Syracuse University

Department of Electrical Engineering

ANTENNA AND ANTENNA SYSTEMS

QUAD-BAND PIFA FOR MOBILE PHONES

Sayuj Haridas

Dr. Jay. K. Lee

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ABSTRACT

Conventional microstrip antennas in general have a conducting patch printed on a grounded microwave substrate, and have the attractive features of low profile, light weight, easy fabrication, and conformability to mounting hosts. Microstrip antennas however have a narrow bandwidth, and bandwidth enhancement is usually demanded for practical applications. In addition to being broadband, they should be capable of operating in multiple frequency bands too. Compactness of structure is another feature desired in present-day mobile communication systems in order to meet the miniaturization requirements of mobile units. Thus, mobile phones antennas require reduction in size and broadband operation for compatibility with different standards essentially operating in different frequency bands.

This paper reviews the techniques used to incorporate these two essential features to a conventional microstrip antenna. The information acquired from these techniques is appropriately used to explain the design and operation of a Quad-Band Microstrip antenna for mobile phones. The quarter-wavelength Planar Inverted-F Antenna (PIFA) combines the use of a slot, shorted parasitic patches and capacitive loads to achieve multi-band operation. The result is a compact structure capable of broadband operation in four different frequency bands used by four standards – GSM900 (Global System for Mobile), DCS1800 (Digital Cellular Systems), PCS1900 (Personal Communication Systems) and UMTS2000 (Universal Mobile Telecommunication Systems).

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INTRODUCTION

The wireless mobile communication industry has exploded over the last decade. Multiple standards and technologies have been developed across the globe and the development of the industry has exceeded even the most optimistic expectations. The mobile radio industry is “hot” and looks to remain so for at least a few years to come. It was not always so in the past. Radio was hot once during the time which can be referred to as the first golden age of wireless about 50 years ago from about 1890-1940. It attracted the best engineers and the huge investors. It created the entrepreneurs like Marconi and Armstrong (inventor of FM technology). The tremendous commercial success of radio did not accelerate the inventive process then. After 1940, the field entered a period of relative quiescence for the next 50 years. Probably the biggest new thing to happen, commercially and technologically in this era was the advent of the “transistor radio”, but not a fundamental advance in wireless technology itself. The reduction in size and cost was impressive, but the performance and basic system capabilities were the same. Then in the mid-eighties came the “cellular” and what happened next from around 1990 to the present day is truly a technological revolution. The cellular concept and digital signal processing changed radio technology fundamentally. The complete development cycle for a new digital air interface has proved to be something between 4 and 7 years, and presented the wireless engineers with more and more challenging physical problems. The technological backwaters began to be flushed out and dynamic innovation was triggered. Radio engineering was suddenly an exciting field again. The entrepreneurs were back. Wireless was hot again.

Present day……….

Today with the emerging wide area wireless services, organizations can provide customers access to any kind of information just about anywhere. The role of personal communication systems in each person’s day to day life has become indispensable. It has transformed itself from a luxury into a necessity. The customer is unaware of the limitations faced by the engineers or more appropriately made invisible to them by the sophisticated functionalities placed at their fingertips. They hardly think about the role played by the small protrusion at the end of their mobile device which most of them refer to as “just an antenna”. The evolution of that antenna has been fundamental to the wireless mobile industry just as any other invention. It is a device that is increasingly being perfected over the years to achieve more and more refinement in its functionality.

ANTENNAS FOR MOBILE PHONES

Antennas refer to gateways of wireless communications interfacing the free-space medium and the RF electronics of transceiver systems. In wireless communication applications, the operational push and the design pull considerations direct the choice of antennas. The overall perspective of wireless communication systems plus the pertinent details on the state-of-the-art aspects of associated technology show that, in the modern deployment profile, the manufacture of mobile phone antennas pose multidisciplinary considerations. A variety of antenna structures – small and large – have been conceived and adopted in modern mobile communication systems. In general, the antennas used in mobile phones are expected to have certain characteristics:

1. Minimum occupied volume with regard to portability and overall size minimization of the mobile terminal and shape.
2. Light weight
3. Conformability to mounting hosts
4. Multi-band operation for different communication standards
5. Adequate bandwidth covering the frequency range used by the system, including a safety margin for production tolerances.
6. Isotropic radiation characteristics (omnidirectional)
7. Negligible human body effect.
8. Low fabrication costs since it is a mass produced consumer item

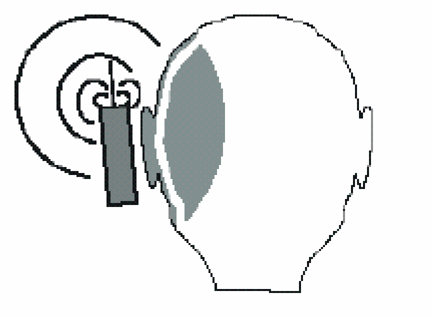
External Antennas

The most common handheld phone antenna is a whip, whose length is typically λ/8 or λ/2 (where λ is the wavelength). A whip antenna is cheap and easy to manufacture. It has a wide bandwidth and a suitable radiation pattern for mobile phone use. The current distribution of the antenna changes so that the current maximum moves from the base of the antenna towards the center point of the antenna when the antenna is made longer. The current maximum of a λ/4 antenna is located closest to the user's head. Relatively strong electrical currents may also be induced on the casing of the phone because the casing acts as a ground plane for the antenna. In the case of λ/8 and λ/2 antennas the currents are weaker, and the current maximum of the antenna is located farther away from the user's head. In addition to whip antennas helical antennas are also used in handheld phones. A helical antenna consists of a wire that is wound in the shape of a helix. The advantage of the helical design is its small size. The height of a whip antenna for 900 MHz is 100 mm whereas the height of a λ/4 helical antenna is only 26 mm. However, the whip and helical antennas will break easily if the phone is mishandled by dropping it, for example.

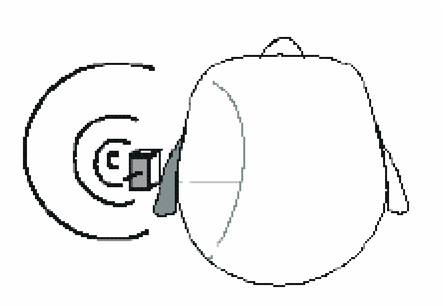
The figure above shows examples of whip antennas commonly used in hand-held devices

Human Absorption of Radiation

Radio-frequency electrical currents in the antenna and in the casing of a handheld mobile phone will induce RF electric fields in tissue. As a result of this a part of the radiated energy will be absorbed into tissue causing an increase in the tissue temperature. The absorption is caused by the power loss involved with dielectric polarization. Vibrations of water molecules, movements of free ions and movements of bound charges attached to macro-molecules contribute most to the dielectric polarization in biological material in radio frequencies.



Back View



Top View

The amount of power absorbed per unit mass is measured by a parameter called Specific Absorption Rate (SAR). Local SAR is given by

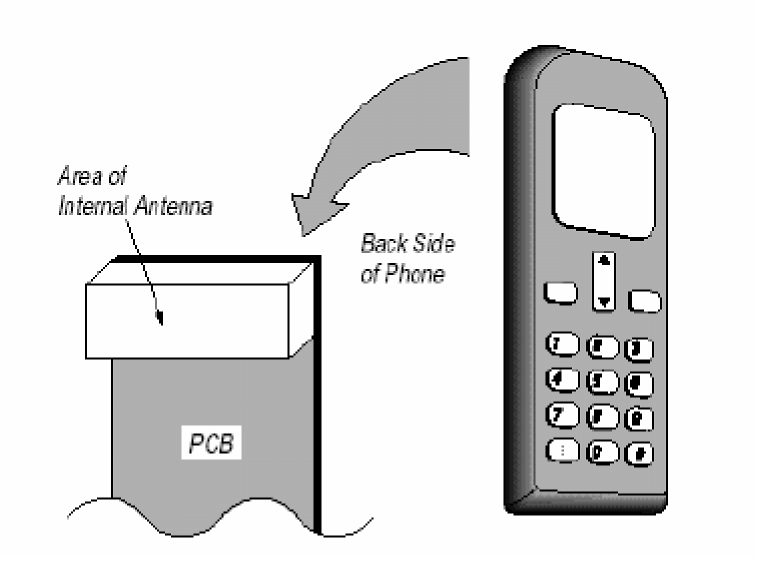
$$\text{SAR} = \sigma E^2/\rho$$

Where σ is the electric conductivity and ρ is mass density. E is the rms value of the electric field strength.

