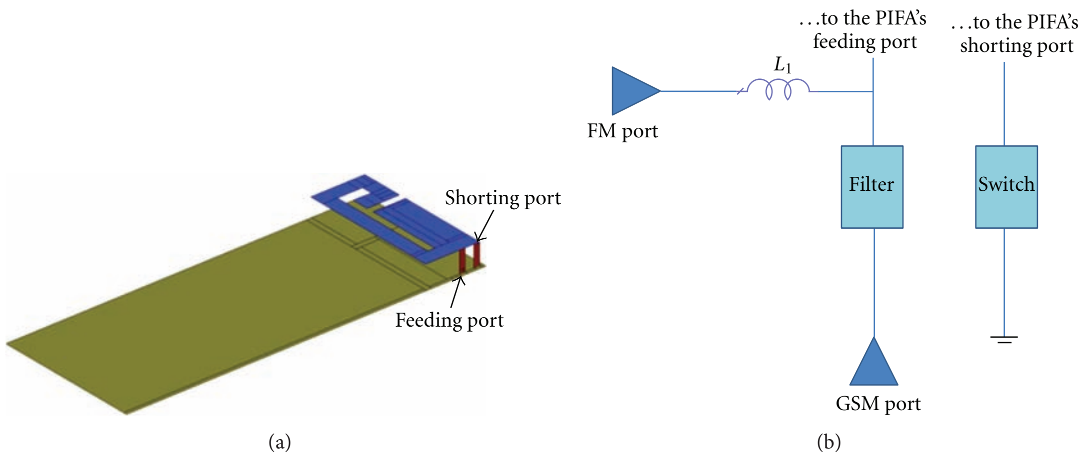


FIGURE 11: (a) 3D view of the PIFA. Ground plane size is 100 mm × 40 mm and PIFA is 38 mm × 15 mm × 6 mm; (b) proposed matching network including a switching circuit, a filter, and a series inductor.

handheld device that goes one step beyond. The proposed technique is focused on reusing an existing antenna operating at cellular bands. In this sense, a PIFA (Planar Inverted F Antenna) designed to operate at two GSM standards (900 and 1800 MHz) (Figure 11(a)) can be reused to become operative at the FM band [15]. The PIFA behaves as a nonresonant element at FM frequencies. The required 75 cm length needed to behave as a $\lambda/4$ monopole is far from the PIFA's dimensions. Therefore, a high series inductor is added in order to compensate for the capacitive behavior of the PIFA at FM frequencies (Figure 11(b)).

The PIFA has a feeding port and a port which short-circuits the antenna with the ground plane. In order to guarantee a good response in the FM band, the shorting connection must be removed because the distance between ports is electrically small at these frequencies, producing a short-circuited antenna with poor electromagnetic performance at the FM band [18]. To guarantee good radiation in the desired frequency bands (FM and GSM900/1800), a matching circuit is needed (Figure 11(b)). The PIFA used here does not need any matching network at GSM frequencies but a 1000 nH series inductor is required at FM. Both ports are isolated by means of a filter and the series inductor. The filter is designed to only reject the FM signal at the GSM port because the GSM signal in the FM port is already rejected due to the series inductor that presents high impedance at GSM frequencies. Finally, a switching circuit is needed in the short port in order to disconnect the antenna from the ground plane when it is operating at FM band.

In [13], it was demonstrated that a high received power does not mean necessarily a better signal quality. In some cases, a low received power offers satisfactory audio

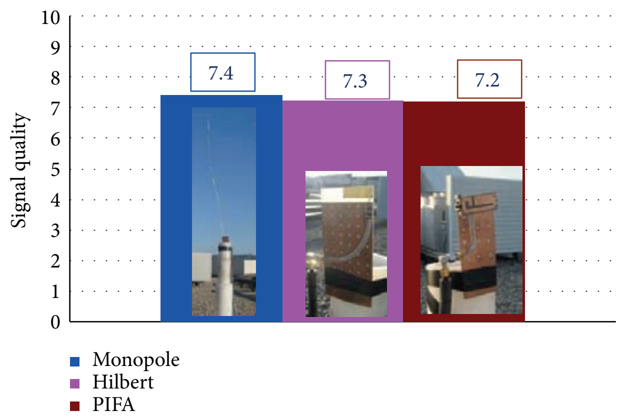


Figure 12: Marks obtained through the quality evaluation after averaging 28 FM channels.

reception, whereas a high received power presents low SNR (Signal-to-Noise Ratio) leading to a decrement of the quality audio reception. For this reason, a subjective procedure [19] for evaluating the demodulated signal quality has been carried out regarding the PIFA, the 75 cm length monopole, as well as the previous fractal-inspired Hilbert-based monopole [20, 21].

This procedure consists in quantifying the quality of the FM signal received by the antenna being tested. The signal quality indicator is ranked from 0 to 10 depending on the quality of the FM channel heard by the user [19].

Despite having the highest received power, the monopole's final evaluation does not differ from the other ones. The final mark for the $\lambda/4$ monopole is 7.4, the final mark for the Hilbert antenna is 7.3, and finally the PIFA's mark is 7.2 (Figure 12), having the advantage that this antenna can also operate in the mobile communication bands.

It is interesting to outline that human body has been also taken into account concluding that, in some position such as holding the device with the hand, the overall efficiency is improved by 10 dB [22, 23]. This improvement is due to the fact that at this low frequency ranges, the human body acts as a dielectric antenna with a size comparable to the wavelength of operation, thus becoming an efficient radiator (a human body of 1.7 m at 100 MHz is 0.56λ).

In conclusion, the PIFA offers the same satisfactory performance as the reference monopole and it ensures the integration of the FM antenna in wireless handheld devices. Moreover, other handset antenna techniques, such as the slotted ground planes (as described in the following sections), can be used in combination with the PIFA to obtain a heptaband antenna (FM, GSM 850/900/1800/1900, UMTS, and Bluetooth/Wi-Fi).

One of the major advantages of the proposed technique is that no extra antenna is needed because the existing mobile antenna is reused.

4.2. Short-Range Wireless. Short-range wireless generally refers to those applications characterized in that they have small transmitted power (order of mW), indoor operation, range of meters, and limited bandwidth (about 4% for Bluetooth application). Examples of short-range wireless systems are Bluetooth, WiFi, ZigBee, and RFID. The vast majority of wireless handheld devices incorporate a short-range wireless antenna for Bluetooth/WLAN services. Antenna size is again an important aspect to consider since the center frequency of operation for Bluetooth is 2.45 GHz, meaning that a $\lambda/4$ antenna is 30 mm. Such antenna size is still large, considering the device's space limitation due to displays, batteries, speakers, as well as the need of integrating other multiple antennas such as the ones intended for mobile communication. Therefore, the challenge relies on making the antenna as small as possible to simplify its integration in a wireless handheld device while preserving its electromagnetic performance.

