DESIGN AND CONSTRUCTION OF A WHEELER CAP TEST SET-UP

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Abstract

In practice, the radiation efficiency of antennas is often measured by the anechoic chambers. For this method, it takes plenty time and cost. In order to bring down the measurement costs, another alternative method was proposed and published by H.A. Wheeler in 1959. The Wheeler Cap method can measure the radiation efficiency of the antenna quickly and easily during the design and development stage. It has the many benefits, such as simple construction, easy and fast to implement, lower cost and accurate enough compared to other methods. Moreover, it is a reliable and extensively used method for measuring the antenna’s radiation efficiency.

The basic concept about Wheeler’s method is to use the "radiansphere" which is the boundary between the near field and the far field of any small antenna to measure the radiation efficiency of antenna under test. The radiation efficiency is obtained by performing measurement in two steps i.e. measuring the antenna under test (AUT) without and with conducting radiation metal shield.

The main objective of this thesis work is to design and construct a Wheeler cap test set-up. This thesis is performed to study a modified Wheeler cap method which is based on constant power loss principle and according to this principle the loss resistance of AUT remains constant whether the Wheeler cap is placed or removed, it means the AUT has zero or finite radiation resistance. Thus, the radiation efficiency can be measured using the return loss magnitude with or without Wheeler cap. The equivalent RLC circuits of AUT in the free space and with a Wheeler cap have been theoretically reviewed and analyzed. At the same time, the mathematical expressions of radiation efficiency were presented in terms of return loss using equivalent RLC circuits.

In this thesis, four types of antenna have been selected to find their radiation efficiency by the Wheeler cap method using HFSS software. To compare the simulation and measurement results of radiation efficiency, lossless wire monopole antenna and lossy loop antenna are simulated, fabricated and measured. It is found that the measurement results correlates with the simulation results.

Keywords:

Wheeler Cap, Radiation Efficiency, Monopole Antenna, Loop Antenna
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Abbreviations:

HFSS – High Frequency Structure Simulator  
QoS – Quality of Service  
3G – Third Generation  
WC – the Wheeler Cap  
FS – Free Space  
RLC Circuit – Resistor, Inductor and Capacitor Circuit  
IEEE – Institution of Electrical and Electronics Engineers  
RF – Radio Frequency  
RE – Radiation Efficiency  
BW – Band Width  
FBW – Fractional Band Width  
RL – Return Loss  
dB – Decibel  
EM – Electromagnetic  
ESA – Electrically Small Antenna  
WCDMA – Wideband Code Division Multiple Access  
HSPA – High Speed Packet Access  
GSM – Global System for Mobile communications  
AUT – Antenna under Test  
MLA – Meander Line Antenna  
VNA – Vector Network Analyzer  
PNA – High Performance Network Analyzer  
ADS – Advanced Design System  
CPW – Coplanar Waveguides  
PCB – Printed Circuit Board  
S-parameters – Scattering Parameters  
IFBW – Intermediate Frequency Band Width
# Table of Contents

Abstract .................................................................................................................................................. 2  
Acknowledgements .............................................................................................................................. 3  
Abbreviations ...................................................................................................................................... 4  
Table of Contents ................................................................................................................................. 5  
List of Figures ....................................................................................................................................... 8  

Chapter 1  INTRODUCTION .................................................................................................................. 11  
1.1 Background .................................................................................................................................... 11  
1.2 Objectives ...................................................................................................................................... 12  
1.3 Organization of the Thesis ............................................................................................................. 13  

Chapter 2  ANTENNA THEORY ............................................................................................................ 14  
2.1 Antenna Definition ......................................................................................................................... 14  
2.2 Review of Fundamental Parameters and Definitions ........................................................................ 14  
2.2.1 Efficiency .................................................................................................................................... 14  
2.2.2 Return Loss ................................................................................................................................ 16  
2.2.3 Field Regions ............................................................................................................................. 16  
2.2.4 Input Impedance ....................................................................................................................... 17  
2.2.5 Bandwidth and Radiation Quality Factor .................................................................................. 18  
2.2.6 Impedance Bandwidth ............................................................................................................... 19  
2.2.7 Radiation Pattern of Gain ......................................................................................................... 19  
2.3 Electrically Small Antenna ............................................................................................................. 19  
2.3.1 Monopole Antenna .................................................................................................................... 19  
2.3.1.1 Overview of Monopole Antenna ........................................................................................ 20  
2.3.1.2 Impedance of Monopole Antenna ..................................................................................... 21  
2.3.2 Antenna’s Miniaturization Techniques ...................................................................................... 21  
2.3.2.1 Meander Line .................................................................................................................... 21  
2.3.2.2 High Dielectric Material .................................................................................................... 22  
2.3.2.3 Ground Plane ..................................................................................................................... 22  
2.3.2.4 Shorted Circuit in Planar Antenna ..................................................................................... 23
Chapter 3  WHEELER CAP METHOD ................................................................. 24
 3.1 Introduction ................................................................................................. 24
 3.2 Wheeler Cap Theory .................................................................................. 25
    3.2.1 Overview of Wheeler Cap Method ....................................................... 25
    3.2.2 The Equivalent Circuit of AUT without or with Wheeler Cap .......... 25
    3.2.2.1 AUT without Wheeler Cap (Free Space) ................................... 25
    3.2.2.2 AUT with Wheeler Cap ............................................................. 27
    3.2.3 The Calculation of Radiation Efficiency by Wheeler Cap Method .......... 32
Chapter 4  DESIGN AND SIMULATION RESULTS ........................................... 34
 4.1 Wheeler Cap Designs and Simulations ..................................................... 34
    4.1.1 Monopole Antenna ............................................................................ 34
    4.1.1.1 Design in HFSS .......................................................................... 34
    4.1.1.2 Results ....................................................................................... 35
    4.1.1.3 Radiation Efficiency Calculation and Conclusions ...................... 37
    4.1.2 Single Ground Stub Antenna .............................................................. 38
    4.1.2.1 Design in HFSS .......................................................................... 38
    4.1.2.2 Results ....................................................................................... 39
    4.1.2.3 Radiation Efficiency Calculation and Conclusions ...................... 41
    4.1.3 Loop Antenna ..................................................................................... 42
    4.1.3.1 Design in HFSS .......................................................................... 42
    4.1.3.2 Results ....................................................................................... 43
    4.1.3.3 Radiation Efficiency Calculation and Conclusions ...................... 45
    4.1.4. Meander Monopole Antenna ............................................................ 46
    4.1.4.1 Design in HFSS .......................................................................... 46
    4.1.4.2 Results ....................................................................................... 47
    4.1.4.3 Radiation Efficiency Calculation and Conclusions ...................... 51
Chapter 5  MEASUREMENTS ............................................................................. 52
 5.1 Efficiency Measurements Set-up .............................................................. 52
 5.2 Monopole Antenna .................................................................................... 53
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig.2.1</td>
<td>Antenna losses</td>
<td>14</td>
</tr>
<tr>
<td>Fig.2.2</td>
<td>Antenna’s field regions</td>
<td>16</td>
</tr>
<tr>
<td>Fig.2.3</td>
<td>Antenna’s input impedance</td>
<td>17</td>
</tr>
<tr>
<td>Fig.2.4</td>
<td>(a) A vertical monopole antenna above ground</td>
<td>20</td>
</tr>
<tr>
<td>Fig.2.4</td>
<td>(b) A corresponding center-fed dipole</td>
<td>20</td>
</tr>
<tr>
<td>Fig.2.5</td>
<td>Equivalent circuit of monopole antenna in free space</td>
<td>21</td>
</tr>
<tr>
<td>Fig.2.6</td>
<td>Typical structure of the meander line antenna</td>
<td>22</td>
</tr>
<tr>
<td>Fig.2.7</td>
<td>(a) A patch antenna without shored-circuit</td>
<td>23</td>
</tr>
<tr>
<td>Fig.2.7</td>
<td>(b) A patch antenna with shorted circuit</td>
<td>23</td>
</tr>
<tr>
<td>Fig.3.1</td>
<td>Calculation of RL of AUT without Wheeler cap</td>
<td>25</td>
</tr>
<tr>
<td>Fig.3.2</td>
<td>Calculation of RL of AUT with Wheeler cap</td>
<td>27</td>
</tr>
<tr>
<td>Fig.4.1.1.1</td>
<td>Designed monopole antenna in HFSS</td>
<td>34</td>
</tr>
<tr>
<td>Fig.4.1.1.2</td>
<td>(a) Return loss of AUT without Wheeler cap (in free space)</td>
<td>35</td>
</tr>
<tr>
<td>Fig.4.1.1.2</td>
<td>(b) Return loss of AUT with six different Wheeler caps</td>
<td>35</td>
</tr>
<tr>
<td>Fig.4.1.1.3</td>
<td>(a) Normalized impedances in free space and with different Wheeler caps</td>
<td>36</td>
</tr>
<tr>
<td>Fig.4.1.1.3</td>
<td>(b) Normalized impedances in free space and with different Wheeler caps</td>
<td>36</td>
</tr>
<tr>
<td>Fig.4.1.1.3</td>
<td>(c) Normalized impedances in free space and with different Wheeler caps</td>
<td>36</td>
</tr>
<tr>
<td>Fig.4.1.1.3</td>
<td>(d) Normalized impedances in free space and with different Wheeler caps</td>
<td>36</td>
</tr>
<tr>
<td>Fig.4.1.1.3</td>
<td>(e) Normalized impedances in free space and with different Wheeler caps</td>
<td>36</td>
</tr>
<tr>
<td>Fig.4.1.1.3</td>
<td>(f) Normalized impedances in free space and with different Wheeler caps</td>
<td>36</td>
</tr>
<tr>
<td>Fig.4.1.1.4</td>
<td>Radiated efficiency of the monopole antenna</td>
<td>37</td>
</tr>
<tr>
<td>Fig.4.1.2.1</td>
<td>Designed single ground stub antenna in HFSS</td>
<td>38</td>
</tr>
<tr>
<td>Fig.4.1.2.2</td>
<td>Return loss of AUT without Wheeler cap (in free space)</td>
<td>39</td>
</tr>
<tr>
<td>Fig.4.1.2.3</td>
<td>Return loss of AUT with six different Wheeler caps</td>
<td>39</td>
</tr>
<tr>
<td>Fig.4.1.2.4</td>
<td>(a) Normalized impedances in free space and with different Wheeler caps</td>
<td>40</td>
</tr>
<tr>
<td>Fig.4.1.2.4</td>
<td>(b) Normalized impedances in free space and with different Wheeler caps</td>
<td>40</td>
</tr>
<tr>
<td>Fig.4.1.2.4</td>
<td>(c) Normalized impedances in free space and with different Wheeler caps</td>
<td>40</td>
</tr>
</tbody>
</table>
Fig.4.1.2.4 (d) Normalized impedances in free space and with different Wheeler caps ........................................ 40
Fig.4.1.2.4 (e) Normalized impedances in free space and with different Wheeler caps ........................................ 40
Fig.4.1.2.4 (f) Normalized impedances in free space and with different Wheeler caps ........................................ 40
Fig.4.1.2.5 Radiated efficiency of the single ground stub antenna ........................................................................ 41
Fig.4.1.3.1 Designed loop antenna in HFSS ....................................................................................................... 42
Fig.4.1.3.2 (a) Return loss of AUT without Wheeler cap (in free space) .............................................................. 43
Fig.4.1.3.1 (b) Return loss of AUT with six different Wheeler caps ................................................................. 43
Fig.4.1.3.2 (a) Normalized impedances in free space and with different Wheeler caps ........................................ 44
Fig.4.1.3.2 (b) Normalized impedances in free space and with different Wheeler caps ........................................ 44
Fig.4.1.3.2 (c) Normalized impedances in free space and with different Wheeler caps ........................................ 44
Fig.4.1.3.2 (d) Normalized impedances in free space and with different Wheeler caps ........................................ 44
Fig.4.1.3.2 (e) Normalized impedances in free space and with different Wheeler caps ........................................ 44
Fig.4.1.3.2 (f) Normalized impedances in free space and with different Wheeler caps ........................................ 44
Fig.4.1.3.4 Radiated efficiency of the loop antenna ............................................................................................ 45
Fig.4.1.4.1 Designed meander monopole antenna in HFSS ................................................................................ 46
Fig.4.1.4.2 Return loss of AUT without Wheeler cap (in free space) ................................................................. 47
Fig.4.1.4.3 Return loss of AUT with six different Wheeler caps (position 1) ......................................................... 47
Fig.4.1.4.4 (a) Normalized impedances in free space and with different Wheeler caps (position 1) ................. 48
Fig.4.1.4.4 (b) Normalized impedances in free space and with different Wheeler caps (position 1) ................. 48
Fig.4.1.4.4 (c) Normalized impedances in free space and with different Wheeler caps (position 1) ................. 48
Fig.4.1.4.4 (d) Normalized impedances in free space and with different Wheeler caps (position 1) ................. 48
Fig.4.1.4.4 (e) Normalized impedances in free space and with different Wheeler caps (position 1) ................. 48
Fig.4.1.4.4 (f) Normalized impedances in free space and with different Wheeler caps (position 1) ................. 48
Fig.4.1.4.5 Return loss of AUT with six different Wheeler caps (position 2) ....................................................... 49
Fig.4.1.4.6 (a) Normalized impedances in free space and with different Wheeler caps (position 2) ................. 50
Fig.4.1.4.6 (b) Normalized impedances in free space and with different Wheeler caps (position 2) ................. 50
Fig.4.1.4.6 (c) Normalized impedances in free space and with different Wheeler caps (position 2) ................. 50
Fig.4.1.4.6 (d) Normalized impedances in free space and with different Wheeler caps (position 2) ................. 50
Fig.4.1.4.6 (e) Normalized impedances in free space and with different Wheeler caps (position 2) ................. 50
Fig.4.1.4.6 (f) Normalized impedances in free space and with different Wheeler caps (position 2) ........................................... 50
Fig.4.1.4.7 Radiated efficiency of the MLMA placed on position 1 .................................................................................................. 51
Fig.4.1.4.8 Radiated efficiency of the MLMA placed on position 2 ............................................................................................ 51
Fig.5.1.1 (a) Measurement set-up without Wheeler cap (free space) ............................................................................................... 52
Fig.5.1.1 (b) Measurement set-up with Wheeler cap ........................................................................................................................ 52
Fig.5.2.1 Fabricated lossless monopole antenna ............................................................................................................................ 53
Fig.5.2.2 Fabricated Wheeler cap ......................................................................................................................................................... 53
Fig.5.2.3 Monopole AUT measurement without Wheeler cap (in free space) ................................................................................ 54
Fig.5.2.4 Monopole AUT measurement with Wheeler cap .................................................................................................................. 54
Fig.5.2.5 Normalized impedances in free space and with Wheeler cap ............................................................................................ 55
Fig.5.2.6 Radiation efficiency of lossless monopole antenna ............................................................................................................. 55
Fig.5.3.2 (a) Fabricated lossy loop antenna ...................................................................................................................................... 56
Fig.5.3.2 (b) Fabricated Wheeler cap ................................................................................................................................................. 56
Fig.5.3.3 (a) Loop AUT measurement without Wheeler cap (in free space) .................................................................................... 57
Fig.5.3.3 (b) Loop AUT measurement with Wheeler cap ...................................................................................................................... 57
Fig.5.3.4 Normalized impedance in free space and with Wheeler cap .............................................................................................. 58
Fig.5.3.5 Radiation efficiency of lossy loop antenna .......................................................................................................................... 58
Fig.6.1.1 Comparison about return loss of monopole antenna in free space ................................................................. 59
Fig.6.1.2 Comparison about return loss of monopole antenna with Wheeler cap .............................................................. 60
Fig.6.1.3 Radiation efficiency of lossless monopole antenna ................................................................................................. 60
Fig.6.2.1 Comparison about return loss of loop antenna in free space .............................................................. 61
Fig.6.2.2 Comparison about return loss of loop antenna with Wheeler cap ............................................................................. 61
Fig.6.2.3 Radiation efficiency of lossy loop antenna ................................................................................................................... 62
Chapter 1