In order to avoid human exposure to radiation, internal antenna can be used. They are placed on the backside of the phone thus avoiding human interference.

Internal Antennas

The structure of an internal mobile antenna is as shown below. The user holds the device at the lower end and the antenna is installed at the upper end of the device on the backside in order to prevent direct radiations towards the user.



The antenna and the user are now separated by the Printed Circuit Board (PCB) which acts as a ground plane for the antenna. The ground plane now can reflect most of the back radiations of the antenna that is directed towards the user, thus lower the SAR value to very much below acceptable limits.

Once such antenna that suits this kind of installation is the microstrip antenna, which is a conducting patch printed on a grounded microwave substrate. It has thin profile, light weight, compact size and volume, conformability to mounting hosts and low fabrication costs as its attractive features. A particular subclass of microstrip antennas that is gaining more and more popularity recently is the Planar-Inverted-F Antenna (PIFA). Numerous research articles have been published related to PIFA ever since the concept of dual-band and tri-band phones (with an arbitrary separation of bands) came into existence. PIFA renders itself capable of operating in two or more discrete frequency bands usually using the concept of excitation and modification of natural modes in the same structure.

LIMITATIONS OF MICROSTRIP ANTENNNAS

No antenna is perfect for any application. Each of them has their own limitations. Microstrip antennas are no exception. They have certain shortcomings which have to be overcome in order to satisfy certain applications. These are as follows:

1. **Size at lower microwave frequencies:** The microstrip antennas do have a compact size and structure, but at the lower microwave frequency regions (900 MHz – 2GHz) the size of a half-wavelength structure is quite large when compared to the size of the mobile unit that it should be installed in.
2. **Narrowband operation:** This is one of the main limitations of microstrip antennas. The bandwidth of this type of antennas is around 2-3% which is very inadequate to use them as mobile phone antennas. This problem has to be overcome using various techniques.
3. **Poor efficiency of high dielectric substrate antennas:** The microstrip antennas fabricated on a substrate with a high dielectric constant are strongly preferred for size reduction and easy integration with MMIC RF front-end circuitry. However, use of high dielectric constant substrate leads to poor efficiency and narrow bandwidth.
4. **Excitation of surface waves:** The grounded dielectric substrate (without the microstrip line) can guide energy as well. These guided waves are called surface waves. These waves can produce to spurious radiations or couple energy at discontinuities, leading to distortions in the main pattern or unwanted loss of power.

The above mentioned limitations have to be overcome in microstrip antennas to enable them to provide satisfactory performance as an internal mobile phone antenna. The techniques to overcome the first two limitations are discussed extensively in this report. Surface waves are excited only when the dielectric constant of the substrate used is above the value of 1. The surface wave effects can be controlled by the use of photonic bandgap structures or simply by choosing air as the dielectric. This solves the limitation of poor efficiency as well along with certain degree of bandwidth enhancement which would be discussed later.

There are other limitations as well such as difficulty in obtaining polarization purity, low power handling capability, somewhat lower gain, mostly radiation into half-space and poor endfire radiations. But these characteristics are not strictly required for mobile phones.

COMPACT MICROSTRIP ANTENNAS

In general, microstrip antennas are half-wavelength structures and are operated at the fundamental resonant mode TM_{01} or TM_{10}. Based on the cavity model approximation, the fundamental or first resonant frequency of the rectangular patch is given by (valid for a rectangular microstrip antenna with a thin microwave substrate)

$$f_{01} = \frac{c}{2L\sqrt{\varepsilon_r}}$$

where f_{01} denotes the resonant frequency of the TM_{10} mode. Many techniques have been reported to reduce the size of microstrip antennas at fixed operating frequency. The inverse proportionality of the relative permittivity can be exploited to reduce the physical antenna length at a fixed operating frequency. A higher permittivity substrate can significantly reduce the antenna size as large as about 90%.

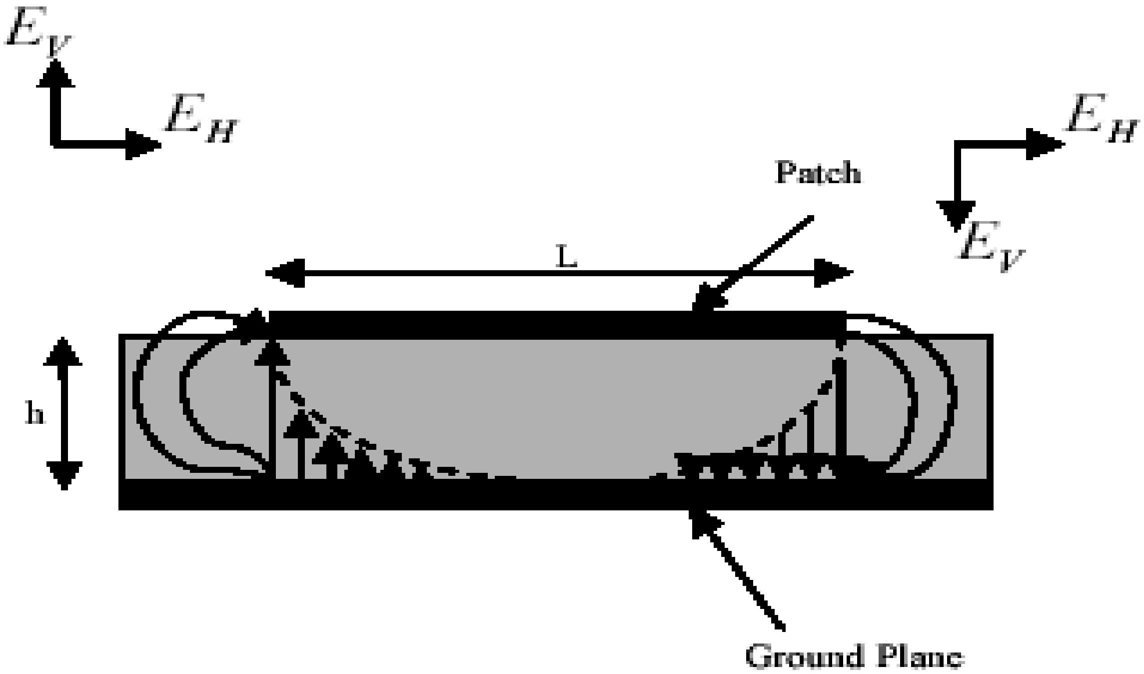
The use of edge-shorted patch for size reduction is also a well known technique, and makes a microstrip antenna act as a quarter-wavelength structure and thus can reduce the antenna's physical length by half at a fixed operating frequency. When a shorting pin is used instead of a shorting wall, the antenna's fundamental resonant frequency can be further lowered and further size reduction can be obtained. An antenna size reduction of about 89% can be obtained using these methods, and when used with an equilateral-triangular microstrip antenna, the size reduction can be made even as large as 94% [3].

Compact operation of microstrip antennas can be obtained by meandering the radiating patch. This kind of patch-meandering technique is achieved mainly by loading several meandering slits at the nonradiating edges of a patch. Capacitive loading of the main patch has also been used for reducing the resonant frequency. All these techniques for size reduction are described in detail in the following subsections.

Edge-shorting Techniques

The conventional microstrip antennas are operated as half-wavelength structures. The electric field distribution under the patch is given by $E_0 \cos(\pi x/L)$, with a maximum at one of the radiating edges, zero in the middle, becoming maximum again at the other radiating edge with 180^o phase reversal.

Since the electric field is zero in the middle (L/2), an electric wall can be erected there without disturbing the field distribution under the patch. Now, the patch can be cut into two halves at the middle and one portion can be discarded. The patch will still be resonant at the original design frequency of the half-wave rectangular patch.



Essentially, this process has converted a half-wavelength structure to a quarter-wavelength patch, provided the electric wall is maintained at its position. Since this patch geometry is a derivative of the half-wave patch, its characteristics can be easily derived from those of the half-wave patch. Among other differences in the characteristics, the most significant one that was found was that the Q factor of a quarter-wave patch for $\varepsilon_r = 1$ is lower than that of the half-wave patch resulting in larger bandwidth. For $\varepsilon_r = 2.1$, both of them have almost the same Q factor and therefore the same bandwidth.

