DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

MASTER'S THESIS

Comparative Study of Increasing Indoor WLAN Coverage by Passive Repeating Systems

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ABSTRACT

Propagation of radio waves is interrupted while traveling through different materials. The architectural beautification and complexity by using various building materials cause attenuation of the signal via: indoor, outdoor to indoor and vice versa wireless communications. It has been found that feeding more power to the transmitter or increasing sensitivity of the receiver is one of the solutions to overcome weak connectivity. However, this approach is not cost effective. Another concern is the ability to amplify the wireless signal, especially in WLAN operation. WLAN is one of the most popular ways of establishing a wireless communication network to connect our daily used devices such as mobile phone, laptop, IP camera etc. Path loss, attenuation by materials and the delivered power from the transceiver are the variables to determine the efficiency of this communication network.

A passive repeating method has been discussed in this thesis which addresses the mentioned concerns. It is cost effective and in a case of power consumption, does not need any energy outside the system. On the other hand, there are few maintenance costs, if any, for this kind of system. To achieve this, a back-to-back antenna approach has been tested in this study. In a back-to-back system, two antennas are connected by a short waveguide connection to decrease attenuation e.g. a wall. The main challenge concerning the effectiveness of this method was to design and fabricate efficient antennas, which are connected with a coaxial cable.

There are multiple frequency bands available for WLAN communication. In this thesis, a frequency of 2.43 GHz is considered. Computer simulation of antennas, fabrication, individual measurement and full passive repeating system measurement has been presented. A prototype of a circular patch antenna is built with a 4.63 dB gain and a return loss of 15.18 dB. The passive repeating system is built by using a commercially available dipole antenna at the other end of the coaxial cable. In various cases, there was an observable improvement of the signal of between 2 dB to 6 dB.

Required background and theoretical studies are presented along with the output of the simulated and measured prototype comparison. It is clear from this study that the passive repeating system can be used in some specific indoor areas.

Keywords: WLAN, passive repeater, path loss, attenuation, indoor communication.

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FOREWORD

This thesis has been carried out as a partial requirement for the completion of the degree towards the Master's Degree Program in Wireless Communication Engineering, at the Center for Wireless Communication (CWC), University of Oulu, Finland.

I am thankful to my supervisors Professor Aarno Pärssinen, DSc (Tech) Marko Sonkki and DSc (Tech) Marko Tuhkala for guiding me for not only on the theoretical studies, but also for the technical support. Their suggestions and comments were required for me to complete this thesis. For theoretical guideline Marko Sonkki made me clear about the related topics to understand. Marko Tuhkala provided me the technical support during several tests for this thesis. I would like to thank my parents for their continuous inspiration for my studies. I am also thankful to all of my friends, especially Shahriar Shahabuddin, Julias Francis Gomes, Sanaul Haque and Joseph Bentley for their moral support.

I dedicate this thesis to my parents for their wonderful support throughout my life and never ending love.

"I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

- Sir Isaac Newton

Oulu, May, 2018

Sadiqur Rahaman

LIST OF ABBREVIATIONS AND SYMBOLS

CST	Computer Simulations Technologies
dB	Decibel
dBm	Decibel Referenced to Milliwatt
dBi	Decibel Referenced to Isotropic Radiator
FNBW	First Null Beam Width
FM	Frequency Modulation
FSL	Free Space Loss
GPS	Global Positioning System
GHz	Gigahertz
HGA	High Gain Antenna
HPBW	Half Power Beam Width
IL	Insertion Loss
IP	Internet Protocol
IoT	Internet of Things
LHCP	Left Hand Circular Polarization
LOS	Line of Sight
MIMO	Multiple Input Multiple Output
PCB	Printed Circuit Board
RBER	Residual Bit Error Rate
RFID	Radio-Frequency Identification
RHCP	Right Hand Circular Polarization
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
WiMAX	Worldwide Interoperability for Microwave Access, Inc
WLAN	Wireless Local Area Network

A	Surface area
A_e	Antenna gain
D	Largest dimension of antenna
D_θ	Partial directivity of elevation plane
D_ϕ	Partial directivity of Azimuth angle
E	Electric field
F	Frequency
F_C	Center frequency
F_L	Lower frequency
F_U	Upper frequency
G	Gain of reflector
G_{TX}	Transmitted antenna gain
G_{RX}	Receiver antenna gain
H	Magnetic field
I_{in}	Input current