INTRODUCTION

1.1 Background

Nowadays, higher speed and higher Quality of Service (QoS) is necessary for all the mobile communication systems. Antenna is one of the irreplaceable elements for an efficient performance of mobile phone. Generally, the radiation efficiency of the antenna has much impact on the QoS, or else, extends the overall performance of the mobile phone. For example, the voice and video quality, data transmission, internet access, etc mostly depend on the radiation efficiency of an antenna [1], [2]. In order to supply a stable performance of mobile phone, so that find out an efficient and simple measurement method of radiation efficiency is significant during the design and development stage of an antenna.

The most common method used to measure the radiation efficiency of an antenna is the anechoic chamber method [2], [3]. The main benefit of using chamber method is its ability to measure accurately [3], [4]. However, this method has some limitations, such as large space to install, complicate to construct and obviously expensive [3]. Moreover, this method is not an optimal solution for measuring the radiation efficiency during entire design and development stage of an antenna. In order to reduce the costs of design and development of an antenna, a simpler and easier method, such as the Wheeler Cap method, is needed [5], [6].

The Wheeler Cap method was introduced by H. A. Wheeler in the late 1950s [5]. The Wheeler Cap method is one classical and remarkable measurement method used to estimate the radiation efficiency of antenna [5], [7], [8]. Currently, the Wheeler Cap method is one of the most widely used techniques for measuring antenna radiation efficiency because of its simple construction, portability, simple to use, quick measurements and low cost [9], [10]. Furthermore, it is an accurate method to compare with the radiometric method and the directivity/gain method [11], [12]. In the original article which was organized by H. A. Wheeler, a creative issue had been presented [5]. The “Radiansphere” is the boundary between the near field and the far field of an electrically small antenna [13], [14], and the radius of the “Radiansphere” can be defined by $\lambda/2\pi$, it is called the “Radianlength” [5]. The radiation efficiency of antenna enables separate measurement of radiation resistance and loss resistance. During time of measurements, a conducting radiation metal shield has been used according to the “Radianlength”. Commonly, this metal shield is called by “Wheeler Cap” [5].

However, the Wheeler cap method has been improved and established by many antenna designers and engineers following the developing antenna techniques and modern wireless communication [15], [16], [17], [18], [19]. Since, this method was become to more valuable and standard in the antenna design and development stage. However, those modified methods are worth attention and thinking which have been represented by several engineers. Such as, W. E. McKinzie III [16], R. H. Johnston [15], [17], D. Agahi [19], W. Domino [19].
Since the 1990s, R. H. Johnston [15] and his colleagues improved and constructed a modified Wheeler Cap method which measures the implied S11 or reflection coefficient instead of the input impedance of antenna. This new efficiency measurement method for small antennas can be regarded as an extension of the Wheeler Cap method and can perform antenna losses whether they consist of a series resistor, parallel conductance or cascaded transmission line losses or other complex antenna structures [15].

In 1997, W. E. McKinzie III [16] has assumed the RLC equivalent circuit model may not be appropriate for all antennas and selected to measure reflection coefficient data so that either a series or parallel RLC approximated circuit is always effective in the neighborhood of resonance. Also, this modified Wheeler Cap technique successfully demonstrates the use of a square resonant waveguide which is excited below cutoff frequency, for use as a Wheeler Cap [16]. In the next year, 1998, R. H. Johnston and J. G. McRory was developed the efficiency measurement method base on achieved results [17]. They introduced and gave detailed results of a presented method which using the two-port’s S parameters to express the radiation efficiency and compare with other two methods. Their measurement can be divided into the transmission measurement and the reflection measurement, and the radiation efficiency can be calculated in terms of the two-port’s S parameters with an error of ±2%. Since, the Wheeler Cap method is become to more accurate and standard.

As a mature, accurate and effective measurement method, the Wheeler Cap method is normally considered and chosen in practice. During our entire research, the radiation efficiencies of four types of antenna have been accomplished by a modified Wheeler Cap measurement method which was presented by D. Agahi and W. Domino [19]. This method derived from the article [15] which was organized by R. H. Johnston, and the authors applied this method to measure the portable-handset antennas [19]. To verify this method, the monopole antenna [20], the loop antenna [21], [22], the single ground stub antenna [23] and the meander monopole planar antenna [24], [25], [26] have been used because they are typical of antennas, simple structure, easily implement and excellent performance.

1.2 Objectives

The most important objective of this thesis work is to measure the radiation efficiency of different antennas using modified Wheeler Cap method. The main task can be achieved by dividing it into the following sub tasks:
- Establish the theoretical model of Wheeler cap method and its mathematical expressions using return loss of AUT without or with Wheeler cap.
- Design the Wheeler cap and simulate the radiation efficiency of monopole antenna.
- Design the Wheeler cap and simulate the radiation efficiency of single ground stub antenna.
- Design the Wheeler cap and simulate the radiation efficiency of loop antenna.
- Design the Wheeler cap and simulate the radiation efficiency of meander monopole planar antenna.
- Manufacture a Wheeler cap and accomplish the radiation efficiency measurement of lossless monopole antenna and lossy loop antenna.
- To give the comparison between simulation and measurement results.
1.3 Organization of the Thesis

The entire thesis can be classified as follows:

Chapter 1 describes the background, the main objectives and the organization of this thesis.

Chapter 2 introduces the antenna’s definition and fundamental parameters, such as, the radiation efficiency, return loss, field regions and so on. It gives an overview about the basic antenna concepts.

Chapter 3 explains deeply the wheeler cap method, includes the definition, equivalent model and mathematical expressions of Wheeler cap method.

Chapter 4 provides the theory of the research approaches to solve the problem about simulating the radiation efficiencies of different antenna. This chapter essentially focuses on the design of various Wheeler cap for measured antenna.

Chapter 5 manufactures the Wheeler cap, the lossless monopole antenna and lossy loop antenna. It carried out the measurement results of radiation efficiencies of the two AUTs.

Chapter 6 makes the comparison between the simulation and the measurement results.

Chapter 7 lists the summary based on the results obtained during the thesis work. It concludes by highlighting the suggestions for the future work.
Chapter 2
ANTENNA THEORY

2.1 Antenna Definitions

For the antenna definition, according to the IEEE standard, it definitions of the antenna is a means of radiating or receiving radio [2].

It also can be defined as a usually metallic device for radiating or receiving radio waves [2].

As an antenna, the direction of radiated power focuses on itself structure or shape in practice. For example, a dipole antenna has the properties of Omni-directional antenna. However, a horn antenna only has a dominated directional radiated power when it is performance.

