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INVESTIGATION OF LOADED MONOPOLE ANTENNA

BY

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The candidate confirms that the work submitted in his own and that appropriate credit has been given where reference has been made to the work of others.

Investigation of Loaded Monopole Antennas

Abstract

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At this point, author does not like to forget **his parents** and **his friends** who still support him during his academic year in Great Britain and especially during this difficult year.

This report is dedicated to all of them with thanks for what they have done to him.

From the bottom of my heart thank you all!

ABSTRACT

Wireless cellular telephony has become one of the most important modes of communication. Mobile telephones have the potential to be a mandatory accessory of our lives. The number of wireless standards (at different frequencies) increases rapidly and makes the operation of communication devices over a broad band necessary.

This report is an M.Sc (Eng.) thesis of a project on loaded monopole antennas. It analyses the monopoles loaded by reactive to obtain antennas broadband characteristics.

The major objective of this project was the minimisation of the antenna losses over the operational broad bandwidth, with bandwidth defined such that the VSWR is than four and the antenna power gain positive.

A bandwidth ratio of 11:1 was achieved with a 0.143-m capacitively loaded monopole of 4 mm-wire radius. The operational bandwidth of this monopole starts at 800 MHz and ends at 4,000 MHz with a VSWR less than 3.5, a power gain nearly 5.0 dB was achieved, and a matching network not required.

Measured results for a capacitively- loaded monopole with 3 mm conductor radius are reported. The results are similar to those simulated. However, the finite ground of the monopole that is used and the imperfect conditions in the laboratory increase the reflections (losses) at the antenna input.

The conclusion of this report and the further work of the project are presented at the end.

Key words: Quarter-wavelength antenna, broadband loaded monopole, capacitively loaded monopole, inductor-capacitive loaded monopole, antenna properties, history of the antennas, Maxwell's electromagnetic equations, standing waves, reflection coefficient ( ), Voltage Standing Wave Ratio (VSWR), matching network, coupling networks, wireless communication standards, monopole antenna radiation resistance, directivity, Numerical Electromagnetic Code (NEC), "Imperfect" ground, N-type and SMA connectors.

TABLE OF CONTENTS

Abbreviations and Symbols

1G	First Generation of mobile telephony
2D	Two Dimensions plane
2G	Second Generation of mobile telephony
3G	Third Generation of mobile telephony
AC	Alternating Current (implying sinusoidal signal)
CDMA	Code Division Multiple Access
DC	Direct Current
DCS	
DECT	initially Digital European Cordless Telecommunications now Digital Enhanced Cordless Telecommunications
ETSI	European Telecommunication Standards Institute
GA	Genetic Algorithms
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communication
IEC	International Electrotechnical Commission
IP	Internet Protocol
ITU	International Telecommunication Union
LC	Inductor and Capacitor
NEC	Numerical Electromagnetic Code
PDC	Personal Digital Cellular
RF	Radio Frequency

TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
WAP	Wireless Application Protocol
a	wire radius of the antenna
B	Magnetic flux density (Tesla)
c	Velocity of light
C	Closed contour
C	Capacitance of capacitor
d	Length of the segment of the antenna
D	Largest dimension of the antenna
D_{dip}	Directivity of the dipole antenna
$D_{dip, /2}$	Directivity of the half-wavelength dipole antenna
D_m	Directivity of the monopole antenna
$D_{m, /4}$	Directivity of the quarter-wavelength monopole antenna
E	Electrical field
f	Frequency
G	Material conductance
H	Magnetic field
h	height of the antenna from its base
I_{dip}	Current of the dipole antenna
I_m	Current of the monopole antenna

j	Notation of imaginary part of complex number
J	Conduction current density (Amp/m^2)
L	Physical length of the antenna
L	Transmission line length
$P_{r,dip}$	Radiation power of the dipole antenna
$P_{r,m}$	Radiation power of the monopole antenna
P_{rad}	Radiated power
P_{in}	Input power
Q	Quality factor
R	General resistance
R_L	Loss resistance
R_r	Radiation resistance
$R_{r,m}$	Radiation resistance of the monopole antenna
S	General closed surface
V	Velocity of radio frequency energy on antenna
V_{dip}	Voltage of the dipole antenna
V_g	Voltage of the generator of the antenna
V_i	Incident voltage wave
V_m	Voltage of the monopole antenna
V_r	Reflected voltage wave
VSWR	Voltage Standing Wave Ratio
X_A	Radiation reactance
Z_A	Antenna impedance
Z_{dip}	Impedance of the dipole antenna
$Z_{dip,\ /2}$	Impedance of the half-wavelength of the dipole antenna
Z_g	Impedance of the generator of the antenna
Z_m	Impedance of the monopole antenna

$Z_{m, /4}$	Impedance of the quarter-wavelength monopole antenna
Z_o	Characteristic impedance of the transmission line
	Propagation constant
	Reflection coefficient
	Permittivity
$_{rad}$	Radiation efficiency
	Elevation angle of an antenna
	Wavelength
	Permeability
	Electric charge density
	Material conductivity
	Phase shift
	Magnetic flux normal to the coil
$_{dip}$	Radiation intensity of the dipole antenna
$_{m}$	Radiation intensity of the monopole antenna

1 INTRODUCTION

Telecommunications are growing very rapidly, with mobile phones rapidly becoming ubiquitous while at the same time becoming multipurpose too. Nowadays, mobile phones are used to access Internet accounts, to listen radio, reading updated news, etc. The number of mobile telephone connections is increasing rapidly (around 100mil. connections worldwide in 1999) and tariffs have fallen around 40% worldwide over the last three years. So mobile phones are everywhere, due to the falling prices, rising quality and clever marketing [1].

1.1 RADIO & MICROWAVE COMMUNICATION SYSTEMS

The major role of a communication system is to transmit data from one side (transmitter) to another (receiver) by electromagnetic energy travelling between the two reference sides (Figure 1.1). Like any other communication system, a microwave communication system uses transmitters, receivers and antennas. The same modulation techniques used at lower frequencies are also used in the microwave range. However, the RF part of the equipment is physically different because of the special circuits and components that are used to implement the system.

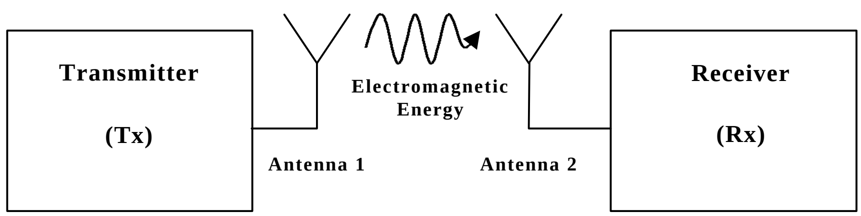


Figure 1.1 General type of communication system

The transmitted signal (electromagnetic wave) of a communication system is always followed by noise, which exists in free space as well as in the transmitter and receiver. Noise always reduces the efficiency of the system and determines the boundaries of the signal detection. The noise level of a communication system can be reduced by a careful design of the transmitter and receiver and by increasing the level of the signal in order to overcome equipment and background (free space) noise. Of course, the easiest solution of these problems is to increase the power at the source, but this method is expensive and limited. Therefore, the communication system must be designed as efficient as possible and the most effective method is that all the components of the system (particular antenna and transmission lines) must be "matched" in order to radiate (or receive) all the available energy from the generator.

1.2 THE ANTENNA

One of the most important components of any communication system, which depends on the free space as the mobile telephone, is the antenna. Most antennas for radio communications consist of metal wires or rods connected to the transmitter or receiver.

In any communication system the roles of the antenna are the radiation of the electromagnetic wave into the free space using the supplied energy of the source. The second role of the antenna is the reception of the transmitted signal and the delivery of the signal to the receiver.

In order for the antenna to transmit electric currents is forced to oscillate along the wire. Energy from this oscillating charge is emitted into space in the form of electromagnetic waves. These waves, on the receiver antenna, induce a weak electric current in the antenna wire. The radio receiver amplifies this current. An antenna can generally be used for reception and transmission on the same wavelength if transmission power is not too great. The dimensions of an antenna usually depend on the wavelength, or frequency, of the radio wave for which the antenna is designed [2].

The general types of antennas according to their performance as a function of frequency are [3]:

- Electrical small antennas; the length of the antenna structure is less than a wavelength , in extent (where $=c/f$, c is the velocity of light and f is the frequency).
- Resonant antennas; operates well at a narrow bandwidth, specific examples the /2 dipole and the /4 monopole antennas.

- Aperture antennas; have a physical aperture through which electromagnetic waves flow to the free space, specific examples are horn and reflector antennas.
- Broadband antennas; the parameters of the antenna's properties are nearly constant over a wide frequency range. Specific examples are the spiral and yagi antennas.

The basic parameters of the properties of an antenna are [4]:

- Input Impedance, at the terminals of the antenna.
- Radiation Pattern, which defines the variation of the antenna radiation according to the characteristic angles.
- Bandwidth that specifies a range of frequencies over which the properties of the antenna are acceptable.
- Radiation Efficiency which is the ratio of the radiated power (P_{rad}) to the input power (P_{in}) of the antenna (i.e. $_{rad} = P_{rad}/P_{in}$).
- Directivity, which is the ratio of the power flux density radiated by the actual antenna in a given direction to the flux density radiated by an isotropic antenna radiating the same total power.
- Far Field, which is the great distance from the origin of the antenna to the points where the Electrical (E) and Magnetic (H) field intensities fall as $1/R$ and the power density $1/R^2$ (where R, distance from an observation point to an origin in the antenna's structure). In addition the E (electrical) and H (magnetic) fields are transverse to the line of sight and in the ratio Z_0 –medium impedance- (where $Z_0 = E_{0x}/H_{0y}$ or for lossless medium Z_0 = Ö(m/e)). The far field requires two conditions: R ³ $2D^2/l$ and $R >> l$, (where D is the largest dimension of the antenna). On the other hand, some antennas are "electrically large" i.e. $D >> l/2$, so at that case the first condition implies the second [5].
- Gain, which defines the ratio of the far-field power flux density radiated by the actual antenna in a given direction to the flux density that would be radiated by an isotropic antenna, accepting the same power at its input port.
- Polarisation, which is the electric field vector of the radiated wave.

1.3 OBJECTIVES

The objectives of this project are to investigate, simulate and fabricate a broadband antenna for mobile telephony in order to improve the quality of operation of the handset according to the market's requirements. This broadband wire monopole antenna can be placed on (e.g. cars, railway trains, ships, etc.).

The initial idea, at the beginning of the project, was to design a wire antenna than could operate at least at the GSM networks at 900 MHz and 1800 MHz. The final objective was to design a loaded monopole antenna, which will cover the most of the common wireless protocols (GSM, DECT, BLUETOOTH, GPS and UMTS).

Another objective is to minimise the power consumption of the antenna and to improve the transmission efficiency. The power loss is a result of mismatch between the antenna impedance (Z_A) and the characteristic impedance of the transmission line (Z_o) and of the losses, which are generated on the conductor, due to its resistance. The minimisation of the power loss can be achieved by using a matching network between the transmission line and the input of the antenna. Nevertheless, a good design can limit reflected waves at the input of the antenna and the matching network can be avoided. This kind of design is not common but eliminates power dissipation in the matching network.

The Voltage Standing Wave Ratio (VSWR) is a measure of the reflected waves and the frequency range it is below a prescribed amount defines the bandwidth of the antenna. Generally the antenna bandwidth is defined as the frequency range over which the VSWR is less than four. (This indicates that the reflected power is 36% of the total input power and so, in the absence of resistive losses on the antenna itself, that 64% of the power is transmitted.)

In addition, the simulations of the antenna e to include the power lost due to the finite wire conductivity. An investigation of the effect of conductivity on the antenna power gain and on the radiation pattern should take place. The power gain of the antenna, at its elevation angle (^{o} = 90^{o}), should be positive.

1.4 ORGANISATION OF THIS REPORT

Chapter 1: Introduction (This Chapter)

Chapter 2: State of the Art; contains a historical review and the theoretical background on general type of antennas based on the published literature and Web sites of antennas.

Chapter 3: Monopole Antenna; defines common types of monopole antenna and their advantages and disadvantages. It presents the fundamental principles of monopole antennas and their applications.

Chapter 4: Designs and Simulations of Loaded Monopole Antenna; contains the methodology and the design concepts for a broadband monopole. It describes the wire antenna simulator and displays the results from the simulations.

Chapter 5: Fabrication and Measurements of Capacitively Loaded Antenna; accommodates the fabrication and the measurements concepts. It describes the connectors at the antenna input and displays the results of the measurements.

Chapter 6: Conclusion; comments on the results of the simulations and fabrications and concludes with the further work on this project.

2 STATE OF THE ART

2.1 HISTORY OF ELECTROMAGNETISM AND ANTENNAS

The first man, who observed the characteristics of the electron and magnet was the Greek mathematician, astronomer and philosopher, Thales of Miletus, in 600 BC. He noticed that when amber is rubbed with silk, it generates sparks and he observed the generation of attractive forces between two pieces of natural magnetic rock called "loadstone". Consequently, the words electron, electricity and their derivatives derived from the Greek word for amber " " (elektron) and the words magnetism and magnet derived from " " (Magnesia), the place in which the loadstones were found. After the first investigation on electromagnetism, the first experiment on it took place after 2200 years by the Englishman William Gilbert, the inventor of the electroscope. Then the American, B. Franklin, defined the positive and negative charges and the Frenchman, C. A. Coulomb, measured electric and magnetic forces. In 1831, M. Faraday, in London discovered the production of electric current from a change in magnetic field [6].

The first radiation experiment took place in Princeton University (1842) by the inventor of wire telegraphy, *Joseph Henry*. The initial transmission range of this experiment was from the upper room to the cellar of Henry's house, but it was extended to a distance of over a kilometre. Thomas Edison built the first loaded antenna in 1885 and it was a top loaded vertical antenna [3].

James Clerk Maxwell set the foundations of antenna design in 1864, with the theory of *electromagnetism*. Maxwell died before he could fully exploit his theory, and it was taken over by *Heinrich Hertz*. Hertz verified the theory of Maxwell experimentally in 1887. He built a resonant dipole antenna half-wavelength (/2) long, at 400MHz, which was called a "Hertzian dipole". Hertz also constructed loop antennas and in 1888 he constructed a parabolic cylinder reflector antenna from a sheet of zinc [7].

Guglielmo Marconi is the pioneer of radio. He was a wealthy student who was astounded by the work of Hertz. In 1895, he built a microwave parabolic cylinder reflector at 1.2GHz. In addition, he discovered that better range could be achieved by placing one end of the antenna on the ground while operating at lower frequencies (<1MHz). According to his observation, Marconi accomplished the first *transatlantic radio communication* in 1901 using a 70 kHz spark transmitter connected between the ground and a system of 50 wires (48-meter fan monopole).

The Second World War saw the launch of the development of radar and the use of microwave frequencies, which were used in astronomy, satellite and mobile communications.

At the beginning of the 60's several studies on loaded antennas and especially on wire passive loaded antennas took place to achieve broad band characteristics. In 1961, *Altshuler* observed that a travelling wave could be maintained along a cylindrical monopole, if a resistive load of appropriate magnitude (240) is set quarter wavelength (/4) from the monopole end [8]. *B. D. Popovic* then explained the effects of lumped loads on a monopole antenna [9]. Popovic calculated the current across a cylindrical monopole with lumped load impedance [10]. During the 70's extensive investigations on *patch* or *microstrip antennas* started, which are popular for their low profile, their low batch production cost and their specialized geometries.

Nowadays, the investigations of both patch and loaded antennas continue with astonishing results. M. Bahr, A. Boag, E. Michielssen and R. Mitra designed an ultra broadband loaded monopole, which operated over the 30-450 MHz band, using genetic algorithms (GA) to achieve an appropriate result [11][12]. Then K. Yegin and A. Q. Martin achieved a broadband characteristic in monopole using capacitively loads [13]. Their initial investigation was extended one year later, achieving very broadband loaded monopole antenna (bandwidth ratio 64:1) [14].

2.2 MAXWELL EQUATIONS

The Scottish James Clerk Maxwell, a professor at Cambridge University (England), was the first who identified the electromagnetic waves of any system of conductors which travel through free space. This work of Maxwell has the title "*Treatise on Electricity and Magnetism*" and it was published in 1873 [15].

Maxwell's equations are generalised equations (laws) of earlier scientists (i.e. Gauss, Faraday and Ampere).

The first equation of Maxwell was based on the law for electric and magnetic fields of a C. F. Gauss (1777-1855), a German mathematician. Gauss's law associates the total flux of electric and magnetic fields through a closed surface with the existed electric charge into this surface. The equations of Gauss have the following form:

$$\iint_S E.ds = \frac{1}{e}\iiint_V r\ dv \qquad (2.1)$$

$$\iint_S B.ds = 0 \qquad (2.2)$$

Where *E* is the electric field strength (V/m), is the electrical permittivity of the medium, is the electric charge density inside the volume *V*, *S* is a general closed surface enclosing the volume *V*, *ds* is the vector surface element and *B* is the magnetic flux density (Webers/m^2 or Tesla).

According to Equation (2.2) the total magnetic flux is always zero, which is verified by the observation that isolated magnetic charges do not exist in nature.

Maxwell's equation from Gauss' law, using the divergence theorem $\iint_S E.ds = \iiint_V div\ E\ dv$ (2.3), where *E* is a vector field and the surface *S* circles the volume *V*, are [16]:

$$div\ E = \frac{r}{e} \qquad (2.4)$$

$$div\ B = 0 \qquad (2.5)$$

The second equation of Maxwell is based on the law of the English physicist M. Faraday (1791-1867). Faraday's law defines the electric field, which is generated by the changes of a magnetic field. It gives the voltage generated in a coil placed in an alternating magnetic field [17]:

$$V = -\frac{\partial \Phi}{\partial t} \qquad (2.6)$$

where is the total magnetic flux normal to the coil. Another expression of the same law that defines the electric field around a closed contour *C* is equal to the time rate of change of the total magnetic flux through the contour:

$$\oint_C E.dl = -\frac{\partial}{\partial t}\iint_S B.ds \qquad (2.7)$$

where *E* is the electric field, *C* is the closed contour, *B* is the magnetic field and *S* the closed surface. Maxwell using the curl of a vector field such as E-field derived that [16]:

$$curl\ E = \nabla \times E = -\frac{\partial B}{\partial t} \qquad (2.8)$$

where curl is a derivative with respect to distance in space and is given by:

$$curl\ E = \nabla \times E = \begin{vmatrix} \hat{x} & \hat{y} & \hat{z} \\ \partial/\partial x & \partial/\partial y & \partial/\partial z \\ E_X & E_Y & E_Z \end{vmatrix} \qquad (2.9)$$

$$where\ \ \hat{x}, \hat{y}, \hat{z}\ are\ unit\ vectors$$

The last equation of Maxwell is based on the law of the French physicist A. M. Ampère (1775-1836). Ampere's law describes the magnetic field set up by a wire carrying a current:

$$\oint_C B.dl = m\iint_S J.ds \qquad (2.10)$$

where *C* is the closed contour,   is the magnetic permeability, *S* is the closed surface and *J* is the conduction current density (Amp/m^2). Again Maxwell using the curl of a vector *B* derived that [16]:

$$\nabla \times B = m\ J \qquad (2.11)$$

2.3 FUNDAMENTAL OF ANTENNAS

The antenna radiates both electric and magnetic fields in the form of electromagnetic field. The antenna can be described by lumped elements such as resistance, inductor and capacitance in order to describe the losses and the radiation efficiency. The Thevenin equivalent circuit of the antenna as part of a transmitter is displayed below [18]:

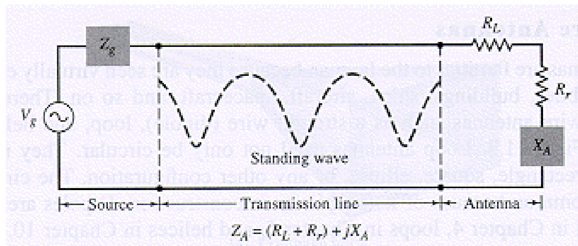


Figure 2.1 Transmission line Thevenin equivalent circuit of an antenna in transmitter (Source: [18])

In Figure 2.1 V_g is the generator voltage, Z_g is the generator resistance, Z_A the antenna impedance: $Z_A = (R_L + Rr) + jX_A$, R_L is the loss resistance, R_r is the radiation resistance and X_A radiation reactance.

