

Microstrip Antennas for Mobile Wireless Communication Systems

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1. Introduction

1.1 Introduction to mobile communications

In the last few years, the trend of the mobile phone technology has been dramatically decreased the weight and size. Due to enhancement in this trend, the antennas used for mobile hand held devices have to be small, light-weighted, low profile, and have an omnidirectional radiation pattern in the horizontal plane. However, still there are challenges in the antenna's performance during interaction with the user's head and hand. The movement of the user during usage of the mobile hand held device often lead to gain, radiation pattern and input impedance change. Therefore, antennas used in hand-held transceivers for personal communications have been recognized as crucial elements that can either improve or limit system performance. This is particularly true in terms of bandwidth and efficiency. Therefore, to carefully design a handset with superior performance, engineers need to give attention to the design of the antenna systems of the mobile transceiver.

1.2 Introduction to antenna systems for mobile wireless communications

Monopole antennas have been the best whelming choice for use in various automobiles and mobile equipments. This is basically due to its simplicity in design and having the characteristics that are essential for mobile communication. For antenna designers, there is always unprecedented demand to create compact or even electrically small antennas that are compatible with the modem technology, which will operate on a small handheld ground plane, and satisfy the performance specifications, particularly with respect to bandwidth and efficiency.

Typical antenna elements used so far for small mobile terminals are the monopole (MP) (M. D. Yacoub, 1993; J. R. James & P. S. Hall, 1989), the dipole, the normal-mode helix (K. Fujimoto, 1998), the planar inverted-F (PIFA) (C. P. Huang, 1999), the microstrip patch (MSA) (J. R. James and P. S. Hall, 1989), and the meander line. Recently, there is a growing tendency in recent mobile phones to employ only a built-in antenna, instead of using a monopole that sticks out of the equipment case (C. P. Huang, 1999; D. M. Pozar and D.H. Schaubert, 1995) so, the use of a chip antenna which is a very small, ceramic encapsulated antenna has become popular.

2. Mobile Antenna Requirements and Challenges

The explosive growth in the demand for wireless communication and information transfer using handsets and personal communication (PCS) devices has created the need for major advancements of antenna design as a fundamental part of any wireless systems. In most cases, the handheld antenna is placed on a small plastic/conducting box that is in close proximity to biological tissue of user body and also the surrounding crowded electromagnetic waves. At the same time, the system must radiate low power and provide reliable communication of voice and possibly data (D. M. Pozar & D.H. Schaubert, 1995). Added to the operational requirements, the user and service providers demand wireless units with antennas that are small and compact, cost effective for manufacturability, low profile and easy to integrate with the wireless communication system. The antenna designer must also consider the following electrical characteristics of the antenna which include (W. Stuzman & G.Theile, 1998; C. A. Balanis, 1997).

- 1-antenna tuning (operating frequency);
- 2- VSWR and Return loss (input impedance);
- 3- Bandwidth;
- 4-Gain and directivity;
- 5- Radiation pattern;
- 6- Diversity;

But significant new variables are introduced as:

- 1-The size of the chassis (expressed as a function of wavelengths);
- 2- SAR (Specific absorption rate) of the antenna.

These design considerations have led antenna designers to consider a wide variety of antenna structures to meet the often conflicting needs for wireless systems as: operation frequency, return loss (VSWR), bandwidth, gain and directivity, location and orientation of the antenna, radiation pattern and diversity.

3. Microstrip Antennas

One type of antennas that fulfills most of the wireless systems requirements are the *microstrip antennas*. These antennas are widely used on base stations as well as handsets. Microstrip antennas have a variety of configurations and have been the topic of what is currently the most active field in antenna research and development. The microstrip patch antennas (J. R. James & P. S. Hall, 1989) has increasingly wide range of applications in wireless communication systems as mobile and satellite communication systems due to their great advantages. Simply, microstrip structure consists of a thin sheet of low-loss insulating material called the dielectric substrate. It is completely covered with a metal on one side, called the ground plane, and partly metalized on the other side, where the circuit or antenna patterns are printed. Components can be included in the circuit either by implanting lumped components or by realizing them directly within the circuit as shown in Figure 1.

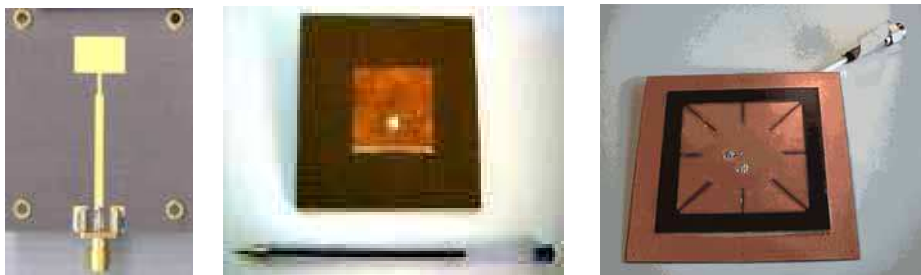


Fig. 1. Microstrip patch antennas

Microstrip antenna offers certain advantages as:

1. *Easy to handle and inexpensive:* as it is small and light
2. *Low power-handling capability* of printed circuits
3. *Topological Considerations:* integral with other circuit devices, hence, improving system reliability.
4. *Reduction in Size:* printed circuits are thin and thus require less volume than their waveguide or coaxial line counterparts.
5. *Large-Scale Fabrication:* once the designer has developed the basic circuit pattern, realized a circuit, and tested it successfully, additional copies can be produced rapidly and consistently in large mass production.

On the other hand, it suffers from some disadvantages as:

1. Narrow bandwidth.
2. Low gain.
3. Large ohmic loss in large feed network.
4. Radiation from feeds contributes to the radiation pattern.
5. Excitation of surface waves.
6. Low polarization purity.

3.1 Applications

Most of the rapid advances in microstrip antennas and arrays took place in the 1980s. Firstly, these were driven by defense and space applications. Then this technology is growing rapidly in the commercial sector. Specifications for defense and space application antennas typically emphasize maximum performance with little constraint on cost. On the other hand, commercial applications demand low cost components, often at the expense of reduced electrical performance. Thus, microstrip antennas for commercial systems require low-cost materials, simple and inexpensive fabrication techniques. Some of the commercial systems that presently use microstrip antennas are listed in the Table 1:

Application	Frequency
Global Positioning Satellite	1575 MHz and 1227 MHz
GSM	890-915 MHz and 935-960 MHz
Wireless Local Area Networks	2.40-2.48 GHz and 5.4 GHz
Cellular Video	28 GHz
Direct Broadcast Satellite	11.7-12.5 GHz
Automatic Toll Collection	905 MHz and 5-6 GHz
Collision Avoidance Radar	60 GHz, 77 GHz, and 94 GHz
Wide Area Computer Networks	60 GHz

Table 1. Microstrip Antenna Applications

3.2 Design Techniques

Another area of research, which is closely linked to advances in antenna development, is the field of *computational electromagnetics*. As antennas become more complex, the use of simple analytical modeling techniques (such as Transmission line model and cavity model) is not sufficient anymore. The use of full-wave modeling techniques, has therefore become inevitable. The most commonly used full-wave modeling techniques are the Method of Moment (MoM), the Finite Element method (FEM) and the *Finite Difference Time Domain (FDTD)*.

3.3 Microstrip antenna structure

A microstrip structure is illustrated in Figure 2.

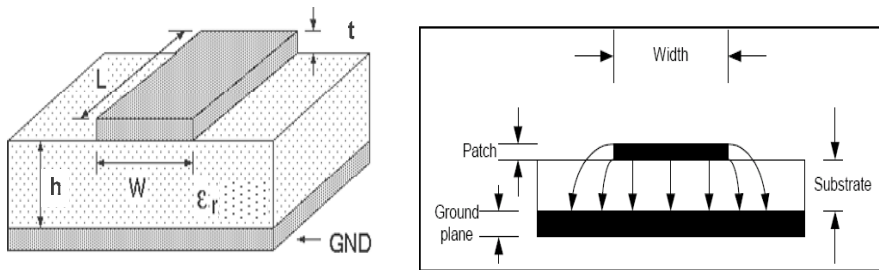


Fig. 2. Microstrip construction

3.3.1 Waves in microstrip structure

Depending on the direction toward which waves are transmitted, waves in microstrip fall within four distinct categories (W. Stuzman & G. Theile, 1998):

- (1) **Space waves:** Waves transmitted upward, with elevation angles between 0 and $\pi/2$, move toward free open space, thus radiated, with field amplitudes decreasing with distance from antenna. In transmission lines and circuits, they are undesirable as they produce spurious leakage, however they contribute directly to antenna radiation efficiency as in figure 3 (a).