2.2 Review of Fundamental Parameters and Definitions

The antenna’s parameters describe the antenna’s performances. In order to much quickly and clearly understand the performances of the antenna, it is essential to give a simple explanation about the antenna parameters for the readers. The antenna’s parameters are represented as follows:

2.2.1 Efficiency

Two elements are considered in the antenna efficiency, which are input terminals and the structure of the antenna. The antenna efficiency which is illustrated in Fig.2.1 [2] means the total antenna efficiency.

![Fig.2.1 Antenna losses](image)

Fig.2.1 Antenna losses [2]
The antenna efficiency can be written as:

\[ e_0 = e_r e_c e_d = e_r e_c d \]  

(2.1)

where \( e_0 \) is the total efficiency;

\( e_r = (1 - |\Gamma|^2) \) is called reflection efficiency;

\( e_c \) is the conduction efficiency;

\( e_d \) is the dielectric efficiency;

\( e_cd = e_c e_d \) is the antenna radiation efficiency.

As the expression of the equation (2.1), antenna efficiency is not only the reflection efficiency derives from the input terminal, and it also includes the radiation efficiency of antenna which contains the conduction and dielectric efficiencies.

For the term of radiation efficiency also can be defined as the total radiated power of an antenna divide the total input power of the same antenna during the antenna operating. Therefore, the radiation efficiency of any antenna can be defined as:

\[ \eta = \frac{P_{\text{Rad}}}{P_{\text{In}}} \]  

(2.2)

where \( P_{\text{Rad}} \) is the total radiated power, \( P_{\text{In}} \) is the total input power. In practical, the input power might be lost in performance, such as mismatching of component, ohmic heating and so on. These unavoidable problems affect the efficiency of antenna directly. Thus the radiation efficiency could be rewritten as:

\[ \eta = \frac{P_{\text{Rad}}}{P_{\text{In}}} = \frac{P_{\text{Rad}}}{P_{\text{Rad}}+P_{\text{Loss}}} \]  

(2.3)

where \( P_{\text{Loss}} \) is the total loss power. During the improvement of antenna theory and manufacture technique, the designed antennas have been become to smaller and smaller. For a small antenna, it can be represented as a simple series or parallel RLC lumped element circuit model. Ideally, \( L \) and \( C \) in the circuit are lossless passive components that only charge and release the electric and magnetic energy without any power loss. Therefore, the radiation efficiency of antenna can also be computed by the real part of the input impedance, i.e., the antenna’s resistance. Thus the radiation efficiency could be rewritten as:

\[ \eta = \frac{P_{\text{Rad}}}{P_{\text{In}}} = \frac{R_{\text{Rad}}}{R_{\text{Rad}}+R_{\text{Loss}}} \]  

(2.4)

where \( R_{\text{Rad}} \) is the radiation resistance and \( R_{\text{Loss}} \) is the loss resistance, the quantity \((R_{\text{Rad}} + R_{\text{Loss}})\) is the real part of the antenna input impedance [2].
2.2.2 Return Loss

The term of return loss was used to express a ratio between the incident power ($P_I$) and the reflected power ($P_R$) because of a mismatch between the transmission line and the load or device. It also can be called the reflection coefficient, $\Gamma$:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$  \hspace{1cm} (2.5)

where the $Z_L$ is the impedance of the antenna, $Z_0$ is the characteristic impedance and the return loss expresses in dB [27]:

$$RL(dB) = 10 \log_{10} \frac{P_I}{P_R} = -20 \log |\Gamma|$$  \hspace{1cm} (2.6)

2.2.3 Field Regions

Normally, the space which surrounding the antenna can be divided into three regions:

(a) Reactive near-field; (b) Radiating near-field; (c) Far-field region. Three different regions can be shown in Fig.2.3 [2].

![Antenna's field regions](image)

(a) Reactive Near-field

The nearest region immediately surrounding the antenna which means the reactive near-field dominates in this region. It can be take a boundary for a distance of the radius.

$$R < 0.62\sqrt{D^3/\lambda}$$  \hspace{1cm} (2.7)

where $D$ is the largest dimension of the antenna. $\lambda$ is the wavelength.

For an electrically small antenna, the region can be defined as

$$R < \lambda/2\pi$$  \hspace{1cm} (2.8)
(b) Radiating Near-field

This is a region of the field of the antenna which is between the reactive field and far field. It can be taken a boundary for a distance of the radius.

\[ 0.62\sqrt{D^3/\lambda} \ll R < 2D^2/\lambda \]  \hspace{1cm} (2.9)

where the parameters \( D \) and \( \lambda \) same as above.

(c) Radiating Far-field

It is a region of the field of antennas which propagates the radiation power well in normally. The radius of the boundary of this region can be presented by a distance, that is

\[ 2D^2/\lambda \ll R \]  \hspace{1cm} (2.10)

where the parameter \( D \) and \( \lambda \) same as above.

2.2.4 Input Impedance

The term of the input impedance of the antenna is presented by the ratio of the voltage to current at a pair of terminals. In other words, it is the ratio of the all components at a point. The input impedance of antenna can be shown in Fig.2.3 [2].

![Fig.2.3 Antenna’s input impedance [2]](image)

\[ Z_a = R_{\text{loss}} + R_{\text{rad}} + jX_a = R_a + jX_a \]  \hspace{1cm} (2.11)

where
- \( R_{\text{loss}} \) is the loss resistance of antenna;
- \( R_{\text{rad}} \) is the radiation resistance of antenna;
- \( R_a = R_{\text{loss}} + R_{\text{rad}} \) is the total resistance of antenna;
- \( X_a \) is the reactance of antenna.
2.2.5 Bandwidth and Radiation Quality Factor

The term of quality factor $Q$ was used to discuss about the loss of a resonant circuit for antenna, which is defined as

$$Q = \omega_0 \times \frac{W_m + W_e}{P_L}$$

(2.12)

where $\omega_0$ is the resonant frequency, $W_m$ is the average stored magnetic energy, $W_e$ is the average stored electric energy, $P_L$ is the power loss in the system. When the average stored magnetic energy $W_m$ is equal to the average stored electric energy $W_e$, the circuit is resonance. Generally, the total quality factor contains quality factor $Q_r$ due to radiation loss, $Q_d$ due to dielectric loss and $Q_c$ due to conduction loss [27].

In general case, the bandwidth and the radiation quality factor ($Q_r$) of an antenna distinguish between good performance and not one.

A theoretical minimum radiation quality factor describes an ideal linearly polarized antenna setting within a conducting radiation shield which is a sphere of radius $r$. The reactive energy have not stored when antenna propagating in this region [5]. In fact, the minimum $Q_r$ for a linearly polarized antenna is mentioned when the ideal antenna excites with lowest order TE$_{10}$ or TM$_{01}$ mode [27]. The theoretical minimum $Q_r$ can be introduced as:

$$Q_r = \frac{1}{(ka)^2} + \frac{1}{(ka)}$$

(2.13)

where $k = \frac{2\pi}{\lambda}$ is the wave number, $a$ is radius of the sphere and $\lambda$ is the wavelength in free space at the operate frequency [31]

Bandwidth of antenna is proportional to the quality factor, a narrow bandwidth was derived from own high quality factor. In the antenna theory, the half-power bandwidth is defined as:

$$\text{BW}(3\text{dB}) = \frac{\Delta\omega}{\omega_0}$$

(2.14)

where $\Delta\omega$ is the angular frequency deviation from center frequency, $\omega_0$ is the resonate angular frequency [27].

The fractional bandwidth of the antenna relates with the radiation quality factor of antenna, and it is defined as:

$$\text{FBW} = \frac{\Delta\omega}{\omega_0} = \frac{1}{Q_r}$$

(2.15)

where $Q_r$ is the radiation factor of antenna.

According to equation (2.15), the fractional bandwidth of antenna is inversely proportional to $Q_r$, and it is increased by lower $Q_r$. 
2.2.6 Impedance Bandwidth

For the term of impedance bandwidth is related to the frequency span which was satisfied with some requirements of the design of antenna. As a mobile phone antenna design, the reflection coefficient ($S_{11}$) is a significant parameter to consider. During the antenna design stage, the impedance bandwidth is a frequency span range from $\omega_1$ to $\omega_2$ which has a requirement of the reflection coefficient, e.g. ($S_{11} < -5 \, dB$) [2].

2.2.7 Radiation Pattern of Gain

Radiation pattern of gain is an important parameter for the antenna’s performance, since it expressed antenna’s ability of accepting power in space [2]. The expression of gain (G):

$$G = 4\pi \times \frac{U(\theta, \phi)}{P_{in}}$$

(2.16)

where $U(\theta, \phi)$ is the radiation intensity in space coordinates, $P_{in}$ is the total accepted power for the antenna.

2.3 Electrically Small Antenna

For the definition of the Electrically Small Antennas (ESAs) [13], [14], its physical dimension related to itself wavelength at the operating frequency. The decision does not base on itself absolute size of the antenna. Due to this reason, Wheeler proposed the limitation of the electrically small antenna in 1947 [13]. It can be described as:

$$ka < 1$$

(2.17)

where $k = \frac{2\pi}{\lambda}$ is the wave number, $a$ is radius of the sphere for the largest dimension of the antenna, and $\lambda$ is the wavelength in free space at the operation frequency.

2.3.1 Monopole Antenna

For the term of antenna, it is defined as a usually metallic device for radiating or receiving radio waves [2]. There are numerous types of antenna in the practice which as the wire antenna, aperture antenna, reflector antenna etc. The simplest structure of monopole antenna can be represented by this definition which “the monopole antenna is above an infinite ground plane can be considered as one-half of a corresponding double-length center-fed linear dipole” [20]. As one perfect ground plane for the monopole antenna, it can be create an image of the monopole with identical current distribution for that missed part of corresponding dipole [20]. Assume the ground plane supports enough big, the monopole antenna has similar performance compare with the dipole antenna. During its radiating, the monopole antenna has identical energy in all azimuth directions, and its Omni-directional radiation can be represented. Otherwise, this type’s antennas have simple structure, thus it can be easily design and fabricate in practical and all their properties make it very attractive for the wireless applications.
2.3.1.1 Overview of Monopole Antenna

Generally, the regular monopole antenna put above a ground plane which has high-quality conductivity. The perfect ground plane yields one corresponding image from monopole real part, and one duplicate current distribution show in both parts. The current distribution for one normal construction of monopole antenna has the height $h$. At feed point has current $I(0)$, the standing wave will assume to following equation [20].

$$I(z') = \frac{I(0)}{\sin kh} \sin k(h - z')$$

(2.18)

where $0 < z' < h$.

According to the same current distribution on both parts, the monopole antenna can be considered by a center feed dipole antenna, and the all radiation power goes to real part of monopole antenna. That will create a power density for anyone angle $\theta$ on this part. The power is also twice higher than a dipole which radiating same quantity power. The monopole antenna has twice directivity and gain compare with corresponding dipole antenna is derived from this condition. Addition, lots of properties of a monopole antenna are based on the ground plane and also related to itself corresponding dipole antenna.

Fig. 2.4 A vertical monopole antenna above ground (a) and the corresponding center-fed dipole (b) [20].
2.3.1.2 Impedance of Monopole Antenna

For input impedance of anyone antenna will represent one equivalent RLC resonant circuit as show Fig. 2.5. Normally, it can write as \( Z_{in} = R_A + jX_A \) [2]. Consider about typical wire and strip dipole antenna, its input impedance can be approximated with following equation (2.19) [29].

\[
Z_{in} = Z_A = R(z) - j \left[ 120 \left( \ln \frac{l_A}{2a} - 1 \right) \cot z - X(z) \right] \quad (2.19)
\]

where \( l_A \) is the dipole length, \( a \) is the dipole radius, \( z = \frac{k l_A}{\lambda} \), and \( k = \frac{2\pi}{\lambda} \) is the wave number.