Therefore, the input and the output of the antenna can be represented by a definite equation of current and voltage. The current produces the magnetic field on the antenna and the oscillating charge originates the electric field. The polarity of the antenna and the amount of charge depend on the nature of the output of the transmitter. The voltage of the antenna, however, depends on the energy source (i.e. battery, *AC/DC* source, *RF* source, etc.). The voltage lags the current when RF source supplies a half-wavelength (/2) antenna; hence it acts as a capacitor.

The flow of charge is related to the magnetic field of the antenna and the magnetic field intensity is proportional to the flow of charge. The current flow is maximum when the antenna is uncharged, due to the absence of an opposing electric field and the opposite occurs when the antenna is fully charged.

The finite length of the antenna is the reason for the existence of the standing waves of the current and the voltage (shown in Figure 2.2). The standing waves are caused by the incident waves of the RF source when these are halted at the end of the finite antenna conductor. When the incident waves reach the end of the conductor the current path is suddenly broken. This interruption is the reason for the collapse of the magnetic field too. Therefore, the wave, which is reflected back to the input terminals, is called a reflected wave. The sum of the incident and reflected waves is the actual current flow.

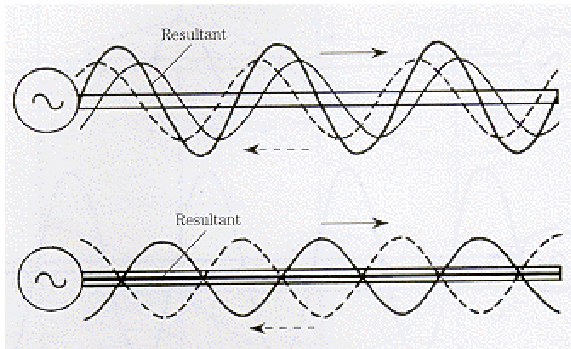


Figure 2.2 Standing waves as result of the incident (→) and reflected (←┈┈) waves on an antenna structure (Source: [19])

The maxima and the minima of the incident and reflected waves are stationary points respectively. Hence, the resultant wave is a standing wave, due to the stationary points on the antenna. A standing wave contains fixed minimum points, which are called *nodes* and the curves are called *loops* [19] (shown in Figure 2.3).

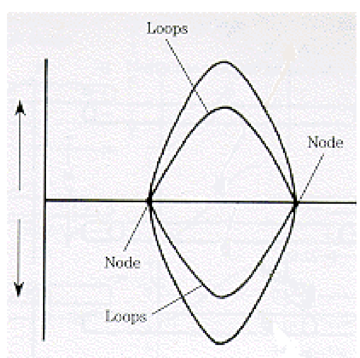


Figure 2.3 Loops and nodes of standing waves (Source: [19])

Reflection Coefficient ( )

The reason for the existence of the standing waves is not only the finite length of the antenna, but also the impedance match between the antenna and the transmission line. Generally, the impedance of the antenna Z_A is quite different from the characteristic impedance of transmission line at the input of antenna Z_o. The poor match causes the reflected waves along the transmission line. The reflection coefficient of these waves is given from the following formula:

$$\Gamma = \frac{V_r}{V_i} \qquad (2.12)$$

where V_r is the reflected voltage wave and V_i is the incident voltage wave.

Another formula of the reflection coefficient is:

$$\Gamma = \frac{Z_A - Z_o}{Z_A + Z_o} \qquad (2.13)$$

Where Z_A is the antenna impedance and Z_o is the characteristic impedance of the transmission line.

The value of during three specific circumstances will be:

- For $Z_A = Z_o \Rightarrow$ = 0
- For $Z_A = 0 \Rightarrow$ = -1
- For $Z_A \to \infty \Rightarrow$ = 1

Voltage Standing Wave Ratio (VSWR)

The voltage standing wave is the most important characteristic because its ratio is used to measure the loss of the antenna due to the reflection waves. The VSWR is defined as the ratio of the maximum point of the standing wave $|V|_{max}$ (where the incident wave $|V_i|$ is in phase with the reflected one $|V_r|$) and the minimum point of the same wave $|V|_{min}$ –(where the incident $|V_i|$ and the reflected waves $|V_r|$ are out of phase 180°).

$$VSWR = \frac{|V|_{\max}}{|V|_{\min}}$$

$$\therefore VSWR = \frac{|V_i| + |V_r|}{|V_i| - |V_r|}$$

$$\therefore VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (2.14)$$

The minimum loss happens when the VSWR is equal to one and the maximum when it tends to infinity.

The value of VSWR during three specific circumstances will be:

- Matched Load: = 0 $\Rightarrow VSWR = 1$
- Open Circuit: = 1 $\Rightarrow VSWR = \infty$
- Short Circuit: = -1 $\Rightarrow VSWR = \infty$

The relation of the *VSWR* with the transmitted power for a mismatched antenna is given by the following table [20]:

Table 2.1 VSWR and Transmitted Power for a mismatched Antenna (Source:[20])		
VSWR	REFLECTED POWER (%) $= \|\quad\|^2$ X 100 $= \left(\frac{VSWR - 1}{VSWR + 1}\right)^2 \times 100$	TRANSMITTED POWER (%) $= \left(1 - \|\Gamma\|^2\right) \times 100$
1.0	0.0	100.0
1.5	4.0	96.0
2.0	11.1	88.9
3.0	25.0	75.0
3.5	30.9	69.1
4.0	36.0	64.0
4.5	40.5	59.5
5.0	44.4	55.6
5.83	50.0	50.0
10.0	66.9	33.1

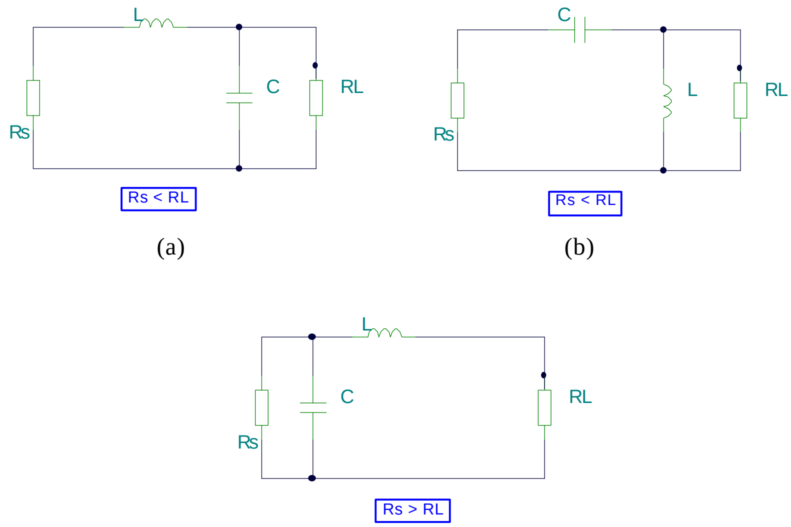
The antenna should have input impedance equal with the characteristic impedance Z_o in order to minimise the losses and the *VSWR*; this can be achieved by using matching networks.

2.4 IMPEDANCE MATCHING AND COUPLING NETWORKS

The fundamental statement in communication systems is that the impedance of the antenna Z_A must be matched to the characteristic impedance of transmission line at the input of antenna Z_o. The transmission line, in turn, has to be matched to the output impedance of the transmitter. The result of this requirement is to maximise the power transfer between the source and the load. Antenna impedance Z_A contains both reactive and resistive components usually, but rarely is it a purely resistive impedance ($Z_A = R$), which is the ideal situation for matching.

As a consequence, the coupling (matching) network consists of lumped, linear, finite, bilateral components or their distributed counterparts depending on the frequency of operation. Lumped elements are used, in the lower frequencies (<100MHz), and the distributed elements are used at higher frequencies. The most common coupling network is the L- section, shown in Figure 2.4 [21].

Several times an additional element has to be added to form a T or section to retain the phase constant especially after its change due to matching network, shown in Figure 2.5.



(a) (b) (c)

Figure 2.4 (a) L-section matching network; (b) reverse L-section network; (c) inverted L-section network (Rs and RL are the source and load impedances respectively) (Source: [21])

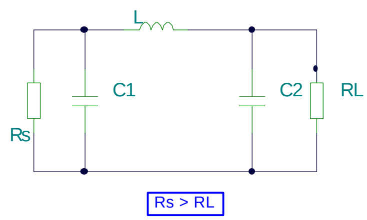


Figure 2.5 Pi ( ) coupling network (Source: [21])

Combination of the above networks can be used to match an antenna to a transmission line. Another commonly used coupling network is the quarter-wave transformer, which is used for matching resistances. However, sometimes the requirement for perfect radiation pattern drives the designer to use a balun, which matches unbalanced resistive source impedance (i.e. coaxial cable) to a “balanced” load (i.e. antenna) [21].

The above common matching networks are considered for a perfect match at specific or narrow frequency bandwidth. In other words, bandwidth is not the major design objective.

The problem of matching starts when a general load has to be matched to a resistance over a large bandwidth. R. M. Fano, in his report “Theoretical limitations on the Broadband Matching of Arbitrary Impedances” [22], gave the solution to this problem. The work of Fano was used for the improvement of antenna matching by R. L. Tanner [23] [24]. The result of these investigations were analysed by J. Hasik [25] and he has shown that the maximum bandwidth can be obtained, when the reflection coefficient ( ) is as constant as possible through the specified bandwidth. After the designer used this analysis and determined the *Q* factor of the matching network, he made it possible to predict the maximum obtainable bandwidth for a given standing wave ratio (*VSWR*). The relationship between antenna *Q*, fractional bandwidth in terms of geometric mean frequency $d = \frac{f_2 - f_1}{\sqrt{f_1 f_2}}$ (2.15) and the maximum VSWR for a matching ladder network of *n* elements is shown in Figure (2.6).

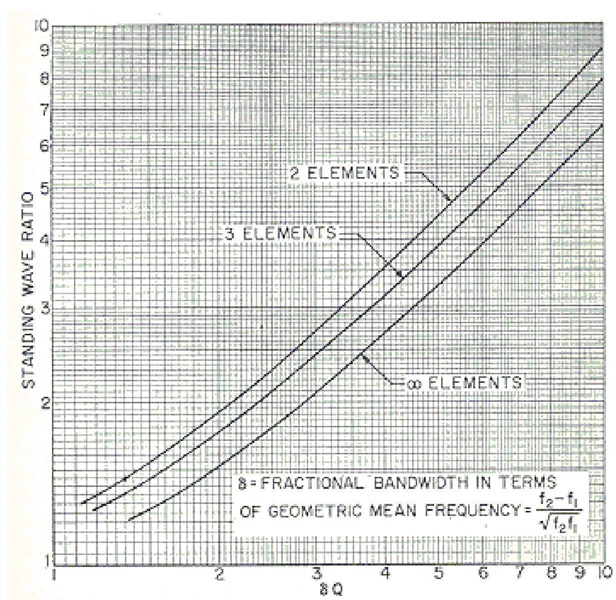


Figure 2.6 Optimum bandwidth curves for an antenna connected to a network with *n* elements (for *n*=2, *n*=3 and *n*=)(Source: [25])

However, there are antenna structures that can be connected directly to a coaxial line without matching network, without any effect on system performance. This situation occurs when the values of the standing wave ratio is small (i.e.< 4) over the specified bandwidth.

2.5 ANTENNA BANDWIDTH AND WIRELESS COMMUNICATION STANDARDS

During the last two decades new wireless standards have covered many bands of the frequency spectrum. The most recent wireless communication systems operate within the 800MHz to 2700MHz range. Therefore the major objective of this project is that the required monopole operate, at least, over this bandwidth with minimum power reflection (i.e. $VSWR < 4$). However, some questions accentuate; why this specified bandwidth is so important for wireless communication system? Which wireless standards belong in this bandwidth?

The most common wireless standards, which belong in the above frequency band, are described below.

2.5.1 Second Generation Cellular Systems (2G)

The major characteristic of the second generation systems is that they are digital and that they provide voice/data/fax transfer as well as a range of other value-added services to their users. Nowadays, this system aims at increasing the data rates using recent technologies such as HSCSD (High Speed Circuit Switched Data) and GPRS (General Packet Radio Service). Second generation systems (2G) contains several wireless communication protocols such as the European GSM (Global System for Mobile Communications), and the American US-TDMA (IS_136), cdmaOne _IS-95) and the Japanese PDC (Personal Digital Cellular). Both American and Japanese protocols are based on the preceding first generation (1G) analogue technology. Unlike these, GSM/IS-95 is based on an exclusively new concept. The major bands of this system are denoted GSM 900, GSM 1800, and GSM 1900. GSM 900, operating in the 850 to 950 MHz band, is the most widely used cellular system worldwide having been adopted in over 100 countries in Europe, Asia, etc. GSM 1800, known also as PCN or PCN 1800 or DCS 1800, operates in the 1800 to 1900 MHz frequency band. This is used in Europe. The third GSM protocol is GSM 1900, known also as PCS 1900 and DCS 1900, which operates in the 1900 to 2000 MHz frequency band; This is used primarily in the USA [26].

2.5.2 Digital Enhanced Cordless Telecommunications (DECT)

Another protocol which belongs in the second generation and it is used in the third also is the DECT. DECT is a European digital wireless technology, which has expanded to be world-wide. DECT technology is designed for voice and data transfer over short distances (i.e. less than 300 m, in open area and less than 50 m, when obstacle exists) [27]. DECT is generated using the best of the existing English cordless telephony standard CT2 and Swedish standard CT3. The European Telecommunication Standards Institute (ETSI) developed the DECT standard, which became reality in 1988. The first ETSI standard for the DECT were published in 1992 (ETS 300 175 and ETS 300 176) and the first product came from Olivetti, in the same year, which was a wireless LAN-type product [28]. The frequency band of the DECT according to the ETSI is between 1880-1900 MHz with 10 carriers of 1728 kHz space. The duplexing technique of DECT is the TDD/TDMA (Time Division Duplex/Time Division Multiple Access), which uses two different time-slots for simultaneous transmission and reception. Nowadays, several new DECT wireless standards are developed such as Extended European DECT (1900-1920 MHz), DECT China (1900-1920 MHz), DECT South America (1910-1930 MHz) [27].

2.5.3 Bluetooth

Bluetooth is a wireless standard promulgated for wireless connection between many mobile devices over a short range, enabling users to connect their mobile phones, laptops, printers and other electronic devices together without using cables [26]. Bluetooth connections are instant without the need for extra settings and all the devices are in standby condition, searching for compatible devices every 1.28 seconds. The connection is maintained even when devices are not within line of sight, but they must be in range longer than 10 cm and approximately less than 10 meters, but this radio range can be extended to around 100 meters with an optional amplifier [29]. The maximum number of devices that can be connected in the same group (piconet) is eight. Bluetooth was generated in February 1998, when five leaders of the electronics industry, Ericsson, Nokia, IBM, Toshiba, and Intel met to constitute Bluetooth SIG (Special Interest Group). The first public presentation of this group took place on the 20th and 21st of May 1998 and in less than a year 500 companies joined the group. Bluetooth operates on the globally available unlicensed radio band, 2.45 GHz, and supports asynchronous data transfer speeds of up to 721 Kbps, as well as three voice channels [30]. The advantages of this standard are the small size of the devices, the low implementation cost and the low power consumption [31].

2.5.4 Third Generation Cellular System (3G)

The third generation systems are developed to unify the existing cellular mobile systems (2G). The main objective is to offer a wide range of services in different radio environments with high quality standards. The 3G systems expect to provide high-speed mobile access to the Internet (based on Internet Protocol (IP)), entertainment, information and electronic commerce (e-commerce) services. Through IP, the user can be connected constantly to the Internet to receive his/her e-mail and to retrieve any information from his/her company network for free. Users will have the opportunity to set up a videoconference, obtain local tour guides, make a last-minute reservation at a hotel/restaurant, find and call the nearest taxi firm, or send video postcards. The high-speed data transfer capability is a result of GPRS (General Packet Radio Service) and EDGE (Enhanced Data rates for Global Evolution). GPRS will increase data rates, from 9.6kbit/s to 115kbit/s. Subscribers, using a packet data service, such as GPRS will always be connected and always on line so services will be easy and quick to access. EDGE will allow GSM operators to use existing frequencies to offer wireless multimedia IP-based services and applications at data rate up to 384 kbit/s or higher. The access to on-line services will be supported by WAP (Wireless Application Protocol). WAP allows user to access any data applications from his/her terminal itself, using a built-in browser [32].

The new mobile terminals for the 3G cellular network will be smaller, “smarter”, they will contain web browser and e-mail capabilities and they will provide world-wide roaming. Their screens will be larger to display the videoconferences and the images captured by the digital camera (shown in Figure 2.7).

Figure 2.7 3G cellular system handheld terminal (Source: [33])

The International Telecommunication Union (ITU) began studies on 3G systems in the mid-1980s. ITU co-operated with FPLMTS (Future Public Land Mobile Telecommunication Systems, lately renamed International Mobile Telecommunications-2000 (IMT-2000) for the development of the 3G cellular systems.

The European development on 3G cellular systems referred to as Universal Mobile Telecommunications System (UMTS) is generated by ETSI. UMTS will offer mobile multimedia services to GSM operators. The major characteristic of UMTS is the duplex scheme technology that will use Wideband CDMA (WCDMA). This duplexing standard provides average data transfer speed of 144 kbps, which can be extended using additional support up to 2Mbps.

ITU has identified the global bands for the 3G systems, which are 1885—2010 MHz and 2110—2200 MHz for IMT-2000, including the mobile satellite bands of 1980—2010 MHz and 2170—2200 MHz [34]. In World Radiocommunication Conference 2000, which took place in Istanbul of Turkey in May 2000, ITU (2037 representatives of 150 countries) identified three new global bands for the 3G systems 806—960 MHz, 1710—1885 MHz and 2500—2690 MHz [35].

2.5.5 Global Positioning System (GPS)

GPS is a navigation satellite system, which is used to point out different position on the Earth surface. This system uses satellites in an orbit 20,200 km (12,500 miles) above the earth and it is more accurate than the older radio navigation systems because it defines position in three-dimensions using latitude, longitude and altitude.

The Global Positioning System was developed by the U.S. Air Force in 1960. The system was renamed Navstar, in 1974, when other branches of U.S. military service joined the research for its development, but the name GPS remained in general usage. GPS became fully operational in 1995 after a development of $10 billion and twenty-four satellites circle the Earth every 12 hours to provide global coverage.

In 1972, the accuracy of the system was tested and it was found that the worst case was 15 m and the best 1 m. The reasons for these wide distances, were the signal time delay and the ionosphere interference from the satellites to the receiver. Nowadays, after long research and development and using expensive instruments (accurate receivers) to avoid the above constraints, the positioning accuracy of GPS has reached 10 mm.

Each satellite has unique P and CA codes, so that the receiver can distinguish between the transmitters (satellites). Satellite transmits the P code on two signals of different frequency ($L1$ = 1575.42 MHz and $L2$ = 1227.6 MHz). A distinct time delay occurs to each radio wave every time that the signals pass the ionosphere. However, the accurate (expensive) GPS receivers are able to track both $L1$ and $L2$ and to measure their difference in arrival. After several calculations, it is easy to determine the delay caused by the ionosphere [36].

3 MONOPOLE ANTENNAS

A monopole antenna is theoretically half a dipole, when the ground plane is infinite, planar and perfectly conducting (i.e. perfect ground). However, it is impossible to have an infinite plane, even a large ground plane results in a different radiation pattern from that of an infinite plane. In addition, the capacitance between the base of the monopole and the ground plane differs from that between two halves of a dipole [37].

This kind of antenna is well known for its compact size, great bandwidth, circular polarisation, desired impedance level, or particular physical characteristics. When a monopole is a quarter wavelength long a resonant action occurs and the resonant resistance is compatible with conventional transmission line feeders. When its electrical size is less than the quarter of the wavelength then matching and efficiency problems occur and the feed radiation can ruin the total pattern characteristic [38].

Most of the monopole antennas are "omnidirectional." It is a cylindrical shaped antenna, which transmits and receives in 360 degrees. The dimensions of this antenna typically do not exceed 9cm in diameter and 4.5 m in height. It is also called a "stick antenna" or "whip antenna" [39].