- (2) **Guided waves:** they are trapped between the upper and lower conductors. They provide the normal operation for transmission lines and circuits but it is not favorable for patch antennas as in figure 3 (b).
- (3) **Leaky waves:** they are directed more sharply downward, with θ lying between $\pi - \arcsin(1/\sqrt{\epsilon_r})$ and $\pi/2$. These waves contribute to radiation thus they are useful for antennas as in figure 3 (c).
- (4) **Surface waves:** the waves transmitted slightly downward, having elevation angles between $\pi/2$ and $\pi - \arcsin(1/\sqrt{\epsilon_r})$, experience total reflection between the two conducting plates. The fields remain mostly trapped within the dielectric, decaying exponentially above the interface as shown in Figure 3 (d). Surface waves take up some part of the signal's energy thus reduces the antenna efficiency.

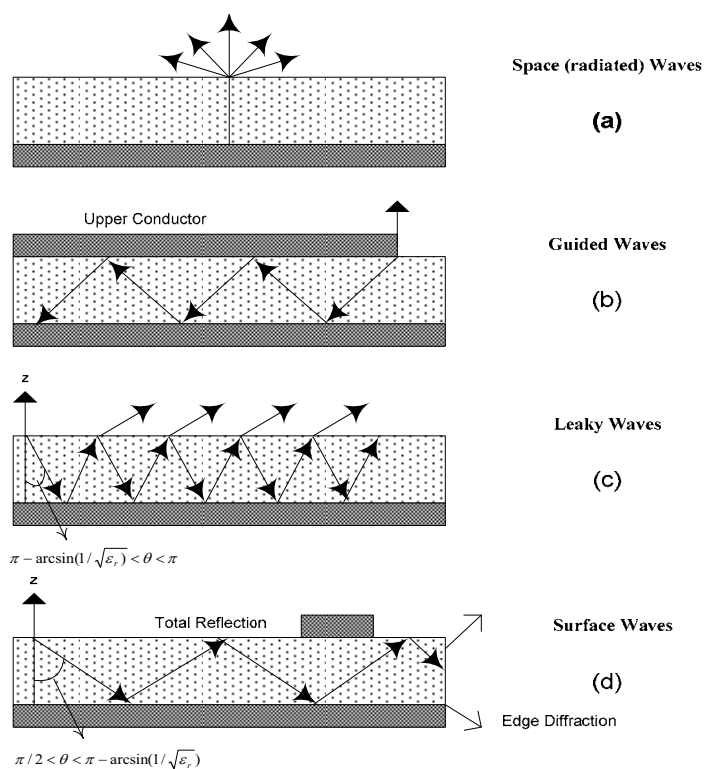


Fig. 3. Waves in microstrip

3.4 Microstrip array

Microstrip patch antenna is important as single radiating element, but the major advantages are realized in applications that require moderate size array as shown in Fig 4. When discrete radiators are combined to form an array, some characteristics can be achieved or enhanced; such as high gain and beam scanning.

The microstrip antenna arrays can be classified with different criteria. The elements of the array can be distributed to form linear, planar or volume array. Several ways of feeding can be used to obtain certain characteristics. The feed network of phased arrays or SISO arrays (Single Input Single Output) can be categorized into parallel and series feed. The parallel (corporate) feed has single input port and multiple feed lines. If the array has multiple inputs and multiple output ports so it is called Multi-element-array (MEA) or MIMO arrays (D. M. Pozar & D. H. Schaubert, 1995).

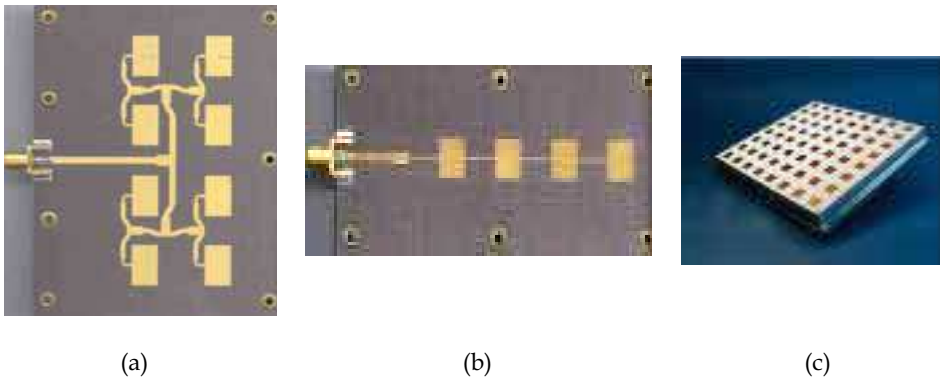


Fig. 4. Microstrip antenna array (a) phased array, (b) series-fed array, (c) Multi-Element Array (MEA)

4. Compact and Multiband Microstrip Antennas

4.1 Introduction to compact and multi band antennas

In wireless communication applications, the demand for low profile compact size planar antenna is increasing day by day. The light weight, small size handheld wireless devices design challenges never stops. Various types of low-profile elements have recently been developed and they are fairly efficient radiators that can be easily manufactured at low cost. The conventional microstrip patch is not a good candidate for the mobile wireless applications, due to certain disadvantages as narrow bandwidth. Therefore, more unusual approaches are investigated for multiband antenna with reduced size operation. Different other microstrip structures are successful candidates as microstrip Planar Inverted F-Antenna (PIFA) with different geometrical radiator shapes. The main goal is to design antennas for wireless communication applications where the space value of the antenna is quite limited while it reserves the characteristics of multiband, light weight, low cost, robustness, diversity, packaging capabilities and ability for MEMs integration for smart antenna systems. Several researches in literature concentrate on these antenna types and their developments. In this part the author will try to highlight the important results and several corresponding shapes.

Famous techniques for antenna size reduction include dielectric loading to reduce the electrical size, top hat loading, and use of shorting pins or plates are summarized in table 2 (Dalia Nashaat et al, 2003). Dielectric loading usually is accompanied by bandwidth reduction and cost increase, so it is not a likely approach. Thus, we will investigate antennas with top hat loading and shorting pins or plates, either separately or in combination.


Performance Down sizing technique 	Geometrical (size reduction with respect to conventional resonant size)	Circuitual (impedance bandwidth enhancement ratio)	Radiation pattern (symmetry vs. low cross polarization)
Material: high dielectric, slow wave, etc.	70%	2%	high
Shorting planes: Walls, pins, etc.	50%	5%	low
Patch etching: slits, slots, notches, etc.	50%	7%	medium
Multilayered: fold, bend, stack, etc.	60%	10%	high

Table 2. Downsizing techniques and performance affecting on antennas

4.2 Compact/small antenna definition

The miniaturization of antenna structure is usually limited by physical laws of nature. Usually, the size reduction is on the expense of other antenna characteristics as bandwidth (BW), gain (g), etc. For small size antennas, there is always a tradeoff among antenna radiation quality factor (Q), BW and efficiency (η) (C. P. Huang, 1999; Dalia Nashaat et al, 2003).

The rule of thumb is:

$$\frac{BW\eta}{V} = \text{Constant} \quad (1)$$

Where BW is the antenna bandwidth, η is the antenna efficiency and V is the antenna volume.

$$BW\eta \cong (Ka)^3 \cong 1/Q \quad (2)$$

Where (a) is a radius of sphere that can include the small antenna. Form Equation 2, it indicates that the smaller the antenna, the higher the Q

So the microstrip antenna can be considered small if its largest dimension is less than or equal to (a) where:

$$a = 1/k = \lambda / 2\pi \quad (3)$$

Where λ is the wavelength of the electromagnetic fields radiated by the antenna.. For example, for antenna operates at 5GHz, $\lambda = 60\text{mm}$ so $a \cong 10\text{mm}$, which means that the antenna can be considered small if its dimensions are less than 10mm.