Use of a Shorting Pin

The reduction in size for the shorting-pin loaded rectangular patch is mainly due to the shifting of the null-voltage point at the center of the rectangular patch (excited at the TM_{01} mode) to their respective patch edges, which makes the shorted patches resonate at a much lower frequency. At a given operating frequency, the required patch dimensions can be significantly reduced, and the reduction in the patch size is limited by the distance between the null-voltage point in the patch and the patch edge. For this reason, compared to a shorting-pin loaded rectangular or circular patch antenna, it is expected that an equilateral-triangle patch antenna would have a much larger reduction in the resonant frequency when applied with the shorting-pin-loading technique on account of the fact that its null-voltage point is at two-thirds of the distance from the triangle tip to the bottom edge of the triangle.

These techniques consider the effect of placing a shorting pin near the radiating edge. The effect of placing a shorting pin on the center line of the patch shows quite different results. In addition to providing a certain amount of reduction in the value of the fundamental resonant frequency, this loading suppresses the excitation of even modes (2, 4, 6…) when more than one mode is excited in the structure. This is because the pin is located at the maximum electric field position corresponding to these modes. This type of loading can produce the excitation of two lowest resonant frequencies with the same polarization and can be excited with good matching using a single probe feed.

Why Shorting pin compared to shorting wall?

The shorted-pin-loaded microstrip antenna is operated with a resonant length less than one quarter-wavelength and a greater reduced antenna size than for the case with a shorting wall can be obtained. In the presence of a shorting pin, the first resonant frequency occurs at about 0.38 f_{01} whereas when a shorting wall is used or for that matter more than one shorting pin is used at the edge of a patch, the first resonant frequency occurs close to or at about 0.5 f_{01}. Here f_{01} corresponds to the resonant frequency of a half-wave patch antenna without any shorting technique.

Approximately, in the case of a shorting-pin loaded technique the resonant frequency is determined by the perimeter of the patch rather than the length L. The approximate expression for the resonant frequency is given by

$$f_r = \frac{1}{4} \frac{c}{(L + W)\sqrt{\varepsilon_r}}$$

That is, the resonant length of the patch is equal to $2(L+W)\sqrt{\varepsilon_r}$ in the case of the shorting-pin loading, instead of $2L\sqrt{\varepsilon_r}$ in the case of shorting-wall loading. The existence of W in the equation for the first resonant frequency makes it approximately 0.38 f_{01} in the case of shoring-pin loading patch and 0.5 f_{01} for shorting wall loaded patch.

Feed Location with respect to shorting pin

The feed location is very much dependent on the location of the shorting-pin in the case of quarter-wave patches. The current distribution is very much different than that of the TM10 mode when a shorting pin is present. It is maximum at the short and decreases away from it. Since the input resistance is defined as the ratio of voltage and current at the feed, it is expected that the input resistance will be minimum near the short position and increases away from it. Therefore, the feed should be located in close proximity of the short to obtain the relatively low 50Ω impedance matching.

Use of Meandering Techniques

Meandering of excited patch surface current paths in the antenna's radiating patch is also an effective method for achieving a lowered fundamental resonant frequency. Several narrow slits at the patch's nonradiating edges leads to a greatly lengthened current path for a fixed patch linear dimension. This way a large antenna size reduction at a fixed operating frequency can be obtained. This technique is based on a coplanar or single-layer microstrip structure. Cutting a pair of triangular notches at the patch's nonradiating edges to lengthen the excited patch surface current path has also been used in designs. The resulting geometry is referred to as a bow-tie patch. Compared to a rectangular patch with the same linear dimensions, a bow-tie patch will have a lower resonant frequency, and thus a size reduction can be obtained for bow-tie microstrip antennas at a given operating frequency.

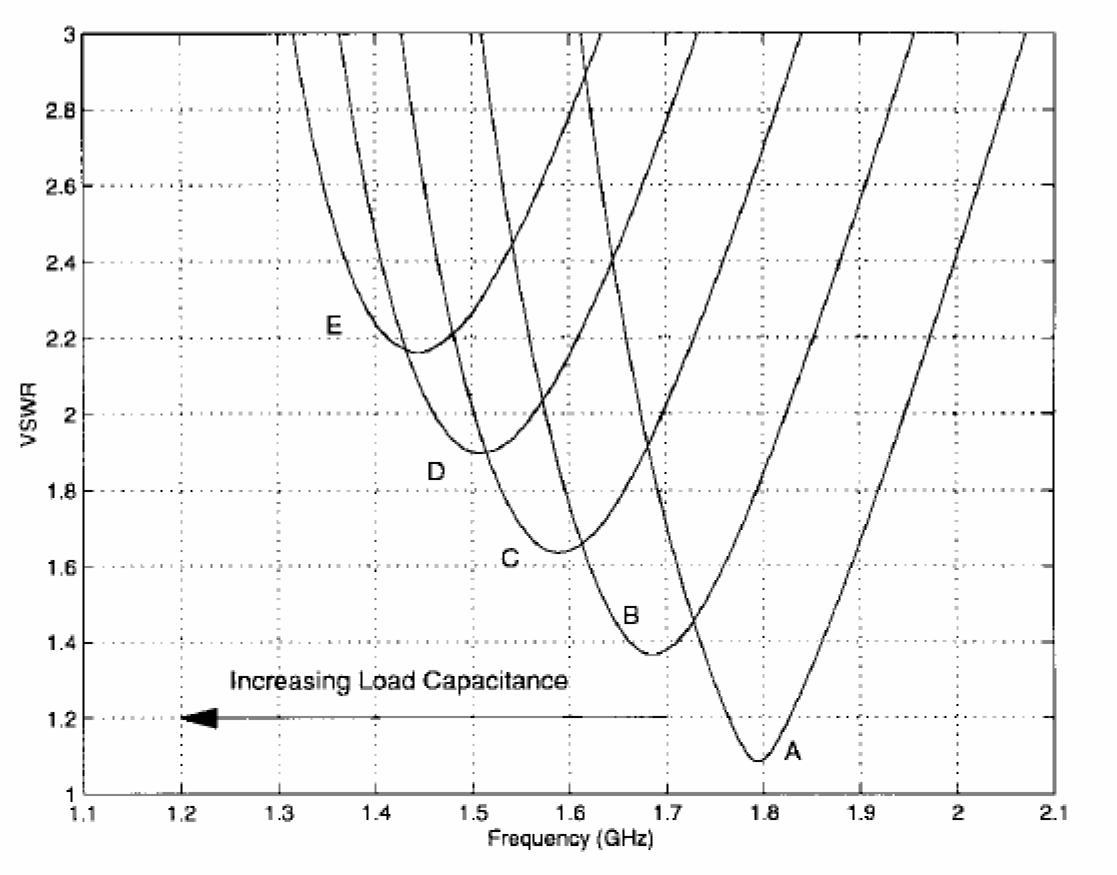
Surface current lengthening for a fixed patch projection area can also be obtained by using an inverted U-shaped patch, a folded patch, or a double-folded patch. This case no lateral current components are created in contrast to the case of the meandering technique. This bending technique results in good cross-polarization levels for frequencies within the operating bandwidth.

Similarly, the antenna's ground plane can also be meandered by inserting several slits at its edges. Moreover, probably because the meandering slits in the ground plane can effectively reduce the quality factor of the microstrip structure, the obtained impedance bandwidth can be greater than the corresponding conventional model.