3.1 FUNDAMENTALS OF MONOPOLE ANTENNA

The linear monopole antenna is half the length of the dipole antenna. However, when this monopole is mounted on a "perfect" ground plane (i.e. planar, infinite in extent, and perfectly conducting) the characteristics of the antenna can be derived from dipole antennas. W. L. Stutzman and G. A. Thiele worked on the perfect ground characteristics and the image of the antenna's fields due to the reflection from perfect ground, which were based on the Snell's law of reflection. This work is called "Image Theory" [40]. The following analysis of the monopole characteristics, on a perfect ground, is also based upon "Image Theory".

The current (I_m) and the charges on a monopole antenna are the same as on the upper half of a dipole (I_{dip}). The voltage of the monopole (V_m) is half the voltage of the dipole (V_{dip}), because the electric field is the same but the length of the antenna is half, hence the same electric field over the half distance gives half the voltage. Therefore, the impedance of the monopole (Z_m) antenna is half that of the dipole (Z_{dip}):

$$Z_m = \frac{\frac{1}{2} V_{dip}}{I_{dip}}$$

$$\therefore Z_m = \frac{1}{2} Z_{dip} \qquad (3.1)$$

The radiation resistance ($R_{r,m}$) of the monopole is half that of the dipole ($R_{r,dip}$), due to the monopole radiation power ($P_{r,m}$), which emits only over the upper hemisphere. Hence, it is half of the radiation power of the dipole ($P_{r,dip}$) that radiates over a full sphere.

$$R_{r,m} = \frac{1}{2} R_{r,dip} \qquad (3.2)$$

The directivity (D_m) of the monopole antenna is double the directivity of the dipole (D_{dip}). The reason for this is that the radiated power of the monopole is half that of the dipole for the same current levels. The radiation intensity in the free space for the monopole ($_m$) is the same with the dipole one ($_{dip}$), due to the unchanged current. Since there are 4 steradians in the total solid angle the monopole directivity is [41]:

$$D_m = \frac{\Phi_m}{P_m / 4p} = \frac{\Phi_{dip}}{\frac{1}{2} P_{dip} / 4p} = 2 D_{dip} \qquad (3.3)$$

Accordingly from the above equations, the impedance of a quarter-wavelength (/4) monopole antenna ($Z_{m,\ /4}$) is half the impedance of the half-wavelength (/2) dipole antenna ($Z_{dip,\ /2}$). Thus

$$Z_{m,l/4} = \frac{1}{2} Z_{dip,l/2}$$

$$\therefore Z_{m,l/4} = \frac{1}{2}(72 + j42.5)$$

$$\therefore Z_{m,l/4} = 36 + j21.3\Omega \qquad (3.4)$$

Similarly the directivity of a quarter-wavelength (/4) monopole antenna ($D_{m, /4}$) is double the directivity of the half-wavelength (/2) dipole antenna ($D_{dip, /2}$) [40].

$$D_{m,l/4} = 2D_{dip,l/2}$$

$$\therefore D_{m,l/4} = 2 \times 1.64$$

$$\therefore D_{m,l/4} = 3.28 = 5.16\,dB \qquad (3.5)$$

3.2 TYPES OF MONOPOLE ANTENNA

The number of different types of monopole antennas is limitless. However, the most characteristic groups of monopole antennas will be described and analysed below.

Linear Monopole

The simplest (structurally) and most widely used antenna is the linear monopole (shown in Figure 3.1). This type of monopole has radiation resistance (R_r = *40* ^{2} *(h/)*^{2}), where *h* is the height of the antenna from the ground plane and   is the wavelength. The linear monopole is highly capacitive and it has low efficiency when it is matched due to power losses in the matching network (typically 30-70%) [42].

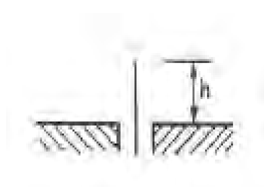


Figure 3.1 Linear monopole (Source: [42])

Top Loaded Monopole

In this category several wire loaded antennas. These antenna structures increase the current in the vertical portion of the antenna and this generates an increment of the radiation resistance (R_r) and a deduction of the input impedance (Z_{in}). The radiation resistance (R_r) becomes very small and the efficiency of the antennas becomes an important factor. The radiation resistance (R_r) was computed by Laport, who defined that the R_r is related to the area '*A*' (Ampere-Degree) of the plot of current distribution on the radiating surface. For example when the current at the base of the monopole is 1 *A* then the $R_r = 0.01215\ A^2$ [37].

"Inverted-L" (shown in Figure 3.2) groups into the top loaded monopole antennas. The characteristic of this design is the uniform current distribution along the antenna's conductor. A consequence of this uniform distribution is to increase the radiation resistance (R_r). This type of antenna is used at HF and its input impedance is about 5 [42].

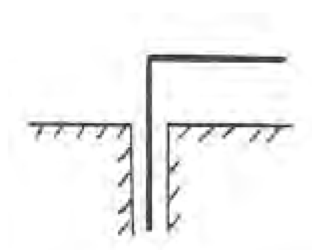
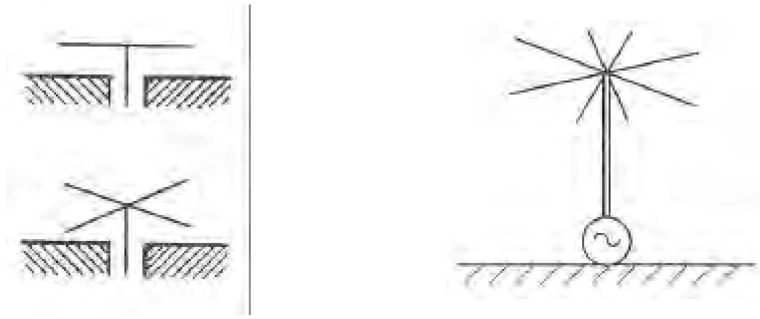


Figure 3.2 Inverted-L monopole (Source: [43])

Another type of top loaded monopole is the "Two or Four Element" top loaded monopole (shown in Figure 3.3). The radiation resistance of these structures is almost the same as the radiation resistance of the inverted-L monopole. However, these antennas need tuning and matching networks because they are frequently operated below self-resonance [42].



(a) *(b)*

Figure 3.3 (a) Two/Four-element top loaded monopole (Source: [42])

(b) N-element top loaded monopole (Source:[37])

"Spiral" top loaded monopole (shown in Figure 3.4) belongs, also, this group of monopoles. It is also self resonant as most top loaded monopoles are. Therefore, it does not need a matching network for tuning. The efficiency of the "spiral" loaded monopole is low, about 10%, when it is placed over lossy ground and its height is around 0.02 . The input impedance of this structure is nearly 6 . It is used at HF and VLF [42].

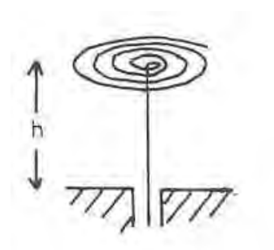


Figure 3.4 Spiral top loaded monopole (Source: [42])

One more top loaded monopole the "Capacitor-Plate" monopole (shown in Figure 3.5) is well known for its great radiation resistance. This antenna has a radiation resistance four times more that of the linear monopole ($R_r = 160\ ^{2} (h/\ )^{2}$), where h is the height of the antenna from the ground plane and is the wavelength [42].

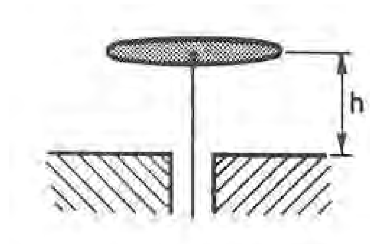


Figure 3.5 Capacitor plate loaded monopole (Source: [42])

Folded monopole

This monopole is used as a director and reflector in directional antennas. The radiation resistance of this monopole is around 10–15 . The most common structure of this antenna is the “Open Folded” monopole (shown in Figure 3.6). The radiation resistance of this antenna is around 10 . The advantages of using this type of monopole are the protection of radio equipment from lightning strikes and the ability to carry shielded cables to a warning light on the top of the antenna without any important effect on the antenna characteristics [37].

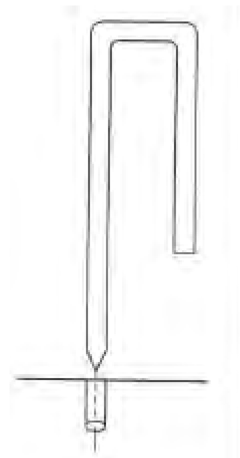


Figure 3.6 Open folded monopole (Source: [37])

Active/Passive Loaded Monopole

These monopoles are loaded with active (transistor, tunnel diode, varactor, etc.) and passive (inductor, capacitor, resistance or combinations) elements. The load is used to increase the radiation resistance, the effective bandwidth and to modify the radiation pattern of the linear monopole. The performance of the monopole changes according to the position of the load on the antenna's conductor [43].

Some examples of this group of monopole antennas are the "Diode Loaded", "Transistor Loaded", "Inductively Loaded" and the "Capacitively Loaded". The last structure is analysed in the following chapters of this dissertation.

"Diode Loaded" monopole (shown in Figure 3.7) uses the properties of the varactor diode. Varying the D.C. biasing of the diode can control the effective height of the antenna. The structure of the monopole can be reciprocal, when the diode operates linearly [43].

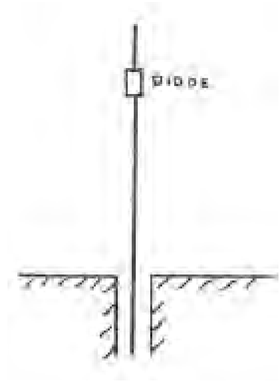


Figure 3.7 Diode loaded monopole (Source: [43])

A “Transistor Loaded” antenna (shown in Figure 3.8) is used to reduce the resonance frequency. Consequently it reduces the effective height of the antenna.

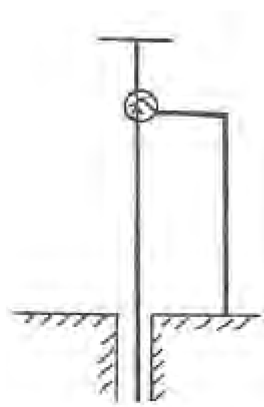


Figure 3.8 Transistor loaded monopole (Source: [43])

The “Inductively Loaded” version (shown in Figure 3.9) increases the efficiency of the antenna from 50 to 70%. The bandwidth of the same antenna can be increased nearly 2%, by choosing an appropriate value for the Q factor of the coil. The radiation resistance of inductively loaded antennas starts from 4 to 23 [42].

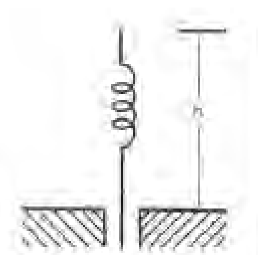


Figure 3.9 Inductively loaded monopole (Source: [42])

Sleeve Monopoles

“Sleeve” monopole (shown in Figure 3.10) is used to increase the radiation resistance of the antenna and to reduce the height of the antenna. R. A. Burberry has calculated the input resistance of the sleeve monopole of height $l =$ /4 compared to a linear one [37]:

$$R_S = \frac{R_m}{\cos^2 b\ h} \qquad (3.6)$$

where R_S is the resistance of the sleeve monopole, R_m is the resistance of the linear monopole, h is the height of the feed-point of the monopole from the ground and is the phase constant ($= 2$ / rad/length).

Other monopole structures, which belong into this group, are “Bent Sleeve”, “Broadband Sleeve” and “Double-band Sleeve”. These monopoles are used at VHF and UHF bands [37].

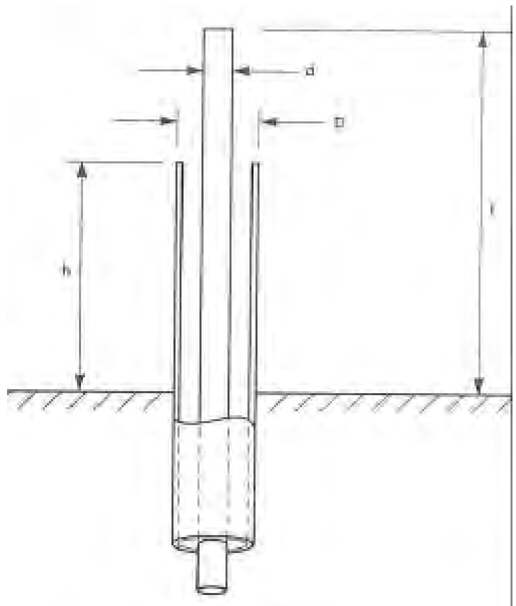


Figure 3.10 Sleeve monopole (Source: [37])

3.3 ADVANTAGES AND DISADVANTAGES OF MONOPOLE ANTENNAS

Monopole is a special case of a wire antenna. All the other types of wire antennas can be considered as a general structure of wire antennas in this paragraph.

Monopole antennas are used in several applications that general structure of wire antennas can be used also. Monopoles have several advantages and disadvantages compared to general wire antennas. The fundamental advantages and disadvantages of using monopole antennas compared to wire antennas are displayed below:

Advantages

- Compact size
- Low fabrication cost and simple to manufacture

- Omni-directional radiation pattern, which allows it to transmit and receive in 360 degrees
- Circular polarisation
- Desired impedance level
- Great bandwidth (using optimum values of loads)
- Resonant antenna

Disadvantages

- Narrow operational bandwidth
- Significant losses in power gain, at high frequencies

The last drawbacks can be minimised by loading the monopole with resonant circuits (such as capacitors, inductors, diodes, etc.) as happens in the designs of this dissertation.

3.4 APPLICATIONS OF MONOPOLE ANTENNAS

Monopole antennas are used in several military and civilian applications. Representative examples are listed in the following table [42], [44]:

Table3.1 Major Applications of Monopole Antennas		
PLATFORM	SYSTEMS	REASONS
Aircraft	Communications, Navigation, Air Traffic Control Identification	Low Drag, Low Side Load, Minimisation of Antenna damage
Vehicles	Communication, Navigation	Small Electrical Size, Low Height, Good Omnidirectional Coverage, Low Drag, Low Weight, Low Wind and Ice Loading, Minimisation of Damages due to Vandals and Environment, Ease of Replacement, Robust
Marine	Communication, Navigation	ELF Propagation (submarine), Small Size, Broadband Coverage (loaded monopoles), Omnidirectional Coverage, Low Water Loading (submarine)
Military	Missiles Control, Vehicles Communication and Navigation	Good Efficiency, Good Omnidirectional Coverage, Broadband Coverage, Robust, Ease of Replacement and Concealment
Terminals	Mobile Telephony, Radio Receivers and Navigation	Compact Size, Low Fabrication Cost, Simple to Manufacture, Broadband Coverage

4 DESIGN AND SIMULATIONS OF LOADED MONOPOLE

4.1 DESIGN REQUIREMENTS AND CONCEPTS

The most important requirements for a mobile antenna, especially for vehicular use, are the operating frequency, bandwidth, directivity, pattern characteristics and polarisation.

It is required that the antenna pattern, for mobile communication, to be 2D omnidirectional, because the antenna has to transmit and receive in 360 degrees. That is, the radiation pattern must be circularly symmetrical in the horizontal plane. Otherwise the propagated signal will vary and it will reduce the communication quality. In addition, it is preferred that the radiation pattern be maximum in the horizontal plane (i.e. elevation angle = 90º). Usually the polarisation of the mobile systems is vertical because it is easier for the designer to model broadband omnidirectional antennas, such as the monopole of this project. The antenna gain requirement is to design an antenna with the lowest loss because the power of mobile devices is limited. The reason for this is the need to battery life of the mobile device [45].

Generally the most important antenna design requirement is that the antenna achieve a resonance condition. Nonresonant antennas, such as Vivaldi antennas, use travelling wave principles and a two or more wavelengths long and so not acceptable in mobile applications at low microwave frequencies such as one or two gigahertz. The reason is that the use of a lossy matching network, for tuning and matching, will then be avoided and the efficiency of the antenna can be kept in high levels.

Apart from the above basic requirements there are several physical, mechanical and environmental constraints which have to take into consideration in order to choose the appropriate antenna. The most important of these constraints are [44]:

Table 4.1 Major Constraints of Vehicular Antenna Design

PHYSICAL	MECHANICAL	ENVIRONMENTAL
Overhead clearance	Low drag	Low & high temperature
Hazard to vehicle passengers	Wind, water & ice loading	Humidity
Concealment of vehicle	Damage due to vandalism & cleaning	Rain & ice (resulting in corrosion)

According to the above requirements and constraints, the optimum type of antenna that will satisfy them is a monopole. The reasons have been analysed in the previous chapter.

4.2 DESIGN METHODOLOGY

The initial design of this project was a quarter wavelength (/4) monopole antenna at 900 MHz. This was an introductory design to observe the characteristics of a simple monopole with narrow band and determine the capabilities of the simulation software.

The next step was to place a passive load on a monopole structure to increase the operational bandwidth. The initial approach was based on the method of K. Fujimoto, A. Henderson, K. Hirasawa and J. R. James [46] for determining the optimum loading of a monopole antenna. This method makes the input impedance of the monopole real in order to avoid a lossy matching network but the operational bandwidth was not satisfactory.

Then different values of passive loads placed along the antenna structure in order the effective electrical height of the monopole to persist approximately a quarter wavelength within 900 MHz to 1800 MHz range. Still the results were not satisfactory.

The design of the loaded monopole continued using the method of K. Yegin and Q. Martin to model a broadband capacitively loaded monopole [13]. The results of this method were satisfactory and they are analysed in this chapter. Then using the approaches of M. Bahr, A. Boag, *et al*. [11], [12] the simulations of loaded monopole continued.

The evaluation of each method was based on the two major requirements:

a) To attain a desired low value for VSWR (i.e. less than four) over the specified bandwidth.

b) To keep the antenna gain positive.

4.3 DESIGN TOOLS

Simulation of the antennas was accomplished using several tools — the most significant are analysed in this section

Antenna Model Scaling

"One of the most useful tools of the antenna engineer is the ability to scale his designs" *H. Jasik*

According to Maxwell's linear equations (shown in Chapter 2), an electromagnetic structure that operates at specified frequency range (*f*) can have the same properties at another scaled frequency range (*nf*). The length of the antenna can be scaled by the ratio 1/n. The only electromagnetic property that cannot be scaled properly, according to H. Jasik, is the conductivity of the antenna [25]. Therefore, the next tool that has been used in this project, is the calculation of the wire conductivity.

Wire Conductivity

The calculation of the wire conductivity requires that the "specific resistance or resistivity" of the conductor material be determined. The specific resistance of a material is the resistance of this material with dimensions of one metre in length and one square metre in cross section and its units are (m). The most significant resistivities of some material, at room temperature, are displayed on the following table [47], [48]:

Table 4.2 Specific Resistance of some Material of Conductors at Room Temperature	
MATERIAL OF CONDUCTOR	RESISTIVITY (M)
Silver	1.6×10^{-8}
Copper	1.7×10^{-8}
Aluminium	2.8×10^{-8}
Brass	7×10^{-8}
Iron	10.1×10^{-8}
Mercury	96×10^{-8}

The resistance of the conductor is given by the following formula [47], [48]:

$$R = \frac{S \times L}{A} \qquad (\Omega) \qquad (4.1)$$

where *R* is the resistance of the conductor, *S* is the specific resistance (resistivity) of the conductor, *L* is the length of the conductor, *A* is the area of cross-section of the conductor.

The conductance (*G*) of the material is the reciprocal of its resistance(*R*):

$$G = 1/R \qquad \text{(Siemens)} \qquad (4.2)$$

And the conductivity (   ) of the material is the reciprocal of its resistivity (*S*):

= 1/S (Siemens/m)

(4.3)

All of these tools used in collaboration with the most important tool of this project, the simulation software package for wire antenna structures, NEC.

4.4 NUMERICAL ELECTROMAGNETIC CODE (NEC)

The Numerical Electromagnetic Code (NEC) is a user-oriented computer code, which is used to analyse the electromagnetic response of antennas and other metal structures. This code is based on the integral equations of the current that can be generated by the source or any other incident field. NEC can analyse any antenna model, which contains transmission lines, perfect or imperfect conductors, lumped elements and the model can be structured over perfect or imperfect ground. It has been developed at the Lawrence Livermore Laboratory, Livermore, California, under the sponsorship of the Naval Ocean Systems Center and the Air Force Weapons Laboratory. It is an advanced version of the Antenna Modeling Program (AMP), which was produced in the 1970's [49].