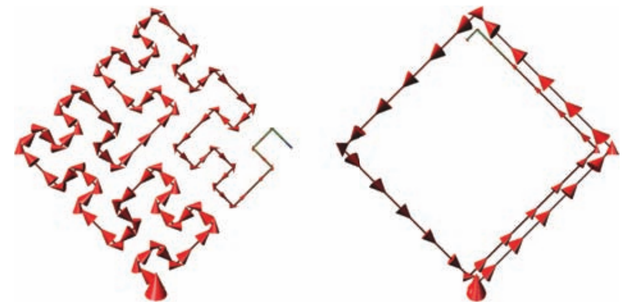


Figure 13: Current vector distribution of the antennas at the resonance frequency of $f = 84.5$ MHz.

In order to face the challenge of antenna miniaturization for short-range wireless applications, two categories described extensively in the literature are proposed:

(i) geometry based,

(ii) material based.

On one hand, geometry-based antenna relies on designing antenna geometries capable of taking the maximum profit of the available space. An example is found in space-filling geometries [24–36]. On the other hand, material-based antennas are focused on using high dielectric materials such as ceramics capable of providing the required miniaturization [37].

The suitability of space-filling geometries in the design of small antennas has been broadly investigated. In this case, small antennas like the Hilbert monopole are described extensively in the literature [24–36], to demonstrate that an antenna can become electrically smaller as the iteration increases. Using this type of miniaturization technique, it is possible to reduce the electrical size of a conventional quarter-wave monopole up to a factor of 11 [24].

To analyze the benefits of the Hilbert curve in designing small antennas, a comparison with a spiral antenna is carried out [31, 36] (Figure 13). Two antennas are designed to resonate at the same frequency of 84.5 MHz occupying the same footprint and having the same wire width. Although the spiral needs less wire for resonating at 84.5 MHz, the

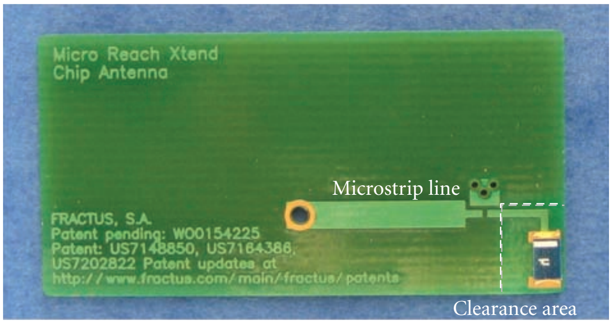


Figure 14: SMD space-filling-based antenna for 2.4-2.5 GHz applications. Antenna is 4.1 mm × 2 mm × 1 mm (4.1 mm is 0.033λ at 2.45 GHz).

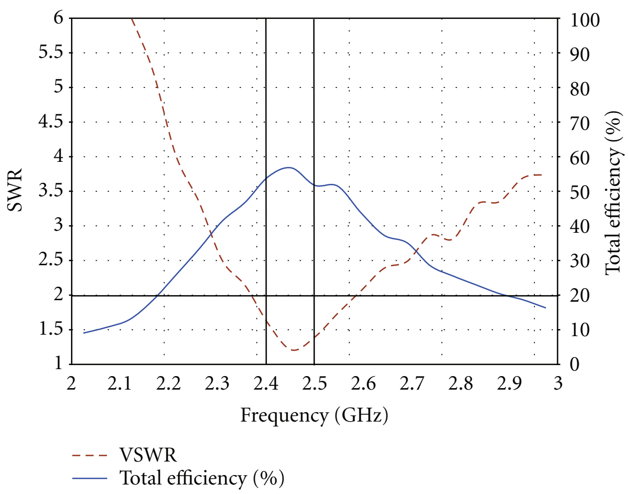


Figure 15: Measured SWR and total efficiency for the 2.4-2.5 GHz antenna shown in Figure 14.

bandwidth of the Hilbert antenna is 1.62 larger for the same radiation efficiency.

Thanks to its miniaturization properties, space-filling based antennas are suitable to make efficient, small, and multiband antennas. Some examples for short-range wireless applications (e.g., wireless headsets, cellular handsets, Bluetooth USB, and serial Dongles) are already adopted in industry (Figure 14).

Space-filling geometry-based antennas have been proven to be efficient radiators showing that, not only size and wire length but also geometry plays a role in the performance of a small antenna. A small antenna featuring 4.1 mm × 2 mm × 1 mm for 2.4-2.5 GHz operation shows a total efficiency more than 50% making it attractive for many wireless handheld devices (Figure 15).

4.3. Mobile Communications. This section discusses some antenna techniques for mobile communications. In the first part, some antenna types are presented based on monopoles, and combination of PIFA (Planar Inverted F Antenna) and slots. Second, an antenna architecture robust to hand loading is discussed. Third, the benefit of manipulating the ground plane is analyzed. Fourth, a particular matching network for enhancing the bandwidth is studied, and finally a novel antenna technology based on the use of compact elements for exciting the ground plane of wireless handheld device is presented.

4.3.1. Radiators. Nowadays, internal antennas such as patch/PIFAs and monopoles are the most common designs for handsets [37–42]. For PIFAs, several well-known techniques are used to provide dual-band or multiband operations such as shaping the radiating path or using slotted ground planes. This fact increases the complexity of the design and makes difficult their integration in slim platforms since, to guarantee good performance, the PIFA antenna has to be arranged at a certain height with respect to the ground plane, hence occupying a considerable volume (≈4500 mm^3). Monopole antennas are an alternative design to provide multiband operation in slim platforms mainly due to its low profile characteristics [43]. In this section two kinds of radiators are briefly discussed. The first one employs monopole antennas. The mechanism to obtain multiband and enough bandwidth is achieved by a structure based on driven parasitic elements. The second radiator combines a PIFA with a slot to make a modular design in the sense that the number of bands is controlled independently from each radiator.

Coupled Monopoles. The use of monopole antennas in wireless handheld devices has increased in the recent years thanks to its low-profile characteristics that simplify their integration in wireless platforms. Many designs have appeared in the literature and industry with the aim of covering the largest number of frequency bands as possible without reducing the antenna performance [44–50].