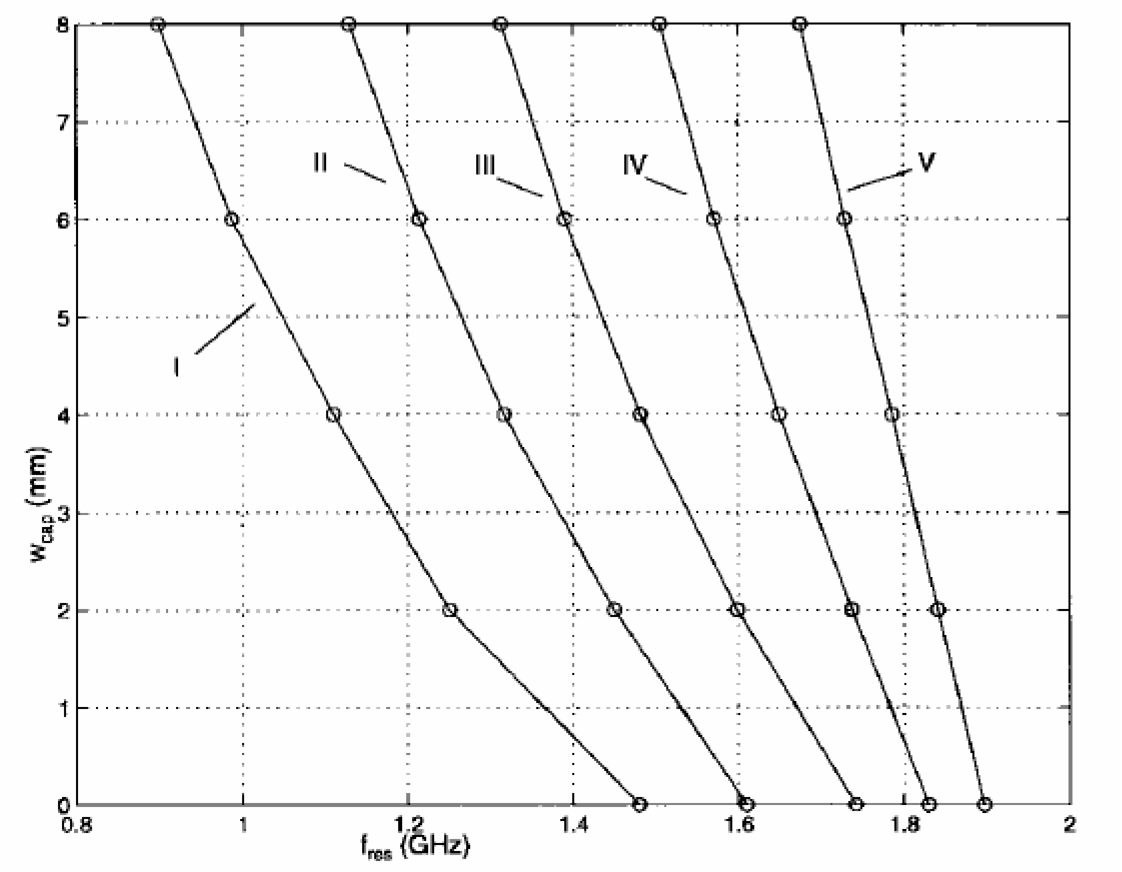
Capacitive Loading

It is found that the capacitive load reduces the resonance length from λ/4 to less than λ/8 [9]. The capacitive load is formed by folding the open end of the patch toward the ground plane and adding a plate (parallel to the ground plane) to produce a parallel plate capacitor.

The effect of the capacitive load on the antenna performance is investigated by varying the capacitive load's width w_{cap} and plate separation d_{cap} while keeping the remaining dimensions of the antenna geometry fixed. The VSWR characteristics for different w_{cap} are as shown below.



It was observed that as the capacitive load increases, (increasing $w_{\text{cap}}/d_{\text{cap}}$) the resistive and reactive peaks in antenna impedance increase while the width of these peaks contract, thereby increasing the bandwidth of the structure. From these results it is realized that the capacitive load reduces the resonant frequency but at the expense of bandwidth and good matching [9].



The plot above shows the resonant frequency for various d_{cap} (I-V in the figure refers to 0.5, 1.0, 2.0, 3.0, 4.0 mm respectively) when w_{cap} is varied between 0.5 and 8 mm. It can be observed that the larger capacitive loads offer reductions in resonant frequency of nearly 1 GHz compared to unloaded antennas.

BROADBAND MICROSTRIP ANTENNAS

This section intends to provide an overview of the bandwidth-enhancement techniques that are used in Microstrip antenna design. The impedance bandwidth of a typical microstrip patch antenna is less than 2-3%. This is in contrast to 15% to 50% bandwidth of commonly used antennas such as dipoles, helices and waveguide horns. Ever since its invention around 20 years ago, researchers have constantly addressed this limitation of microstrip antennas and come up with a wide variety of compensation techniques over the years. Most of these innovations utilize more than one mode, and give rise to increase in size, height or volume. A suitable choice of feeding techniques and impedance matching networks can also provide increase in bandwidth.

First let us define bandwidth. There are many antenna characteristics that vary with frequency. One of them, input impedance is found to vary faster with frequency, thus limiting the frequency range over which the antenna can be matched to its feed line. Thus impedance bandwidth is used mostly for microstrip antennas. Some researchers define impedance bandwidth in terms of VSWR = 2 bandwidth. The half power beamwidth is equivalent to VSWR = 2.4 bandwidth. The microstrip antenna being a standing wave structure, the definition of bandwidth in terms of VSWR makes more sense than other parameters.

The next two subsections describe the effect of substrate parameters and dimensions of the ground plane on the impedance bandwidth of the patch antenna. This is followed by descriptions of the most common broadbanding techniques used for microstrip antennas.

Effects of Substrate Parameters on Bandwidth

Impedance bandwidth of a microstrip antenna is inversely proportional to the quality factor Q which is defined for a resonator as

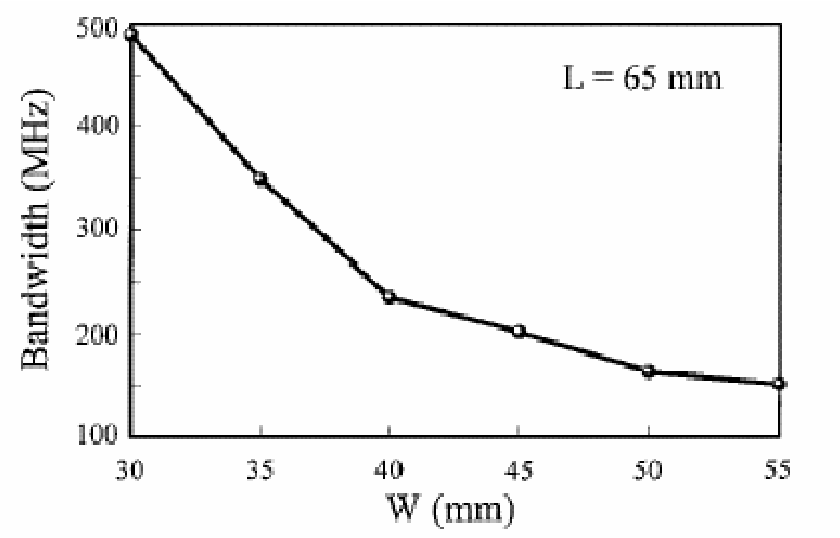
$$Q = \frac{\text{Energy stored}}{\text{Power lost}}$$

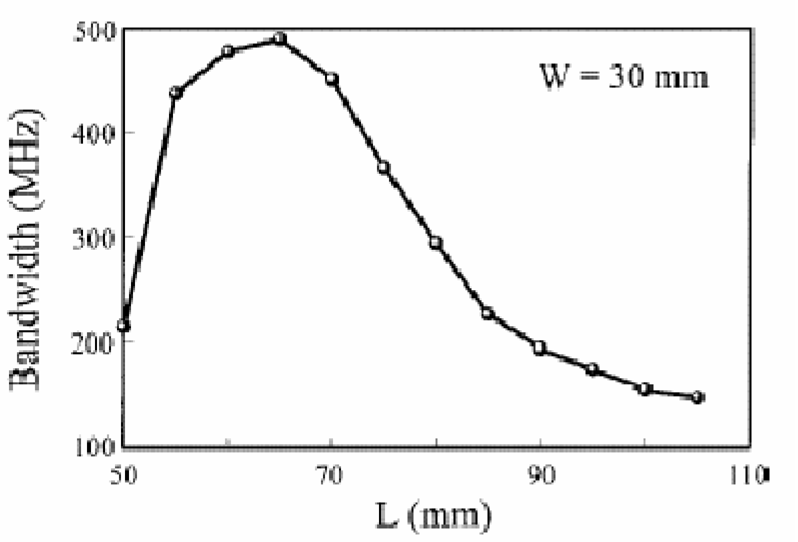
Substrates with high dielectric constant tend to stored energy more than radiate it. This can be explained by modeling the patch as a lossy capacitor with high ε_r, thus leading to a high Q value. This would obviously reduce the bandwidth. Similarly, when the substrate thickness is increased, the inverse proportionality of thickness to the capacitance decreases the energy stored in the patch and subsequently the Q factor also. In summary, the increase in height and decrease in ε_r can be used to increase the impedance bandwidth of the antenna.