The antenna structure is modelled with strings of segments following the path of the wire. The number of segments should be the minimum required for accuracy. The wire segment is defined by the co-ordinates of its two terminals and its radius. A wire structure model contains both geometrical and electrical factors. The geometrical factor is the close sequence of the paths on the conductor and the electrical factor is the length of the segment (*d*) relative to the wavelength ( ). A segment length (*d*) less than 0.1 and more than 0.001 should be prefered i.e.:

$$0.001\, l \le d \le 0.1\, l \qquad (4.4)$$

The approximation of the electric field integral equation is based on the Kernel theory; hence there are two approaches available according to the size of the wire radius (*a*):

- The thin-wire Kernel approximation
- The extended thin-wire Kernel approximation

The first approximation should be used when the ratio $d/a > 8$ for errors less than 1%. For the same accuracy on the results when the ratio d/a 2 the extended thin-wire kernel approximation should be used.

For a segment model, some further hints are important [49]:

- Segments should not overlap since the current is indeterminate between two overlapping segments.
- Analysis accuracy may be reduced when a large radius change takes place between two connected segments
- At the point at which a voltage source or a network connection is located, a segment is needed.
- When the voltage source is at the base of a segment connected to a ground plane, the segment should be vertical.
- The maximum number of wires joined at a single junction is 30 because of a dimension limitation in the code.
- The segments should be aligned to avoid incorrect current perturbation from the offset match point and segment junctions, when the wires are parallel and very close together.

4.4.1 NEC Input Commands (Cards)

The input commands of NEC for executing the antenna structures are called “Cards”. These cards are divided in three groups, the “Comment Cards”, the “Structure Geometry Input Cards” and the “Program Control Cards”. The Comment Cards group contains the NEC commands, which displays the comments of the simulation program. The second group consists of the cards that defines the antenna geometrical structure. The last group includes the NEC cards for the electrical parameters of the model, the simulation procedures and the data computation parameters.

A brief description of the cards that have been used in this project are displayed below [49]:

Comment Cards (CM, CE)

A simulation program must begin with a comment card in order to describe the code that follows. A comment begins with the "CM" card and it is terminated using the "CE" card.

Wire Specification Card (GW)

This card is one of the Structure Geometry Input Cards. The purpose of this card is to specify the string of segments required to represent a straight wire. This command is used to represent the structure (i.e. segments, dimensions) of the simulated monopole.

End Geometry Input Card (GE)

This card is also a Structure Geometry Input Cards. It is used to terminate reading of geometry data cards and reset the geometry data if a ground plane is following.

Ground Parameters Card (GN)

This is one more card of the third group. Its purpose is to specify the type of ground used in the simulation. It can define the relative dielectric constant and conductivity of ground in the proximity of the antenna. Moreover, a second medium (part) of the ground can be specified using a second set of ground parameters and a radial wire ground screen can be modeled using a reflection coefficient approximation.

Frequency Card (FR)

This card belongs into the third group of cards (i.e. Program Control Cards). It is used to specify the frequency range (in MHz) of the simulation.

Loading Card (LD)

This Program Control Card can be used to specify the impedance loading on one segment or a number of segments of the antenna structure. There are several options for defining series and parallel R-L-C loads. One more option is the definition of a finite conductivity for each segment of the antenna structure.

Excitation Card (EX)

EX card belongs in the third group of cards. Its purpose is to define the antenna structure excitation. The excitation can be voltage sources on the antenna structure, an elementary current source, or a plane wave incident on the antenna structure.

Radiation Pattern Card (RP)

RP is a Program Control Card that specifies the sampling parameters for the radiation pattern calculation and initiates execution of the program.

End of Run Card (EN)

This card also belongs to the third group and is used to indicate the end of all program execution. It is placed at the end of each program.

4.5 QUARTER-WAVELENGTH MONOPOLE SIMULATION

According to Carr [19] the Radio Frequency (RF) energy on an antenna moves at velocity less than the velocity of light ($c = 3x10^8$ m/sec). This happens due to the dielectric constant of the air, which is greater than the dielectric constant of free space (≈1). The formula of velocity is given by:

$$V = fl \qquad (4.5)$$

Where V is the velocity, f is the frequency and is the wavelength.

Based on this formula, it is clear that velocity of RF energy is proportional to the wavelength. Hence, a reduction on the velocity will cause a reduction of the physical length of the antenna too. Therefore, the physical length of the antenna is less than its electrical length.

The formula for calculating the physical length of an antenna is:

$$L_{(m)} = 0.30\left(\frac{492}{f_{(MHz)}}\right) \qquad (4.6)$$

where $L_{(m)}$ is the physical length of the antenna in meters and $f_{(MHz)}$ is the frequency (in MHz)

Hence, the physical length (in meters) of an antenna at 900 MHz is: $L_{(m)} = 0.1585$ m and for a quarter-wavelength monopole $L_{(m)} = 0.0792$ m.

The range of the segment length (d) for this antenna according to the Equation (4.4) should be:

$$0.000333 \text{ m} < d < 0.0333 \text{ m}$$

Consequently, the length of each segment can be 0.0099 m in order to have eight segments on the antenna structure.

Then the ratio of the segment length (d) to the wire radius (a) becomes:

$$d/a = 0.0099/0.001 = 9.9 > 8$$

The ratio is greater than eight and according to the NEC-2 manual the thin-wire Kernel approximation can be used.

Using the above calculations, the initial antenna model for a quarter-wavelength monopole at 900 MHz (shown in Figure 4.1) was implemented in the NEC simulator. The input code is given in **Appendix A**.

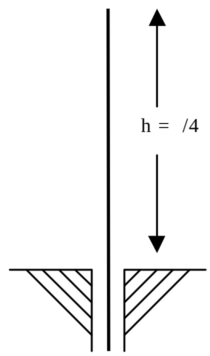


Figure 4.1 /4 monopole antenna

VSWR Output Graph

According to the output graph (shown in Figure 4.2), the VSWR for the /4 wavelength is expected to have minimum values at 900 MHz and at 2750 MHz due to the resonant characteristic of the /4 monopole, at the even multiples of its operational frequency.

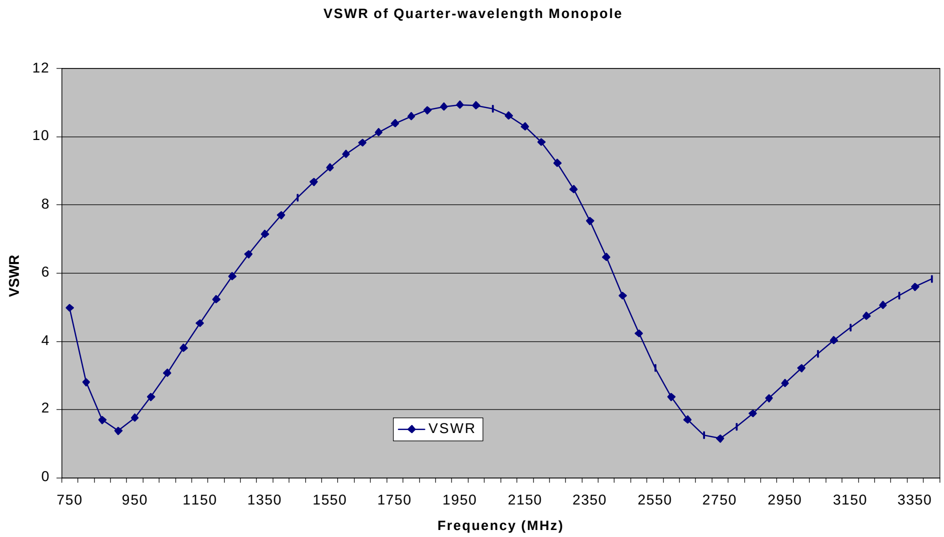


Figure 4.2 VSWR of / 4 monopole at 900 MHz.

The maximum value of VSWR (i.e. maximum reflection) takes place at 1900 MHz, which is also expected, as long as this frequency is an odd multiple of the resonant frequency of the /4 monopole. It is clear that the operational bandwidth of the monopole, according to the design requirements (VSWR < 4), is from 800 MHz to 1100 MHz and from 2550MHz to 3100MHz.

Input Impedance Output Graph

The response of a monopole can also be displayed on the Input Impedance graph (shown in Figure 4.3).

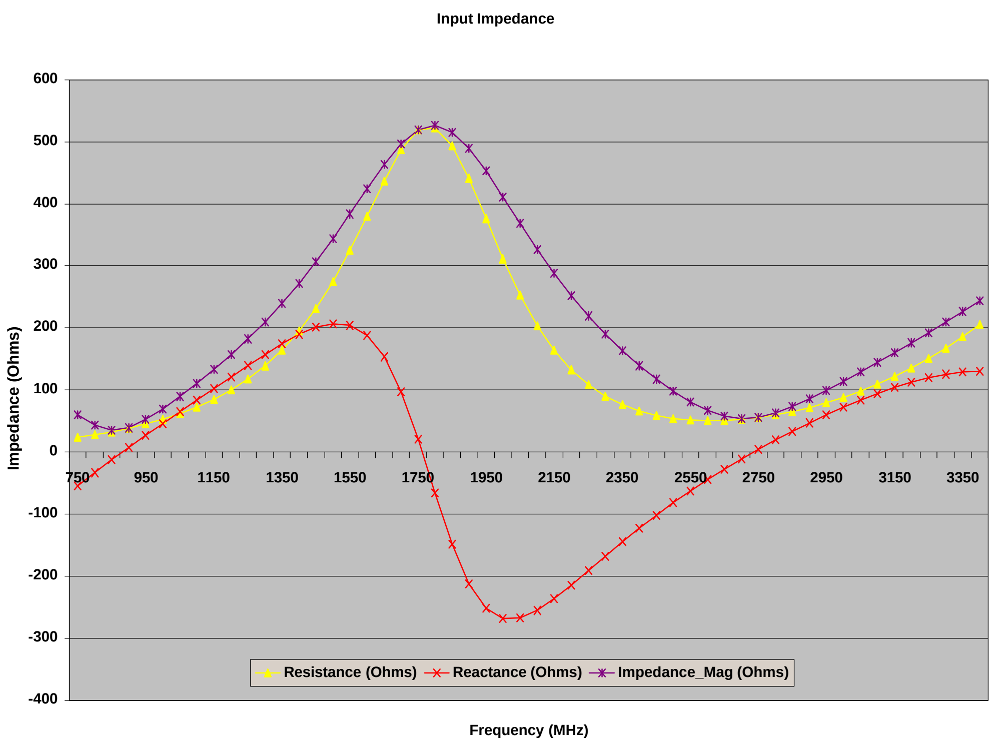


Figure 4.3 Input impedance of /4 monopole at 900 MHz

The reactance of the input impedance at 900 MHz is close to zero and its resistance tends to 40 , which is close to the radiation resistance of a /4 monopole (36). Hence, most of the input power of the antenna is radiated and just a very small amount is dissipated due to the loss resistance of the antenna. The input impedance also is close to the characteristic impedance of the transmission line (Z_o = 50) and consequently the standing waves are minimised.

In contrast, at 1900 MHz the impedance has its maximum value due to the maximum value of its resistance and is far away from the characteristic impedance of the transmission line.

Current Output Graph

The Current graph (shown in Figure 4.4) displays the magnitude of the current along the antenna structure (i.e. antenna's segments) at specific frequencies. This graph shows that the maximum current obtained at 900 MHz where the input impedance of the monopole has its minimum value. However, the current magnitude is very low at 1800 MHz, where the VSWR reaches the highest level.

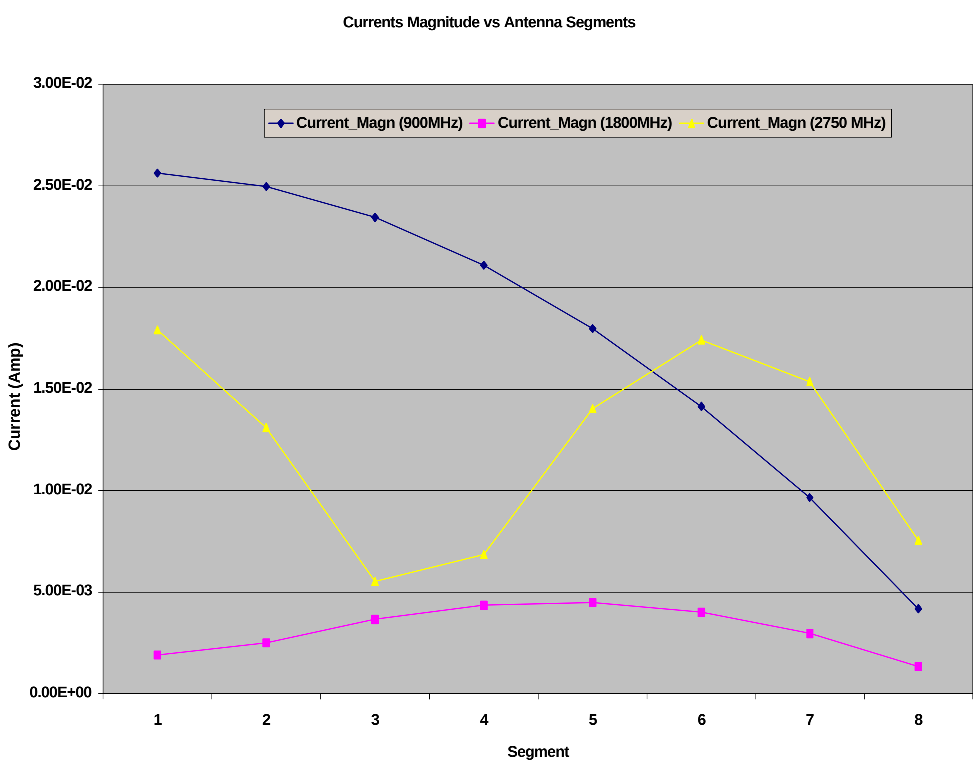


Figure 4.4 Current magnitude along antenna's segments at specific frequencies

The graph of the current phase (shown in Figure 4.5) along the antenna structure and at the same frequencies displays the rapid phase change of the current at 2750 MHz, while at the other frequencies the phase changes at a slow rate. The current phase at 2750 MHz takes place at a distance three-quarters of the way along the antenna from the ground.

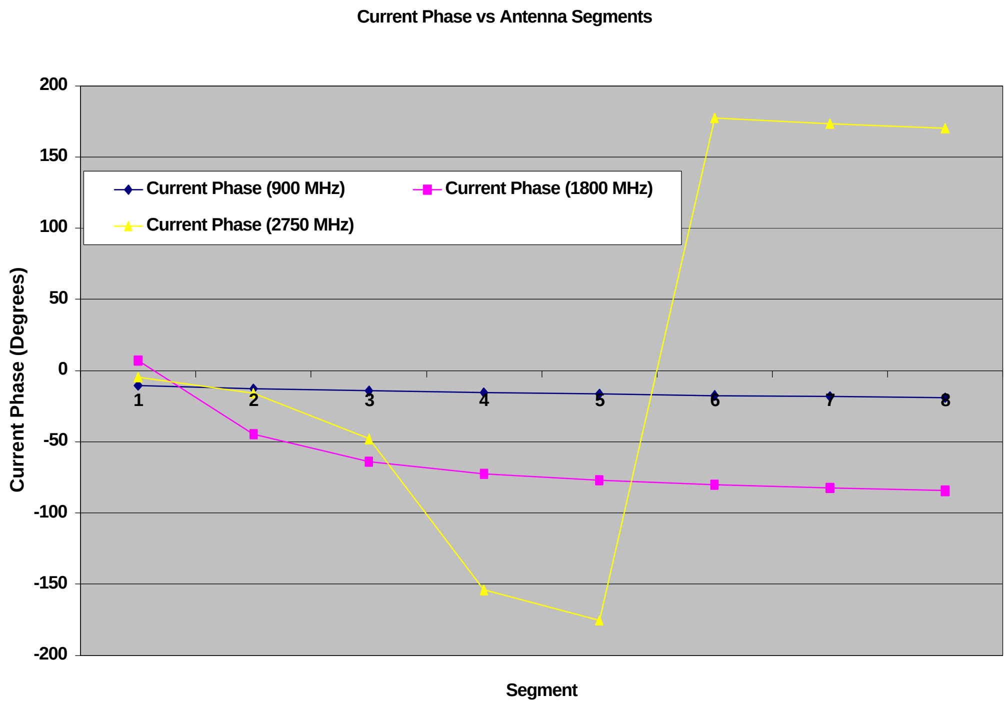


Figure 4.5 Current phase along antenna at specific frequencies

E-Field Pattern Output Graph

The graph shown in Figure 4.6 displays the E-field of the monopole along the elevation angle of the antenna. The Electric field takes its maximum value (0.5 V/m) at the elevation angle   = 90° (i.e. horizontal plane).

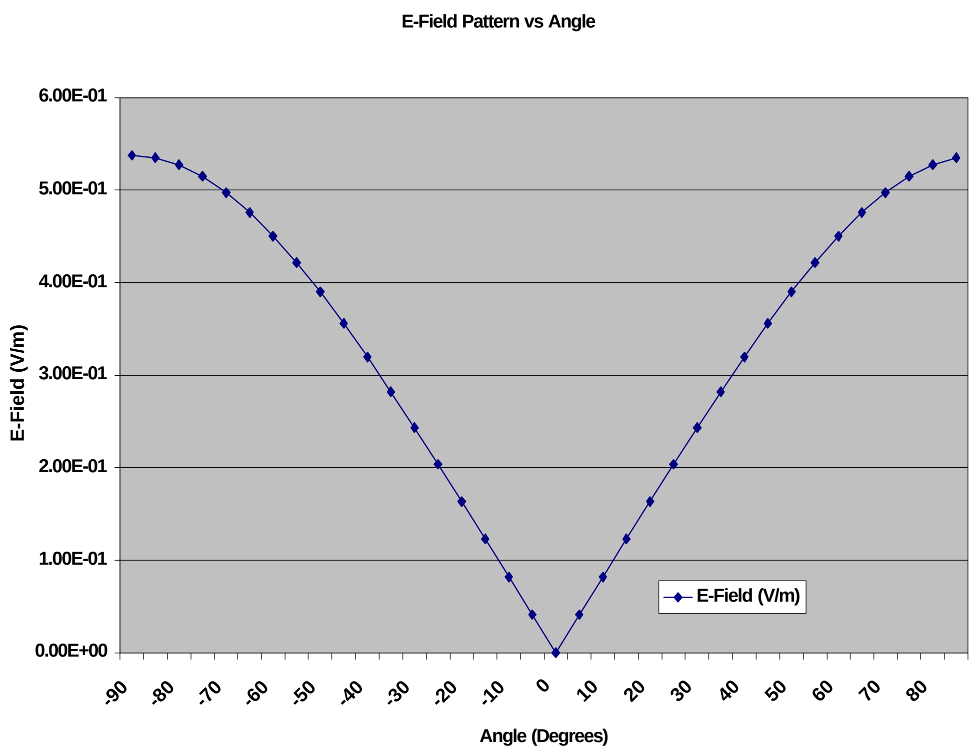


Figure 4.6 E-field pattern vs antenna elevation angle (º)

Power Gain Output Graph

The same happens with radiation pattern power gain of the antenna (shown in Fig. 4.7), which takes the maximum value of 5 dB at the horizontal plane (i.e. elevation angle = 90°).