I_z	Density of current
J_z	Density of current
L	Length of antenna
L_p	Miscellaneous signal propagation loss
L_{TX}	Transmitter feeder and associated loss
L_{FS}	Free space path loss
P_{in}	Input power
P_r	Radiated power
P_{RX}	Received power
P_{TX}	Transmitted power
P_{rad}	Radiated power
T	Time per cycle of a wave
Q	Total charge
R	Reactive near-field
R_a	Total resistance of antenna
R_r	Radiation resistance of antenna
R_L	Internal resistance of antenna
R_l	Loss resistance of antenna
V	Volume
U	Radiation intensity
U_0	Radiation intensity for isotropic case
U_{max}	Maximum radiation intensity
P	Phase
V_{in}	Input voltage
W_{rad}	Radiation density
X_a	Frequency dependent reactance
Z_a	Input impedance
Z_0	Characteristic impedance of the transmission line
a	Radius of the patch
a_e	Effective radius of the patch
a_z	Acceleration of the current
c	Speed of light
e	Total efficiency
e_{rad}	Radiation efficiency
e_{ref}	Reflection efficiency
f	Frequency
f_r	Resonance frequency
h	Substrate height
i	Source port of VNA
j	Destination port of VNA
l	Length of wire

q_l	Charge of thin wire per unit length
q_v	Density of electric volume charge
r	Radius
v_z	Velocity of charge
v_0	Velocity of light

Ω	Resistance
ϵ_r	Dielectric constant
θ	Elevation angle
ϕ	Azimuth angle
π	Pi (constant)
Γ	Voltage reflection coefficient
λ	Wavelength
ω	Angular frequency
γ	Propagation constant

1. INTRODUCTION

In the near future all electronic devices will be connected to several other electronic devices and this phenomenon is known as “Internet of Things” (IoT). These devices can be connected to internet directly through cellular network, Wi-Fi or indirectly via Bluetooth technology. Connectedness through wireless medium is the solution to the mobility of those devices. On the other hand, availability of the network by which that wireless connection will be made, is a greater challenge because it is not convenient in terms of overhead cost to make sure that the whole area is under the communication network. The modern architecture of bigger office spaces is designed by various materials which tend to attenuate the signal of Wireless Local Area Network (WLAN). Repetition of signal is required to the indoor area to keep the wireless communication uninterrupted. Because the frequency band is limited for WLAN and also the cost of power consumption of those devices is a factor to mitigate, passive repeating of the signal can be a solution in some cases to overcome these problems. This thesis addresses one of the probable solutions.

A back-to-back antenna passive repeating system, where two antennas are connected with a short waveguide, has been used to figure out the variation or improvement of the indoor signal from a single source (e.g. Base Transceiver Station (BTS)) to the wirelessly connected device (mobile phone, laptop, IP camera etc.). A prototype of an antenna has been built for the WLAN frequency range which is 2.43 GHz and CST Microwave Studio has been used to simulate beforehand. For the real time measurement the Vector Network Analyzer and Satimo StarLab have been used to determine the performance of those antennas and cables used for the measurement. A free version mobile application has been used for the final test setup of the passive repeating system to measure signal levels.

A coaxial cable of 50Ω impedance has been used as a waveguide to make the physical connection between the two antennas in the back-to-back antenna model. As the whole system is passive, the goal is to keep the gain performance of the antennas as much as possible. The concept is to capture the microwave energy from a BTS, guide the energy through a coaxial cable and radiate the captured signals on the other end by using another antenna to improve the signal level in that area.

Theoretical background has been discussed at the beginning of the thesis along with the discussion of some previous relevant works which one need to study in order to clarify the concept and approach of this thesis. The simulation results, individual measurement results and the measurement results, and the main goal of this thesis have been presented on the result chapter.

1.1. Objective

Objective of this thesis is to build a passive repeating system for the indoor wireless communication. The targeted is to increase the coverage in places where the signal strength is poor because of the distance from the base transceiver, or the huge attenuation caused by building materials. For instance, thick walls, glass walls or different architectural obstacles can attenuate the signal for several tens of dBs.

1.2. Limitations

The objectives have been initiated by using the simulation software which can provide the tentative results of the real objects, more specifically of an antenna which has been built and used later on. The software does not take into consideration of some practical factors such as surface roughness of the materials and purity of components which are not unique in terms of real-life cases. In the measurement section there is another limitation of the mobile application which has been used for the main repeating system. The sensitivity of the received signal depends on the efficiency of the mobile device. It might vary from device to device. To reduce the error rate, the output of that mobile application has been averaged after several measurements.

1.3. Related Research

In consideration of building designs in the Nordic countries, the materials used have a higher thermal resistance. Many insulation materials are also used to make the indoor temperature comfortable for the human being. These materials determine the properties of radio waves received from the transmission station. Some materials have high attenuation for the radio wave which is frequency dependent. For example, Celotex thermal insulation causes around 50 dB of RF attenuation for Wi-Fi frequency [1]. Because of the complexity of the system design sometimes, it is required to improve the signal strength in a certain areas of the building. Installation of passive repeating systems is much more convenient rather than placing any active repeater on that niche area. No electrical power and least maintenance are the key features of this approach.