A multiband behavior (GSM850/900/1800/1900 and UMTS) is obtained with a technique using parasitic elements coupled to a primary driven element. At the same time, the proposal maximizes the space on the PCB to integrate other cellular components [51, 52]. The proposed antenna has also a planar profile which is attractive for slim platforms (Figure 16). The driven element is located closer to the ground plane, separated at a distance from the parasitic elements. The ground plane area located at the right side of the antenna provides a useful space to integrate some typical elements of this kind of devices, such as a camera or a speaker. On the other hand, the design takes into account the most critical variables when defining the operating frequency ranges. These variables are the element lengths and the gap between them, which determines their coupling effect. Furthermore, the location of the elements determines the correct behavior, especially at the low frequency bands (GSM850/GSM900).

Coupling between the driven and a parasitic element allows the apparition of an impedance loop in the Smith chart. By properly controlling the coupling between both elements, the performance can be wideband or multiband. Electrical models can be used to give a physical insight into the coupling mechanism [52]. In this particular case a first parasitic element is tightly coupled to the driven element to obtain two separated bands (Figure 16). Another

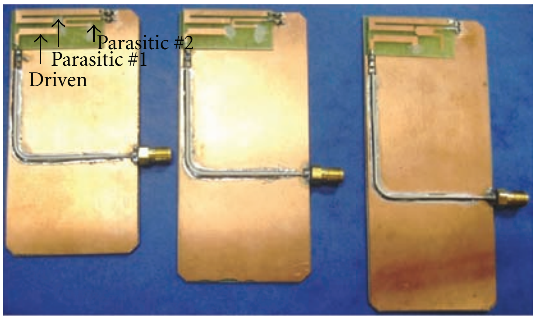


Figure 16: Prototypes regarding a ground plane of 45 mm × 90 mm, 100 mm, and 110 mm. The driven element is fed through a 50Ω transmission line.

parasitic element (parasitic #2, Figure 16) is weakly coupled to the driven to obtain a wideband at the upper region. It is interesting to outline that similar effect is found in microstrip antennas formed by a driven and a parasitic element. Therefore, the use of electric models is useful to understand the behavior of the impedance performance of antennas.

The design features a footprint of 35 mm × 15 mm and 1 mm height achieving pentaband behavior for GSM850, GSM900, GSM1800, GSM1900, and UMTS.

Combination of PIFA and Slots. PIFA and slots have been widely studied in the literature [38, 53, 54]. Basically, the PIFA needs a 3D volume to radiate efficiently whereas the slot antenna can be completely flat. However, due to the ground plane, the space underneath the antenna cannot be reused to place other handset components (such as a speaker, a battery, and shieldings) since they would affect significantly the antenna performance. In order to combine the benefits of PIFAs and slot antennas (planar structures), a concept that combines a PIFA with a slot antenna is discussed here. Other kinds of combination such as monopole and slot antennas using a self-complementary structure have been proposed in [55].

An illustration on how the concept works is shown next [56, 57]. Figure 17(a) depicts a slot in a ground plane having 100 mm × 40 mm. In this case, the slot is excited around 1900 MHz which results in a $\lambda/4$ slot antenna. The obtained bandwidth covers GSM1800-UMTS at SWR $\leq$ 3. Figure 17(b) shows a 900 MHz PIFA on the same ground plane. The feeding mechanism is in the same position used to excite the previous slot. Both designs are combined, that is, the PIFA and the slot share the same feeding mechanism (Figure 17(c)). The antenna combines both reflection coefficients (Figure 17(d)). To increase the bandwidth at the second band, slot width may be increased [58].

Since the PIFA has only one branch, the space can be reused to allocate more branches and therefore increasing the number of bands [56]. For this technique it can be concluded that

(a) number of bands = number of PIFA bands + number of slot bands,

(b) bands due to the PIFA and the slot can be adjusted independently.

This concept is based on a parallel excitation of a PIFA-slot that becomes particularly useful to design multiband handset antennas where the number of frequency bands is given by the sum of the bands given by each radiator. Moreover, said bands can be controlled independently which adds an additional degree of freedom to the design.

Thanks to the slot radiator, the PIFA volume can be reused to add more bands. With this structure, an extra band centered at S-DBM has been added to finally design a pentaband prototype including GSM900, 1800, 1900, UMTS, and S-DMB [56]. The total antenna volume is 39 mm × 11 mm × 2 mm (h). Results for total efficiency taking into account several components (battery, display, speaker, camera, and phone covers) are satisfactory and make this concept attractive for the new generation of low-profile multiband handset phones.

4.3.2. Robust Architectures to Hand Loading. The challenge for the antenna community is not only to design small-multiband antennas but also make them robust to human interaction, that is, to minimize the radiation toward the human body and make the antenna behavior independent, for instance, from the hand loading that detunes and absorbs the radiated power [59–62].

Several techniques have appeared in the literature. In [63], two strips are located at the edges of the PCB to make the system robust to hand loading. Some schemes propose the compensation of the finger effect by an antenna selection which requires a switching mechanism that involves an increment in the battery consumption [64, 65].

A technique named distributed antenna system is presented here to provide robustness to the hand-loading effect. The technique proposes a handset antenna architecture based on an array of small monopoles strategically arranged along a PCB in order to provide robustness to the human loading effect and, in particular, to the finger loading effect (Figure 18) [66–68].

It is well know from microwave theory that an array of in-phase radiating elements presents the same return loss at the input port of the feeding system as the return loss of the single element. However, if a phase delay is introduced, for example, to achieve a certain beam tilting, the bandwidth may be enhanced at the input port due to the nonconstructive sum of all the reflections coming from each radiator. This principle of array theory is applied here in order to obtain not only a broadband antenna, but also a more insensitive system to finger loading effect than the one using a single element.

The proposed system is completely passive, which in terms of simplicity and battery consumption is considerably advantageous.

Electric models have been used to give a physical insight on the broadbanding mechanism of the distributed antenna systems [69].

A prototype having a single monopole, another prototype comprising two monopoles, and a third one integrating three small monopoles combined in a single port are built and