4.3-PIFA as compact multiband antenna

PIFA is well-known as terminal antenna design. These antennas offer reduced size over traditional microstrip antennas because the resonance frequency is at about quarter wave rather than at half wave in conventional ones due to the shorting pins/walls in its structure as shown in figure 5 (T. Taga, 1992).

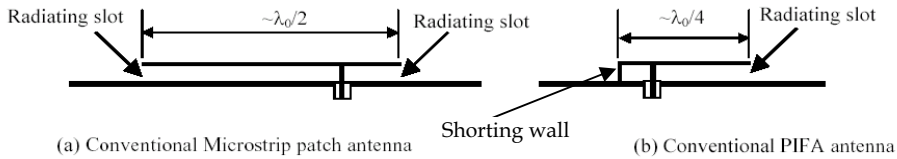


Fig 5. Comparison between conventional microstrip patch antenna and conventional PIFA antenna

The selection of PIFA is due to certain advantages as

The PIFA bandwidth is affected very much by varying the size of the ground plane, generally, reducing the ground plane can effectively broaden the bandwidth of the antenna system.

PIFA impedance matching can be obtained by the correct positioning of feeding and grounding pins. Thickness of the antenna and permittivity of the substrate material used also affect the impedance of the feeding point. To shrink the size of the PIFA, high constant dielectric substrate materials can be used. This weakens the performance of the antenna, because dielectric material gathers electromagnetic fields and therefore it doesn't radiate as good as the air insulated PIFA. Also part of the feed power goes into the dielectric losses of the substrate material. The height of the PIFA is a very critical dimension since it has a great effect on the antenna's radiation and also its impedance bandwidth (J. Elling et al, 1991; C. R. Rowell & R. D. Murch 1997). The basic rule is that the bigger the air gap between the radiator and ground plane is, the better the gain and the broader the impedance bandwidth will be. Table 3 summarizes the effect of different PIFA design parameters, (height, width, length, location of feed and shorting pin/wall and size of the ground plane) on its characteristics.

Parameters	Effect
Height	Control bandwidth
Width	Control impedance matching
Length	Increase inductance of the antenna and determine resonance frequency
Width of short strip	Affect on the anti-resonance and increase bandwidth
Feed position from short strip	Affect on resonance frequency and bandwidth

Table 3. The effect of PIFA parameters on its characteristics

4.4 PIFA structures for multiband and compact size applications:

4.4.1 Rectangular PIFA shape with U-shaped slots

A practical method to design a single feed multiband PIFA that covers both the cellular and non cellular bands is developed (Dalia Nashaat et al, 2005; Hala Elsadek, 2005; R. Chair et al, 1999). From the commercial point of view, there are now different frequency bands for portable cellular/non cellular devices as the conventional 0.9GHz GSM band for mobile phones and 1.8GHz DCS band for wireless cellular applications. Furthermore the Bluetooth wireless technology at 2.4 GHz is already applied in many portable devices and in most wireless communication systems as mobile phones, laptops, PDAS, car stereos, audio speakers, toys, etc (Bluetooth information web site). Moreover the band of WLAN at 5.2GHz is being applied in some applications. The compact and multiband functionality is not the only required demand in such antenna systems for wireless communication applications but, also other characteristics should be satisfied as small size, light weight, omni directional radiation pattern, reasonable gain and acceptable bandwidth.

Quad band PIFA with single coaxial probe feeding is investigated. Foam substrate is used for light weight, rigid structure and easy shielding purposes. Three U-shaped slots are added with certain dimensions and at appropriate positions for operation at the aforementioned four frequency bands. The size reduction is 30% from conventional quarter wavelength PIFA. Additional reduction by 15% is achieved by adding a capacitance load in the vertical direction. The impedance bandwidth is fairly acceptable. The antenna gain is satisfactory and the radiation pattern is quasi isotropic at the respective four bands of interest. The proposed concept of adding U-shaped slots is a distinct advantage of the design since the bands of operation are independent on each other except the small controllable mutual coupling between the slots. Figure 6 illustrates the suggested antenna design.

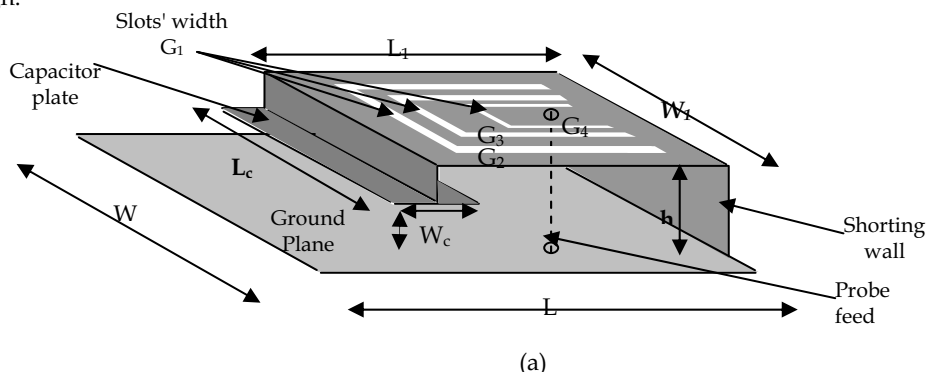


Fig. 6. Geometrical dimensions of the fabricated quad band antenna

The rule of thumb in antenna design is:

$$f_i = \frac{c}{4(L_i + W_i)} \quad (4)$$

The length L_i and width W_i are replaced by L_1 and $W_1 = (61\text{mm}, 40\text{mm})$ of the PIFA rectangular radiating surface to determine the first resonance frequency f_1 (0.9GHz). While, (L_i, W_i) are replaced by the dimensions of the largest U-slot $(L_2, W_2) = (23\text{mm}, 30\text{mm})$ to

generate the second resonance frequency f_2 (1.8GHz). They are also replaced by the length $(L_3, W_3)=(18\text{mm},20\text{mm})$ of the middle U-slot to get the third resonance frequency f_3 (2.45GHz). Finally, (L_i, W_i) are replaced by $(L_4, W_4)=(9.5\text{mm},8\text{mm})$ of the smallest U-slot to have the fourth resonance frequency at f_4 (5.2GHz). This multi-band antenna has approximately the same size as a single-band PIFA operating at the lowest frequency band. The radiating element is grounded with a shorting wall. It is found that the widest bandwidth is achieved when the width of this wall is equal to the width of the PIFA radiating plate. The antenna is fed using coaxial cable at the appropriate matching point for the four bands of operation. The antenna impedance can be matched to 50Ω by controlling the distance between the feed point and the shorting wall. The PIFA antenna is fabricated on a foam substrate with dielectric constant $\epsilon_r=1.07$ in order to have rigid structure that can be easily shielded. Adding U-slots on the PIFA radiating surface, reduces its size by about 30% from the conventional PIFA shape. For further reduction in size, a capacitor plate load is added between the radiating surface and the ground plane. This increases the reduction in size to be about 45%. The results of the structure simulations as well as experimental measurements are illustrated in following three figures.

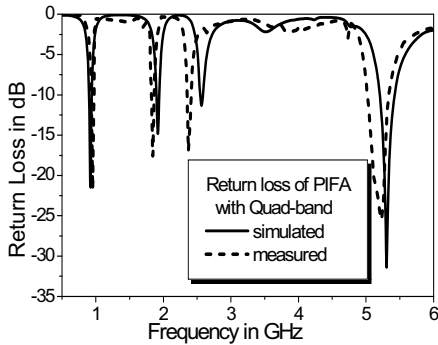


Fig. 7. Comparison between measured and simulated reflection coefficients of quad band PIFA with three U-shaped slots at operating frequencies of 0.95, 1.8, 2.45 and 5.2GHz, respectively.

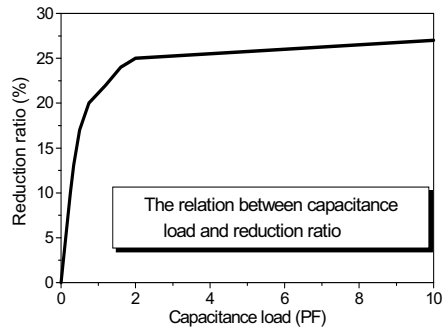


Fig. 8. The relation between capacitor load in PF and antenna percentage reduction ratio compared to conventional PIFA.