In practical, the impedance of half wavelength dipoles have the typically approximated value that is 73 + j43 ohms. The ordinary dimension of monopole is represented by quarter wavelength. The impedance is 36 + j21 ohms.

2.3.2 Antenna’s Miniaturization Techniques

Generally, the monopole antenna has been widely used in many applications, and its physically theoretical size is more than 0.15\( \lambda_0 \), here \( \lambda_0 \) is the operating wavelength in the free space [30]. However, the typically size of monopole antenna is 0.25\( \lambda_0 \) in practice. [31].

Nowadays, the designers have to find out one way which reduces the size of antennas, according to the developed trend of the miniaturization of mobile phone. Frequently, there are lots of available methods to reduce the size of antenna. For instance, the antenna uses meandered conductor structure, high-dielectric materials, ground planes, shorted circuit and so on [32]. Actually, in order to get a high-quality antenna, the designer combines several methods to same design.

2.3.2.1 Meander Line

For the meander line antenna, usually, it was designed by the ground plane and the meander structure conductor line. As the main concept of the meander line antenna that reduces its physical dimensions with increasing the electrical length base on the paths of the current in the conductor meander lines. This method can be considered as continued folded conductor line. The meander line might be
established by various structures and shapes [24].

Fig. 2.6 Typical structure of the meander line antenna [26]

2.3.2.2 High Dielectric Material

Antenna miniaturization also can be done by loading high dielectric material surrounding it. The dimension of antenna can be reduced by high permittivity material. Commonly, the permittivity and the shape of the dielectric will affect the size reduction. Furthermore, enhanced Q value is got by reducing bandwidth of the antenna when assumes without dielectric losses of material. However, the disadvantage of high permittivity dielectric is frequently equivalent to higher dielectric losses in practice, and it usually considers in the antenna construction [32].

\[
Q_t = \frac{f_0}{\Delta f}
\]

(2.20)

where \( Q_t \) is total quality factor of the antenna, \( f_0 \) is the operational frequency and \( \Delta f \) is the fractional bandwidth of the antenna [2].

2.3.2.3 Ground Plane

Another popular approach for reducing antennas size that is to use such ground planes. In section 2.3.1.1, a construction of the monopole antenna has been introduced, and it has clearly explained the structures transformation between dipole and monopole antennas. In simply way, the quarter wavelength monopole antenna is modified by a relative dipole which must has a length of half wavelength, and the monopole antenna has been added a surrounding ground plane. In fact, the monopole has one virtually opposite arm by the ground plane, and it can be performed as the typical half wavelength dipole. The dimension of antenna has reduced by this ground plane [32].
2.3.2.4 Shorted Circuit in Planar Antenna

Shorted circuit normally uses to decrease the size of the planar antenna. As the example, Fig.2.7 illustrates a shorted circuit strip which placed at half of original micro-strip patch to reduce the patch size.

In Fig. 2.7 (a), \( a \approx \frac{\lambda_0}{2} = \frac{\lambda_0}{2\sqrt{\varepsilon_e}} \) but the modified length \( a' \approx \frac{\lambda_0}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon_e}} \) shows in Fig. 2.7 (b), where \( \lambda_0 \) is the wavelength of operating frequency, \( \varepsilon_e \) is the permittivity of the dielectric material [32].
Chapter 3

WHEELER CAP METHOD

3.1 Introduction

Nowadays, the designs for small size mobile phone antenna are become to harder and harder associate with the fast development of 3G wireless communication system in the world. As of early April 2010, the global total of WCDMA/HSPA commercial network is 341 and they were distributed in 144 countries and regions, the global GSM and WCDMA/HSPA subscribers have been already over 4 billion [28]. As the demand for smaller and lighter mobile phone is growing, the size of antennas has to be as small as possible. Due to small size of the antenna, the efficiency is lowered. But the radiation efficiency of antenna is one of the most important parameters, it directly affect into the performance of modern mobile phone.

The one of the simplest, most cost and efficient methods to determine the antenna radiation efficiency is the Wheeler Cap method which is presented by H. A. Wheeler in 1959 [5]. In this article [5], Wheeler was presented one method for measuring the efficiency of electrically small antennas (ESAs) [13], [14] and it is more accurate compare with other methods, such as, gain comparison, radiometric and pattern integration [11], [12].

The basic concept about Wheeler's method is to use the "radiansphere"[5] which is the boundary between the near field and the far field of any small antenna [5] to reject the radiation of antenna under test. The distance between AUT and the walls of wheeler cap is called "radianlength" and it is represented by \( \frac{\lambda}{2\pi} \) [5]. The “radiansphere” can be made of this distance which use as the radius. The measurement separate into two parts which are without cap (measures in free space) and with cap, and they will respectively get the radiation resistance and loss resistance. The cap is one conducting radiation metal shield and its limitation of dimension should to absolute focus on itself “radiansphere”.

However, this method has already extended and modified by different people for using practical cases. The efficiency measurement set-up of different antenna also could be based on this method to accomplish.
3.2 Wheeler Cap Theory

3.2.1 Overview of Wheeler Cap Method

In 1959, H.A. Wheeler has presented one effective, simple and accurate method for measuring efficiency of the electrically small antennas (ESAs) in his article [5]. The basic concept for which uses the theory of antenna propagation to operate antenna under test or reject it. The measurement separates into two steps that are without conducting radiation metal shield (measures in free space) and with it. Usually, this conducting radiation metal shield is called by Wheeler Cap.

In article [5], author has mentioned the word that is the “radiansphere” once. And the “radiansphere” is introduced by one distance which calls “radianlength”. As practical view, antenna only can radiate in far field region well. Hence, this distance of “radianlength” defines same as the distance from antenna to the boundary which is between the near field and the far field.

The “radianlength” equals to \( \frac{1}{2\pi} \) of one wavelength, i.e. \( \frac{\lambda}{2\pi} \). And it also defines to the radius of the conducting radiation metal shield. The circle about this radius is called by the “radiancircle”. Base on the radius, the theoretical wheeler cap can be designed.

In the practical, there have many factors will influence the accurate measurement, such as the degree of closed Wheeler cap and the reflections by walls, floors and roof of the room if it is indoor radiation resistance measurements. Otherwise, the different material of caps and variable shape of caps will get inconsistent results during measurement.

3.2.2 The Equivalent Circuit of AUT without or with Wheeler Cap

3.2.2.1 AUT without Wheeler Cap (Free Space)

![Fig. 3.1 Calculation of RL of AUT without Wheeler Cap](image)

where

- \( Z_A \) is the impedance of antenna
- \( R_1 \) is the resistance of antenna
- \( L_1 \) and \( C_1 \) are the inductance and capacitance of antenna.
\[ Z_A = R_A + jX_A = \left( \frac{1}{R_1} + \frac{1}{j\omega_1 L_1} + j\omega_1 C_1 \right)^{-1} \quad (3.1) \]

where

\[ \omega_1 \] is the resonant frequency of antenna.

\[
\begin{align*}
Z_A &= \frac{j\omega_1 L_1}{1 - \omega_1^2 L_1 C_1} \cdot R_1 \quad = \quad \frac{j\omega_1 L_1 R_1}{j\omega_1 L_1 + R_1 (1 - \omega_1^2 L_1 C_1)} \cdot \frac{1}{j\omega_1 L_1} \\
&= \frac{R_1}{\frac{j\omega_1 L_1}{1 + j\omega_1 R_1 C_1}} \quad = \quad \frac{R_1}{-j\omega_1 L_1 + 1 + j\omega_1 R_1 C_1} \quad = \quad \frac{R_1}{1 + jR_1 \left( \omega_1 C_1 - \frac{1}{\omega_1 L_1} \right)}
\end{align*}
\]

\( Z_A \) can be transformed into Eq. (3.2)

\[
Z_A = \frac{R_1}{1 + jR_1 \left( \omega_1 C_1 - \frac{1}{\omega_1 L_1} \right)} \quad (3.2)
\]

At the resonate frequency, \( \omega_0 = \frac{1}{\omega_1 L_1} \), i.e., \( C_1 = \frac{1}{\omega_0^2 L_1} \), thus Eq. (3.2) yields to

\[
Z_A = \frac{R_1}{1 + jR_1 \left( \omega_1 - \frac{1}{\omega_0 L_1} \right)} \quad (3.3)
\]

Now, \( \frac{(\omega_1^2 - \frac{1}{\omega_0})}{\omega_0} \) was considered in order to normalize equation (3.3)

\[
\left( \frac{\omega_1}{\omega_0^2} - \frac{1}{\omega_0} \right) = \frac{\omega_1^2 - \omega_0^2}{\omega_0^2 \cdot \omega_1} = \frac{1}{\omega_1} \cdot \frac{(\omega_1 + \omega_0)(\omega_1 - \omega_0)}{\omega_0^2}
\approx \frac{1}{\omega_0} \cdot \frac{2\omega_0 (\omega_1 - \omega_0)}{\omega_0} = \frac{\omega_1 - \omega_0}{\omega_0} \cdot \frac{2}{\omega_0} = \delta_1 \cdot \frac{2}{\omega_0} \quad (3.4)
\]

where \( \delta_1 = \frac{\omega_1 - \omega_0}{\omega_0} \). So equation (3.3) will be normalizing to equation (3.5).

\[
\begin{align*}
Z_A &= \frac{R_1}{1 + jR_1 \left( \omega_1 - \frac{1}{\omega_0 L_1} \right)} = \frac{R_1}{1 + R_1 \left( \frac{2\delta_1}{\omega_0 L_1} \right)} - j \cdot \frac{1}{\left( \frac{2\delta_1}{\omega_0 L_1} \right)^2 + \left( \frac{1}{\omega_0 L_1} \right)^2} \quad (3.5)
\end{align*}
\]

Assume the input impedance \( Z_{in} = Z_A \).