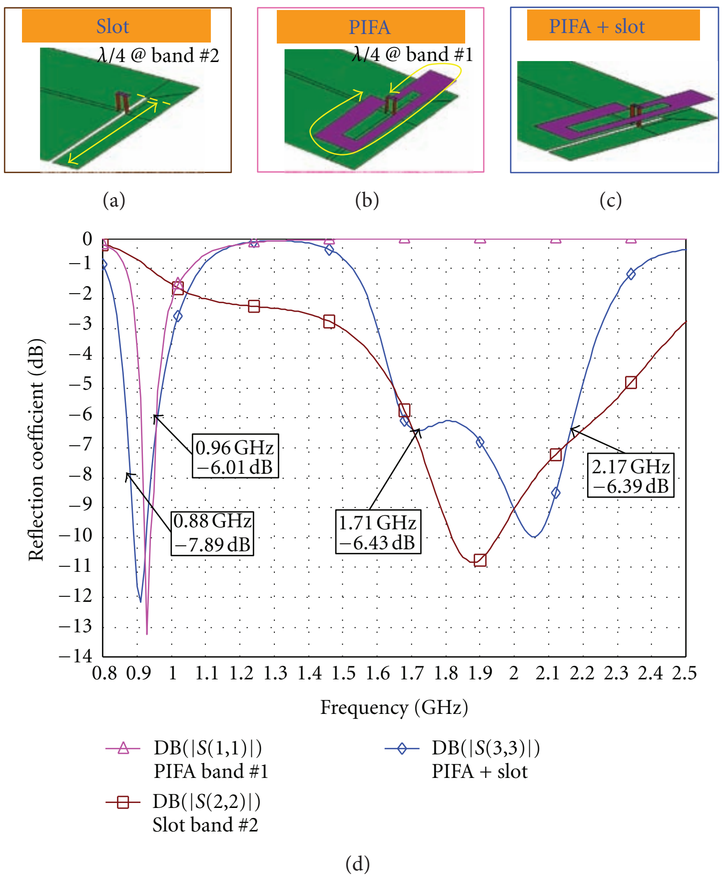


Figure 17: Sequence showing the antenna concept. (a) A slot on the ground plane is tuned at 1900 GHz (band #2); (b) PIFA is tuned at 900 MHz (band #1); (c) parallel excitation of both antennas (PIFA + slot); (d) reflection coefficient of the antenna system. Ground plane is 100 mm × 40 mm for all cases.

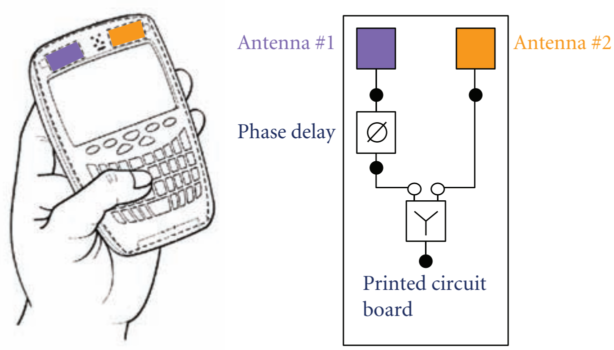


Figure 18: Illustration of a distributed antenna system having two elements placed at different locations of a handset device.

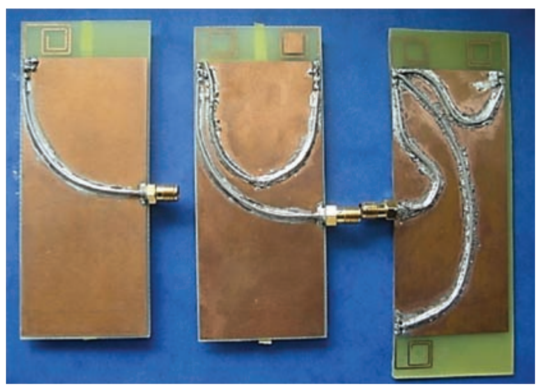


Figure 19: Single monopole (left); an array of two monopoles (middle); an array of three monopoles (right). Ground plane is 90 mm×40 mm printed on an FR4 substrate 1 mm thick. Monopoles are 13 mm × 11 mm.

measured in order to demonstrate the effectiveness of the proposal (Figure 19) [68]. The bandwidth (SWR ≤ 3) for the system with three monopoles is broader than that attained by the other prototypes. The bandwidth is 15.6%, 23.6%, and 34.0% for the single, two, and three antenna cases, respectively. It is worth to note that the three prototypes operate across the GSM850-GSM900 mobiles services. However, it should be taken into account that the array with three antennas operates also from 700 MHz to 824 MHz where neither the array of two antennas nor the single antenna present a good reflection coefficient. This is particularly useful for providing operation in the emergent communication standards, such as LTE700.

To determine the robustness to human loading, a hand phantom is used (Figure 20). The hand phantom is filled

(a) (b)

Figure 20: (a) Common holding position during a call; (b) the hand phantom emulating the real situation illustrated in (a).

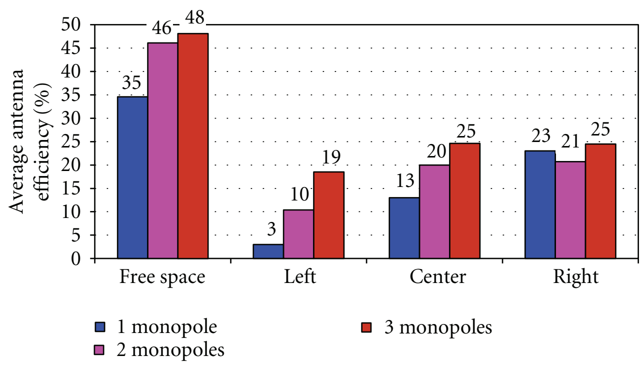


Figure 21: Comparisons of the measured average antenna efficiency (824–960 MHz) in free space and regarding hand loading for the proposed antenna systems depicted in Figure 19 and regarding the three positions of the finger.

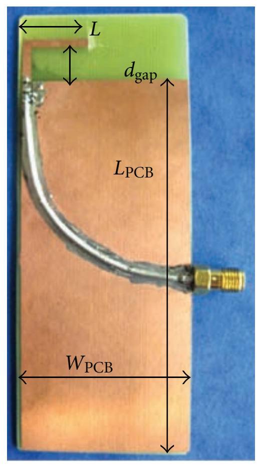


Figure 22: L-shaped monopole printed on a ground plane. The dimensions of the monopole antenna are $L = 23$ mm with a strip width of 2 mm, and it is located in the shorter edge of a PCB at a distance $D_{gap} = 4$ mm from the ground plane. The PCB dimensions are $L_{PCB} = 90$ mm and $W_{PCB} = 40$ mm.

with liquids emulating the electromagnetic properties of the human hand at the frequencies of interest [70]. Different experiments with the finger located 1 mm away from the antenna have been carried out considering three distinct positions: left, middle, and right. The palm is 20 mm spaced from the ground plane in order to characterize a realistic scenario when the user is holding the phone. For the three monopoles, the same scheme is used (the bottom monopole does not suffer from the finger loading effect).

For the single antenna, the finger in the right position is critical since the finger totally covers the antenna, whereas for the left position the finger is far away (Figure 21). It should be outlined that these experiments consider a critical scenario in which the finger is only 1 mm above the antenna.

For the array of two elements, efficiency is better for all cases except for the left position where the single antenna does not suffer from the finger effect since it is far away. However, in the best case of the single antenna, antenna efficiencies for the single and the array of two elements are quite comparable. The advantage of the array of two elements is demonstrated for the other cases, where the efficiency is above the efficiency of the single antenna case.