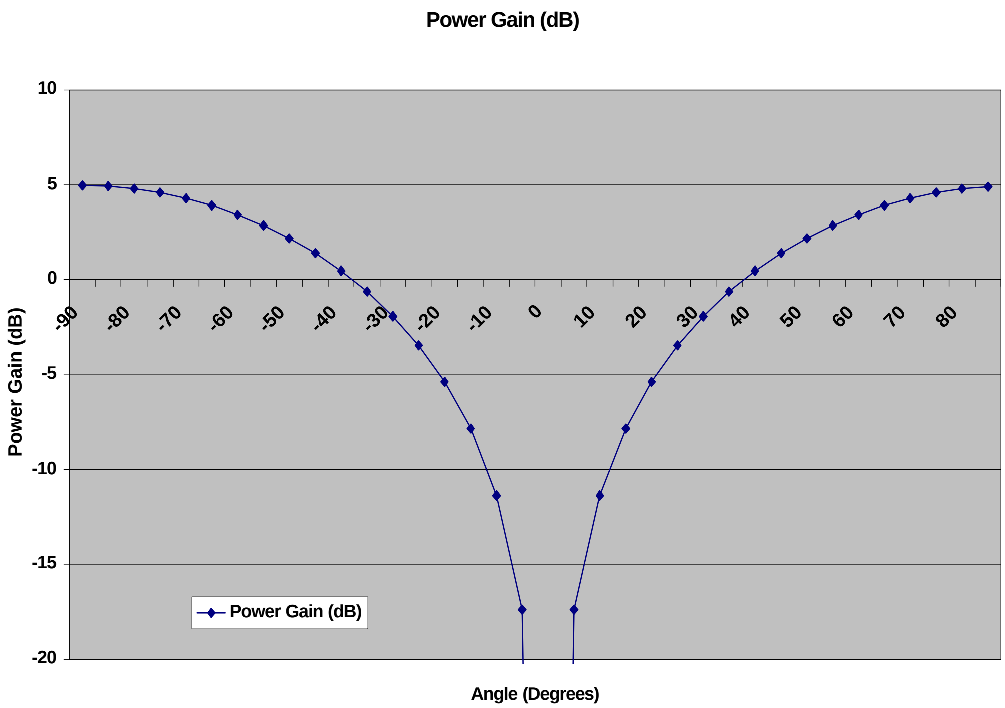


Figure 4.7 Power gain (dB) vs antenna elevation angle (º)

4.6 CAPACITIVELY LOADED MONOPOLE ANTENNA

4.6.1 Capacitively Loaded Monopole with 3 mm Radius of Conductor

The design of a capacitively loaded monopole was based on the method of Yegin and Martin [13]. This method was analysed and exploited using the antenna design tools, which were analysed at the beginning of this chapter.

The major problem, during the simulations, was the lack of Genetic Algorithm software, which could be used to obtain the optimum values of load and their optimum positions along the monopole. Therefore, the author spent much time changing the values and the positions of the loads manually.

After a large number of simulations an acceptable result was derived using two capacitors C_1 = 0.537 pF and C_2 = 0.245 pF at the specific positions from the base of the monopole t_1 = 0.055 m and t_2= 0.105 m, respectively and 3 mm radius of conductor (shown in Figure 4.8). The total length of the monopole is 0.143 m.

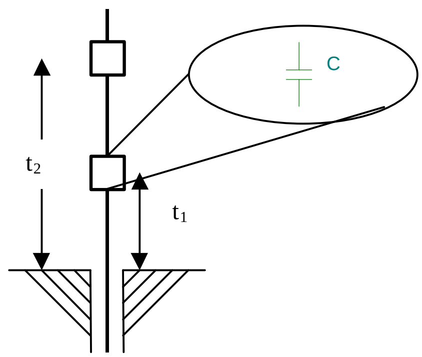


Figure 4.8 Capacitively loaded monopole antenna

The model of the broadband antenna was placed on a "Perfect Ground" and it does not contain a matching network. Even without a matching network the output files of the simulation indicates that the Voltage Standing Wave Ratio (VSWR) is less than 4 from 800 MHz to 3650 MHz. The maximum power gain is around 5.0dB over the required bandwidth.

The input file from the simulation of this antenna is given in **Appendix B**.

VSWR Output Graph

Based upon the results of the simulation of the broadband monopole, its VSWR (for a reference characteristic impedance of Zo=50) shown in Figure 4.9 has minimum value at 950 MHz and at 3600 MHz. The maximum values of VSWR (maximum loss) occur at the frequencies from 2400 to 2450 MHz. is graph indicates that the value of VSWR is less than 4 over the required bandwidth. The maximum values of the graph are close to 3.5, which correspond to a radiation efficiency of 69.1%, (according to the Table 2.1, in the second chapter of this report). Significantly, this is achieved over a broad bandwidth without a matching network.

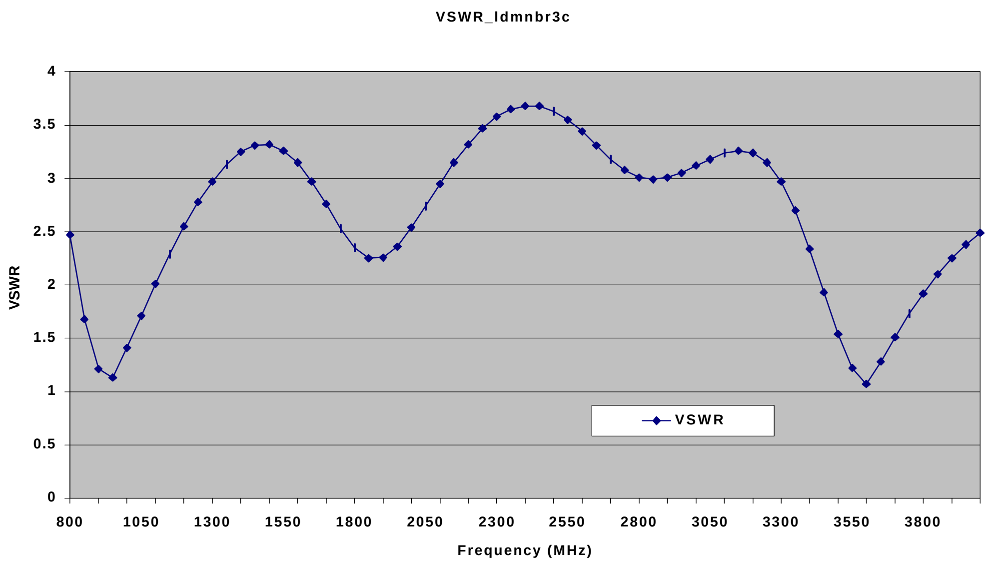


Figure 4.9 VSWR of capacitively loaded monopole (wire radius 3mm & Zo=50)

A better VSWR result is achieved by referencing the antenna to a transmission line of characteristic impedance, Zo, of 75) is shown in Figure 4.10.

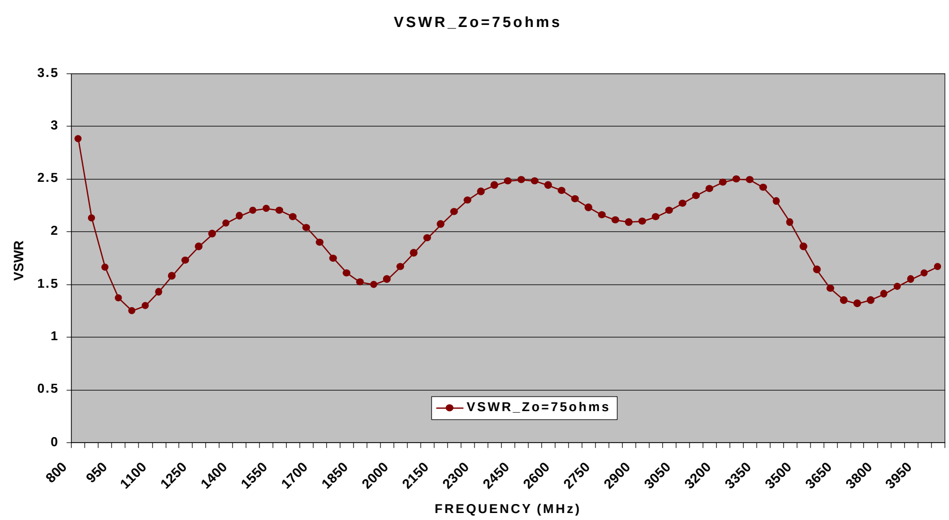


Figure 4.10 VSWR of capacitively loaded monopole (wire radius 3mm & Zo=75)

Input Impedance Output Graph

The characteristics of the above antenna are displayed in Figure 4.11 as the input impedance. The input reactance is close to zero over most of the required bandwidth. Thus the antenna is self-resonant across its operational bandwidth. In contrast, at 2450 MHz the impedance has its maximum value because of the maximum value of its resistance (175) and far away from the 50 , which is the characteristic impedance of the transmission line. Similarly the reactance tends to its maximum negative value (-75) , so the VSWR at this frequency takes its maximum value.

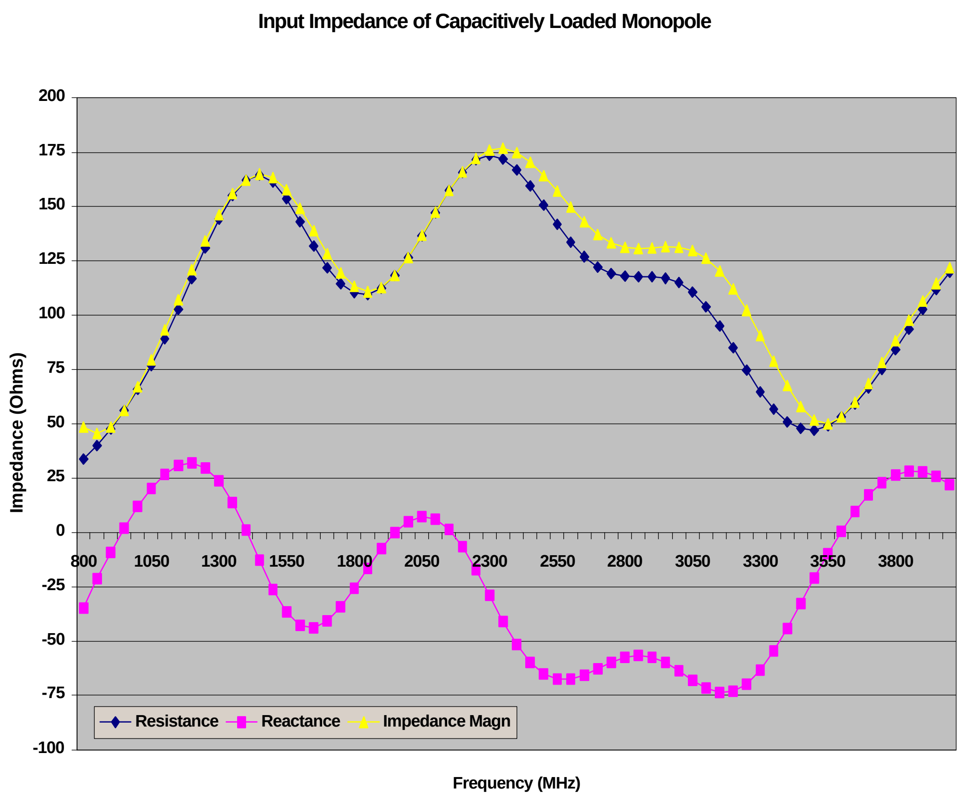


Figure 4.11 Input impedance of capacitively loaded monopole (wire radius 3mm)

Current Output Graph

The currents distribution along the antenna is shown in Figure 4.12 at specific frequencies. This figure shows that the maximum current is obtained at 800MHz where the input impedance of the monopole has its minimum value and is close to the characteristic impedance of the transmission line. Likewise, the current at 3600 MHz takes large values over the operational bandwidth and its VSWR reaches the minimum value (VSWR = 1.07). Besides, the currents at the frequencies, where the VSWR is large (f = 2400 MHz), are very small.

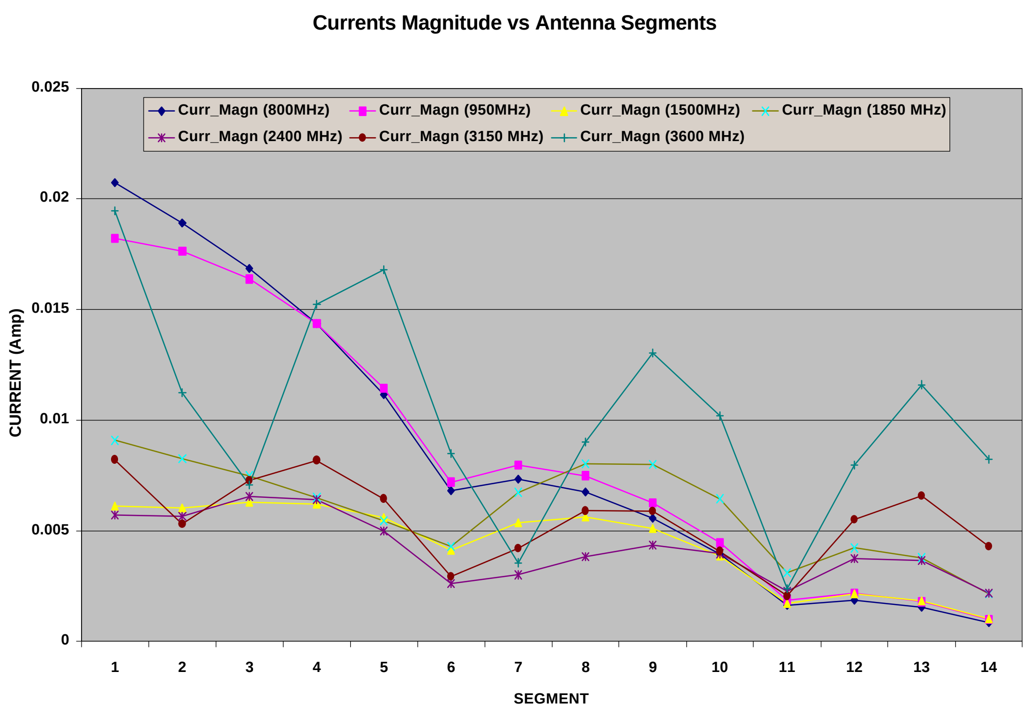


Figure 4.12 Current magnitude along the monopole at specific frequencies

The graph of the current phase, (shown in Figure 4.13) along the antenna structure and at the same frequencies, displays the rapid phase change of the current at the frequencies above the 1850 MHz. The current phase, at the frequencies below the 1850 MHz changes slowly.

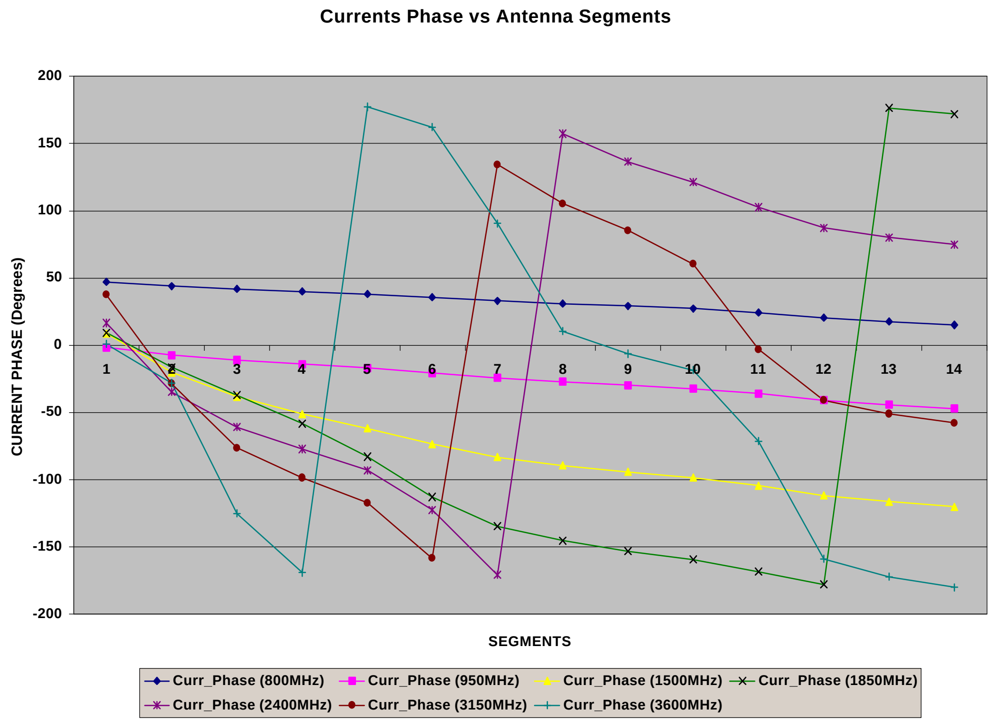


Figure 4.13 Currents phase along the monopole at specific frequencies

E-Field Pattern Output Graph

The E-field Pattern at 800 MHz is shown in Fig. 4.14 and its normalised output confirm the omni-directional characteristic of the monopole antenna. The electric field takes its maximum value (1.2 V/m) at the elevation angle = 90° (horizontal plane).

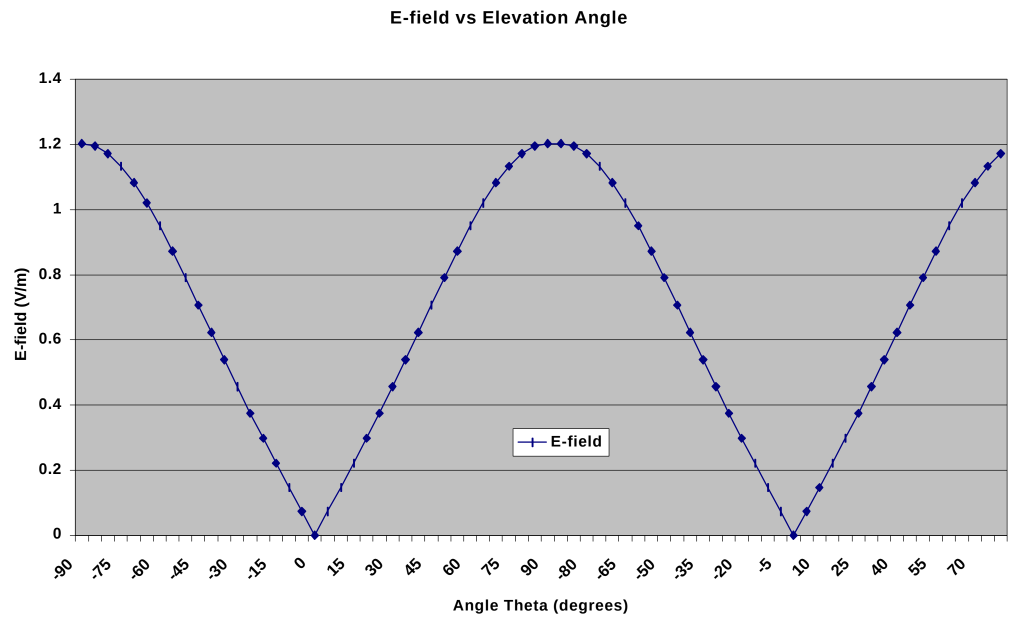


Figure 4.14 E-Field pattern of the capacitively monopole (wire radius = 3mm)

Power Gain Output Graph

The same happens with the radiation pattern power gain of the antenna, shown in Figure 4.15, which takes the maximum value of around 5.3 dB at 800 MHz and at the horizontal place (elevation angle = 90°). The maximum value of the power gain over the operational bandwidth of the antenna can exceed the 5.3 dB but at different elevation angle each time. On the other hand, the power gain at the same elevation angle can become negative at some points of the operational bandwidth.

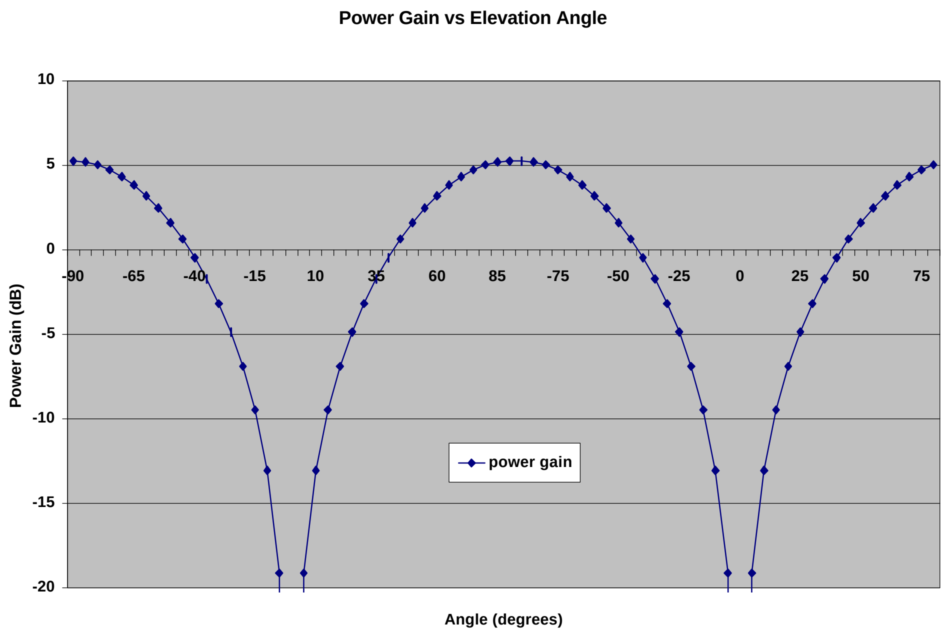


Figure 4.15 Radiatted power gain as a function of elevation angle

4.6.2 Capacitively Loaded Monopole with 4 mm Radius of Conductor

This design is based on the same method as the previous simulation the only difference being the radius of the antenna conductor, which is increased here from 1 mm to 4 mm. The length of the antenna and the positions of the two capacitors (as shown in Figure 4.8) C_1 = 0.537 pF and C_2 = 0.245 pF remain constant; and t_1 = 0.055 m and t_2 = 0.105 m, respectively.