And the reflection function is \( \Gamma = \frac{Z_A - Z_0}{Z_A + Z_0} \). The reflection coefficient can be calculated according to Eq. (3.5).
\[
\Gamma = \frac{Z_A - Z_0}{Z_A + Z_0}
\]
\[
= \frac{\frac{1}{R_1} - j \cdot \frac{2\delta_1}{\omega_0 L_1}}{\left(\frac{1}{R_1}\right)^2 + \left(\frac{2\delta_1}{\omega_0 L_1}\right)^2} - R_0
\]
\[
= \frac{\frac{1}{R_1} - j \cdot \frac{2\delta_1}{\omega_0 L_1}}{\left(\frac{1}{R_1}\right)^2 + \left(\frac{2\delta_1}{\omega_0 L_1}\right)^2} + R_0
\]

\[
\left[\left(\frac{1}{R_1}\right)^2 + \left(\frac{2\delta_1}{\omega_0 L_1}\right)^2 - R_0\right] - j \cdot \frac{2\delta_1}{\omega_0 L_1}
\]

\[
\left[\left(\frac{1}{R_1}\right)^2 + \left(\frac{2\delta_1}{\omega_0 L_1}\right)^2 + R_0\right] - j \cdot \frac{2\delta_1}{\omega_0 L_1}
\]

\[
(3.6)
\]

When \( \omega_0 \approx \omega_1, \delta_1 = 0. \)

\[
\lim_{\delta \to 0} \Gamma_1 = \lim_{\delta \to 0} \frac{R_1 - R_0}{R_1 + R_0} \quad (3.7)
\]

Assume operational antenna was matched by 50 ohms system, that means \( R_1 \approx R_0, \lim_{\delta \to 0} \Gamma_1 = 0, \)
i.e., return loss equals to

\[
\text{RL} = -20 \log |\Gamma_1| = \infty \quad (3.8)
\]

### 3.2.2.2 AUT with Wheeler Cap

![Fig. 3.2 Calculation of RL of AUT with Wheeler Cap](image)

where
- \( Z_A \) is the impedance of antenna
- \( R_1 \) is the resistance of antenna
- \( L_1 \) and \( C_1 \) are the inductance and capacitance of antenna
- \( Z_C \) is the impedance of Wheeler cap
R_2 \text{ is the resistance of antenna.}
L_2 \text{ and } C_2 \text{ are the inductance and capacitance of antenna.}

\[ Z_C = R_C + jX_C = \left( \frac{1}{R_2} + \frac{1}{j\omega_2 L_2} \right)^{-1} \tag{3.9} \]

According to equation (3.1), \( Z_A \) is

\[ Z_A = R_A + jX_A = \left( \frac{1}{R_1} + \frac{1}{j\omega_1 L_1} \right)^{-1} \]

The equivalent input impedance of this circuit is denoted by \( Z_{eq} \), and

\[ Z_{eq} = \frac{Z_A \cdot Z_C}{Z_A + Z_C} = R_{eq} + jX_{eq} \tag{3.10} \]

where \( R_{eq} \) and \( X_{eq} \) are resistance and reactance of \( Z_{eq} \).

\[ Z_{eq} = \frac{(R_A + jX_A) \cdot (R_C + jX_C)}{(R_A + jX_A) + (R_C + jX_C)} \]

\[ Z_{eq} = \frac{(R_A R_C - X_A X_C)(R_A + R_C) + (X_A R_C + X_C R_A)(X_A + X_C)}{(R_A + R_C)^2 + (X_A + X_C)^2} \]

\[ + j \cdot \frac{(X_A R_C + X_C R_A)(R_A + R_C) + (R_A R_C - X_A X_C)(X_A + X_C)}{(R_A + R_C)^2 + (X_A + X_C)^2} \tag{3.11} \]

\[ R_{eq} = \frac{(R_A R_C - X_A X_C)(R_A + R_C) + (X_A R_C + X_C R_A)(X_A + X_C)}{(R_A + R_C)^2 + (X_A + X_C)^2}; \tag{3.12a} \]
\[ X_{eq} = \frac{(R_A R_C + X_C R_A)(R_A + R_C) + (R_A R_C - X_A X_C)(X_A + X_C)}{(R_A + R_C)^2 + (X_A + X_C)^2}. \tag{3.12b} \]

For parallel RLC circuits, the normalize equations derived from general forms. Those can shows following equations.

\[ Z = \left( \frac{1}{R} + \frac{1}{j\omega L} + j\omega C \right)^{-1} = \frac{1}{\left( \frac{1}{R} + \frac{1}{j\omega L} + j\omega C \right)} \]

\[ = \frac{1}{\left( \frac{1}{R} - \frac{1}{j\omega L} \right) + j\omega C} \]

\[ = \frac{1}{R + j\left( \omega C - \frac{1}{\omega L} \right)} \]

\[ = \frac{1}{R - j(\omega C - \frac{1}{\omega L})} \]

\[ \left( \frac{1}{R} \right)^2 + (\omega C - \frac{1}{\omega L})^2 \tag{3.13} \]

Equation (3.13) can be wrote normalized form that is following.
\[ Z = R + jX = \frac{1}{R} \left( \frac{1}{R} \right)^2 + (\omega C - \frac{1}{\omega L})^2 - j \cdot \frac{1}{R} \left( \frac{1}{R} \right)^2 + (\omega C - \frac{1}{\omega L})^2 \]  

(3.14)

At the resonant frequency, \( \omega_0^2 = \frac{1}{LC} \), i.e., \( C = \frac{1}{\omega_0^2 L} \). Equation (3.14) was considered by two parts which are real and imaginary parts.

\[ R = \frac{1}{\left( \frac{1}{R} \right)^2 + (\omega C - \frac{1}{\omega L})^2} \]  

(3.15a)

\[ X = -\frac{\left( \omega C - \frac{1}{\omega L} \right)}{\left( \frac{1}{R} \right)^2 + (\omega C - \frac{1}{\omega L})^2} \]  

(3.15b)

According to the relationship between angular frequency and correlative inductance and capacitance, equation (3.15) become to

\[ R = \frac{1}{\left( \frac{1}{R} \right)^2 + \left( \frac{\omega}{\omega_0^2 L} - \frac{1}{\omega L} \right)^2} = \frac{1}{\left( \frac{1}{R} \right)^2 + \left[ \frac{1}{L} \left( \frac{\omega}{\omega_0^2} - \frac{1}{\omega} \right) \right]^2} \]  

(3.16a)

\[ X = -\frac{\left( \omega C - \frac{1}{\omega L} \right)}{\left( \frac{1}{R} \right)^2 + (\omega C - \frac{1}{\omega L})^2} = -\frac{1}{\left( \frac{1}{R} \right)^2 + \left[ \frac{1}{L} \left( \frac{\omega}{\omega_0^2} - \frac{1}{\omega} \right) \right]^2} \]  

(3.16b)

In practical, the \( Z_A \) and \( Z_C \) have the same form of equivalent circuit that is a parallel RLC circuit, so that the antenna impedance, \( Z_A \), and the Wheeler cap impedance, \( Z_C \), are

\[ Z_A = \frac{1}{R_1} + \frac{1}{\left( \frac{1}{R_1} \right)^2 + \left( \frac{\omega_1}{\omega_0^2} - \frac{1}{\omega_1} \right)^2} - j \cdot \frac{1}{\left( \frac{1}{R_1} \right)^2 + \left[ \frac{1}{L_1} \left( \frac{\omega_1}{\omega_0^2} - \frac{1}{\omega_1} \right) \right]^2} \]  

(3.17)

\[ Z_C = \frac{1}{R_2} + \frac{1}{\left( \frac{1}{R_2} \right)^2 + \left( \frac{\omega_2}{\omega_0^2} - \frac{1}{\omega_2} \right)^2} - j \cdot \frac{1}{\left( \frac{1}{R_2} \right)^2 + \left[ \frac{1}{L_2} \left( \frac{\omega_2}{\omega_0^2} - \frac{1}{\omega_2} \right) \right]^2} \]  

(3.18)

The authors have discussed this part which includes angular frequency before, i.e., \( \frac{\omega}{\omega_0^2} = \frac{1}{\omega} \). The result can be substituted directly in equation (3.17) and (3.18) for rewriting \( Z_A \) and \( Z_C \).
\[ Z_A = \left( \frac{1}{R_1} \right)^2 + \left( \frac{1}{L_1} \right)^2 - j \left( \frac{1}{\omega_0 L_1} \right) \frac{2}{\delta_1} \left( \frac{1}{\omega_0 R_1} \right) \frac{1}{\delta_1} \frac{1}{\delta_1} \] 

\[ Z_C = \left( \frac{1}{R_2} \right)^2 + \left( \frac{1}{L_2} \right)^2 - j \left( \frac{1}{\omega_0 L_2} \right) \frac{2}{\delta_2} \left( \frac{1}{\omega_0 R_2} \right) \frac{1}{\delta_2} \frac{1}{\delta_2} \] 

As the authors showed above equation (3.11), it includes few complex parts, such as, \( X_A X_C \), \( X_A^2 R_C \), \( X_C^2 R_A \), \( X_A X_C R_C \) and \( X_A X_C R_A \).

\[ X_A X_C = - \frac{\delta_1 \delta_2 \left( \frac{2}{\omega_0} \right)^2 \frac{1}{L_1 L_2}}{\left( \frac{1}{R_1} \right)^2 + \left( \frac{2\delta_1}{\omega_0 L_1} \right)^2} \cdot \left( \frac{1}{R_2} \right)^2 + \left( \frac{2\delta_2}{\omega_0 L_2} \right)^2 \] 

\[ X_A^2 R_C = - \left[ \frac{1}{(R_1)^2 + \left( \frac{2\delta_1}{\omega_0 L_1} \right)^2} \right]^2 \cdot R_2 \] 

\[ X_C^2 R_A = - \left[ \frac{1}{(R_2)^2 + \left( \frac{2\delta_2}{\omega_0 L_2} \right)^2} \right]^2 \cdot R_1 \] 

\[ X_A X_C R_C = - \frac{\delta_1 \delta_2 \left( \frac{2}{\omega_0} \right)^2 \frac{1}{L_1 L_2} \frac{1}{R_2}}{\left( \frac{1}{R_1} \right)^2 + \left( \frac{2\delta_1}{\omega_0 L_1} \right)^2} \cdot \left( \frac{1}{R_2} \right)^2 + \left( \frac{2\delta_2}{\omega_0 L_2} \right)^2 \] 

\[ X_A X_C R_A = - \frac{\delta_1 \delta_2 \left( \frac{2}{\omega_0} \right)^2 \frac{1}{L_1 L_2} \frac{1}{R_1}}{\left( \frac{1}{R_1} \right)^2 + \left( \frac{2\delta_1}{\omega_0 L_1} \right)^2} \cdot \left( \frac{1}{R_2} \right)^2 + \left( \frac{2\delta_2}{\omega_0 L_2} \right)^2 \] 

Take equations (3.21) into (3.11), it will easily to get final \( Z_{eq} \) and analyze the reflection coefficient or return loss. For the reflection coefficient of this equivalent circuit, some assumptions have to consider at first.

Obviously, the Wheeler cap’s resistance is much less compare with the radiation resistance of antenna, and the quantity of Wheeler cap’s resistance almost equals zero Ω. Secondly, the cap can be represented by one resonant cavity, which means one equivalent RLC circuit supporting. According to the condition of both resistances which are cap and antenna resistances, the antenna under test was rejected by a Wheeler cap, and it means the AUT was not operating during the second step of Wheeler.
cap method. Hence the resonant frequency of circuit can be considered to similarly equal the lowest resonant frequency of cavity. As the above assumptions, these conditions will support to analyze the reflection coefficient or return loss of equivalent antenna circuit when AUT with a Wheeler cap.

(a) $R_C \ll R_A$, $R_C \approx 0 \, \Omega$;
(b) $\omega_{2\text{Lowest}} > \omega_1, \omega_{2\text{Lowest}} = \omega_0$.