For the array of three elements, the advantages are even better since it presents the best results among the three prototypes. For example, for the right case, the efficiency in the 824–960 MHz frequency range is 2.5 dB higher than the array using two elements and 7.9 dB higher than the single antenna case, showing that this technique may be useful to mitigate the efficiency drop due to the finger loading that can be directly related to a decrement of the battery duration, reduction of coverage, and eventually call drops.

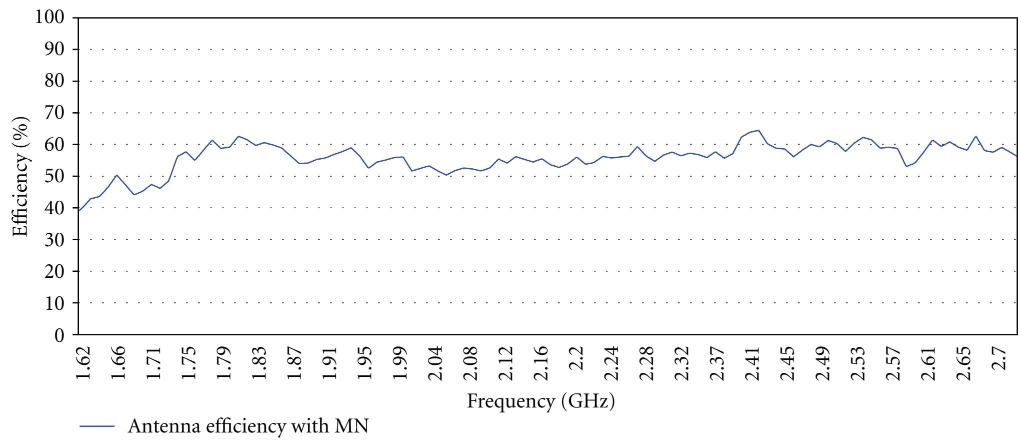


Figure 23: Measured antenna efficiency of the L-monopole shown in Figure 22. Broadband matching network consisting of a shunt $L = 3.3$ nH and a shunt $C = 1.3$ pF.

A distributed handset antenna system using three small monopoles has been described featuring enough bandwidth to cover the communication standards in the range of 686 to 970 MHz. This concept uses an array of monopoles with a proper phase shift to improve the bandwidth compared with a single antenna element. Moreover, the proposed system is robust to the finger effect because, when one element is interfered by the finger, there are still two more elements that efficiently contribute to the radiation. Finally, it should be emphasized that the proposed distributed system is completely passive, being advantageous in terms of simplicity and battery consumption.

4.3.3. Matching Networks. In combination with antenna techniques, matching networks play a significant role not only in tuning the band location but also in providing greater bandwidth [71–75]. A technique consisting of a simple circuit is discussed to enhance the bandwidth of a simple antenna by a factor of about 2.45 times for SWR = 3 [72, 73].

Matching networks using lumped components are widely used in many commercial handset devices. In many situations, the use of a matching network helps to fine tune the operating bands. Here, a technique for broadening the inherent bandwidth of a handheld antenna is reviewed. Basically, the technique consists in adding an LC shunt circuit that allows creating an impedance loop of proper size to be inscribed inside the circle of a given target SWR [73].

A circuit analysis shows that the bandwidth of an antenna featuring an input impedance similar to that produced by an RLC series circuit around the central operating frequency can be improved by a theoretical factor of 2.45 regarding an SWR = 3 [73]. To demonstrate the potential of this technique, a single L-shaped monopole featuring an RLC series input impedance along the central frequency of operation is matched with a broadband matching network (Figure 22). Bandwidth and efficiency measurements demonstrate that this single element of reduced dimensions can be operative at GSM1800, GSM1900, UMTS, LTE2100, LTE2300, and LTE2500 (Figure 23).

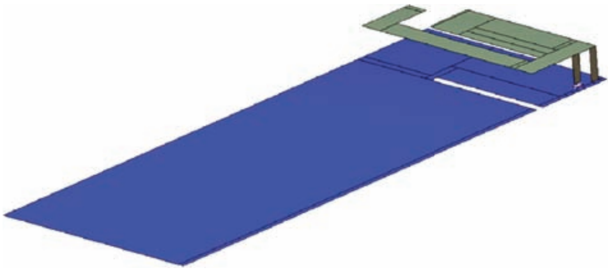
Measured radiation patterns are stable across the frequency range of operation being omnidirectional and having a minimum along the long axis of the PCB. Measured directivities range from 2.8 to 4.4 dB. As a result, a BW enhancement of at least one half of Fano's limit [76] is achieved with a simple two-stage matching network. As a practical example a monopole with an inherent BW_0 of 14.21% SWR $\leq$ 3 has been improved to achieve a BW_f of 52.4% SWR ≤ 3 with an average measured antenna efficiency of 56.5%.

As a conclusion, matching networks and in particular the proposed broadband matching network allows increasing the bandwidth of the antenna element without the necessity of increasing the antenna size.

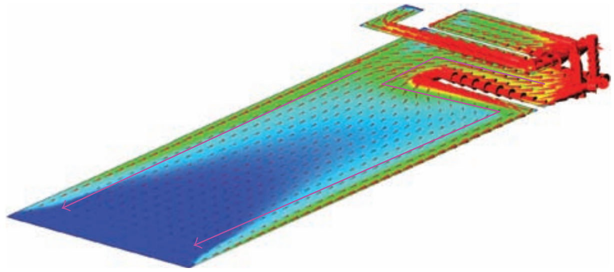
4.3.4. Intelligence in the Ground Plane. The efforts on the antenna design have been mainly addressed to the antenna geometry and not to the ground plane, since its relevance in the radiation process was underestimated. Accordingly, the antenna element was typically a self-resonant element that provided an efficient radiation independently from the ground plane structure. Nevertheless, the ground plane is progressively acquiring relevance since several studies have demonstrated its strong contribution to the radiation properties [77–90].

The future generations of mobile phones will need to operate over as much frequency bands as possible, such as LTE700, GSM850, GSM900, DCS1800, PCS, UMTS, LTE2300, LTE2500, among others. It has been shown that a ground plane length of 0.4λ effectively excites the ground plane which improves bandwidth and efficiency [37].