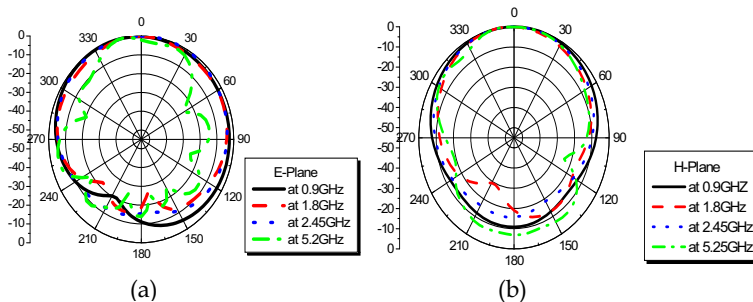


Fig. 9. The simulated radiation pattern of quad-band PIFA with 10PF shunting capacitor plate at four different resonating frequencies, a) at parallel E-plane at $\phi=0$ and b) at perpendicular H-plane at $\phi=90$.

4.4.2 Compact PIFA size with E-shaped radiator

Ultra compact PIFA with dual band resonant frequencies are investigated (Hala Elsadek, 2006). The antenna is designed and fabricated on both foam and FR4 cheap substrates with dielectric constants $\epsilon_r = 1.07$ and 4.7, respectively. Over 95% reduction in the antenna size is achieved from conventional $\lambda_0/4$ rectangular PIFA resonating at same frequencies. This is done by implementing two oppositely shorting capacitive straps under the radiating surface. Dual band operation is achieved by inserting two parallel slots on the edges of the PIFA radiating surface forming an E-shape. In this case, the center wing resonates at the higher frequency while the two side wings resonate at the lower frequency. The antenna resonance frequencies on FR4 substrate are 1.07GHz and 2.77 GHz with areas' reduction ratios of 97% and 81% for the lower and upper resonance frequencies, respectively. The antenna size on FR4 substrate is 13 x 11 x 8mm³. The antenna directivity is 3.73 with radiation efficiency 97%. The radiation pattern has acceptable shape with low cross polarization in both resonances and at both E-plane and H-plane directions. It is worth to mention that, with frequency scaling, the same antenna structure can resonate at 2.4GHz and 5.2GHz with dimensions 8mmx8mmx8mm Figure 10 shows the antenna geometry, while figure 11 illustrates a comparison between simulated and measured results with capacitive load reduction effect. There are different approaches for multiband compact antenna design; however, we concentrated on PIFA with shorting plates and capacitive loads with different radiator shapes. Since these shapes give excellent results for antenna candidates in mobile communications.

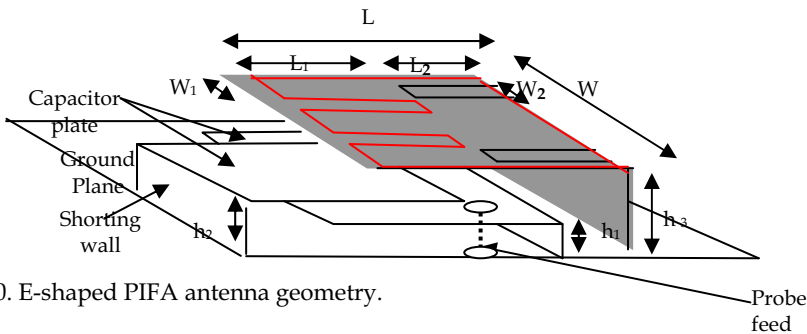
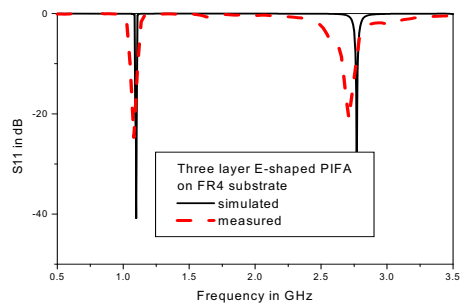


Fig. 10. E-shaped PIFA antenna geometry.



(a)



(b)

Fig. 11. Photo of fabricated E-shaped PIFA on commercial FR4 substrate and (b) comparison between simulated and measured antenna reflection coefficients.

5. Broad band and UWB Antennas

5.1- Introduction to broad band and UWB antennas

In last sections, we illustrate the challenge of small and multiband antenna that can fit in several wireless communication systems at same time. In all previous designs, acceptable antenna bandwidth was achieved. However, several other applications of wireless communications require broadband and even ultrawideband antenna rather than directional one. Broad band antennas are desired for the increasing demand of communication bandwidth that accommodates high data rate application like video-on-demand. Moreover UWB technology attracts a lot of attention from the researchers in recent years because of the various advantages it offers. UWB technology depends on transmitting pulses of width in order of nano seconds instead of modulating sinusoidal signal and, hence broadening its spectrum and tuning its power density beyond noise level (FCC, 2002). This method in transmission exhibit many advantages as immunity to jamming and ability to combat fading due to multipath effects. Also it has penetration capability as its spectrum include low frequency components. Because of these advantages UWB technology has enormous applications in wireless communications. One of the major application is the wireless sensor network (WSN) which is useful in medical, tracking and localization applications (remote sensing) (Ian Opperman et al., 2004; K.P. Ray, 2008). As UWB provide security and low power consumption that increase the battery life of the portable terminals. On the other hand, broad band communication systems as well as UWB technology faces a lot of challenges as the radiation pattern stability and polarization purity along the whole band of operation.

5.2-Different types of broad band antennas

Many designs have been investigated in literature for broadening the bandwidth of antennas. This can be achieved by using different probe feeding shapes as L-shape, adding parasitic elements to the radiator, folding the ground plane, etc. (Fan Yang, 2001; Yasshar Zehforoosh, 2006). Taking in consideration for the stability of the beam pattern and polarization purity along the bandwidth, the design quality is judged. Among the basic ideas for broadening the band are inserting slots of different shapes (U,H,V) on the radiating patch antenna to introduce longer current paths and hence add other staggered resonating modes. The rule of thumb in adding another resonance to the antenna structure is the same as that discussed in previous section for multiband antenna designs however, in case the resonating modes are far from each other, the structure will act as multiband antenna. But if the design is changed to let these resonances near from each other, they will complement each other forming staggered resonating behavior and broadband antenna structure. Also adding parasitic or stacked patch has been proposed in (Mohamed A. Alsharkawy et al., 2004). Another types as aperture stacked and multi resonator stacked patches in (Ki-Hakkim et al, 2006; Jeen Sheen Row, 2005) .In these types multi patch antenna are printed on different layer forming multi resonators and hence broaden the antenna band. These types are bulky and not adequate enough to be integrated with the modern wireless devices in spite there are successful attempts for this. In addition they don't exhibit enough bandwidth to cover all wireless communication band nowadays (3.1-10.6GHz). Recently UWB slot antenna in (Girish kumar, 2003; Yashar Zehforoosh et al, 2006) and printed monopole antenna in (Soek H. Choi et al., 2004) are proposed. They attract a lot of interests due to their

low profile, ease of integration and very wide bandwidth. Next section will focus on the UWB printed monopole antenna.

5.3- UWB antenna Design

Some considerations should be taken for UWB antenna design such (Hung-Jui Lam, 2005):

1-It should have bandwidth ranging from 3.1GHz to10.6GHz in which reasonable efficiency is satisfactory.

2-In this ultra-wide bandwidth, an extremely low emission power level should be ensured. (In 2002, the Federal Communication Commission (FCC) has specified the emission limits of -41.3 dBm/MHz).

3-The antenna propagates short-pulse signal with minimum distortion over the frequency range.