Assume AUT operates on 50 Ω system, and antenna has excellent matching with transmission line. Equation (3.11) can rewrite base on the above conditions and the reflection coefficient $\Gamma_2$ can get this limitation.

$$Z_{eq} = \frac{R_A R_C (R_A + R_C) + X_A^2 R_C}{(R_A + R_C)^2 + X_A^2} + j \frac{X_A R_C (R_A + R_C) - R_A R_C X_A}{(R_A + R_C)^2 + X_A^2}$$

(3.22)

$$Z_{eq} = \frac{R_A R_C (R_A + R_C) + X_A^2 R_C}{(R_A + R_C)^2 + X_A^2} + j \frac{R_C^2 X_A}{(R_A + R_C)^2 + X_A^2}$$

(3.23)

The reflection coefficient of equivalent circuit is

$$\Gamma_2 = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \frac{Z_{eq} - Z_0}{Z_{eq} + Z_0}$$

(3.24)

where $Z_{in} = Z_{eq}, Z_0 = R_0$.

$$\Gamma_2 = \frac{\left[ R_A R_C (R_A + R_C) + X_A^2 R_C - R_0 \right] + jR_C^2 X_A}{\left[ R_A R_C (R_A + R_C) + X_A^2 R_C + R_0 \right] + jR_C^2 X_A}$$

(3.25)

$$\lim_{\delta \to 0} \Gamma_2 = -1$$

(3.26a)

$$\text{RL} = -20 \log|\Gamma_2| = 0$$

(3.26b)

For multi-band antenna, its impedance can be introduced by one complex impedances derived from several serial or parallel RLC resonant circuits. The equivalent impedance will take into the equation (3.11) and re-compute the new reflection coefficient. However, the results will take into the equation for calculating the radiation efficiency of antenna under test.
3.2.3 The Calculation of Radiation Efficiency by Wheeler Cap Method

The radiation efficiency can be introduced by radiation power directly proportional to input power, where input power is the combination parameter about radiation power and loss power, i.e., reflection power. Thus the radiation efficiency, \( \eta \), is given by

\[
\eta = \frac{P_{\text{Rad}}}{P_{\text{In}}} = \frac{P_{\text{Rad}}}{P_{\text{Rad}} + P_{\text{Loss}}} \tag{3.27}
\]

where
- \( P_{\text{Rad}} \) is radiation power of antenna
- \( P_{\text{In}} \) is input power
- \( P_{\text{Loss}} \) is loss power (reflection power).

Assume antenna has identical current distribution, the equation (3.27) will re-write to following equation.

\[
\eta = \frac{P_{\text{Rad}}}{I^2 R_{\text{Rad}} + I^2 R_{\text{Loss}}} = \frac{R_{\text{Rad}}}{R_{\text{Rad}} + R_{\text{Loss}}} \tag{3.28}
\]

where
- \( I \) is the input current
- \( R_{\text{Rad}} \) is radiation resistance of antenna
- \( R_{\text{Loss}} \) is loss resistance.

This concept has introduced in article [5], [15], [19]. Practically, the resistance of antenna does not easily find out directly by several measurement equipments. This will require another simple and general parameter to solve the radiation efficiency during the measurement.

Reflection coefficient is one of most important parameter during antenna measurement. And it shows on the VNA with another corresponding parameter which called return loss (S11). As we know, the reflection coefficient can also represent by the real part of impedance. So the relationship between resistance and reflection coefficient will be built.

\[
\Gamma_1 = \text{Re} \left[ \frac{(R_{\text{Rad}} + R_{\text{Loss}}) - R_0}{(R_{\text{Rad}} + R_{\text{Loss}}) + R_0} \right] \tag{3.29}
\]

\[
\Gamma_2 = \text{Re} \left[ \frac{R_{\text{Loss}} - R_0}{R_{\text{Loss}} + R_0} \right] \tag{3.30}
\]

where
- \( \Gamma_1 \) is the reflection coefficient measurement without Wheeler cap (measure in free space)
- \( \Gamma_2 \) is the reflection coefficient measurement with Wheeler cap
- \( R_{\text{Rad}} \) is radiation resistance of antenna
- \( R_{\text{Loss}} \) is loss resistance
- \( R_0 \) is the characteristic resistance.

Equation (3.30) will transform into
Get equation (3.31) back into equation (3.29).

\[
R_{\text{Loss}} = \frac{(1 + \Gamma_2)}{(1 - \Gamma_2)} \cdot R_0
\]  

(3.31)

The radiation efficiency can represent by (3.31) and (3.32), so the radiation efficiency, \( \eta \), is

\[
\eta = \frac{R_{\text{Rad}}}{R_{\text{Rad}} + R_{\text{Loss}}} = 1 - \frac{(1 - \Gamma_1)(1 + \Gamma_2)}{(1 + \Gamma_1)(1 - \Gamma_2)}
\]  

(3.33)

According to equation (3.27), and assume the power of loss resistance is a constant. The loss power and input power are given by

\[
P_{\text{Loss}} = (1 - \Gamma_2^2) \cdot P_0
\]  

(3.34)

\[
P_{\text{In}} = P_{\text{Rad}} + P_{\text{Loss}} = (1 - \Gamma_1^2) \cdot P_0
\]  

(3.35)

The equation (3.28) about radiation efficiency becomes to (3.36) [15], [19].

\[
\eta = \frac{P_{\text{Rad}}}{P_{\text{Rad}} + P_{\text{Loss}}} = \frac{(1 - \Gamma_1^2) - (1 - \Gamma_2^2)}{(1 - \Gamma_1^2)} = \frac{\Gamma_2^2 - \Gamma_1^2}{1 - \Gamma_1^2}
\]  

(3.36)

where
- \( \Gamma_1 \) is the reflection coefficient measurement without Wheeler cap (measure in free space)
- \( \Gamma_2 \) is the reflection coefficient measurement with Wheeler cap
- \( P_{\text{Rad}} \) is radiation power of antenna
- \( P_{\text{Loss}} \) is loss power
- \( P_0 \) is the available power.
Chapter 4

DESIGN AND SIMULATION RESULTS

4.1 Wheeler Cap Designs and Simulations

4.1.1 Monopole Antenna

4.1.1.1 Design in HFSS

This designed monopole antenna has a normal structure, which a dominant radiated wire (quarter wavelength as the dimension) above a ground plane. The monopole antenna has same properties of center fed linear dipole. This antenna is operating around 2.1 GHz, radiated wire length is 35.7 mm (λ/4) with corresponding ground plane that is a 100mm *100 mm square with 2mm thickness copper.

To verify the proposed method, this monopole antenna was simulated in HFSS, and calculated its radiation efficiency using the proposed method. According to the concept of wheeler cap, six caps have been designed, 2 mm thickness copper as the material of all caps. The designed monopole antenna model in HFSS shows in Fig. 4.1.1.1.

![Fig. 4.1.1.1 Designed monopole antenna in HFSS](image)

Simulation will divide into two steps that were introduced by free space simulation and with Wheeler cap. Both simulations have been performed with same frequency setup, sweep type, solution frequency and so on.
4.1.1.2 Results

The simulation results majorly focus on return loss (S11), because of return loss will be the basis to calculate the radiation efficiency of antenna and it is considered by practical measurement as the remarkable characteristics. The simulated return loss in free space and with cap of testing monopole antenna is shown in Fig. 4.1.1.2 (a) and (b). The parenthetical values are return loss at resonant frequency. Fig. 4.1.1.3 (a) to (f) show the comparison of normalized impedances in both situations that means between free space and different caps on the smith chart. The red line performs the antenna in free space and the blue line is antenna with cap. The radiated efficiency of monopole antenna under test has been shown in Fig. 4.1.1.4.

Fig. 4.1.1.2 (a) Return loss of AUT without Wheeler cap (in free space)

Fig. 4.1.1.2 (b) Return loss of AUT with six different Wheeler caps
Six different Wheeler caps have been designed in HFSS to modify the “radianlength” of AUT. The dimension of six Wheeler caps is following as Tab. 4.1.

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<tr>
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</tr>
<tr>
<td>Cap 6</td>
<td>75</td>
<td>75</td>
<td>140</td>
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</tbody>
</table>

Tab. 4.1 Dimension of designed Wheeler caps

![Normalized impedances in free space and with different Wheeler caps](image-url)

Fig. 4.1.1.3 (a-f) Normalized impedances in free space and with different Wheeler caps
4.1.1.3 Radiation Efficiency Calculation and Conclusions

The radiation efficiency of the monopole antenna under test can be calculated by the equation (3.36). The simulated frequency span starts at 1 GHz and stops at 3 GHz. The Fig. 4.1.1.4 shows the radiation efficiency proportional to operating frequencies. The monopole antenna under test has high efficiency which achieves 99%. An extremely low loss resistance has been certified by Fig. 4.1.1.3 (a) to (f). As one kind of popular application in mobile antenna, it satisfies with high efficiency.

![Radiation Efficiency of The Monopole Antenna Under Test](image)

Fig. 4.1.1.4 Radiated efficiency of the monopole antenna
4.1.2 Single Ground Stub Antenna

4.1.2.1 Design in HFSS

For the single ground stub antenna [23], its performance is similar with a regular monopole antenna with one open stub instead of that infinite ground plane. According to mirror theory, an infinitely large ground plane will replaces one arm of the dipole antenna for reducing the antenna size, this new structure is normally called monopole antenna which only contains one arm of the dipole and an infinite large ground plane. However, an infinitely large ground plane can’t be made in practice, thus a monopole antenna will not achieve its perfectly theoretical performance. Further, the ground plane was instead of several open-ended $\lambda/4$-Stubs and has same function as ground plane, this new antenna was called Marconi antenna. Obviously, there is only one open-ended $\lambda/4$-Stub to perform as same as the several stubs of Marconi antenna that is the reason of reducing the complexity structure of original Marconi antenna. This kind of antenna was named single ground stub antenna. This structure looks like bent dipole and the bends will reduce the radiation resistance and efficiency of radiator. It also has an attractive property such as Omni-directional radiation pattern, high radiation efficiency and so on [23].

Fig.4.1.2.1 displays the proposed single ground stub antenna which is made of copper and has the operated frequency at 2.8GHz. The vertical wire line and the ground radial wire line have same dimension, i.e., $\lambda/4 = 26.8$mm.

![Image](image_url)

Fig. 4.1.2.1 Designed single ground stub antenna in HFSS

The aim of simulation is measuring the single ground stub antenna’s radiation efficiency using the Wheeler cap method. In the light of Wheeler method, there are different sizes of Wheeler caps were designed in HFSS. The radiation efficiency of the AUT will be given by the results of return loss which AUT without and with Wheeler cap.
4.1.2.2 Results

To find out the radiation efficiency of designed single ground stub antenna, the return loss of designed AUT was attended. Fig. 4.1.2.2 shows the result of return loss for the single ground stub antenna without Wheeler cap (simulate in free space). Fig. 4.1.2.3 displays the result of return loss with six different Wheeler cap. Fig. 4.1.2.4 (a) to (f) illustrates the normalized impedance (denoted as blue line) with Wheeler caps. The result of the normalized impedance (denoted as red line) without Wheeler cap (in the free space) is shown on the same Smith chart as comparison.

Fig. 4.1.2.2 Return loss of AUT without Wheeler cap (in free space)

Fig. 4.1.2.3 Return loss of AUT with six different Wheeler caps
Six different Wheeler caps have been designed in HFSS to modify the “radianlength” of AUT. The dimension of six Wheeler caps is following as Tab. 4.2.

<table>
<thead>
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<th>Length (mm)</th>
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<td>Cap 6</td>
<td>55</td>
<td>55</td>
<td>102</td>
<td>2</td>
</tr>
</tbody>
</table>

Tab. 4.2 Dimension of designed Wheeler caps

Fig. 4.1.2.4 (a-f) Normalized impedances in free space and with different Wheeler caps
4.1.2.3 Radiation Efficiency Calculation and Conclusions

Based on the simulated results and equation of (3.36), the single ground stub antenna’s radiation efficiency could be solved. Shown in Figure 4.1.2.5 is the single stab ground antenna’s radiation efficiency from 2.2 GHz to 4 GHz. As it was shown, the single ground stub antenna has lower radiation efficiency compare with monopole antenna, but it is still a high efficiency antenna cause of the identical properties with dipole. Observably, the various results of radiation efficiency generate with the different dimension of designed Wheeler caps, but these curves have similar shape in the simulated frequency range.