Most of the problems associated with microstrip antennas can be overcome by using a thick air dielectric substrate.

Effects of finite ground plane on Bandwidth

It has been assumed in the analysis of microstrip antennas that the size of the ground plane is infinite. In actual implementation, the ground plane size is finite, especially in handheld receivers where space is at a premium. The impedance bandwidth of PIFA is greatly affected by the length and width of the ground plane. The bandwidth variations are larger for the design frequency of 900MHz and 1800MHz. The variation of bandwidth for various lengths and widths for fixed widths and lengths respectively are shown below.





Hence the dimensions of the ground plane have to be optimized to obtain good return loss and bandwidth. The optimized length and width of the ground plane was around 45% and 25% of the design wavelength respectively.

One of the most popular methods is using additional microstrip resonators. Both directly coupled and gap-coupled coplanar microstrip resonators are used to achieve an impedance bandwidth larger than 10% (with a thin dielectric substrate). Promising methods of embedding suitable slots and using stacked elements are discussed in this section as well.

Use of Additional Coplanar Microstrip Resonators

By using additional microstrip resonator patches directly coupled to radiating edges or gap-coupled to the nonradiating edges of a microstrip main patch, a broadband antenna can be designed. The impedance bandwidth for such a design with two additional parasitic patches can be five times that of a single rectangular microstrip antenna. The directly coupled patch can be connected to the radiating edge of the main patch through a narrow conducting strip. By selecting the additional patches to have slightly different resonant lengths, different resonant modes equal to the number of patches can be excited at frequencies close to each other as well as the fundamental frequency of the main patch. The resulting broadband microstrip antenna also has a much increased antenna size compared to a single rectangular microstrip antenna, but choosing each of these resonators to be quarter-wavelength structures by edge-shorting each of them, the size of these parasitic patches can also be reduced.

Coplanar parasitically coupled patch resonators have been analyzed using the integral equation approach, multiport network method and the transmission line model. The basic principle underlying the operation of these antennas is the capacitive coupling between the driven patch and the parasitic patches. The loading effect produced by the parasitic patches lowers the Q, thereby increasing the impedance bandwidth [2].

Use of Slot-Loading Technique

By embedding suitable slots in the radiating patch of a microstrip antenna, enhanced bandwidth with a reduced antenna size can be obtained. Exciting two resonant modes, the dimensions of the slots can be adjusted to perturb these resonant frequencies and make them close to each other, thus providing a wide impedance bandwidth. The same principle can be applied for dual-frequency operation as well. In this case, suitably shaped slits (usually L-shaped or a folded shape) are cut in the main patch and the slit dimensions are varied to make the second resonant frequency occur at a particular value demanded by the application. This antenna can be considered to consist of two connected resonators of different sizes. The smaller resonator is encircled by the slit and resonates at a higher resonant frequency; the larger resonator encircles the smaller one and resonates at a lower resonant frequency [3].

Thus the lower resonant frequency is decided by the external dimensions of the antenna. There are no closed form approximations that calculate the upper resonant frequency since there are too many parameters controlling it. But the critical parameters that influence it are the length and width of the slit and the position of the slit along the length of the patch.

Using Stacked Elements

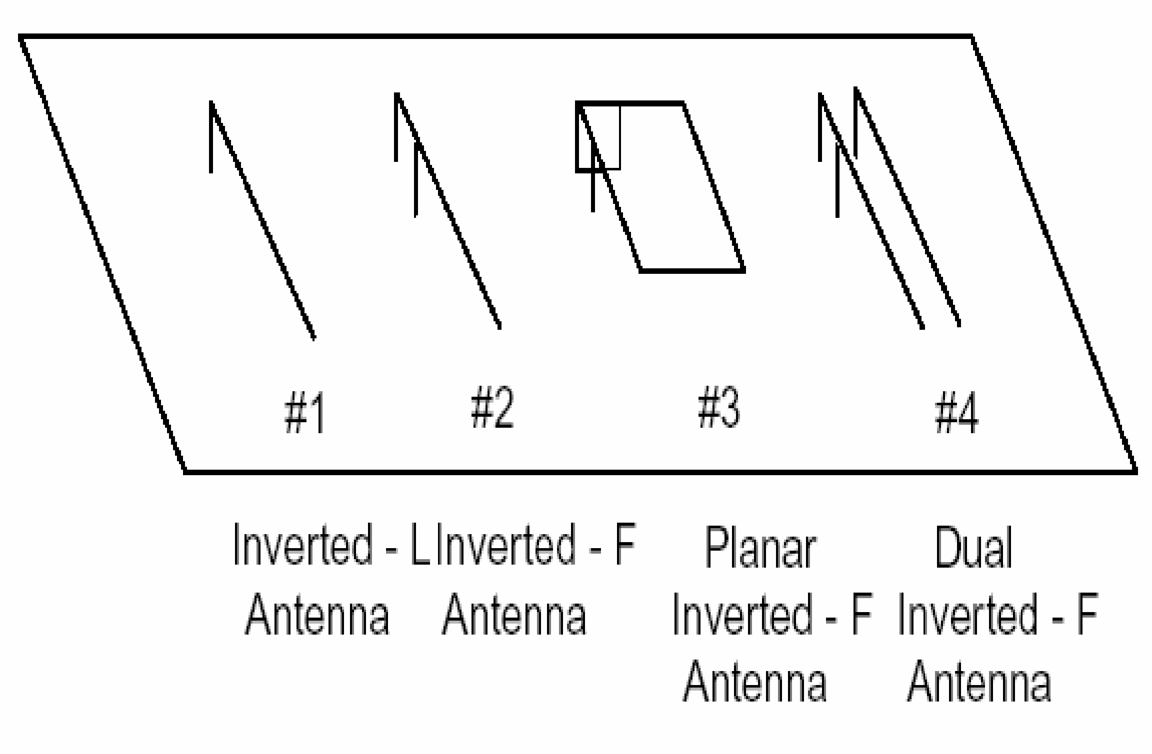
The effect of stacking of patches was first studied in 1978 [5]. Multiple patch elements are stacked on top of each other. The bottom patch can be fed by a coaxial probe or by a microstrip line. The upper patch is proximity coupled to the excited bottom patch. The size of the upper patch is slightly different from that of the lower patch to obtain a slightly different resonant frequency. A number of variables are used in this configuration and each of them can be adjusted for various applications. For broadband operation, various parameters are optimized for maximum bandwidth. A study has shown that although offset patches give rise to a wider bandwidth, the structural asymmetry gives rise to beam squint in the E plane. It is possible to use more than two stacked elements, but the improvement in bandwidth over that obtained from a properly optimized two-element design may not be considerable.

It has been suggested in [4] that the bandwidth of an antenna is governed by the volume occupied by it. Comparisons have found that the stacked geometry can provide a large bandwidth for the same volume. This is due to the fact that the volume in this geometry comprises larger height and lesser surface area, and larger height represents more efficient utilization of volume. However, the large bandwidth of the stacked geometry is accompanied by poor front-to-back ratio and these antennas are not amenable to mass production due to critical alignment of the patches and feed.