The antenna structure is placed on a "Perfect Ground" and does not contain a matching network. The results of this simulation are much better than the results of the previous antenna structure with radius of 3 mm.

The input file from the simulation of this monopole is given in **Appendix C**.

VSWR Output Graph

The VSWR of the monopole (shown in Figure 4.16) connected to transmission line with characteristic impedance of Zo=50 , has minimum value at 950MHz and at 3600MHz. The maximum values of VSWR (maximum loss) are taking place at the frequencies from 2400 and 3150MHz. However, the most important outcome of this graph is that the value of VSWR is less than 3.5 over the required bandwidth. The maximum values of the graph are close to 3.0, which correspond to a radiation efficiency of more than 75%, (according to the Table 2.1, in the second chapter of this report). This is a much greater achievement than the previous design.

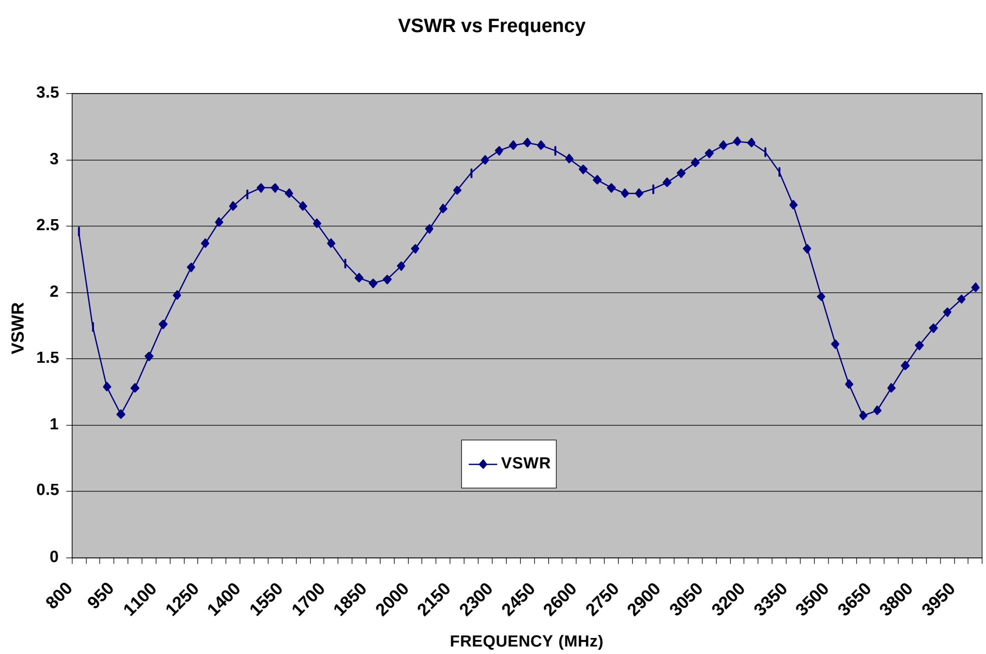


Fig. 4.16 VSWR of capacitively loaded monopole (wire radius 4mm & Zo=50)

A better VSWR output achieved by connecting the antenna with a transmission line of characteristic impedance Zo = 75 (shown in Figure 4.17). The maximum value of the graph is approximately 2.85 but the most values in the operational bandwidth are close to 2.00.

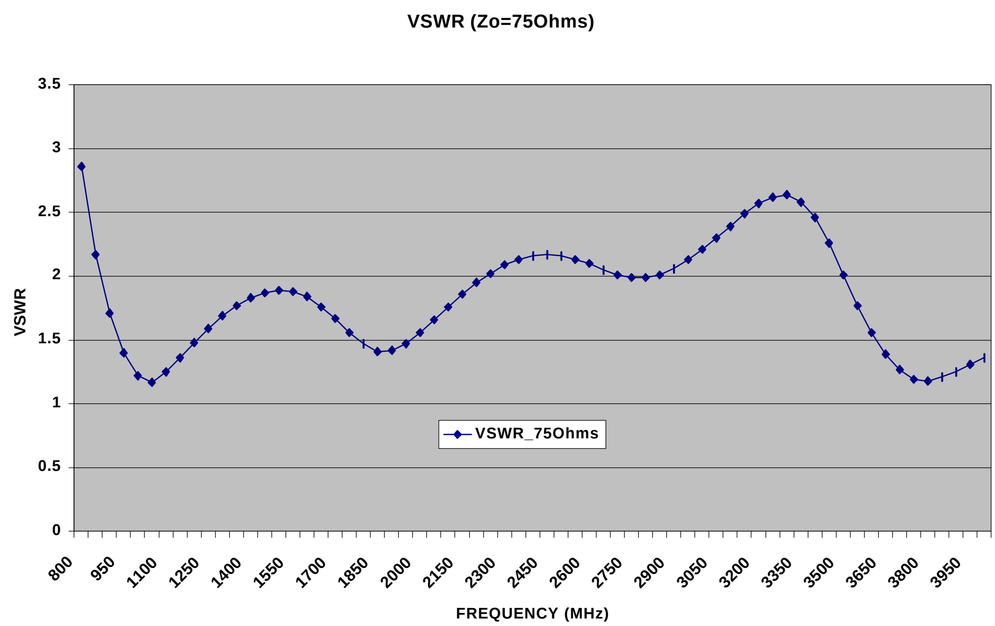
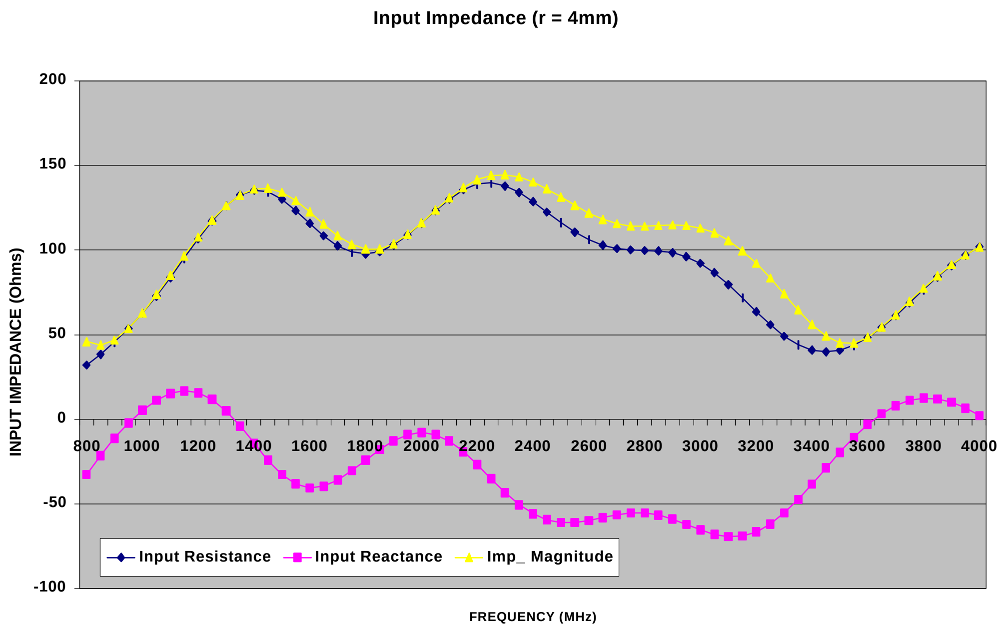


Figure 4.17 VSWR of capacitively loaded monopole (wire radius 4mm & Zo=75)

Input Impedance Output Graph

The certification of the above results comes from the Input Impedance graph (shown in Figure 4.18). The susceptance of the input impedance is close to zero and the impedance magnitude is very close to the antenna resistance over the most of the required bandwidth. Therefore, the antenna becomes self-resonant along its operational bandwidth. In contrast, at 2300 MHz the impedance has its maximum value because of the maximum value of its resistance (145) and far away from the 50 , which is the characteristic impedance of the transmission line. Similarly the susceptance tends to (-43) . The VSWR reaches its maximum value at 3150MHz where the input reactance has its maximum value (-69).



4.18 Input impedance of capacitively loaded monopole (wire radius 4mm)

Current Output Graph

The current magnitude graph, Fig. 4.19, shows that the maximum current is obtained at 800 MHz where the input impedance of the monopole has its minimum value and close to the characteristic impedance of the transmission line. Characteristic of this graph is the fluctuation of the current at 3600 MHz, where the VSWR reaches the minimum value (VSWR = 1.07). Besides, the currents at the frequencies, where the VSWR is large (f = 2400 MHz), are very small, as in the previous simulation.

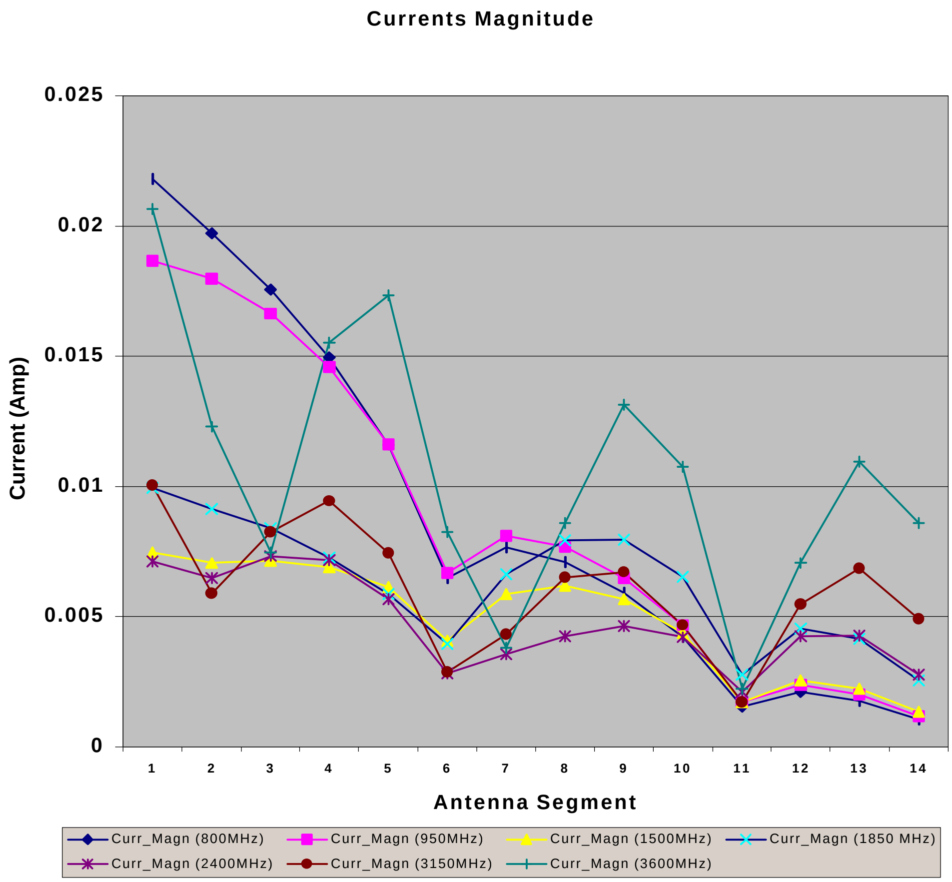


Figure 4.19 Current magnitude along the monopole at specific frequencies

The graph of the current phase, (shown in Figure 4.20) along the antenna structure and at the same frequencies, displays the rapid phase change of the current at the frequencies above the 1850 MHz. The current phase, at frequencies below 1850 MHz changes slowly.

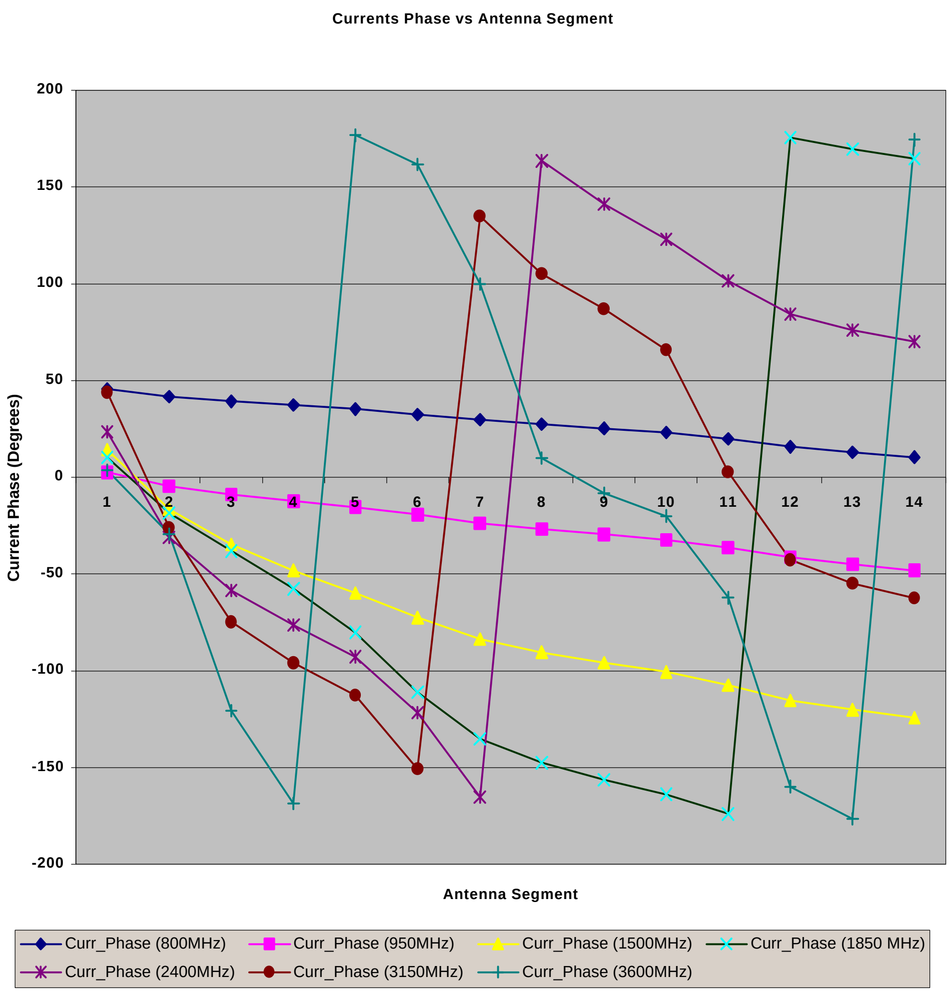


Figure 4.20 Currents phase along the monopole at specific frequencies

E-Field Pattern Output Graph

The E-field Pattern at 800 MHz, shown in Figure 4.21, and its normalised output confirm the omni-directional characteristic of the monopole antenna. The electric field takes its maximum value (1.25 V/m) at the elevation angle = 90° (horizontal plane).

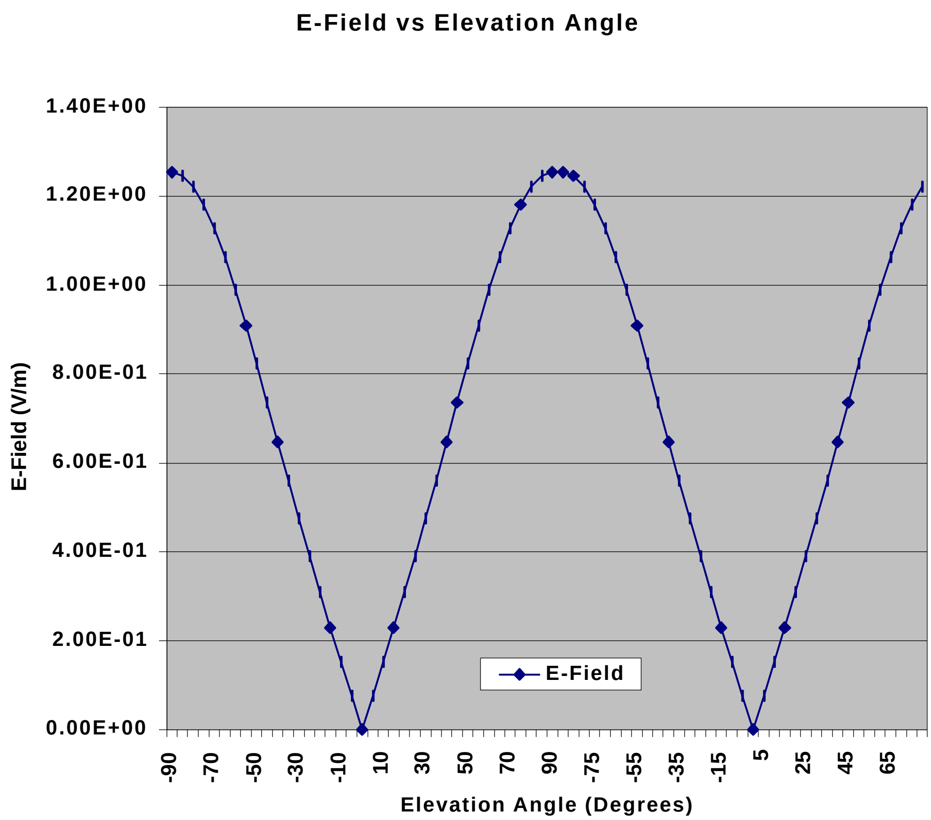


Figure 4.21 E-field pattern of the capacitively-loaded monopole (wire radius = 4mm)

Power Gain Output Graph

The same happens with the radiation pattern power gain of the antenna at 800 MHz, shown in Figure 4.22, which takes the maximum value of around 5.37 dB at the horizontal place (elevation angle = 90°). The maximum value of the power gain over the operational bandwidth of the antenna can exceed the 5.37 dB but at different elevation angle each time. On the other hand, the power gain at the same elevation angle can become negative at some points of the operational bandwidth.

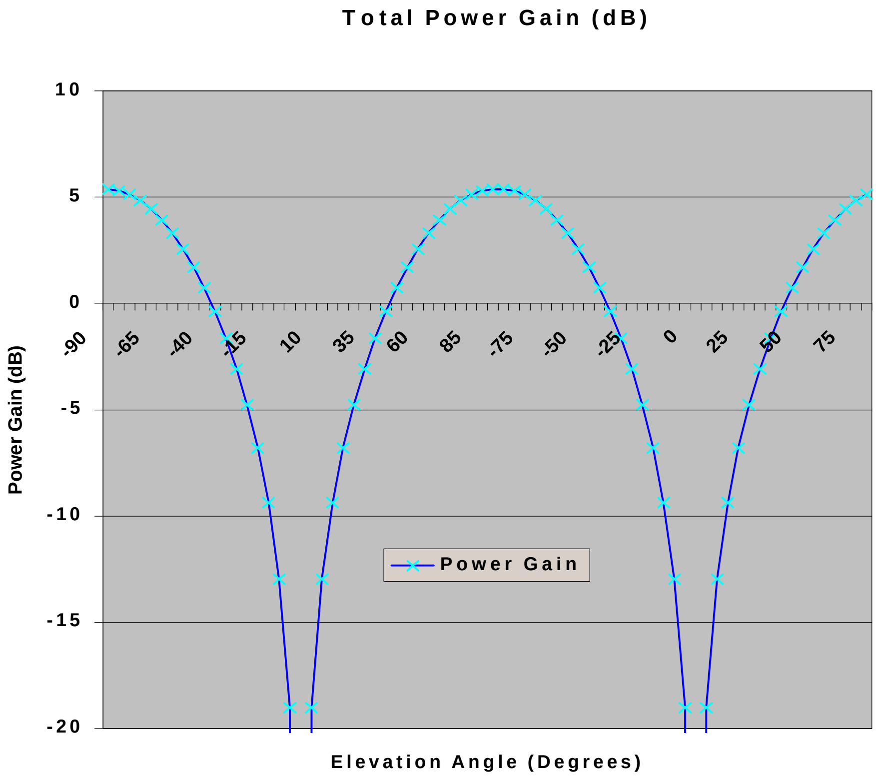


Figure 4.22 Radiatted power gain as a function of elevation angle

4.7 LOADED MONOPOLE WITH L-C CIRCUITS

This antenna design is a monopole loaded by parallel L-C circuits, is based on a "Perfect Ground", and without a matching network (shown in Fig. 4.23).