Thus, the antenna design is mainly determined by the PCB dimensions, which are fixed by the size of the handset or wireless device. A further important limitation is the antenna height, which should be small enough as for allowing the emergent generation of ultraslim phones. Moreover, such new mobile phones also incorporate extra-large number of extra services, such as photo-video cameras, big displays to watch television, and several speakers for high-fidelity audio

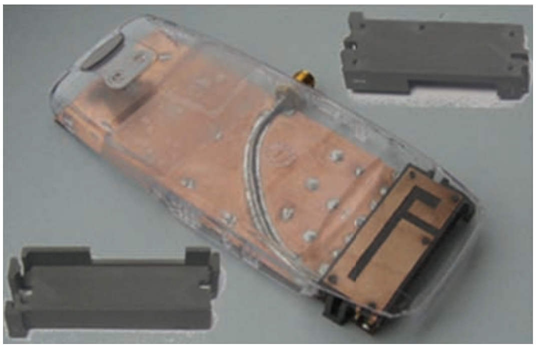


(a)



(b)

Figure 24: (a) Introducing slots in the ground plane to electrically lengthen the current path. (b) Continuous arrows are a qualitative representation of the main current distribution for 900 MHz which is distributed along the long edges of the PCB. PCB is 100 mm × 40 mm.



(a)

(b)

(c)

Figure 25: Manufactured antenna prototypes: (a) dual-band PIFA and rear view of the, (b) quad-band, PIFA, and (c) the hexaband PIFA. In (a) the carrier to attach the metal plate and the plastic cover are also shown.

which undesirably contribute to the reduction of the available space to fit the antenna. Therefore new techniques are needed in order to attain the maximum performance with an antenna that occupies the smallest possible space. Three techniques to manipulate the ground plane are revisited:

(i) use of slot to lengthen the ground plane,

(ii) use of a conductive strip to lengthen the ground plane,

(iii) use of traps to electrically reduce the ground plane.

Lengthen the Ground Plane by Using Slots. To effectively enlarge the ground plane, slots can be used. The idea is illustrated in Figure 24 where the slot is used to tune the ground plane mode (enlarging the current path) at the low frequency range (900 MHz) while placed underneath the antenna area to act as a parasitic element at higher frequencies (1800–2100 MHz).

Prototypes of three PIFA antennas, namely, a dual-band PIFA without slots, a quad-band PIFA with one slot, and the proposed hexaband PIFA with multiple slots on the ground plane, have been constructed and studied (Figure 25) [88]. The simulation software IE3D was used for optimizing the design parameters.

In this concept, a slotted ground plane is used to improve the bandwidth at both low and high frequency regions without increasing the volume of the antenna. On one hand, at low frequencies, the slot is below resonance but forces the ground plane mode to be excited so as to increase the bandwidth at low frequencies; on the other hand, the slots are comparable to $\lambda/4$ at high frequencies, and therefore they enhance the bandwidth (Figure 26). This solution does not excite directly the slots as the case with PIFA and slots explained in Section 4.3.1 but by coupling being the PIFA the driven element.

The placement of a component (speaker) over the slot (without any metallic contact between the speaker and the ground plane) does not affect the antenna performance at low frequencies. However, it is critical at high frequencies when the component is close to the open edge of the slot [88]. The effect is minimized at the center and at the short end of the slot. Also, the SAR has been evaluated for this concept and the ones using slots in the ground plane. Results show that this concept presents a similar SAR to that of the PIFA on the bare PCB with the advantage that more bands are covered with the slotted ground plane solution [89].

This new design has been compared with the same design without the slots. Results show that the bandwidth and, as a consequence, the total efficiency are improved, obtaining a radiator useful for multiband handset applications.

Lengthen the Ground Plane by Using Conductive Strips. As discussed above, the ground plane plays an important role in the electromagnetic behavior of a handset antenna. The next technique uses a conductive strip on the ground plane to effectively produce an electromagnetic enlargement capable

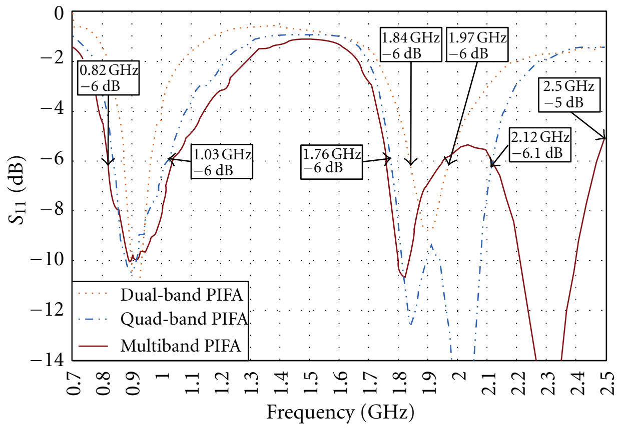


FIGURE 26: Measured reflection coefficient for the three studied prototypes. It can be seen how the proposed multiband design can operate at least over the GSM850, GSM900, DCS, PCS, UMTS, and Bluetooth bands.

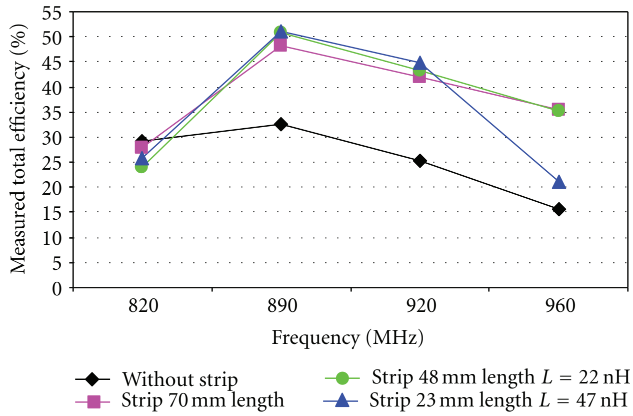


FIGURE 28: Measured total efficiency without the strip and with the strip considering loading inductors for the case shown in Figure 27. The case having L of 22 nH and 48 mm length effectively enhances the efficiency across the 820–960 MHz band.

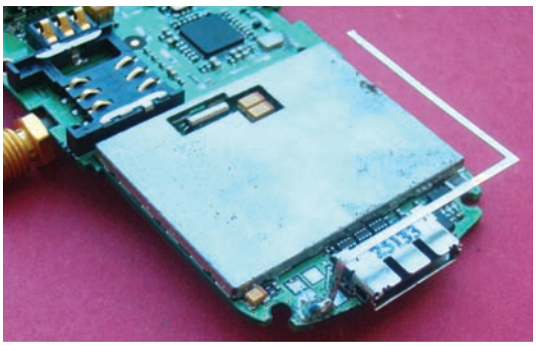


FIGURE 27: Conductive strip on a real handset PCB.

of tuning the resonant frequency of the fundamental mode to lower values close to 900 MHz (Figure 27). Basically, to make the ground plane larger, a strip at the opposite edge of the antenna location is used. Such a strip is designed to tune the ground plane mode [91]. As a result, the bandwidth and efficiency are increased. The length of the strip can be reduced by inductive loading and/or dielectric loading. Physical insight is given by electrical models [91] and using radar cross-section analysis [92].