PLANAR-INVERTED-F ANTENNA (PIFA)

A Planar-Inverted-F Antenna (PIFA) is a post loaded rectangular microstrip antenna fed by a probe. It is called an inverted-F antenna because the side view of this antenna for air dielectric resembles the letter F with its face down. The size of PIFA with the post or pin located at a corner of a rectangular plate can be determined approximately from [6]

$$f_r = c / 4(L + W)$$

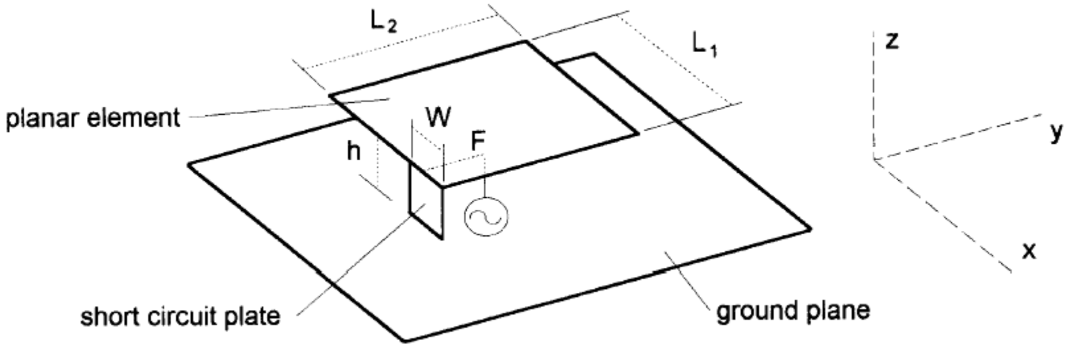


The planar-inverted-F antenna evolved gradually from other antennas in order to overcome certain limitations in its preceding structure. The first in line the Inverted-L antenna consists of a short vertical monopole with the addition of a long horizontal arm at the top. Its input impedance is nearly equivalent to that of the short monopole with the addition of the reactance caused by the horizontal wire above the ground plane [7]. The ILA is generally difficult to impedance match to a feedline since its input impedance consists of a low resistance and high reactance. Since loss due to mismatch decreases radiation efficiency, it is desirable to modify the structure of the ILA to achieve nearly resistive input impedance that is easily matched to a standard coaxial line.

The ILA structure is commonly modified by adding another inverted-L element to the end of the vertical segment to form the Inverted-F Antenna (IFA) as shown in the figure below

The addition of the extra inverted-L element behind the feed tunes the input impedance of the antenna. One disadvantage of an IFA constructed using thin wires is low impedance bandwidth. Typically, a single IFA element experiences an impedance bandwidth of less than 2% of the center frequency. [7] One way to increase the bandwidth of the IFA is to replace the top horizontal arm with a plate oriented parallel to the ground plane to form the Planar Inverted-F Antenna (PIFA).

To improve the narrow impedance bandwidth of the IFA, the thin wire horizontal segment is replaced by a flat conducting plate oriented parallel to the ground plane. The result is the Planar Inverted-F Antenna (PIFA) shown in figure below



The electric field under the planar element of the PIFA is *z*-directed. The *z*-directed electric field, E_z, is zero at the short circuit and maximum at the free end of the planar element. The electric fields, E_x and E_y are generated at all open edges of the planar element. These fringing fields are a radiating mechanism of the PIFA [8].

QUAD-BAND PIFA FOR MOBILE PHONES

The techniques used for size reduction and bandwidth enhancement are combined together to design a quad-band PIFA antenna for mobile phones. The proposed antenna is called quad-band because it is capable of multi-frequency band operation as follows:

1. GSM900 – In the region of 880 MHz – 960 MHz
2. DCS1800 – In the region of 1710 MHz – 1880 MHz
3. PCS1900 – In the region of 1850 MHz – 1990 MHz
4. UMTS2000 – In the region of 1920 MHz – 2170 MHz

This antenna combines several of the techniques discussed in the earlier section as follows:

1. The main resonator is a dual-band PIFA antenna tuned to operate at center frequencies of 935 MHz and 1930 MHz. This is possible due to the introduction of an L-shaped slit cut into the main patch.
2. The introduction of the slot also reduces the element fundamental resonance frequency.
3. The end positioned capacitive loading introduced by folding over the patch on itself, can be used to control the resonant frequencies of the higher modes excited in the main patch. It was successfully demonstrated in [10] that the resonant frequencies of the higher modes can be controlled by increasing or decreasing the metal facing surfaces of the folded edges. The decrease in the bandwidth due to this folding operation can be compensated by adding parasitic resonator elements.
4. Three additional gap-coupled parasitic elements are used to create new resonances near the lower and upper resonant frequencies of the main patch. Thus it is possible to enlarge both the lower and upper impedance bandwidth. These new resonances can also be tuned using capacitive loading at the end of each additional resonator.
5. A thick air substrate is used to provide additional bandwidth enhancement by lowering the Q factor. This choice also provides good antenna efficiency and also keeps the antenna free of surface excitation issues.

6. All the four elements – the main patch and the three additional resonators – are made quarter-wavelength structures by the introduction of shorting strips (or pin) to each of these resonators.
7. Impedance matching to a 50Ω source is obtained by placing the feed through a coaxial line very close to the shorting strip of the main patch, thus providing an efficient antenna-chassis configuration.

Antenna Structure and Design

The Printed Circuit Board (PCB) of the antenna is chosen to be that of a typical mobile phone: 40.5mm x 105mm. As mentioned earlier, the size of the PCB which acts as the finite ground plane for the antenna has a strong influence on the performance of the mobile phone antennas. In this case, the chosen length is not the best choice for an optimum GSM bandwidth or the DCS bandwidth. The optimum value for GSM is found to be around 130mm and for DCS is found to be near 70mm. Since both these bands have to be integrated on the same PCB, an intermediate value was chosen that would equally help in both these bands for an efficient antenna-chassis combination. This selection was reached upon on the basis of acceptable performance results.

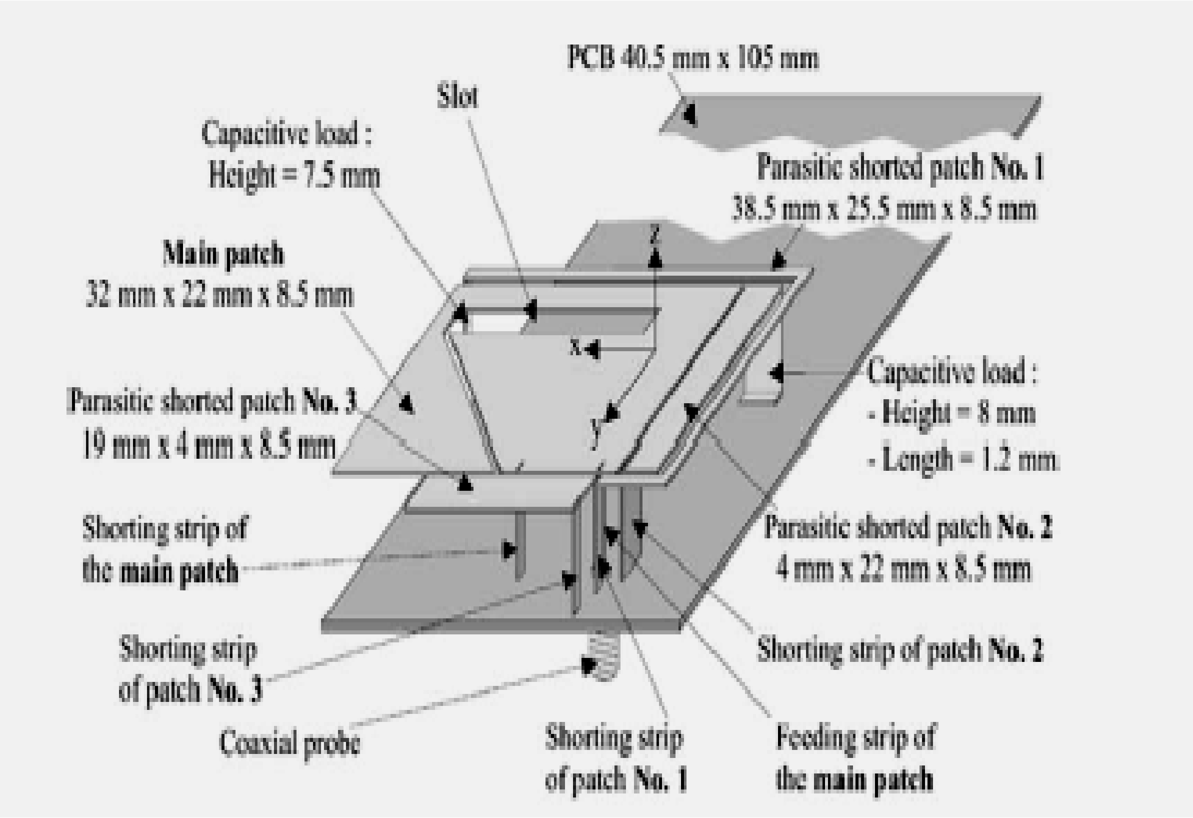
During the design phase, the first objective is to get a proper resonance in the lower GSM band, where the approximate formula as mentioned before