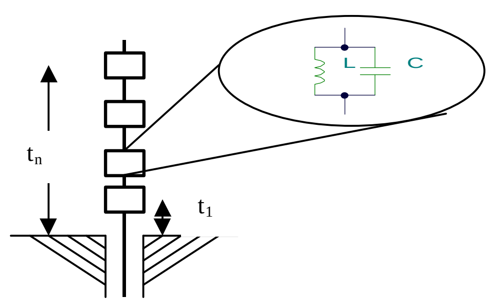


Figure 4.23 L-C loaded monopole

The total length of the monopole is h = 6.6 cm and the four LC circuits are located at t_1 = 0.012 m, t_2 = 0.014 m, t_3 = 0.016 m and t_4 = 0.018 m above the base of the monopole.

The values of the inductors and capacitors of the loaded circuits along the monopole is given in the following table:

Table 4.3 Components Values of L-C Circuits

L-C CIRCUITS AT	INDUCTOR (L)	CAPACITOR (C)
t_1	1.5nH	0.45pF
t_2	1.5nH	0.40pF
t_3	1.5nH	0.35pF
t_4	1.5nH	0.30pF

This design is based on the method of Bahr, Boag, Michielssen and Mittra [11], [12]. This method was analysed and it was exploited using the antenna design tools described at the beginning of this chapter.

The values of the components and their locations along the antenna structure were obtained after manual iteration. In the centre of the antenna structure, a resistance of 240   was placed to reduce the impedance variation. The VSWR was effected by this variation, but using the resistance, became flat. The authors of this method mentioned in [12] that they used a 400   resistance at a height 1/3 below the top of the antenna to reduce this variation. Even so, in a design without a matching network this value of resistance did not work as desired and the value suggested by Altshuler [8] was chosen. The only drawback of incorporating the resistance was the sacrifice of the antenna radiated power gain.

The results of these simulations were not as good as for the previous simulations. However, this is not significant because the use of an optimization procedure such as the "genetic algorithm" could provide better values for the components and their locations in order to derive better results. In addition, this method of antenna design probably needs a matching network that was not used in this simulation. The best results of this simulation are presented below.

The input file from the simulation of this monopole is given in **Appendix D**.

VSWR Output Graph

The VSWR graph of the *LC* loaded monopole is shown in Figure 4.24 with reference to a transmission line with characteristic impedance, Zo, of 50 , has a minimum value at 1100 MHz. The maximum values of VSWR are taking place at the upper end of the simulation band (i.e. above 2900 MHz). It is clear that the fluctuations of the graph are limited, due to the resistance that is used. However, mostly the VSWR exceeds 4 and hence the antenna does not satisfy the project.

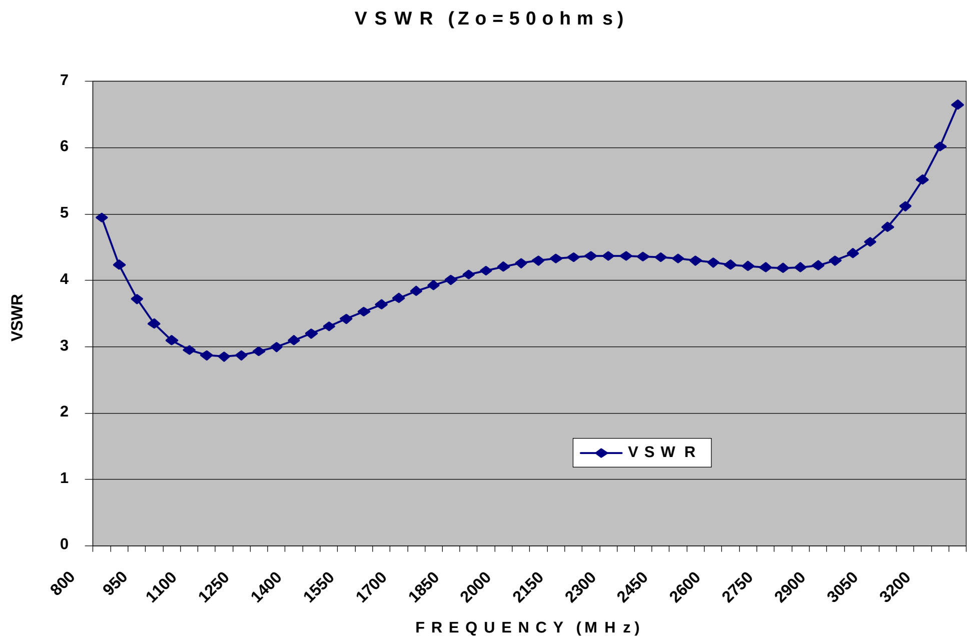


Figure 4.24 VSWR of LC loaded monopole

Input Impedance Output Graph

The graph of Figure 4.25 presents the input impedance of the *LC* loaded monopole. The reactance of the input impedance is not close to zero; hence the impedance magnitude differs to the antenna resistance over most of the required bandwidth. Therefore, the antenna is not self-resonant thus its VSWR reaches high levels.

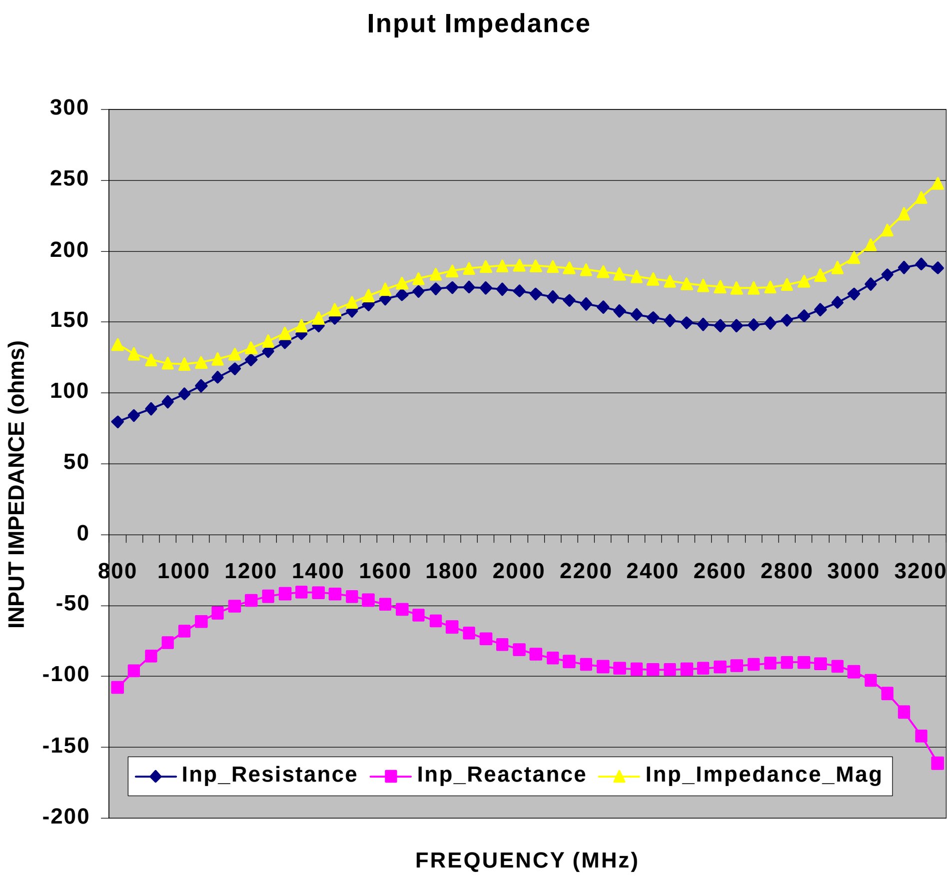


Figure 4.25 Input impedance of L-C loaded monopole

Power Gain Output Graph

The radiation pattern power gain of the antenna (shown in Figure 4.26) reaches negative values due to the resistance in the centre of antenna. The peak value of the power is approximately –3.0 dB along the horizontal place (elevation angle = 90°). However, this negative value does not satisfy the requirement of the project.

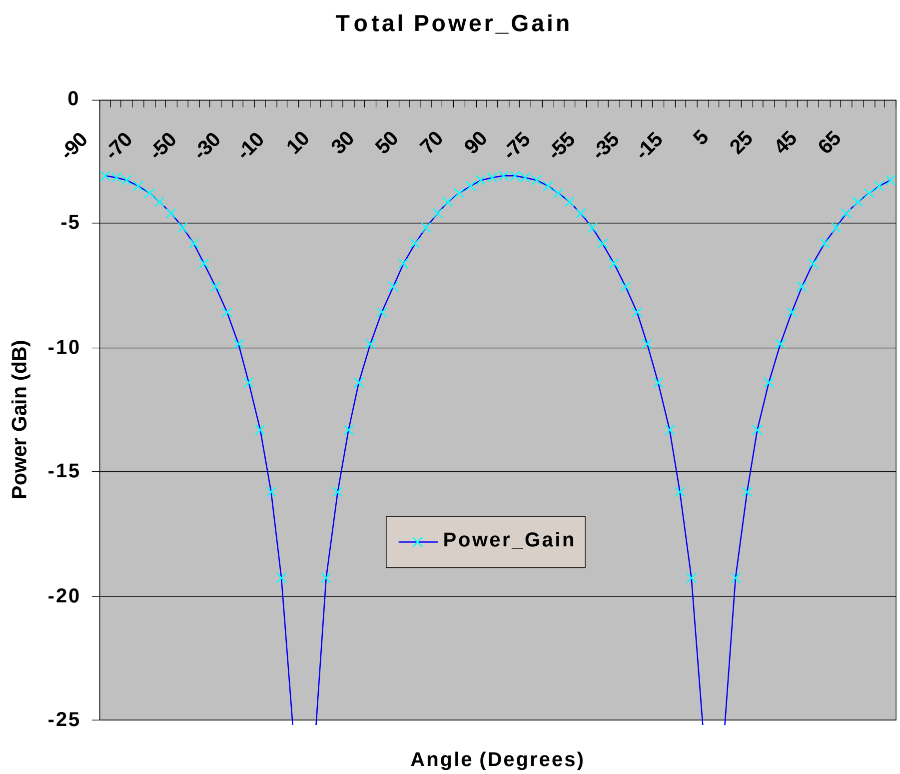


Figure 4.26 Radiatted power gain as a function of elevation angle

4.8 SUMMARY

In conclusion, based on the output figures of the above antenna models, it is clear that the power losses are minimised when the input impedance of the antenna (Z_A) is close to the characteristic impedance (Z_o) of the transmission line connected to it and used as a reference impedance. Additionally, when the reactance X_A of the antenna is close to zero, the input impedance (Zin) of the antenna approximates its resistance (R_A). As a result, the antenna becomes self-resonant and its VSWR gets low values.

Moreover, the current has large value at the frequencies where Z_A is low. Therefore, the impedance of the antenna (Z_A) has to be close to Z_o in order to minimise losses on the antenna and to increase its efficiency. At the same time, the current reaches a peak value, but along the loads of the antenna, it should be close to zero in order to minimise the losses of the monopole.

The power gain is sacrificed by placing a resistance along the antenna structure. Therefore, resistance should be avoided in antenna design, where the major objective is the maximisation of its power gain.

5 FABRICATION & TESTING OF CAPACITIVELY LOADED MONOPOLE

According to the above simulations, satisfactory results were obtained in the simulation of the capacitively loaded antennas of three and four millimetre conductor radius. Therefore, the project continues with the fabrication and testing of the capacitively loaded antenna with a brass conductor of 3mm radius.

5.1 FABRICATION PROCEDURES AND CONCEPTS

The fabrication procedure for the capacitively loaded monopole is analysed below.

- The first step of the fabrication was the manufacturing of several brass conductor rods of 3 mm radius, in different lengths. The lengths of rods that were used for the fabrication of the prototypes are displayed on the following table:

Table 5.1 Lengths of monopole rods

Number of Rods	Length of Rods (mm)
2	50
2	45
2	40
1	35
1	30
2	5
2	3

The turning of the rods took place in the workshop of mechanical and electrical engineering departments at the University of Leeds. The conductors of the monopole are shown in the Figure 5.1 and Figure 5.2.

Figure 5.1 Brass rods of the monopole (The scale is in centimetres.)

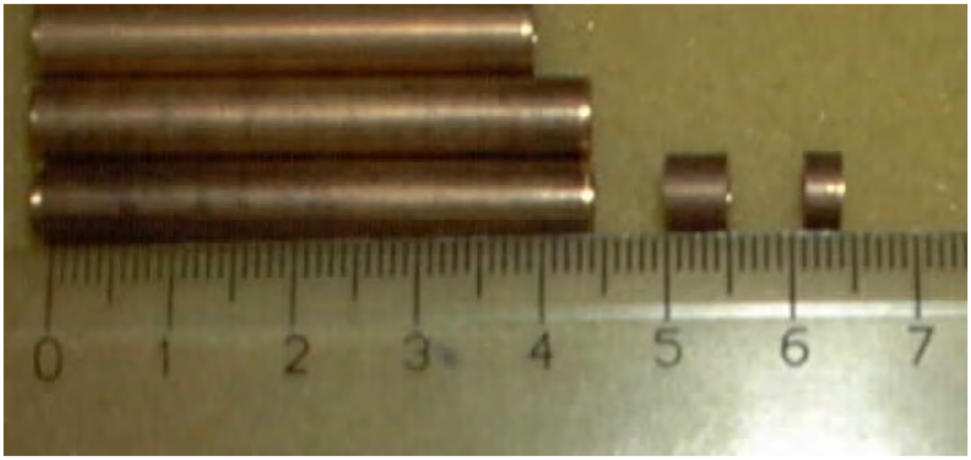


Figure 5.2 Brass rods of 40mm, 45mm, 5mm and 3mm (The scale is in centimetres.)

- The next step in fabricating for the monopole structure was the cutting of the nylon screws, which were to be used to connect the pieces of brass. Each nylon screw connects two different rods together, possibly leaving a small gap between them to simulate a capacitor. This assembly is shown in Figure 5.3.

Figure 5.3 Gap between rods (Simulation of Capacitor)

The length of the gap, which simulates the capacitor, was calculated using the following formula for parallel-plate capacitor:

$$C = \frac{eA}{d} \qquad (5.1)$$

Where *C* is the capacitance of capacitor, is the dielectric of permittivity (8.854 x 10^{-12}), *A* is the area of the capacitor plates (i.e. A = r^2, for the cylindrical rods) and *d* is the distance between the two plates (i.e. gap between the brass rods).

In order to keep the distance between the two rods stable during antenna testing, a specific number of films of 1 mm thickness were used, according to the above calculation of *d* (shown in Figure 5.4).

Figure 5.4 Prototype capacitively loaded monopole (the films keep the gaps stable)

At the end of the fabrication procedures, the antenna was placed on an “imperfect ground” and it was connected to the network analyser, using an N-type connector and an SMA adapter, in order to start with the measurements.

5.2 FINITE GROUND PLANE ("IMPERFECT GROUND")

According to Nelson [51], who analysed the method of Meier and Summers on ground plane design [52], a square ground plane with a side dimension equal to the diameter of a circular ground plane introduces a small error of the antenna input impedance. A finite square ground plane is suggested for a monopole antenna design, as it is easier to be constructed than a circular ground but has comparable error.

Nelson in his analysis of ground plane design, suggested that the correct dimensions of a finite ground are not the same for all antenna designs. Therefore, the designer should take into account all the factors, which effect the ground plane of a specific antenna. A suggested approach is the use of Meier and Summers' experimental values [52]. A satisfactory finite ground plane for a monopole with $h/a = 150$, where (h) is the length of the monopole and (a) is the radius of its cylindrical conductor, is 6 wavelengths square at its resonance frequency. This ground plane provides an error of 3% at both resonance and antiresonance and an ohmic error of 20 at antiresonance [51].

In this project the height of the monopole was h = 0.143 m and the radius of its conductor was a = 0.001 m, so that $h/a = 143$. The wavelength at 800MHz is = 0.375 m, according to the above theory, the sides of the ground plane should be approximately 6 , hence they should be 2.25m each. However, it was not feasible to construct so large a ground plane, because of the limited laboratory space and the lack of a large aluminium sheet in the departmental workshop.

Thus the square side of the ground plane, which was used in this project, was just 0.35m (shown in Figure 5.5). It is clear that the dimensions of that square ground were much smaller than the acceptable values determined using the above theory. Consequently, the author could not expect the result of the testing to be the same as those of simulations.

Figure 5.5 Capacitively loaded monopole on a finite square ground plane

5.3 N-TYPE AND SMA CONNECTORS

N-Type Coaxial Connectors

The N-type connector is one of the most popular coaxial connector for microwave applications. There are male and female N-type connectors. In this project a female connector was used to connect the antenna to an SMA adapter and then to the network analyser.

A pair of N-type connectors for 50 ohms systems is shown on the following figure [50].

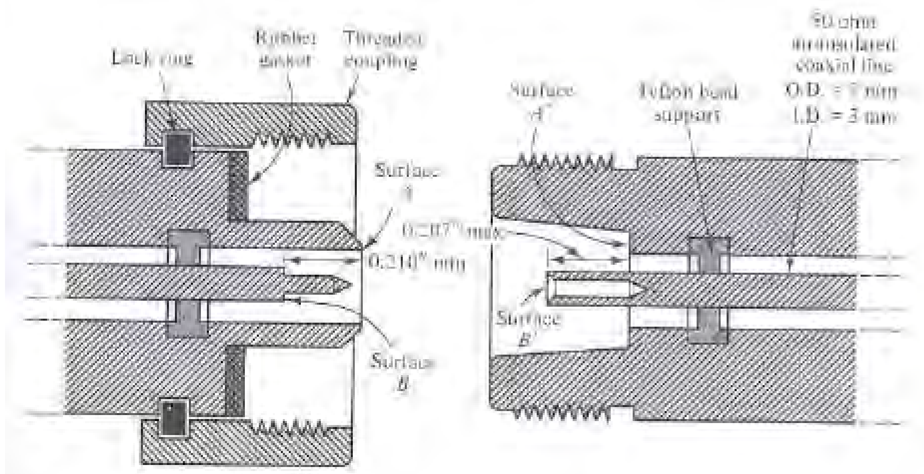


Figure 5.6 Male and female N-type connectors and their dimensions (Source: [50])

This type of connectors has very small reflection and its Voltage Standing Wave Ratio (SWR) does not exceed 1.07 between DC and 18GHz [50]. The design of N-type connectors has been improved to prevent damages at their inner parts due to careless connection. Therefore, during connection of the female with the male connector, the surface A (shown in Figure 5.6) seats on surface A' and the surface B touches the surface B'.

However, coaxial connectors have to always be gently screwed together.

SMA Coaxial Connectors

This type of coaxial connectors is used in low-power microwave applications. The maximum operational frequency of an SMA connector is approximately 20 GHz. An SMA connector, like an N-type connector, has small reflection and its SWR is given by the following formula [50]:

$$SWR_{max}\ \ 1.05 + 0.005f_{\ GHz} \tag{5.2}$$

Where *f* is the operational frequency (in GHz)

The design of SMA connectors has been developed to protect their inner parts from an inattentive use, as was incorporated in N-type connector design. Therefore, the surface A of the male connector touches the surface A’ of the female and the surface B stops on the surface B’, during connection. (This is shown in Figure 5.7).