5.4 UWB Printed Monopole Antenna

Printed monopole antenna structure is shown in Figure 12 and it could be explained as an evolution of the conventional microstrip antenna with ground plan eliminated (K.P. Ray, 2008). From the analysis of the microstrip antenna, (Hirasawa and K. Fujimoto, 1982; C.A. Balanis, 1997) it is known that the substrate thickness (h) is directly proportional to the BW and as (h) is extended to infinity by eliminating the ground plan the BW become very wide. Also, the resonant frequency is function of the patch length, width and height. So when patch printed on very thick substrate it excites higher order modes each enables broad

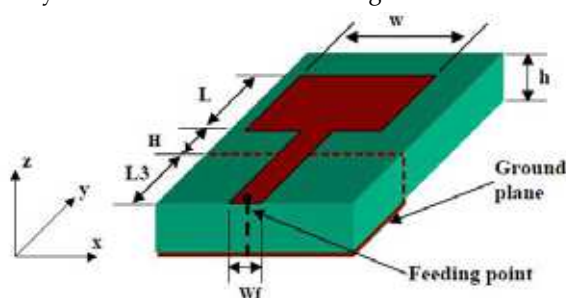


Fig. 12. Geometry of the rectangular printed monopole antenna

bandwidth case. If these higher order modes are close to each other the overall bandwidth is ultrawideband. Another explanation for the printed monopole that it could be seen as conventional monopole but with the cylindrical metallic rod flatted to be plane of any different shapes (K.P. Ray, 2008) (rectangular, circular, elliptic) as it is known that impedance bandwidth increase by increasing the diameter of the metallic rod. The printed plane that alternate the metallic rod is considered of diameter extended to infinity exciting higher order modes of large bandwidth. Upon optimizing the dimensions of the antenna, these higher order modes could be close to each others to yield very broad bandwidth as will be elaborated in next sections.

5.4.1 Analysis

As mentioned in previous section, printed monopole antenna is analog to the wire quarter wave monopole antenna. This could be used to analytically design the antenna for the lower edge frequency by equating its area (in this case rectangular monopole) to an equivalent cylindrical monopole antenna of same height L and equivalent radius r as following:

$$2\pi rL = WL \quad (5)$$

The input impedance of thin $\lambda/4$ monopole is half the input impedance of thin $\lambda/2$ dipole and equal is slightly less than quarter wavelength and given by (15, 38)

$$\begin{aligned} L &= 0.24 \times \lambda \times K \\ \text{where} \\ K &= (L / r) / (1 + L / r) = L / (L + r) \\ \lambda &= \frac{(L + r)}{0.24} \\ \text{therefore} \\ f_l &= \frac{c}{\lambda} = \frac{(30 \times 0.24)}{L + r} = 72 / (L + r) \dots \text{GHz} \end{aligned} \quad (6)$$

Previous equation doesn't account for the distance between the radiator and the ground plane (h)

$$f_l = 72 / (L + r + h) \dots \text{GHz} \quad (7)$$

where all dimensions are in millimeters. This analysis is valid for free space but in our case where antenna is printed on a dielectric substrate which decrease the effectiveness of the wavelength (λ_g). Modification on the lower edge frequency is required and can be given by

$$f_l = 72 / (L + r + h) \times k \dots \text{GHz} \quad (8)$$

It is worthwhile to mention although previous analysis was on rectangular shape printed monopole, it is valid on other various shapes of radiators but only L and r will differ according to the geometry of the shape. (K. P. Ray, 2008).

After inspecting the lower edge frequency we need to control the bandwidth of the antenna. Actually the L , r and h affects both lower edge frequency as well as the bandwidth too so optimization is needed to give the required bandwidth as well as the lower frequency. Another important thing that affects severely the bandwidth is the bottom shape of the radiator in contact with the 50Ω feeder. As long as we avoid abrupt change in the dimensions of the transition from the feeder to the radiator as long as we obtain broader bandwidth. That's why circular radiator inherent wider band than rectangular one. Abrupt transition from feeder to radiator is overcome by using stepped or tapered feeders (S. I. Latif at el., 2005; A.P. Zhao and J. Rahola, 2005). Finally using CPW (coplanar waveguide feed) instead of microstrip feed enhances the bandwidth. As printed monopole antenna resonating around quarter wave length so they have similar radiation pattern as normal

monopole. It is omni in the H-plane and eight shaped in the E-plane. Following are examples about broad band and UWA antenna designs.

5.5 Examples on broadband and UWB microstrip antenna designs

5.5.1 Broad band antenna

The geometry of the proposed antennas is as shown in figure 13. The antenna consists of V-shaped patch with V- unequal arms with dimensions (L_1, W_1) and (L_2, W_2) . The isosceles triangular antenna is with dimensions (L_T, W_T) . The shorting wall width is equal to W_T for maximum size reduction (Hala Elsadek and Dalia Nashaat, 2008). The ground plane is with rectangular shape of dimensions (L_g, W_g) . The two parts of the structure, V-shaped patch and triangular PIFA, are coupled through a V-shaped slot with unequal arms with slots' lengths and widths are (L_{s1}, W_{s1}) and (L_{s2}, W_{s2}) . The two arms of the V-shaped patch excite TM_{01} mode. The length of the two arms of the V-shaped patch is different in order to excite two different staggered resonant modes. The unequal spacing/ widths between the coaxially fed triangular shorted patch and the V-shaped patch are for different values of coupling thus, excite two more different modes. To add two more resonating modes, equal arms V-shaped slot can be loaded on the triangular patch radiation surface. The substrate is foam with dielectric constant $\epsilon_r=1.07$ and substrate height $h=6\text{mm}$. The antenna geometry is illustrated in figure 13. When the ground plane size is reduced to certain proper value, the antenna behavior changes to be wide bandwidth antenna rather than multiband antenna. The resonating frequencies can be approximately determined from following equation (Yujiang Wu and Zaiping Nie, 2007).

$$f_i = \frac{c}{4L_i} \quad (9)$$

Where: f_i is resonant frequency at band i , C is the velocity of light $= 3 \times 10^8$ m/s and L_i is the half length of the radiating surface or the length of the slot at the corresponding operating band i . The Triangular PIFA part is excited by coaxial probe feed. The probe is positioned in the centerline of the shorted patch at distance d_f from shorting wall. The d_f value controls the antenna characteristics. For multiband operation, the resonating frequencies are at 2.88GHz, 3.64GHz, 3.95GHz, 4.38GHz, 4.81GHz and 5.6GHz, the distance d_f is 16.75mm while for broadband operation, the distance d_f increased to be 18.5mm.

Figure 14 illustrates comparison between the simulated and measured results for the multiband structure. The radiation pattern of the antenna is approximately omni directional in both E-plane and H-plane with back to front ratio of less than 5dB and 3dB beamwidth of about 60° .

Moving coaxial feeding towards open end of triangular PIFA antenna at $d_f = 18.5\text{mm}$, the resonant frequencies of the antenna become staggered close to each other so achieving wideband operation. The bandwidth is 3% at the fundamental mode 2.95 GHz, hence the fundamental resonating frequency will approximately not affected by changing the feed

position. The higher resonance bandwidth is 27% at 4.721GHz. Figure 15 presents the comparison between the simulated and measured results of the wideband antenna structure.

Folding the shorting wall of the triangular PIFA as in figure 13, converts the antenna to UWB with bandwidth of 53% at same resonating frequency 4.65GHz. The antenna gain is 10.5 dBi

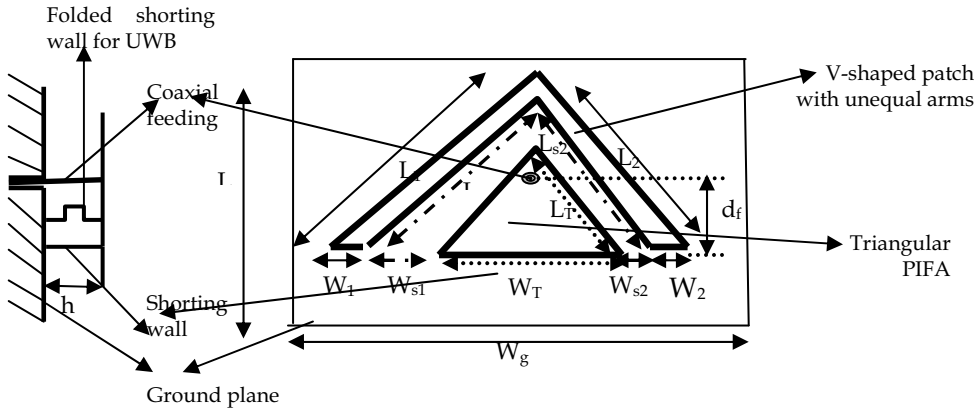


Fig. 13. Configuration of the proposed antenna of V-shaped patch with unequal arms coupled to isosceles triangular PIFA through V-shaped slot of unequal arms