Other authors have used the strip to mitigate the hand loading effect [63]. In [93], a mechanism to control near electrical and magnetic fields is used for hearing-aid compatibility.

To give a better perspective of the efficiency improvement, four case studies are selected (Figure 27): handset phone without strip, with the strip, with the strip length having 48 mm and 23 mm, and with the respective loading inductor. On one hand, it is clearly shown how the efficiency is improved at the low frequency region (Figure 28). The unloaded strip and the inductive loaded strip having 48 mm length perform very similar demonstrating the benefit of the inductance loading. The 23 mm case improves the efficiency peak but the efficiency drops at 960 MHz. In summary, the strip with 48 mm length improves the efficiency across the band. In particular, the improvement at 960 MHz is very significant: 3.5 dB. On the other hand, the strip does not alter the performance in the high frequency region [91].

As a conclusion, this technique is useful to improve the bandwidth and efficiency at the low frequency region where the ground plane is smaller than 0.4λ, which is approximately the optimum length to excite the fundamental mode of the ground plane and, thus, to maximize the bandwidth and efficiency.

Reducing the Ground Plane Using Stubs. In some platforms such as, for example, clamshell type handsets, the ground plane is large in open position. Moreover, if the antenna is placed at one edge instead of that in the hinge, it may excite a particular mode that results in a radiation pattern with many lobes and a minimum in the horizontal plane. In this regard, the present technique consists in reducing the electrical length of the ground plane by adding a trap (Figure 29) [94]. In [95], the technique of using traps increases the bandwidth at the high frequency region. In effect, at this frequency, a typical length of a bar-type handset of 100 mm is $0.63\lambda_0$ at 1900 MHz, being larger than $0.4\lambda_0$. Therefore, the strip forces the ground plane to be $0.4\lambda_0$ in length at such frequencies. Similar effects can be obtained by introducing a slot in the ground plane [96].

When the antenna is placed at one edge of a clamshell platform, the radiation in the horizontal plane does not present a maximum radiation due to a multilobe pattern. By adding the trap which is a short-ended $\lambda/4$ stub at the central frequency of operation, the current is blocked due to the high impedance of the stub. In this way, the current is minimized. As a result, the higher order mode has been removed at the ground plane that supports a fundamental mode which radiates with a maximum in the horizontal plane.

4.3.5. Ground Plane Boosters. Wireless device manufacturers regard the volume dedicated to the integration of the radiating structure and in particular the antenna element, as being

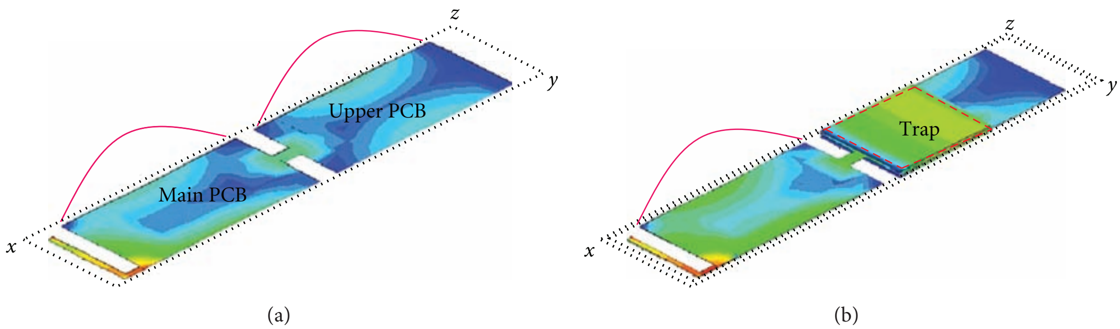


Figure 29: Simulated current distribution at 1.82 GHz without and with a shortening mechanism consisting of a short circuit plate of $\lambda/4$ at 1.82 GHz. The continuous line is a qualitative approach of the currents on the ground plane. For (a), a current mode having two sinusoids is supported causing a multi-lobe pattern. For (b), the current in the upper PCB board has been mitigated due to the trap.

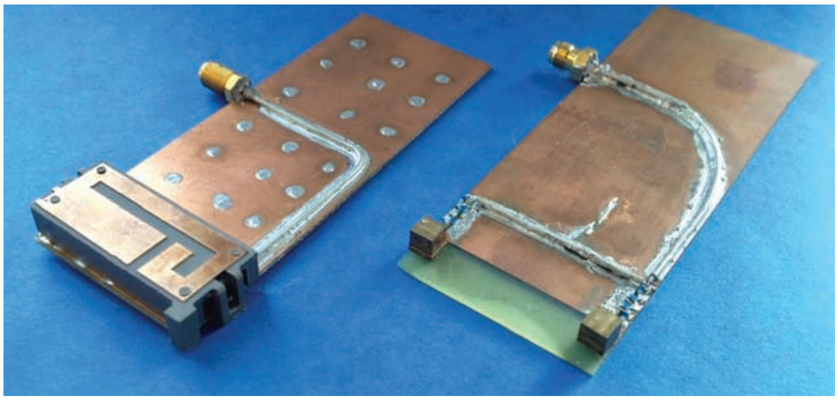


Figure 30: Comparison of a PIFA antenna and the solution based on ground plane boosters for operation at GSM850/900, DCS, PCS, and UMTS. The volume of the PIFA is 4600 mm^3, whereas the compact solution is only 250 mm^3.

a toll to pay in order to provide wireless capabilities to the handheld or portable device.

The new technique named ground plane booster antenna technology provides very compact elements, easy to integrate, and able to be used as standard elements [97–106]. This technique is based on the concept of using the ground plane as the main radiator. An element, called ground plane booster, is in charge of properly exciting the efficient radiation modes that the inherent ground plane of any wireless platform features at mobile frequencies. Its proper location together with a radiofrequency system allows multiband operation with significant small dimensions (e.g., only 250 mm^3 to obtain multiband performance at GSM850, 900, 1800, 1900, and UMTS), thus making the new architecture attractive to emergent multifunction wireless devices.

Other different approaches have appeared in the literature. In [107] two antenna structures based on coupling elements designed to transfer energy to the ground plane mode are presented. They are intended for covering the communication standards GSM900 and GSM1800 separately by means of a single-resonant matching circuit based on distributed matching elements. Other reference based on coupling elements is given in [108], where an antenna structure consisting in two coupling elements and two resonant circuits is proposed. The proposal achieves a quad-band behavior. Nevertheless, the coupling elements presented for covering each frequency region (624 mm^3 and 64 mm^3, resp.), and especially the one in charge of providing operability in the low frequency region, still present a considerable volume compared to the 250 mm^3 disclosed herein for providing pentaband operation. In [98, 100], the pentaband behavior is achieved by means of two ground plane boosters and two matching networks capable to provide multiband operation at each frequency region (Figure 30).