![Radiation Efficiency of The Marconi Antenna Under Test](image)

Fig. 4.1.2.5 Radiated efficiency of the single ground stub antenna
4.1.3 Loop Antenna

4.1.3.1 Design in HFSS
The loop antenna is one type of simplicity, low cost and versatility antenna application. Loop antenna can have different shapes, such as circular, square, triangular and so on, and they are widely used in microwave band’s applications. According to size of the loop antennas, they can be divided into electrically small loops and electrically large loops.

The classical definition of electrically small loops that is the circumference of designed antenna less than one tenth wavelength. A very small radiation resistance is contained within electrically small loops of single turn. In a practical way, the radiation resistance can be improved by adding more turns, however, multi-turn loops’ efficiency is still very poor. That is one reason of the loop antennas is used dominantly as receiving antennas, where losses are not so important. The small loops have a similar shape of the far-field pattern to compare with a small dipole, which is to be expected because of the equivalence of a magnetic dipole. Obviously, the field polarization is vertical to that of a dipole.

The normal loop antenna or electrically large loop which is circumference approximates one wavelength, regardless of its frequency. Their characteristics are same as normal loop antennas. Especially, they are often used as electromagnetic (EM) field probes in the microwave bands’ applications, too.

As the designed loop antenna, a normal or electrically large square loop antenna has been chosen. The designed model in HFSS is shown on Fig. 4.1.3.1. This loop antenna can be operating 3 GHz in the free space and the circumference is approximate 100 mm, i.e. one wavelength. The copper wire diameter estimates 1 mm as the material. To verify the Wheeler cap method which is to be referred to above, various Wheeler caps have been designed and simulated by HFSS at the same situation, where 2 mm thickness copper as the material. The simulations will be separated two steps that are without and with Wheeler cap.

Both simulations have been performed with same frequency setup, sweep type, solution frequency and so on.

![Fig. 4.1.3.1 Designed loop antenna in HFSS](image)
4.1.3.2 Results

To prove the Wheeler cap method and calculate the radiation efficiency of the designed loop antenna. The efficiency is shown in following figures according to the return loss of both situations. The Fig. 4.1.3.2 shows the return loss (S11) without Wheeler cap (in free space) and with various Wheeler caps. The normalized impedances are shown by Fig. 4.1.3.3 (a) to (f), and the comparisons between both situations have been given. In Fig. 4.1.3.4, the radiation efficiency results of the loop AUT have been given, all datum are calculated by equation (3.36).

Fig. 4.1.3.2 (a) Return loss of AUT without Wheeler cap (in free space)

Fig. 4.1.3.2 (b) Return loss of AUT with six different Wheeler caps
Six different Wheeler caps have been designed in HFSS to modify the “radianlength” of AUT. The dimension of six Wheeler caps is following as Tab. 4.3.

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Tab. 4.3 Dimension of designed Wheeler caps

Fig. 4.1.3.3 (a-f) Normalized impedances in free space and with different Wheeler caps
4.1.3.3 Radiation Efficiency Calculation and Conclusions

The radiation efficiency of the loop AUT is shown by Fig. 4.1.3.4, and the simulations of various Wheeler caps are introduced by six different traces. Obviously, the poorest efficiency can be less than 60%, and the average value is around 66.8% at resonant frequency. The theoretical radianlength ($\frac{\lambda}{2\pi}$) for this AUT is approximated 16 mm, it is the dominant condition for designing the Wheeler caps.

Otherwise, the Fig. 4.1.3.2 (a) figures out a profile of AUT which has poor return loss. To compare the return loss with Wheeler caps, Fig. 4.1.3.2 (b) shows the various traces base on six designed caps. This simulation has been verified a poor radiation efficiency for loop antennas.

![Radiation Efficiency of The Loop Antenna Under Test](image)

Fig. 4.1.3.4 Radiated efficiency of the loop antenna
4.1.4. Meander Line Monopole Antenna

4.1.4.1 Design in HFSS

Meander Line planar antenna has a meander conductor line printed on a dielectric substrate. It has many benefits, such as physically small, high volumetric efficiency and the ability achieve multi-frequency operation. That is the reason of MLA is used widely in many applications, for example, mobile handset, wireless in the laptops, PC card and access point and UWB applications [34].

The meander line monopole antenna was selected because of simple structure, easy to implement and similar properties with a regular wired monopole antenna. Fig.4.1.4.1 shows the HFSS designed model of the meander line monopole antenna which has the resonant frequency about 900 MHz, and it is printed on the dimension of 43.37 × 80.5 × 1.6 mm Rogers RO3010(tm) substrate. The meander conductor line was bending by a length of $\lambda/4 \approx 83.4$ mm, where $\lambda$ is the wavelength at the operated frequency (900 MHz). In order to match the 50 Ω excited ports, a CPW transmission line was designed [25].

The dimension of CPW transmission line can be computed by calculator tool in ADS, some significant input parameters are listed in Tab. 4.4.

| PCB dielectric constant: $\varepsilon_r = 10.2$ | Conductor thickness: $T = 0$ mm |
| Operating frequency: $f = 0.9$ GHz | Substrate height: $H = 1.6$mm |
| Characteristic impedance: $Z_0 = 50$ Ohm | |
| Under the above parameters, the conductor parameters can be get as followed: | |
| Conductor width: $W = 1.2$mm | The separation of ground plane $G = 0.5$mm |
| Conductor length: $L = 34$mm | |

Tab. 4.4 Parameters of the coplanar waveguide (CPW transmission line) design

To figure out the radiation efficiency of the meander line monopole antenna, the simulation has been operated without (in free space) or with Wheeler cap.
4.1.4.2 Results

To demonstrate the meander line monopole antenna’s radiation efficiency, return loss of AUT was considered. The return loss result of AUT without Wheeler cap is plotted in Fig. 4.1.4.2. In order to estimate the “radianlength” of this meander monopole antenna carefully, AUT has been located in two kinds of spatial positions when AUT with the Wheeler cap. Six designed Wheeler caps with different dimension used into each position. The spatial position 1 that is AUT inserted into designed caps and placed it vertical to the $a \times b$ plane of the rectangular resonator [27], i.e. Wheeler cap. Base on first position, this AUT will rotate 45 degree to the diagonal of the $a \times b$ plane as a new position, and it is called spatial position 2.

Fig. 4.1.4.2 shows the result of return loss for AUT without Wheeler cap which means AUT operating in free space. The results of return loss for AUT located at position 1 with different dimension Wheeler cap have been plotted in Fig. 4.1.4.3. Normalized impedances in free space and with different Wheeler cap are plotted in Fig. 4.1.4.4 (a) to (f). And the dimension of six Wheeler caps is following as Tab. 4.5 which has been designed in HFSS to modify the “radianlength” of AUT.

![Fig. 4.1.4.2. Return loss of AUT without Wheeler cap (in free space)](image1)

![Fig. 4.1.4.3. Return loss of AUT with six different Wheeler caps (position 1)](image2)
<table>
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Tab. 4.5 Dimension of designed Wheeler caps (position 1)

Fig. 4.1.4.4 Normalized impedances in free space and with different Wheeler caps (position 1)
Similarly, according to the spatial position 2, Fig. 4.1.4.5 displays the result of return loss for AUT in the different Wheeler cap. Meanwhile, the normalized impedances are plotted in Fig. 4.1.4.6 (a) to (f).

4.1.4.5. Return loss of AUT with six different Wheeler caps (position 2)

Six different Wheeler caps have been designed in HFSS to modify the “radianlength” of AUT. The dimension of six Wheeler caps is following as Tab. 4.6.

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<tr>
<td>Cap 6</td>
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<td>124</td>
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Tab. 4.6 Dimension of designed Wheeler caps (position 2)
Fig. 4.1.4.6 Normalized impedances in free space and with different Wheeler caps (position 2)
4.1.4.4 Radiation Efficiency Calculation and Conclusions

According to the simulated result, the radiation efficiency of the meander monopole antenna can be obtained by the equation of (3.36).

Fig. 4.1.4.7 shows the radiation efficiency of AUT placed at spatial position 1, and the Fig. 4.1.4.8 shows the radiation efficiency of AUT placed at spatial position 2.

![Graph of Radiation Efficiency of The Meander Monopole Antenna Under Test](image1)

**Fig. 4.1.4.7** Radiated efficiency of the MLMA placed on position 1

![Graph of Radiation Efficiency of The Meander Monopole Antenna Under Test](image2)

**Fig. 4.1.4.8** Radiated efficiency of the MLMA placed on position 2
Chapter 5
MEASUREMENTS

5.1 Efficiency Measurements and Set-up

The measurements have been used the Wheeler cap method as same as the simulations. The measurement divides into two steps which are without Wheeler cap and with it. To verify this measurement method about radiation efficiency of antenna, two kinds of AUT have been estimated that are lossless monopole antenna and lossy loop antenna according to HFSS designed models. All AUTs were handcrafted so that the specifications with un-avoidable error.

A PNA-X Network Analyzer (N5242A) which is produced by the Angilent Technologies has been used to all measurements. The PNA-X (N5242A) has excellent quality for measurement, such as measured frequency span from to 10 MHz to 26.5 GHz, it can do the 2- or 4-ports measurements, 130 dB system and 132 dB receiver dynamic range, low noise floor of -114 dBm at 10 Hz IFBW and so on [33]. Entire measurement has been done the Radio Center Gävle.

Fig. 5.1.1 shows the measurement set-up of radiation efficiency using Wheeler cap method. Both AUTs are abide by same measurement set-up and testing environment. According to mentioned method, measurements are focus on the result of return loss in both steps, so that one-port measurement was considered.

![Fig. 5.1.1 (a) Measurement set-up without Wheeler cap (free space)]

![Fig. 5.1.1 (b) Measurement set-up with Wheeler cap]
5.2 Monopole Antenna

The structure of measured lossless monopole antenna is shown in Fig.5.2.1. It is a 35.7mm copper wired monopole on a 100 mm *100 mm square copper ground plane, where the ground plane has the 2mm thickness.

To measure radiation efficiency of this antenna, a suitable Wheeler cap was made of 2mm thickness copper. This Wheeler cap is shown in the Fig. 5.1.2. Actually, it is also a rectangular resonant cavity using the dominant resonant mode (lowest resonant frequency) TE_{101} as another design condition. At the same time, the “radianlength” has to satisfy the operating frequency of AUT (2.1 GHz) and lower than the resonant frequency of cavity (3.5 GHz), where the designed Wheeler cap has dimension with 45 mm *45 mm *140 mm.

The measurement was achieved by designed measurement set-up which was mentioned in Sec.5.1. In order to carry out the monopole antenna’s radiation efficiency, the result of return loss was measured during the frequency span from 1 GHz to 3 GHz.

![Fabricated lossless monopole antenna](image1)

![Fabricated Wheeler cap](image2)
5.2.1 Measurement Results
Fig. 5.2.3 shows the measured return loss of the fabricated antenna in free space. Meanwhile, the measured return loss of AUT with Wheeler cap is plotted in Fig. 5.2.4. Fig. 5.2.5 illustrates normalized impedance versus frequency for this measured antenna. It is a comparison of the normalized impedance in free space and with Wheeler cap. The line of red and blue are for without and with Wheeler cap respectively.