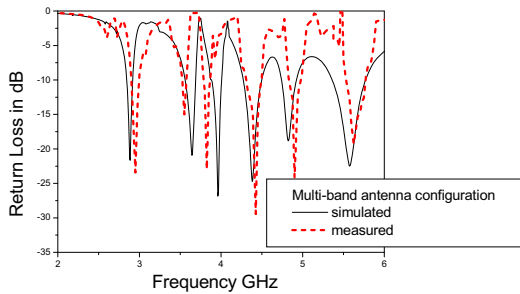


Fig. 14. Comparison between simulated and measured results of the multi-band antenna

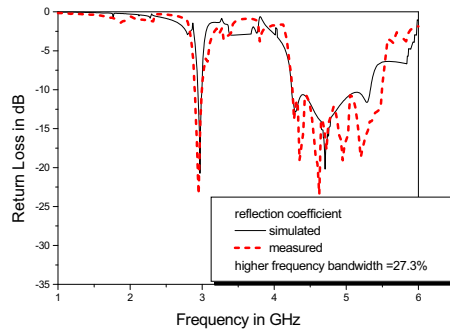


Fig. 15. Comparison between simulated and measured results of broad band antenna

5.5.2 UWB antenna

Consider we have substrate material of $\epsilon_r=3.38$ and $h=0.813\text{mm}$ and we need to design printed rectangular monopole shown in figure 12 so we need to know the values L,W,H for obtaining lower edge resonance frequency at 5GHz and obtain BW as Wide as possible. From above equations in subsection 5.4.1, to satisfy 5GHz a lot of solutions could be obtained for L, W, h but not all of them will give the maximum BW, so optimization is

needed for obtaining the optimum dimensions. Parametric analysis for the effects of these three dimensions on bandwidth is shown in figures 16-18 (Hakim Aissat et al, 2006; Min Hau Ho et al, 2005). Starting with $L=W=0.25\lambda_0/\sqrt{\epsilon_r}=8\text{mm}$ and $h=2\text{mm}$. From the three figures below, the optimum dimensions are $W=12, L=11.5$ and $H=0.75$.

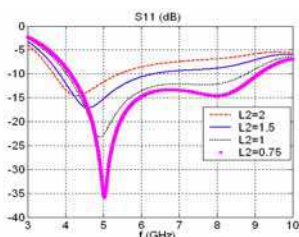


Fig. 16. The effect of changing W on the return Loss at $L=5$ mm and $h=2$ mm.

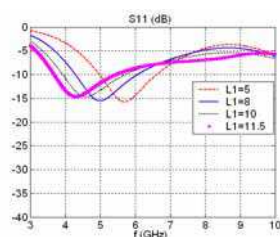


Fig. 17. The effect of changing L on the return loss at $W=12$ mm and $h=2$ mm.

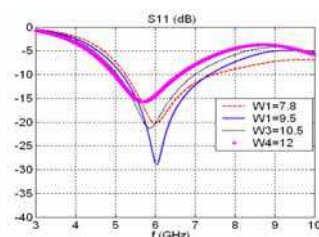


Fig. 18. The effect of changing h on the return loss at $W=12$ mm and $L=11.5$ mm.

6. Reconfigurable microstrip antenna

6.1 Introduction to reconfigurable antenna system

Due to the increasing demand of multipurpose antennas in the modern wireless communication devices and radar systems, reconfigurable antennas have attracted a lot of researcher's attention. One type of these antennas capable for operation at mutli bands and hence could intercept various communication systems (KPCS/WiMAX/GSM/WCDMA) with lower co-site interference. Other types exhibit diversity in transmission or reception to combat fading effects and enhance signal quality. Reconfigurable antennas are similar to the conventional antennas but one or more of its specification or characteristics could be adjusted or tuned using RF switches/MEMs or variable capacitors/inductors. They have four types: 1-Frequency reconfigurable, 2-poolrization diversity, 3-radiation pattern steering, 4-combination of the three previous types. Advantages of reconfigurable antennas are integration with wireless and radar devices instead of multiple antenna systems, compactness, cost reduction, etc. Frequency reconfigurable antenna could decrease interference and make efficient use of the electromagnetic spectrum. Polarization diversity and radiation pattern steering antennas could lead to increase in the communication system capacity and fading immunity. Moreover they open the way of emerging some modern communication systems like MIMO and cognitive radio. Also from future potential for the introduction of smartness and intelligence to the handheld terminals. Switching and/or tuning takes place with the aid of PIN diodes or MEMs switches or varactors adopted with the antenna structure. Pin diodes are reliable and experience high switching speed but introduce non linearity and need complex bias circuitry to be integrated with the antenna. On the other hand MEMs have lower insertion loss, easier in integration (no need for biasing circuitry), less static power consumption and have higher linearity, but it needs high static bias voltage. According to the various advantages of reconfigurable antennas they are currently part of many modern wireless communication systems such as (DCS/GSM/WCDMA/Bluetooth/WLAN), hand held GPS and other navigation systems,

MIMO Systems and steerable arrays. In the following different examples and kinds of reconfigurable antennas will be presented.

6.2 Polarization Diversity

The work proposed by Hakim Aïssat in (Hakim Aissat et al, 2006) provide circular antenna with switchable polarization as shown in Figure 19 in which 2 diodes in the ground 45° slot are ON and the others in the 0° slots are OFF make the antenna linear polarized on contrary, when the other 2 diodes in the 45° are ON and in the 0° are OFF make the antenna circular polarized. Thin slits (130 μm) were made in the ground plane to avoid DC short on the switches. A rule of thumb for the switches biasing circuitry design that the RF shouldn't go to the DC and the DC shouldn't affect the RF. So for DC blockage from RF, large capacitors are built over the slits by stacking copper strips and adhesive tapes (upper layer on Figure 19). The slits are first covered by an isolating adhesive layer, which insures a dc isolation maintaining RF continuity. The adhesive layer is then topped with four copper tapes to shield the slits at RF frequencies. This antenna enables diversity in TX/RX and hence could enhance signal quality or increase system capacity by polarization multiplex.

For other shapes of microstrip antenna in (Yujiang Wu & Zaiping Nie, 2007) proposed square patch with switchable polarization RHCP/LHCP using 4 pin diodes. The antenna is shown in Figure 20. Circular polarization is synthesized by truncating two opposite corners of the patch. And both LHCP/RHCP are generated by double feeding the patch from two orthogonal sides. Switching ON/OFF diodes 1&2 shown in the Figure 20 in opposite manner achieve RHCP and LHCP, respectively. Also linear polarization could be obtained by attaching triangular small strips connected to the truncated corners and connecting them to the patch via pin diodes 3&4 as shown in Figure 20. When these diodes are ON linear polarization is exhibited.

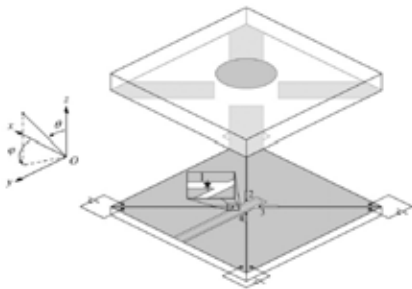


Fig. 19. Circularly polarized reconfigurable antenna

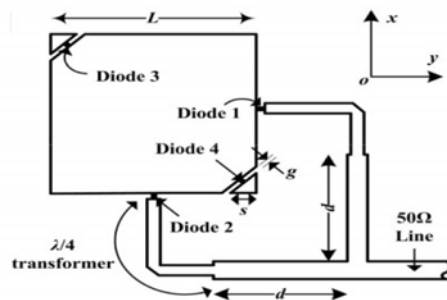


Fig. 20. Configuration of the corner-truncated square microstrip antenna with switchable polarization

6.3 Radiation pattern Steering

Adaptive beam spiral antenna found in the work done in (Greg H. Huff et al, 2004). The geometry of the antenna is shown in Figure 21 where positioning of open circuit in the spiral arm change current distribution leading to steering the beam direction. Two switches are used to open/close the open circuit in the spiral arm and hence the pattern direction is two bit controllable.