$$f_r = c / 4(L + W)$$

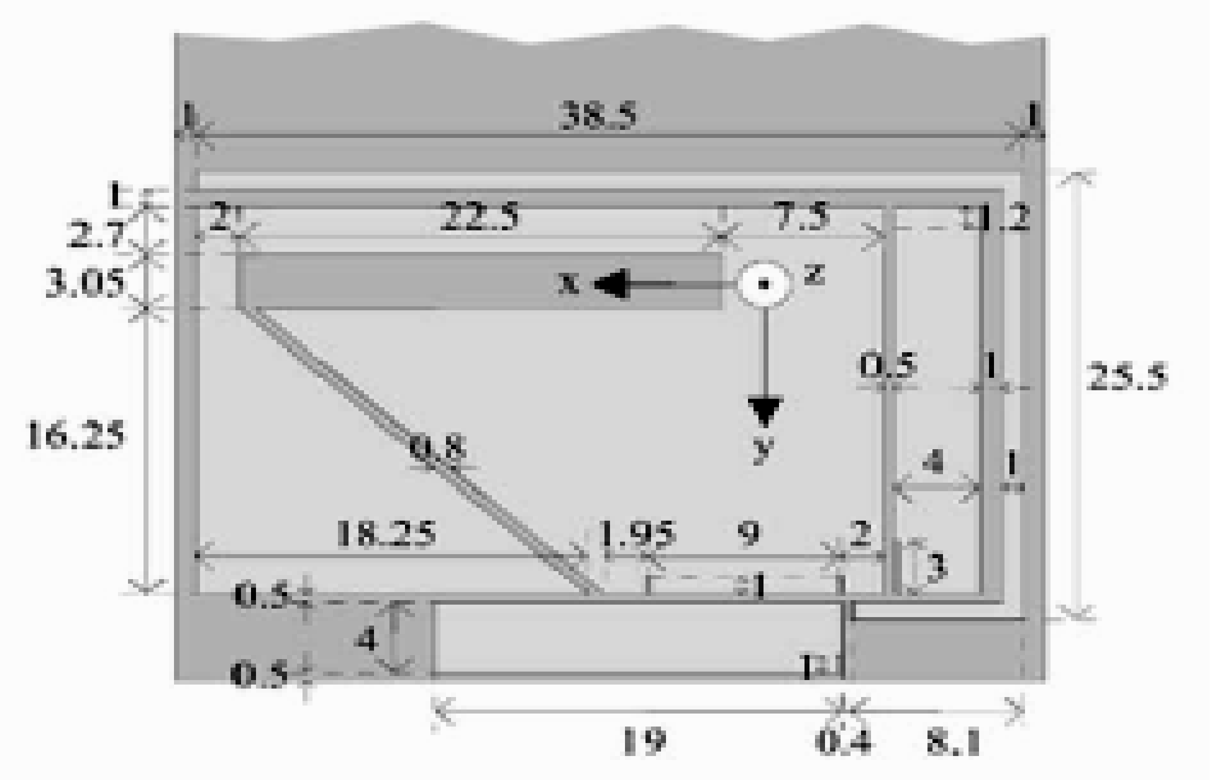
is used as a starting rule for the design of the patch. The analytical length obtained is an approximate value that is used to start the simulations. The correct value is agreed upon at the end of implementation of all the other techniques. The length is reduced by almost half due to the addition of the shorting strip. The matching of the main patch to the coaxial feed is done next by placing the feed spatially not far from the shorting strip for a 50Ω source.

Due to its intrinsic properties, the design at 935 MHz of a rectangular quarter-wavelength patch with its length aligned with the PCB length, will only lead to an odd number of higher resonant frequencies [1] and the suppression of even modes. This leads to a second resonant frequency in the range of 2805 MHz which has to be reduced to bring it down to our required 1710-2170 MHz band. This is done using the capacitive loading technique by folding the patch over on itself. This operation reduces the resonant frequency of the third harmonic. This is overcome using two additional parasitic elements, quarter-wavelength long, connected to the ground plane by metallic strips and located near the main patch in order to be correctly electromagnetically excited. These element lengths are chosen to be resonant at 1760 MHz and 2120 MHz so that they enhance the bandwidth of the third harmonic resonant frequency which was reduced by the capacitive loading. The lengths of these additional resonators can also be reduces using capacitive loading. One more parasitic element is added to enlarge the GSM bandwidth which has a resonant length corresponding to 888 MHz.

The final structure of the quad-band antenna is as shown below.

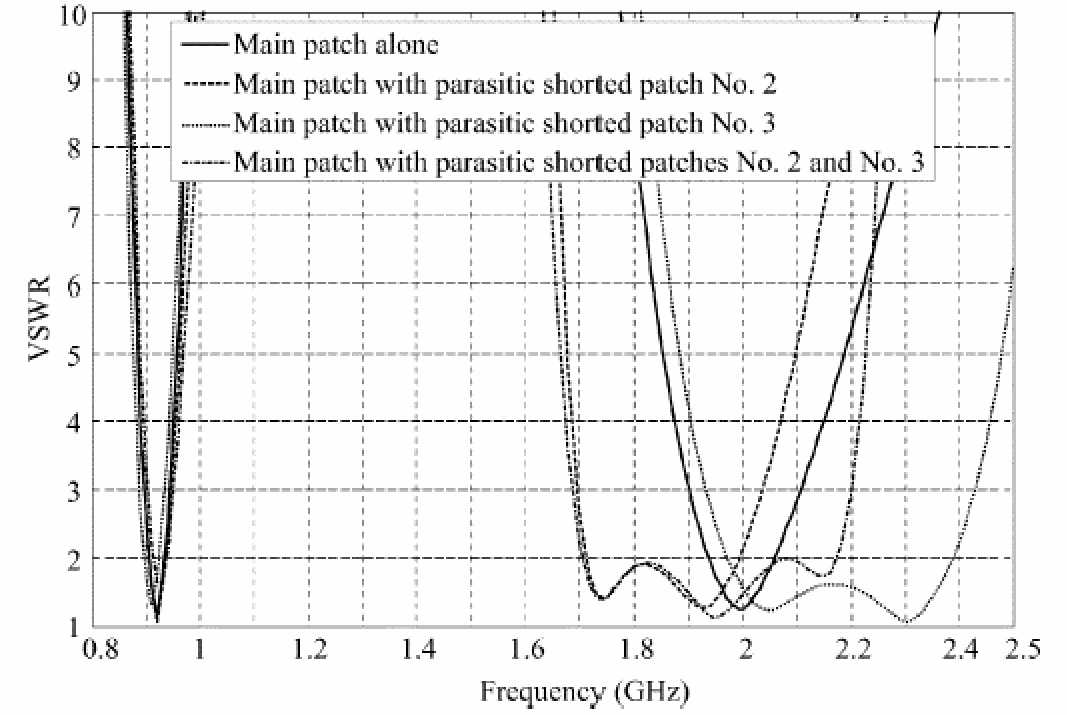


The top view of the antenna is as shown below. All dimensions are given in millimeters