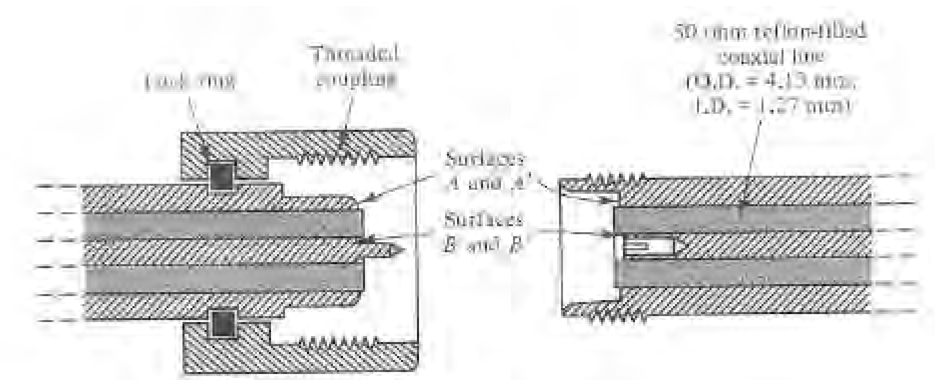


Figure 5.7 Male and female SMA connectors and their dimensions (Source: [50])

The loaded monopole and its connectors are displayed on the Figure 5.8.

Figure 5.8 Loaded monopole and N-type connector with SMA adapter, under the ground plane

5.4 ANTENNA MEASUREMENT CONCEPTS

The International Electrotechnical Commission (IEC) has established standards for the methods of antenna measurement. These regulations are accepted and applicable world-wide.

IEC has set three stages of measurement for an antenna design, which are [53]:

- Measurement during development
- Measurement during the testing of design
- Measurement during production testing

The major parameters of the antenna measurements according to IEC are:

- Impedance and VSWR measurements
- Gain Measurement

- Efficiency Measurement
- Radiation Pattern Measurement

These parameters were taken into consideration during the development of the loaded monopoles of this project. However, all of them could not take place during the testing procedures, due to the lack of some equipment for antenna measurements. Therefore during the testing of the prototypes only the Impedance and the VSWR measurements were performed.

5.5 ANTENNA TESTING AND RESULTS

During the testing of the capacitively loaded monopoles in this project, nineteen prototypes of different lengths were tested. (An assembled capacitively loaded monopole is shown in Figure 5.9).

Figure 5.9 Loaded monopole of total height 137.04mm

The prototype, which has been analysed in Section 4.6.1 of this report, produced the best outcomes, during the testing. The characteristics of this antenna are given in the following table.

Table 5.2: Characteristics of the tested monopole			
	Height from the Ground (cm)	Values of Capacitor (pF)	Gap Distance (d) between Antenna's Rods (Simulating Capacitors) (mm)
Load 1	5.5	0.537	0.467
Load 2	10.5	0.245	1.02
Total length of Loaded Monopole: 14.3cm Radius of antenna Conductor (Brass): 3.0mm			

Loaded monopoles of 4 mm radius were not been tested due to the lack of 4 mm brass conductors.

Testing Procedures

The procedures that were followed to test the above capacitively loaded monopole are as follows.

- The first step was the calibration of the Network Analyser and its fixturing. A reference plane was established at the input of the antenna. The calibration of the network analyser was done using the components of Hewlett Packard (shown in Fig. 5.10).

Figure 5.10 HP components for the calibration of network analyser

- The test frequency range was from 500MHz to 4,000MHz and the resolution was 201 points (i.e. frequencies) between the frequency range.
- The next step was the measurement of the reflection parameter (S11) and VSWR of the antenna prototypes. During this procedure the author was changing the length of the monopole and the height of the loads from the antenna base. As was mentioned above, the best results were derived for the capacitively loaded monopole of Table 5.2.

VSWR Measurement Output

The VSWR derived from the measurements of the capacitively loaded monopole, specified in Table 5.2, is displayed in the following figure.

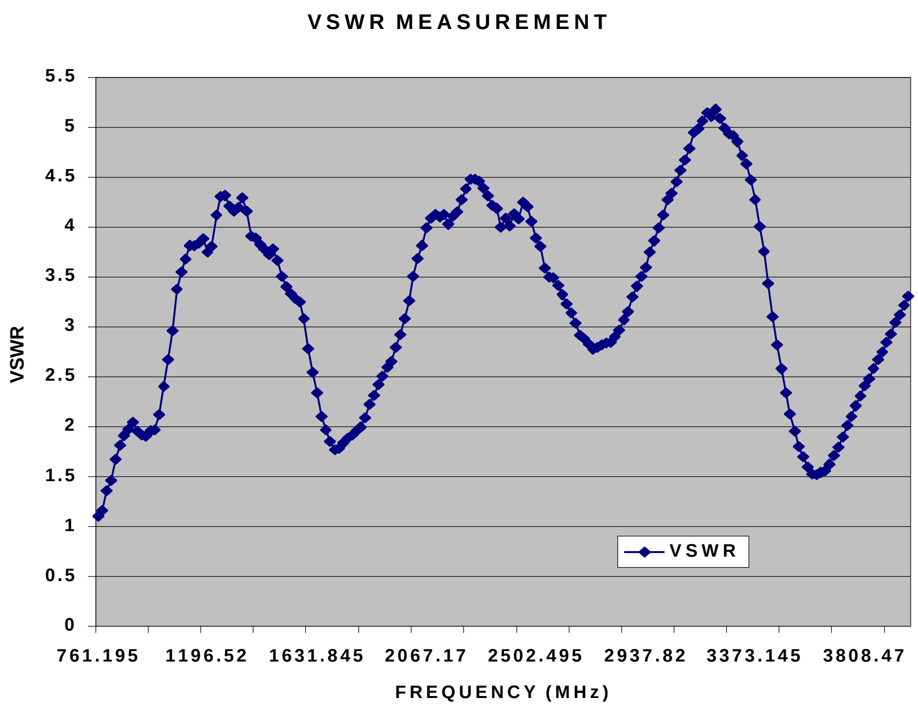


Figure 5.11 VSWR measurement of capacitively loaded antenna

Input Impedance Measurement Output

The graph of the input impedance (shown in Fig. 5.12) was derived from the antenna reflection parameter (S11) using the MATLAB program. (The program listing is given in **APPENDIX E**). The network analyser measures the antenna impedance at the end of its cable. Thus, the MATLAB program is used to calculate the impedance at the input of the monopole. MATLAB code computes the phase shift of the impedance via the transmission line that exists between the cable of network analyser and the antenna input. In order to determine the input impedance, an assumption that the transmission line is lossless, took place. Therefore, the phase shift of the impedance was computed by using the following formula:

$$f = b\, l \qquad (5.3)$$

Where is the phase shift, is the propagation constant and *l* is the length of the transmission line.

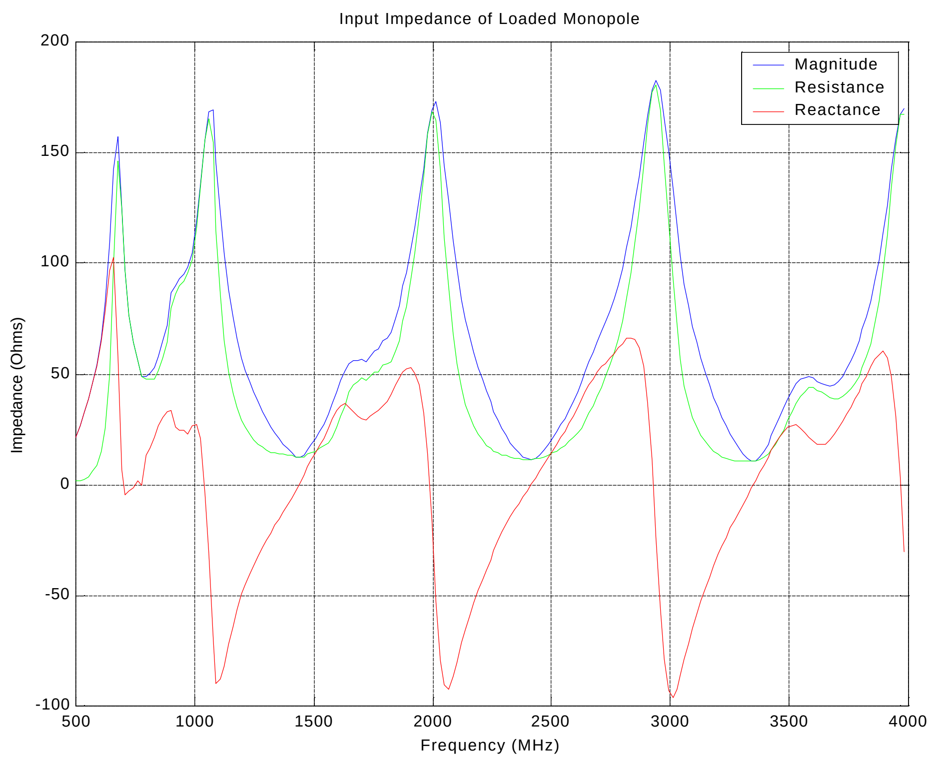


Figure 5.12 Input impedance measurement of loaded monopole

5.6 SUMMARY

According to the graphs of VSWR and input impedance it is clear that the results of the testing are not the same as those simulated. Nevertheless, it was expected that there would be a difference. This difference is a result of the finite ("imperfect") ground that was used as a base of the antenna during the testing. As was mentioned in Section 5.2, the dimensions of the ground were not satisfactory. Another measurement constraint was the laboratory area (shown in Figure 5.13) where the testing took place. The reflections of metal elements in the laboratory environment affected the antenna performance.

Figure 5.13 Laboratory environment

In addition, the rods of the antenna were not exactly in a vertical direction due to the existence of slightly bending of the nylon screws. One more constraint was the films between the two rods. These films were used to keep the distance between the two rods fixed (i.e. the capacitor plates stable). These discontinuities create "fringing" fields, which store additional energy from the signal transmission along the antenna structure. This storage is operating as an additional capacitor.

6 CONCLUSIONS

Mobile telephony is one of the major communication tools in our lives. It is increasing rapidly with mobile phones rapidly becoming important accessories and their users being around 100 millions all over the world at the end of 1999. On the other hand, new standards of wireless telecommunication transferred from the research centres in short time intervals, which make the need for broadband equipment mandatory. Thus, companies are endeavouring to develop broadband devices such as the first dual-band vehicular mobile handsets, which was presented during the international exhibition of mobile telephony, CEBIT 2000.

The major objective of this project was the construction of a broadband monopole antenna for vehicular use, which can be operated with the latest protocols of wireless communication. In particular the objective in this study was minimisation of the antenna losses, including that of a matching network if present, over the operational broad bandwidth. The bandwidth was taken to be the frequency range over which the VSWR was less than four and the antenna power gain positive.

The monopole antenna has interesting characteristics such as its omni-directional radiation pattern and its easy construction. However, at high frequencies its operational bandwidth becomes narrow and the losses affecting power gain are significant. Loading the monopole with reactive elements (such as capacitors, inductors, etc.) can reduce these disadvantages.

The last statement is verified by considering the outputs of the simulation of a loaded broadband monopole. According to the simulation presented here the broad operational bandwidth of the loaded monopole (800 to 4,000 MHz) enables it to be used with several protocols such as GSM (900MHz/1800MHz/1900MHz), DECT (1900 MHz), Bluetooth (2.45GHz), UMTS and GPS. This operational bandwidth corresponds to a ratio of 11:1 achieved using a 0.143 m capacitively-loaded monopole.

The VSWR of the capacitively loaded monopole with a conductor radius of 4 mm, over the operational bandwidth and without matching network, was close to three. This indicates that the reflected power is 25% of the total input power and so, in the absence of resistive losses on the antenna itself, it further indicates that 75% of the power is transmitted. This efficiency is much better than the efficiency of previous designs, especially without using matching network and it denotes a great achievement.

Based on the simulation outputs of the loaded monopoles, it is clear that the power losses are minimised when the input impedance of the antenna (Z_A) is close to the characteristic impedance (Z_o) of the transmission line which is connected to it. Additionally the antenna becomes self-resonant and its VSWR yields low values when the reactance (X_A) of the antenna is close to zero, and the input impedance (Z_{in}) of the antenna approximates its resistance (R_A).

Moreover, the current has a large value at the frequencies where Z_A is low, but along the antenna loads it should be close to zero in order to improve the antenna efficiency.

Resistances should be avoided in antenna design, where the major objective is the minimisation of losses, because they sacrifice antenna power gain.

According to the fabrication of the capacitively loaded monopole of 3mm conductor radius, the outcomes of testing did not agree very closely with the simulated results. However the broadband response was demonstrated. The major reason for the variation between the simulation and measured input impedance was attributed to the finite ground. The ground that was used during the measurements was much smaller than the appropriate size for approximating an infinite ground, hence a phase shift in the input impedance was generated. With a small ground plane the antenna radiation pattern has several large sidelobes. The dimensions of a square ground plane should be approximately 200 (estimation) to obtain an almost perfect monopole radiation [37]. Moreover the laboratory environment was not the best for testing an antenna because the reflections of neighbouring metal elements reduced the antenna performance.

Further reasons for this variation were the slight bending resulting from the use of nylon screws (required as they are non-conducting). The nylon screws could not keep the rods of the antenna in a precise vertical orientation.

The achievements of the project were satisfactory; all the deliverables of proposal were achieved. Extra deliverables took place and the whole project was finished according to plan.

6.1 RECOMMENDATION FOR FURTHER WORK

The following section contains a number of suggestions for further work which might be carried out in order to further elucidate what factors govern the design, performance and fabrication of the prototype loaded monopole and how these can be manipulated. The Project fulfils the design requirements and it has achieved all the objectives. However, the following suggestions would improve the functionality of the loaded antenna.

First of all a capacitively-loaded antenna with 4 mm conductor radius should be manufactured and tested in order to compare its results with those of the 3 mm wire radius. According to the simulations of these antennas the conductor of 4 mm radius provides better results and broader bandwidth that the wire of 3 mm radius.

The testing of the existing capacitively loaded monopoles should be continued over a broader bandwidth. A number of simulations over the frequency range from 800MHz to12GHz gave acceptable results but there was not enough time to test it.

A very important tool that could improve the existing designs is a Genetic Algorithm (GA). This code could achieve better values and locations for the loads of the antenna in order to improve its characteristics over broadband operation. GA could be used to obtain values for the elements of a matching network, if the latter is necessary in a broadband antenna design.

The last but not the least suggestion for the continuation of the project is the conversion of the existing prototype designs to a patch microstrip antenna design. The patch antenna is constructed on a microstrip using printed circuit fabrication techniques and the microstrip layer guides the antenna radiation. Such an antenna with the characteristics of the existing prototypes could be used in any handheld terminal or even in base stations for broadband transmission and reception.

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APPENDIX A

APPENDIX A

Simulation Code

of /4 Monopole Antenna at 900 MHz

```
CM This is an Input file of a Monopole Antenna with radius 0.001m
CM and length 0.079m(divided in 8 segments)at 900MHz and
CM excitation source 1V at base, over a perfect ground.
CM Wire (Brass) Conductivity: 14285714.3 S/m
CE
GW 1,8, 0,0,0, 0,0,0.079, 0.001
GE 1
GN 1
FR 0 55 0 0 700 50
LD 5 1 1 8 14285714.3
EX 0 1 1 00 1.0 0.0
RP 0 36 73 1000 -90 0 5 5
EN
```

APPENDIX B

APPENDIX B

Simulation Code

of a Capacitively Loaded Antenna

(with radius a = 3 mm)

```
CM This is the Input file of a Loaded Broadband Monopole Antenna
CM with radius 0.003m and length 0.143m
CM Capacitive Loaded monopole at L1=0.055m and at L2=0.105m
CM with C1=0.537pF and C2=0.245pF respectively.
CM Conductivity of Brass 14285714.3 S/m is included.
CM Excitation source 1V at base, over a perfect ground.
CE
GW 1,14, 0,0,0, 0,0,0.143, 0.003
GE 1
GN 1
FR 0 65 0 0 800 50
LD 5 1 1 14 14285714.3
LD 0 1 6 6 0 0 0.537E-12
LD 0 1 11 11 0 0 0.245E-12
EX 0 1 1 00 1.0 0.0
RP 0 72 72 1000 -90 0 5 5
EN
```

APPENDIX C

APPENDIX C

Simulation Code

of a Capacitively Loaded Antenna

(with radius a = 4 mm)

```
CM This is the Input file of a Loaded Broadband Monopole Antenna

CM with radius 0.004m and length 0.143m

CM Capacitive Loaded monopole at L1=0.055m and at L2=0.105m

CM with C1=0.537pF and C2=0.245pF respectively.

CM Conductivity of Brass 14285714.3 S/m is included.

CM Excitation source 1V at base, over a perfect ground.

CE

GW 1,14, 0,0,0, 0,0,0.143, 0.004

GE 1

GN 1

FR 0 65 0 0 800 50

LD 5 1 1 14 14285714.3

LD 0 1 6 6 0 0 0.537E-12

LD 0 1 11 11 0 0 0.245E-12

EX 0 1 1 00 1.0 0.0

RP 0 72 72 1000 -90 0 5 5

EN
```

APPENDIX D

APPENDIX D

Simulation Code

of a L-C Loaded Antenna

```
CM This is the Input file of a Loaded Broadband Monopole Antenna
CM with radius 0.001m and length 0.066m
CM Parallel L-C Loaded monopole at l1=0.012m, l2=0.014m, l3=0.016m
CM and l4=0.018m with C1=0.45pF, L1=L2=L3=L4=1.5nH C2=0.398pF,
CM C3=0.353pF
CM and C4= 0.293pF respectively. Resistance 240 Ohms at 3.3cm
CM Conductivity of Brass 14285714.3 S/m
CM Excitation source 1V at base, over a perfect ground.
CE
GW 1,66, 0,0,0, 0,0,0.066, 0.001
GE 1
GN 1
EK 0
LD 1 1 12 12 0 1.5E-9 0.45E-12
LD 1 1 14 14 0 1.5E-9 0.398E-12
LD 1 1 16 16 0 1.5E-9 0.353E-12
LD 1 1 17 17 0 1.5E-9 0.293E-12
LD 0 1 33 33 240
LD 5 1 1 66 14285714.3
FR 0 50 0 0 800 50
EX 0 1 1 00 1.0 0.0
RP 0 72 72 1000 -90 0 5 5
EN
```

APPENDIX E

APPENDIX E

MATLAB Code

for the Input Impedance Measurement

of Capacitively Loaded Antenna

(with radius a = 3 mm)

```
clear;
clc;

Zo=50;

load s11reim21.txt;      %Load file of S11 real & imaginary array
                         matrix

freq = s11reim21(:,1);  %Set the frequency range
s11re =  s11reim21(:,2);   %Set the values of S11 real parts
s11im =  s11reim21(:,3);   %Set the values of S11 imaginary parts

   lamda = 3*10^2./freq;   %Set the wavelength
   beta = 2*pi./lamda;     %Set the propagation constant

   S11 = (s11re)+j*(s11im);%Reflection Parameter S11

   l = 0.05;               %Distance between Antenna Input and
                           Network Analyser Cable
   phi = l.*beta;          %Electrical Length of this Distance

   Gamma = S11.*exp(-j*2.*phi)%Set Reflection Coefficient
   Gammag = abs(Gamma);          %Magnitude of Reflection Coeff.
   Gammarg = angle(Gamma);       %Phase of Reflection Coeff.
   theta = -2.*phi+Gammarg;

   Zin =Zo.*(1+Gamma)./(1-Gamma); %Input Impedance
   Zinmag = abs(Zin);          %Magnitude of the Input Impedance
   Zinre = real(Zin);          %Input Resistance
   Zinim = imag(Zin);          %Input Reactance

   vswr = (1+Gammag)./(1-Gammag)  %VSWR at the antenna Input

figure(1)
plot(freq,Zinmag,'b',freq,Zinre,'g',freq,Zinim,'r');
title('Input Impedance of Loaded Monopole');
xlabel('Frequency (MHz)');
ylabel('Impedance (Ohms)');
grid;

figure(2)
plot(freq,vswr);
title('SWR of Loaded Monopole');
xlabel('Frequency (MHz)');
ylabel('VSWR');
grid;

figure(3)
polar(phi,Gammag);
title('Reflection Coeff. of Loaded Monopole');

figure(4)
polar(theta,Gammag);
title('Reflection Coeff. of Loaded Monopole (Input)');
```