In (Yong Zhang et al, 2005), a fractal Hilbert microstrip antenna with reconfigurable radiation patterns using 8 switches is proposed. The antenna is shown in Figure 22. By turning switches on and off interesting results can be obtained. For example at switch pairs (a3, a4) & (a7, a8) are OFF and the others, (a1, a2) & (a3, a4) are ON and then alternates between the status of the maximum radiation patterns in E-plan steer from $\pm 30^\circ$ among two states. The radiation patterns in the H-planes of the two states are almost the same.

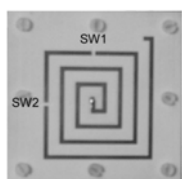


Fig. 21. reconfigurable rectangular spiral antenna (SPRL)

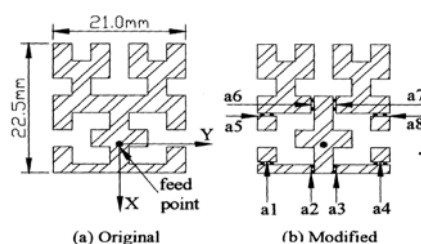


Fig. 22. Geometry of the original and modified reconfigurable fractal Hilbert microstrip antennas

6.4 Frequency reconfigurable antennas

(Ahmed Khirde & Hala Elsadek, 2009) proposed simple design for a low cost band notch UWB printed monopole antenna with reconfigurable capability in a way you are able to create and cancel band notch in the UWB spectral mask covering the in-band IEEE802.11a/h co-existing systems. The antenna dimensions are shown in Figure 23(a) and Figure 23(b). A patch is added in the back plane as a parasitic half wave resonator coupled electrically to the rectangular monopole. Slot is cut into the parasitic patch as shown in Figure 23(b). The two patch parts are connected by means of two RF switches S1 and S2 which are modeled as metal pad with dimension 0.3×0.9 mm. Although this model is ideal, it gives a very good approximation for the real commercial pin diode switch HPND-4005 manufactured by HP. The role of the switches here is to reconfigure the antenna between the ON/OFF states. The ON state where the antenna exhibit a band notch covering the bandwidth of the WLAN for IEEE 802.11a/h which is 5.15-5.825 GHz. The OFF state the band notch is removed and the antenna bandwidth returned flat. The simulation and experimental results comparison for the ON state and OFF state are presented in figures 24 and 25, respectively. The antenna gain over the whole band is presented in figure 26.

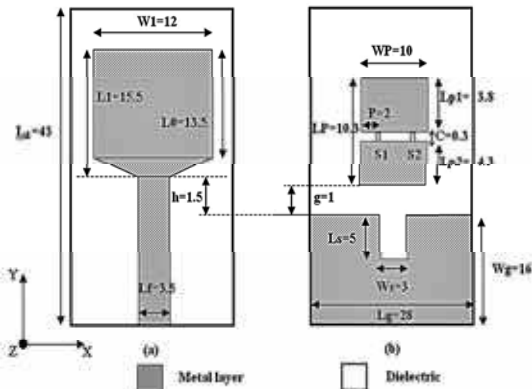


Fig. 23. Geometry of band notch monopole antenna

Fig. 23. Geometry of band notch monopole antenna

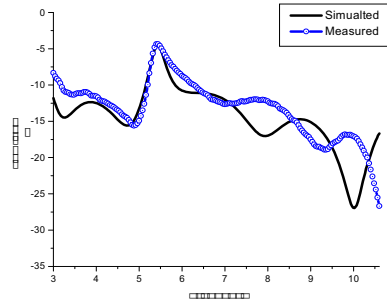


Fig. 24. Comparison between simulated and measured return loss of the ON state

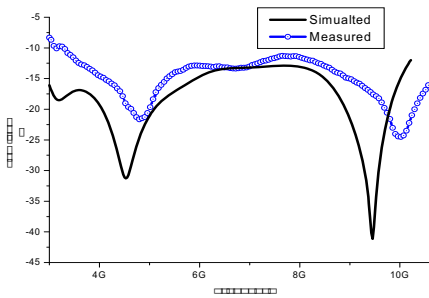


Fig. 25. Comparison between simulated and measured return loss of the OFF state

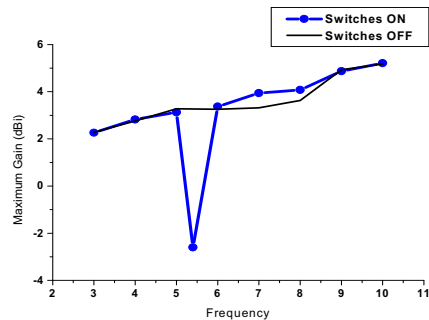


Fig. 26. Antenna gain in the on and off states

As mentioned above reconfigurability could be achieved using RF Micro Electro-Mechanical (MEMs) switches or actuators. An example for a frequency tunable antenna using MEMs micromachining is proposed in (R. Al-Dahleh et al, 2004). It is a simple patch printed on Silicon using VLSI microelectronics technology and an air gap is beneath the patch. MEMs actuator is to change the thickness of the air gap beneath the patch, hence changing the effective substrate dielectric so the resonance frequency is changed. The antenna structure is shown in Figure 27. This kind of antenna is very important for antenna on chip and modern Soc technology that are vital for compact handheld devices.

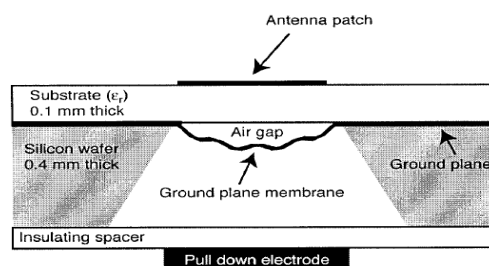


Fig. 27. Schematic of the frequency tunable microstrip patch antenna showing the MEMs membrane in the ground plane below the antenna

7. Smart Microstrip Antennas

7.1 Introduction to smart antenna system

A smart antenna system consists of either single antenna element or combines multiple antenna elements with a signal processing capability to optimize the radiation and/or reception pattern automatically in response to the required signal environment. Different technologies are combined and defined today as smart antenna system. These ranges from simple diversity antennas to fully adaptive antenna array systems. In truth, antennas are not smart by itself—antenna systems are smart. In other words, such a system can automatically change the directional of its radiation patterns or any other characteristic like resonating frequency, polarization direction, antenna gain, antenna bandwidth, etc. in response to its surrounding signal environment. This can dramatically improve the performance (such as capacity and coverage range) of the wireless system.

7.2 Smart antenna systems classifications

Sectorization schemes, which attempt to reduce interference and increase capacity, are the most commonly spatial technique that have been used in current mobile communication systems for years. Cells are broken into three or six sectors with dedicated antennas and RF paths. Increasing the amount of sectorization reduces the interference seen by the desired signal. One drawback of the sectorization techniques is that the efficiency decreases as the number of sectors increases due to antennas' patterns overlap. Any reduction in the interference level translates into system capacity improvements. Smart antennas could be divided into two major types, fixed multiple beams and adaptive array systems. Both systems attempt to increase gain in the direction of the user. This could be achieved by directing the main lobe, with increased gain, in the direction of the user, and nulls in the directions of the interference (Ahmed Elzooghy The international engineering consortium; 2005).

The following are distinctions between the two major categories of smart antennas regarding to the choices of transmit strategy:

Fixed multiple switched beam: A finite number of fixed, predefined patterns or combining strategies (sectors) are transmitted

Adaptive array: an infinite number of patterns (scenario-based) are adjusted in real time.

7.2.1 Switched beam smart antenna system

Switched beam antenna systems form multiple fixed beams with heightened sensitivity in particular directions. These antenna systems detect signal strength, choose from one of several predetermined, fixed beams, and switch from one beam to another as the user moves throughout the sector. In terms of radiation patterns, the switched beam approach subdivides macrosectors into several microsectors as a means of improving range and capacity. Each microsector contains a predetermined fixed beam pattern with the greatest sensitivity located in the center of the beam and less sensitivity elsewhere.