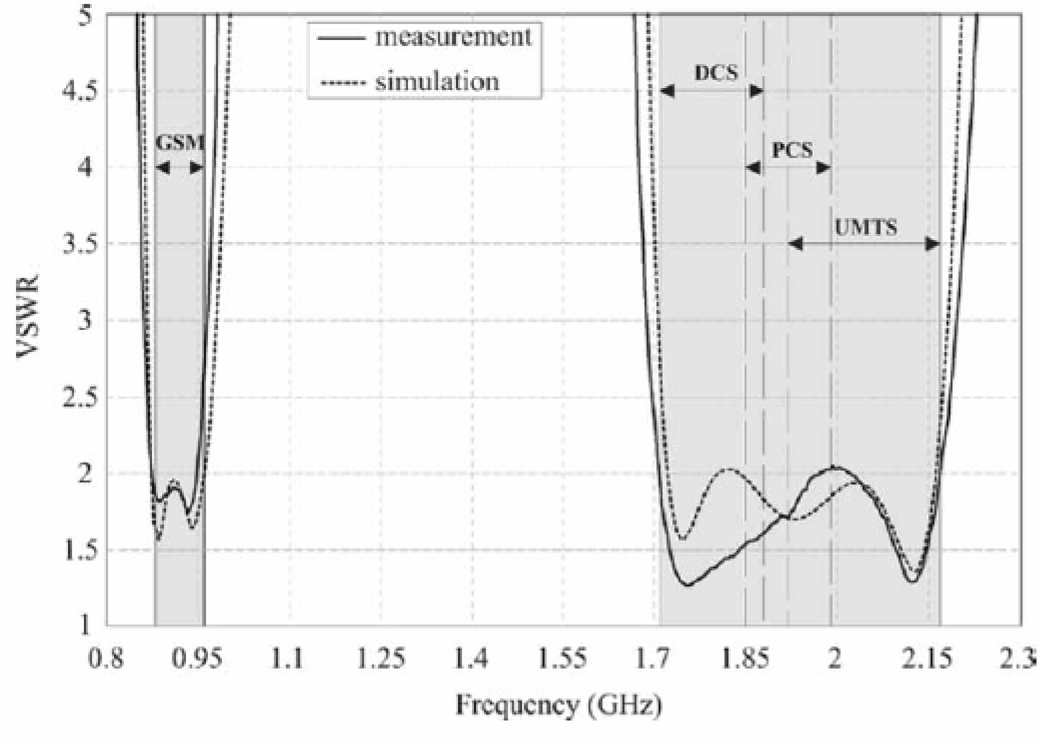


Results and Observations

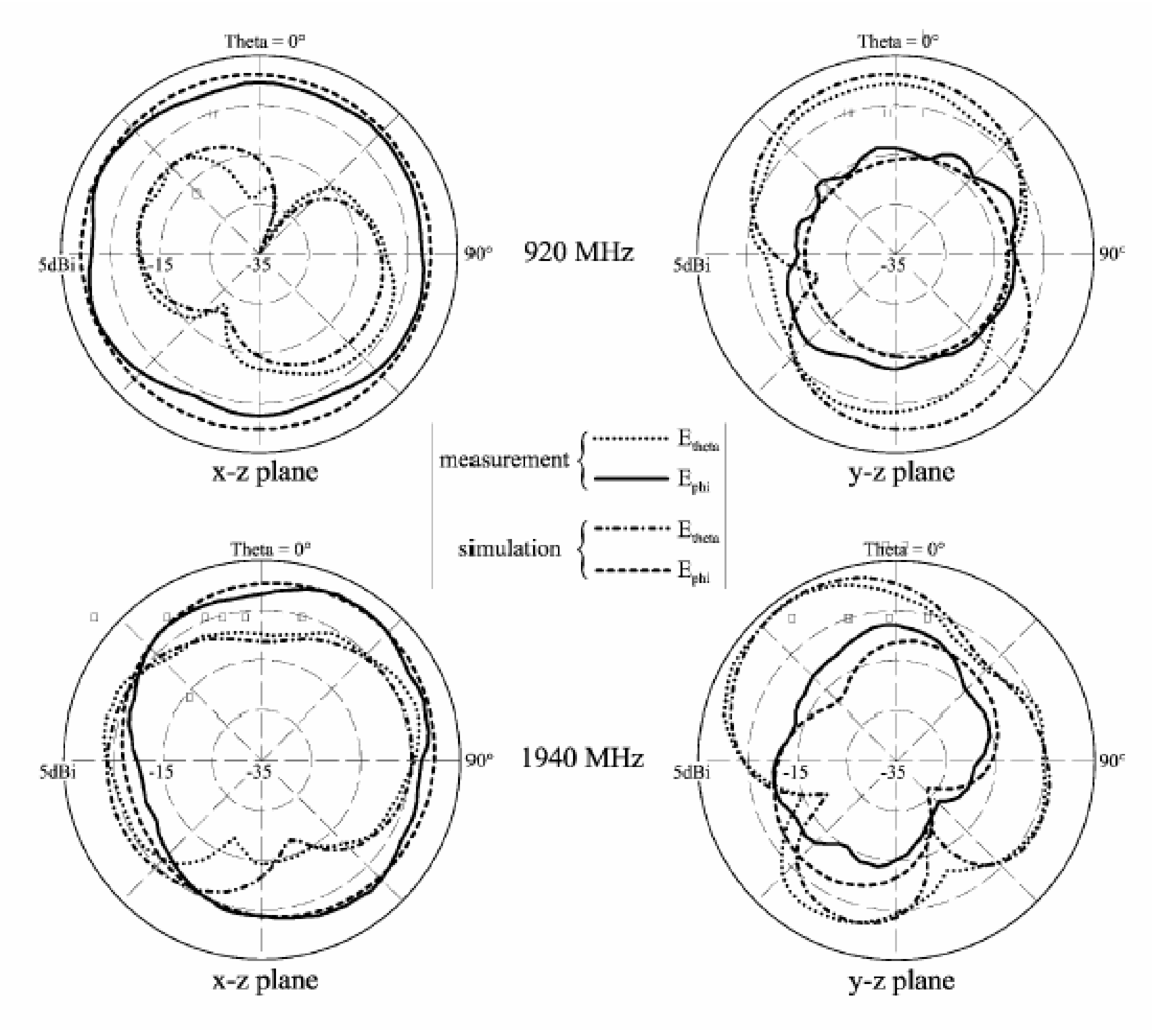
The quad-band antenna was first designed using the theoretical design rules and optimized using a simulation too based on the method of moments (MOM) called IE3D from Zealand Software. First simulations were done with only the main resonant patch. Results were taken and then the parasitic patches No.2 and No.3 were separately and simultaneously added to this main patch. At last, parasitic patch No.1 was built to achieve the final goal. All structures were fine tuned to achieve the best possible coupling between the resonators i.e. the largest possible bandwidths. The VSWR bandwidths of each of the main patch, with simultaneous additions of the other parasitic patches are shown in the figures below. Finally the structure was fabricated and measured results and the comparison with the simulated results are also shown. The small discrepancies between theses values comes from the theoretical formula which doesn't take into account localized and distributed capacitive loading effects. This capacitive effect is very strong in the case of parasitic elements No.3 where two high impedance portions of metal face each other [1].



A good agreement between theoretical and experimental results is observed. The measured lower bandwidth is 90 MHz (870-960 MHz) with a VSWR better than 2.5 while the upper bandwidth is 460 MHz (1710-2170 MHz) with a VSWR less than 2.



The measured and simulated radiation gain patterns of the antenna at 920 MHz and 1940 MHz are depicted below



These patterns reveal a quasi-omnidirectional character in the x-z plane as well as lack of polarization purity due to the radiations from the PCB. The former characteristic is acceptable for mobile phones and the latter one is not a drawback for this application since both horizontal and vertical polarizations occur in urban environments.

The computed antenna efficiency was respectively above 69% and 74% in the GSM and DCS/PCS/UMTS bands which is suitable for mobile phone communication terminals.

CONCLUSIONS

- The proposed antenna successfully makes use of various techniques to compensate for the inherent drawbacks of the conventional microstrip patch antenna on a realistic PCB ground plane.
- The antenna provides acceptable performance in form of low return loss in all four frequency bands – GSM900, DCS1800, PCS1900 and UMTS2000.
- The radiation pattern of the antenna shows almost omnidirectional characteristics and antenna efficiency is within acceptable limits for handheld mobile terminals.
- Due to its internal structure, the proposed antenna causes lesser health hazards than the traditional whip antenna.
- Extensive research in the field of PIFA antennas can further yield improvements in the proposed structure.
- Future work will be concentrated on other frequency bands like 2.4 GHz and 5.8 GHz.

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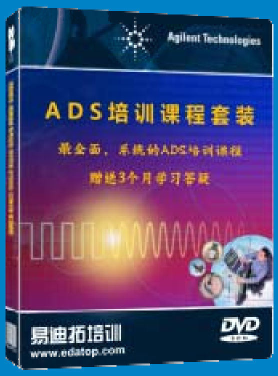

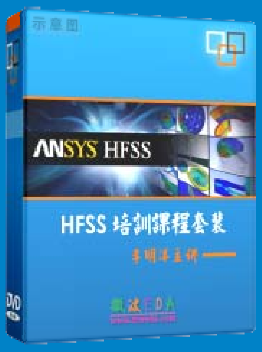

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