![Fig. 5.2.3 Monopole AUT measurement without Wheeler cap (in free space)](image1)

![Fig. 5.2.4 Monopole AUT measurement with Wheeler cap](image2)
5.2.2 Conclusion
Looking at Fig. 5.2.4, it is observed that the return loss is -0.2476dB when AUT with Wheeler cap, the result is far away from the -17.4828dB which measured in free space. That means the Wheeler cap has rejected the antenna when it is with Wheeler cap, in other words, AUT does not work in the Wheeler cap. This is satisfied with Wheeler’s concept. Based on the equation (3.36), the monopole antenna’s radiation efficiency is obtained and shown in Fig. 5.2.6. Looking into the result of this measured antenna’s radiation efficiency, its radiation efficiency is more than 90% at the operating frequency, 2.1GHz. It is noted that the monopole antenna has very good radiation efficiency and low loss resistance.
5.3 Loop Antenna

The fabricated lossy loop antenna can be operated at 3 GHz. It is made of 100 mm (one wavelength) and diameter 1.4 mm copper. This loop antenna chooses square shape, and quarter wavelength as each side.

A related Wheeler cap was made of 2 mm thickness copper. It is a rectangular resonant cavity using the dominant resonant mode (lowest resonant frequency) $\text{TE}_{101}$ as one of the design conditions. At the same time, the “radianlength” has to satisfy the operating frequency of AUT (3 GHz) and lower than the resonant frequency of cavity (3.5 GHz). According to above conditions, the dimension of the fabricated Wheeler cap is 45 mm * 45 mm * 140 mm.

The measurement have accomplished with two steps. For free space measurement, the AUT connect with one port of the calibrated PNA-X (N5242A). The frequency span starts at 2 GHz and stops at 4 GHz with 1001 samples. After recording all data have been measured in free space, put the AUT into the Wheeler cap and carry out same measurement again. A remarkable problem is making sure the metal shield closed completely, because of the entire “Cap” divide by two parts so that a perfectly closed can figure out accurate results. The S-parameter measuring has been implemented in both steps. The fabricated lossy loop antenna and Wheeler cap are shown Fig. 5.3.1. (a) and (b).

![Fabricated lossy loop antenna](image1.jpg)  ![Fabricated Wheeler cap](image2.jpg)

Fig. 5.3.1 (a) Fabricated lossy loop antenna; (b) Fabricated Wheeler cap
5.3.1 Measurement Results

The measurement results focus on the results of return loss in both steps. The results in both situations are shown in Fig. 5.3.2. Both measuring frequency span is from 2 GHz to 4 GHz, with 1001 samples. The inset of Fig. 5.3.3 is the comparison of normalized impedances on the smith chart in free space and with Wheeler cap. Point A expresses the data is operating frequency, point B shows the normalized impedance located in the correlated frequency when adding the Wheeler cap. The radiation efficiency of fabricated loop antenna is shown in Fig. 5.3.4, and it is computed by equation (3.36).

![Return Loss Measurement in Free Space](image)

**Fig. 5.3.2 (a) Loop AUT measurement without Wheeler cap (in free space)**

![Return Loss Measurement with Metal Shield](image)

**Fig. 5.3.2 (b) Loop AUT measurement with Wheeler cap**
5.3.2 Conclusion

Fig. 5.3.4 is shown the radiation efficiency of loop AUT in measurement. The first lowest peak is presented the efficiency when AUT achieves to operated frequency in free space, the value is around 62%. According to return loss in both situations, a property of loop antenna that is weak efficiency has been proved.

Fig. 5.3.3 Normalized impedances in free space and with Wheeler cap

Fig. 5.3.4 Radiation efficiency of lossy loop antenna
Chapter 6
COMPARISON OF SIMULATION AND MEASUREMENT RESULTS

6.1 Monopole Antenna Results

In order to estimate designed monopole antenna’s radiation efficiency properly, six different dimensions of Wheeler caps were designed during simulation. Meanwhile, as the limitation of the resource, only one dimension with 45 mm * 45 mm * 140 mm Wheeler cap was fabricated. By comparison, the simulated result and measured result are followed. Fig. 6.1.1 shows the return losses of simulation and measurement in free space. The comparison of return loss about AUT with Wheeler cap between simulation and measurement is illustrated in Fig. 6.1.2.

This monopole antenna can perform at 2.1 GHz, its minimum value of return loss locate around -12.7 dB for simulation and -17.5 dB for measurement, both of results perform at resonant frequency 2.1 GHz. It has good performance in the free space, base on the lossless profile of wire monopole antennas.

![Comparison of return loss of monopole antenna in free space](image)

Fig. 6.1.1 Comparison about return loss of monopole antenna in free space
Fig. 6.1.2 Comparison about return loss of monopole antenna with Wheeler cap

Fig. 6.1.2 is the comparison of return loss with Wheeler cap. Obviously, this result is higher which compare with the results in free space, and the results of simulation and measurement are approximate 0 dB, because of AUT do not propagation around the resonant frequency (2.1 GHz), and only perform a small loss resistance.

The radiation efficiencies of simulation and measurement are shown in Fig. 6.1.3, and all of data details illustrate in Tab. 6.1.1.

![Graph of Radiation Efficiency](image)

**Fig. 6.1.3 Radiation efficiency of lossless monopole antenna**

<table>
<thead>
<tr>
<th>Cap Dimension (mm)</th>
<th>S11 (FS) (dB)</th>
<th>S11 (WC) (dB)</th>
<th>Radiation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>45×45×140</td>
<td>-12.7</td>
<td>-0.03</td>
</tr>
<tr>
<td>Measurement</td>
<td>45×45×140</td>
<td>-17.5</td>
<td>-0.25</td>
</tr>
</tbody>
</table>

*Tab. 6.1.1 Radiation efficiencies of lossless monopole antenna*
6.2 Loop Antenna Results

According to the simulation and measurement, a comparison of the radiation efficiencies of lossy loop antenna has been given. Figure 6.2.1 illustrates the return losses of simulation and measurement in the free space. To estimate the loss resistance, the return losses of lossy loop antenna with Wheeler cap between simulation and measurement have been shown in Figure 6.2.2. During the simulations, six Wheeler caps have been mentioned with different dimension, to parallel with the Wheeler cap which has been fabricated in the “real life”, one of the six Wheeler cap has been selected which close to the practical one.

Obviously, the loop antenna is one type of poor efficiency antennas, and this profile depends on the principles of loop antenna, because of they have very small radiation resistance compare with their loss resistance [22]. The designed lossy loop antenna can performs at 3 GHz, the minimum values of return loss locate around -6 dB for simulation and -7.6 dB for measurement, and both of results perform at resonant frequency 3 GHz.

![Fig. 6.2.1 Comparison about return loss of loop antenna in free space](image1)

![Fig. 6.2.2 Comparison about return loss of loop antenna with Wheeler cap](image2)
Fig. 6.2.2 shows the return loss of lossy loop antenna with the Wheeler cap. According to the illustration, the results of return losses are -1.1 dB of simulation and -1.35 dB of measurement. Perceptibly, the resonant frequency was getting few shifts, because of the cavity perturbation which is called shape perturbations [27].

The radiation efficiencies of simulation and measurement are shown in Fig. 6.2.3, and all of data details illustrate in Tab. 6.2.1.

![Radiation Efficiency of The Loop Antenna Under Test](image)

**Fig. 6.2.3 Radiation efficiency of lossy loop antenna**

<table>
<thead>
<tr>
<th>Cap Dimension (mm)</th>
<th>S11 (FS) (dB)</th>
<th>S11 (WC) (dB)</th>
<th>Radiation Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>45×45×140</td>
<td>-6</td>
<td>-1.1</td>
</tr>
<tr>
<td>Measurement</td>
<td>45×45×102</td>
<td>-7.6</td>
<td>-1.65</td>
</tr>
</tbody>
</table>

**Tab. 6.2.1 Radiation efficiencies of lossy loop antenna**
Chapter 7
CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

A design and construction of the Wheeler cap set-up to measure the radiation efficiencies of different antennas is presented. The result of radiation efficiency was using reflection data which obtains from the antenna when placed in free space and with a Wheeler cap (a rectangular cavity). The designed Wheeler cap considers both of antenna’s radianlength and cavity’s resonant frequency, to measure radiation efficiency precisely and evaluate the performances of antenna in both environments. This approves the measurement set-up to be applied to any antenna.

A limitation of Wheeler cap method is described and treated for the reflection measurement, using the RLC equivalent circuits regard to the free space performance and with Wheeler cap of an antenna. The limitation agrees with the theoretical value of reflection coefficient and depends on the Wheeler cap method so that only regards the loss resistance when an antenna located in the Wheeler cap. This limitation applies to a parallel equivalent RLC circuit of any complex antenna, and the results could be extended for multi-band antennas.

A comparison of simulation and measurement regards to both of results, two types of antenna have been estimated, lossless wire monopole antenna and lossy loop antenna. The simulations are achieved by HFSS, various dimension of Wheeler caps are used to investigate radiation efficiencies of antennas, using to verify reflection Wheeler cap method faithfully. A given Wheeler cap has been measured the radiation efficiencies of antennas, to compare with simulation results. The measurement shows an excellent agreement with previous simulation results, since the radiation efficiency of antenna could be demonstrated by the proposed Wheeler cap method.

The simulations include four kinds of antenna, such as, monopole antenna, loop antenna, single ground stub antenna and meander monopole planar antenna. Those antennas regard to different behaviors, whether the antenna structures, principles or characteristics. Obviously, the simulation results agree with their principles and theoretical value of radiation efficiency. These results indicated that even for antennas with different behaviors, the Wheeler cap method with the reflection measurement can provide accurate measurement and easily and quickly test set-up.
7.2 Future work

- To fabricate the single ground stub antenna and meander monopole antenna to measure the radiation efficiencies and give the comparison of simulation and measurement results.
- To accomplish 2-ports reflection measurement instead of current 1-port measurement. To modify the construction of measurement set-up, for example using attenuators to connect antenna under test and confirm the measurement results.
- Using the Wheeler cap method to measure antennas’ radiation efficiency which with more resonances or complicated operating principles.
REFERENCES


[33] Agilent Technologies, “Agilent 2-Port and 4-Port PNA-X Network Analyzer (N5241A, N5242A) Data Sheet and Technical Specifications”.

Appendix A

MATLAB Code for Radiation Efficiency

The Matlab source code is presented which was used to create the radiation efficiency for the antennas. This appendix was used to plot the radiation efficiency for the interested antenna.

% the radiation efficiency plot
% frequency=cap_S11(:,1);
frequency=frequency(p1: p2);
% choose the frequency
Cap_s=cap_S11(:,2);
Cap_s=Cap_s(p3: p4);
% choose the cap S11 value
Cap_s=10.^(Cap_s./20);
% change the cap S11 value into linear value
free_s=free_S11(:,2);
free_s=free_s(p1: p2);
% choose the free space S11 value
free_s=10.^(free_s./20);
% change the free space S11 value into linear value
Efficiency=(( abs(Cap_s) ).^2 -( abs(free_s) ).^2) ./ (1-( abs(free_s )).^2);
% calculate the efficiency
plot(frequency, Efficiency, 'b','LineWidth',2);

% How to shift the frequency
% According to the resonated frequency, free space f1 GHz to cap f2 GHz,
% It leads (f1 - f2 = f3) GHz frequency shift
% According to the responsible frequency range, the relative points in Matlab
% It was selected.
% for the plot, in free space environment, the relative point range as point p1
% to p2. In wheeler cap environment, the relative point range as point p3 to p4.
Appendix B

The Calculation of CPW