7.2.2 Adaptive smart antenna system

Adaptive antenna technology represents the most advanced smart antenna approach to date. Using a variety of new signal-processing algorithms, the adaptive system takes advantage of its ability to effectively locate and track various types of signals to dynamically minimize interference and maximize intended signal reception. Adaptive arrays utilize sophisticated signal-processing algorithms to continuously distinguish between desired signals, multipath, and interfering signals as well as calculate their directions of arrival. This approach continuously updates its transmit/receive strategy based on the changes in both the desired and interfering signal locations (Ahmed Elzooghpy, the international engineering consortium, 2005). Figure 28 illustrates comparison between the two smart antenna systems coverage.

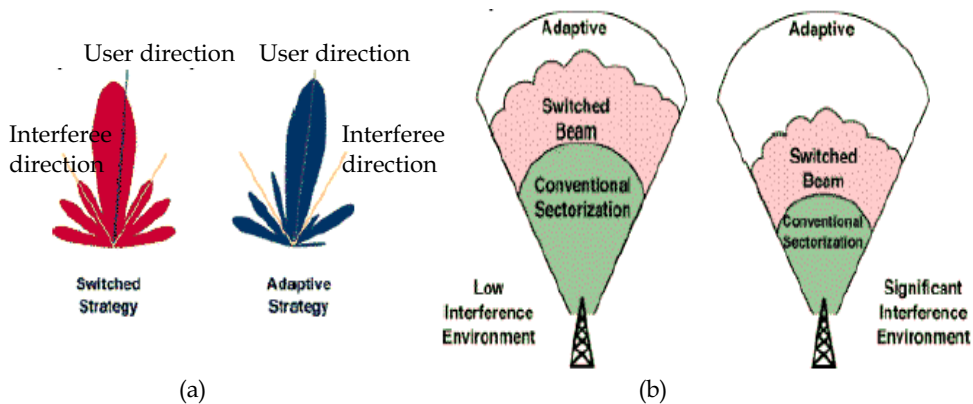


Fig. 28 (a) Beam forming lobes and nulls in switched and adaptive array systems, green lines are the required user direction and yellow lines are for co-channel interference and (b) coverage patterns for switched beams and adaptive array antennas

7.3 Advantages and disadvantages of smart antenna system

7.3.1 Advantages

The dual purpose of a smart antenna system is to augment the signal quality of the radio-based system through more focused transmission of radio signals while enhancing capacity through frequency reuse. The main advantages of the smart antenna system and their reflected effect on system performance are listed in table 4 below (Michael Chryssomallis, 200; Rappaport, T. S., 1998; Tsoulos G. V., 2001).

Feature	Benefit
Signal gain: Inputs from multiple antennas are combined to optimize available power required to establish required level of coverage.	Better range-coverage: Focusing the energy increases the base station coverage range. Lower power requirements also enable a greater battery life and smaller/lighter handset size.
Interference rejection: Antenna pattern can be generated toward co-channel interference sources, thus improving the signal-to-interference ratio of the received signals.	Increase capacity: Precise control of signal nulls and mitigation of interference allows for improving capacity.
Spatial diversity: Composite information from the array is used to minimize fading and other undesirable effects of multipath propagation.	Higher bit rates transfer: multipath rejection reduces the effective delay spread of the channel which allows for higher bit rates to be supported
Power efficiency: It combines the inputs from multiple elements to optimize available processing gain in the downlink (toward the user)	Reduce expense: Lower amplifier costs, reduce power consumption, and increase reliability.

Table 4. Benefits of smart antenna system

7.3.2 Disadvantages

One of the major existing disadvantages of smart antennas is in their complex hardware design and implementation. Multiple RF chains can increase the cost and make the transceiver bulkier. Most of the baseband processing requires coherent signals. This means that all the mixer LOs and ADC clocks need to be derived from same sources. This can present significant design challenges. The phase characteristics of RF components can change over time. These changes are relatively static and hence need calibration procedures to account for phase differences.

7.4 Applications of smart antenna systems

Smart antenna technology can significantly improve wireless system performance and economics for a range of potential users. It enables operators of PCS, cellular, and wireless local loop (WLL) networks to realize significant increases in signal quality, capacity, and coverage.

Adaptive antennas have been used in areas such as radars, satellite communications, remote sensing, and direction finding, to name a few. For instance, radar and secure communications systems take advantage of the ability of these antennas to adapt to the operating environment to combat jamming. Satellite communication systems have used multiple beam and spot beam antennas to tailor their coverage to specific geographic locations. (Kawala P. and U. H. Sheikh, 1993).

7.5 Future perspectives for smart antennas systems

According to recent studies, smart antenna technology is now deployed in one of every 10 base stations in the world, and the deployment of smart antenna systems will grow by 60 percent in the next four years. It was shown in the same study that smart antenna

technology has been successfully implemented for as little as 30 percent more cost than similar base stations without this technology.

Smart antennas are already part of current releases of 3G standards and more sophisticated approaches are considered for future releases. Furthermore, there is currently increasing interest in the incorporation of smart antenna techniques for IEEE wireless LAN/MAN (802.11n and 802.162). However, implementation costs can vary considerably, and cost-effective implementation is still the major challenge in the field. At the base station of particular importance is the development of improved antenna structures (possibly employing MEMS, technology, e.g., micro-switches, or improved cabling structures, and efficient low-cost radio frequency/digital signal processing architectures. At the terminal, the application of smart antenna techniques can have a significant impact, in terms of system performance, cost and terminal physical size (T.L.Roach et al, 2007). The financial impact of the deployment of smart antenna technologies in future wireless systems was studied in (Angeliki Alexiou & Martin Haardt, 2006) for CDMA2000 and UMTS. The results showed that smart antenna techniques are key to securing the financial viability of operators' business, while at the same time allowing for unit price elasticity and positive net present value. They are crucial for operators that want to create demand for high data usage and/or gain high market share. Based on this type of analysis, technology roadmaps along with their associated risks can be concluded that enable appropriate technology intercept points will be determined, resulting in the development of technologies appropriate for each application area.

8. Acknowledgment

The author would like to acknowledge Eng. Ahmed Khidre for his effort and support in discussions, collecting literature material and editing issues that help in complete this research work

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Mobile and Wireless Communications Network Layer and Circuit Level Design

Edited by Salma Ait Fares and Fumiyuki Adachi

ISBN 978-953-307-042-1

Hard cover, 404 pages

Publisher InTech

Published online 01, January, 2010

Published in print edition January, 2010

Mobile and wireless communications applications have a clear impact on improving the humanity wellbeing. From cell phones to wireless internet to home and office devices, most of the applications are converted from wired into wireless communication. Smart and advanced wireless communication environments represent the future technology and evolutionary development step in homes, hospitals, industrial, vehicular and transportation systems. A very appealing research area in these environments has been the wireless ad hoc, sensor and mesh networks. These networks rely on ultra low powered processing nodes that sense surrounding environment temperature, pressure, humidity, motion or chemical hazards, etc. Moreover, the radio frequency (RF) transceiver nodes of such networks require the design of transmitter and receiver equipped with high performance building blocks including antennas, power and low noise amplifiers, mixers and voltage controlled oscillators. Nowadays, the researchers are facing several challenges to design such building blocks while complying with ultra low power consumption, small area and high performance constraints. CMOS technology represents an excellent candidate to facilitate the integration of the whole transceiver on a single chip. However, several challenges have to be tackled while designing and using nanoscale CMOS technologies and require innovative idea from researchers and circuits designers. While major researchers and applications have been focusing on RF wireless communication, optical wireless communication based system has started to draw some attention from researchers for a terrestrial system as well as for aerial and satellite terminals. This renewed interested in optical wireless communications is driven by several advantages such as no licensing requirements policy, no RF radiation hazards, and no need to dig up roads besides its large bandwidth and low power consumption. This second part of the book, Mobile and Wireless Communications: Key Technologies and Future Applications, covers the recent development in ad hoc and sensor networks, the implementation of state of the art of wireless transceivers building blocks and recent development on optical wireless communication systems. We hope that this book will be useful for students, researchers and practitioners in their research studies.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Hala Elsadek (2010). Microstrip Antennas for Mobile Wireless Communication Systems, Mobile and Wireless Communications Network Layer and Circuit Level Design, Salma Ait Fares and Fumiyuki Adachi (Ed.), ISBN: 978-953-307-042-1, InTech, Available from: <http://www.intechopen.com/books/mobile-and-wireless-communications-network-layer-and-circuit-level-design/microstrip-antennas-for-mobile-wireless-communication-systems>

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