A wireless device employing very small elements would be advantageous as it would make the integration of the radiating structure into the wireless handheld device easier. The volume freed up by the absence of the antenna element would enable smaller and/or thinner devices, or even to adopt radically new form factors which are not feasible today due to the presence of an antenna element. Furthermore, by eliminating precisely the element that requires customization, a standard solution is obtained which only requires minor adjustments to be implemented in different wireless devices.

Accordingly, the present solution replaces the self-resonant antenna element by nonresonant ground plane boosters (Figure 31). In this case, a challenge appears since the ground plane resonance is not coupled to the antenna resonance. Thus, the present technique is focused on providing multiband wireless handheld device architecture based on

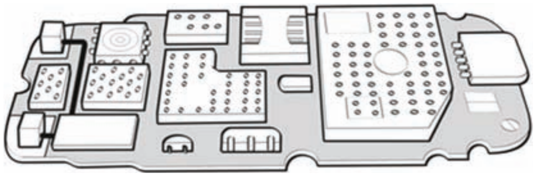


Figure 31: Schematic of a handset phone including two ground plane boosters located at the short edge of the PCB.

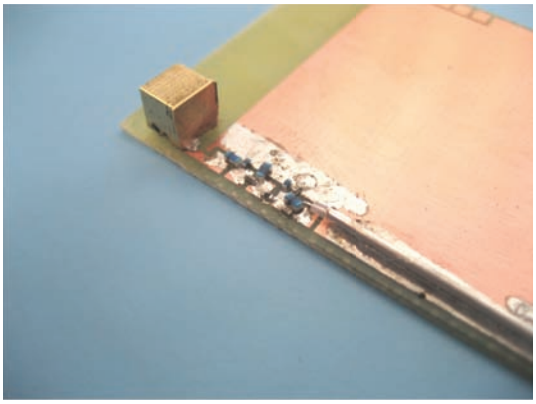


Figure 32: Single-band prototype including the reactance cancellation inductor and the broadband matching network.

the proper excitation of the ground plane without the need of an antenna element [97–100]. This technique demonstrates that no handset antenna is required for effectively exciting the radiation modes of the ground plane. The novel architecture introduced here only requires small ground plane boosters featured by a high quality factor ($Q \approx 2250$ for the low frequency region and $Q \approx 265$ for the high frequency region) and extremely poor stand-alone radiation properties in combination with a matching network for providing simultaneous operability in the main communication standards (GSM850/900, DCS, PCS, and UMTS) [100].

However, the proper excitation of the predominant mode is not enough for providing pentaband behavior and a matching network is required in order to guarantee operability in the aforementioned communication standards. For the present example, each ground plane booster uses a reactance element to cancel out the reactance and a broadbanding circuit as the one described in Section 4.3.3 to achieve enough bandwidth to cover the required standards. Such a broadbanding circuit follows the principles explained in Section 4.3.3 (Figure 32). Also, a combiner is used to merge the two port solution into a single input/output port (Figure 33).

In this sense, the conventional handset antenna featured by a considerable volume ($\approx 4550\,\text{mm}^3$) has been replaced by two low-volume nonresonant ground plane boosters ($250\,\text{mm}^3$) and a matching topology with a systematic design. These elements are in charge of properly exciting the efficient radiation mode of the ground plane, which presents high radiation efficiency and low Q at the frequencies of interest, especially in the low frequency region (GSM850/900). The

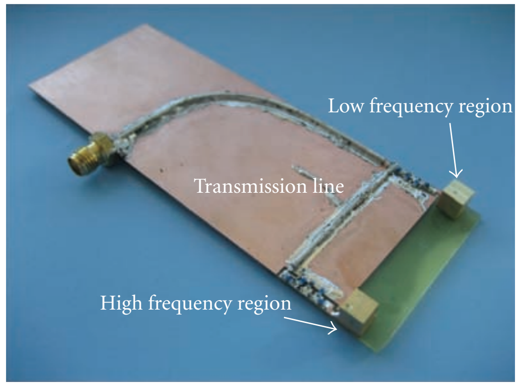


Figure 33: Pentaband prototype designed including the reactance cancellation inductor, the broadband matching network, and the notch filters required for providing isolation between both frequency regions.

systematic matching network design enables the operability in the desired frequency regions. The radiation contribution provided by such small boosters is negligible and they should not be considered as antennas. Consequently their integration in the handset platform removes the need of including a dedicated antenna in the wireless handheld device [97–106].

The effects of head absorption and SAR have been compared to other technologies such as PIFA using slots in the ground planes and the coupled monopoles presented in this paper, resulting in a technique more robust to the effects of the head [109].

This proposal becomes an alternative to current antenna technology and appears as a promising standard solution for being integrated in emergent multifunctional wireless devices since the available space in handset platforms for integrating new functionalities is further increased while the radiating performance is preserved. New advances in this field show the possibility of adding new bands such as LTE700 and LTE2100/2300/2500.

5. Conclusions

The apparition of new wireless communications systems with new platforms makes the antenna design a difficult challenge since not only more antennas are needed to operate at new bands but also the antennas require multiband operation and small size to be integrated into the wireless handheld devices.

However, the characterization of the antennas is as important as their design. The antennas integrated in wireless handheld devices operate in singular environments, like for example, the presence of the human body and the multipath signal propagation, which add additional challenges. These particular environments force the antenna community to characterize the integrated antennas in wireless handheld device to attain efficient antenna systems for this kind of situations. On one hand, head and hand phantoms are used to analyze the effect that the human body has on the electromagnetic performance of the antennas and also how the radiation of the antennas affects the human body. This characterization facilitates the understanding of the antenna behavior which at the end serves to make robust antenna systems. On the other hand, the multipath environment fosters new measurements systems such as reverberation chambers which can emulate a real propagation environment.

Finally, smaller and multiband radiating systems are required to allow the integration of other handset components such as, for example, big displays which are a common feature of current smartphones and an important factor for the final user. In this regard, the ground plane boosters presented herein offer an alternative to current antenna technologies, since they significantly reduce the volume occupied by the radiating system while preserving the electromagnetic performance. An example of two ground plane boosters having a size of only 5 mm × 5 mm × 5 mm has been proved to operate at GSM850, GSM900, GSM1800, GSM1900, and UMTS. Therefore, the ground plane boosters become a promising technology for the new generation of wireless handheld devices.

Acknowledgments

The authors would like to thank the following institutions for their financial support: Spanish Ministry of Industry, Commerce, and Tourism and ACC1Ó.

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