So far, many researchers have been conducted with different kinds of antennas and also using passive repeating methods to measure the improvement of signal strength tested in various cases. In this literature review part, the discussion has been made by dividing it into following four major parts.

1.3.1. Directional Antennas

The directional antenna is also known as a beam antenna as its radiation pattern is pointed in a certain direction for increased performance and low interference. High gain is another important feature of this antenna. In the case of receiving and transmitting signal, this high gain antenna (HGA) captures and radiates respectively more of the signal with higher signal strength compared to an isotropic antenna. On the other hand, it will not be effective on the other direction rather than the directed angle. The operation is similar to the flashlight mechanism. Instead of spreading the light in every direction, the light is focused in a narrow projection angle by using a reflector. Similar things are done here for example using large ground plane (which helps to reflect the signal in certain direction like flash light) or directing the wave guide through a cone. In this way the direction of propagation can be determined. In Figure 1 a typical horn antenna is shown. It is one of the widely used directional antennas. Different kinds of directional antenna and their features are discussed below.

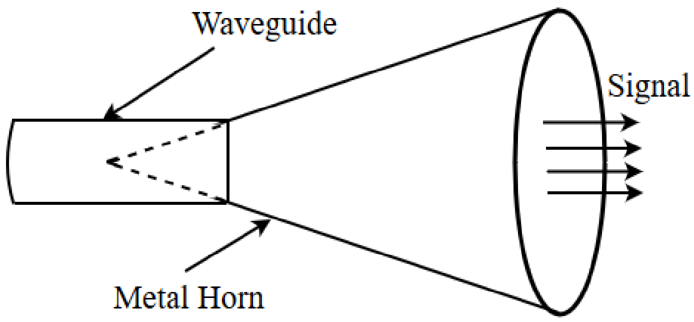


Figure 1. Horn antenna is an example of directional antenna.

In 2016 Li Guo et al. proposed a dual frequency band tunable patch antenna [2]. For creating the second resonance frequency, a mender shaped metallic parasitic loop has been used in this case. The resonance frequencies are 2.34 GHz and 2.45 GHz with -10 dB relative bandwidths of 1.2% and 0.8%, respectively. The gains are 7.48 dBi and 6.25 dBi respectively where the radiation efficiencies are 85% and 72%. For dual band operational purpose this antenna could be used because of its radiation pattern is quite directive.

Array of antennas to increase the gain is presented in the conference paper of IEEE in 2016 Galih Mustiko et al [3]. Total 16 antennas in 4x4 arrangements have been used in this design. It has higher bandwidth of 130 MHz in the resonance frequency with Voltage Standing Wave Ratio (VSWR) of 1.24. The main feature is its gain which is 15.59 dB with return loss of 19.52 dB.

Triple band improved gain microstrip patch antenna with gain of 2.4 dB and 2.76 dB by using superstrate and without superstrate respectively, implemented for the WLAN purpose which is 2.45 GHz, is proposed by Pragati et al in 2016 [4]. Other frequency bands are 3.5 GHz for WiMAX and 4.65 GHz for fixed mobile frequency band. In terms of directivity and radiation pattern the performance for 2.45 GHz was quite satisfactory compared to the other two frequency bands.

In a paper of Fei Yu, patch antenna with mono-pulse patterns with 345 MHz at 10 dB bandwidth has been focused. It has two symmetric probes feed with a 180 degree directional coupler [5]. Mono-pulse antennas are used in radars and in that kind of communication systems where rapid direction finding is required. This proposed antenna can operate in the frequency range of 2.11 GHz to 2.45 GHz. Two different slots are used for the patch, which is adopted to compensate the probe inductance. Additional sum-difference comparator, power divider and slot sub-arrays are required to make it operate for the desired communication systems.

Six series-fed patch antennas operating at 2.4 GHz with suppressed side lobe has been developed by Haris Hadzic et al [6]. To minimize the interference, reduction of sidelobes is effective. This antenna configuration has comparatively lower bandwidth of 18.7 MHz at -10 dB impedance matching. Kaise-Bessel amplitude coefficient implementation was another main feature of this design consideration to suppress the side lobes.

Shape based performance analysis for microstrip patch has been showed by Rajan Fotedar et al [7]. Wireless communication was the main focus of operation and for that they varied the shapes while the resonant frequency was kept constant at 2.4 GHz. Mainly a rectangular, a triangular and a circular patch has been analyzed in their work. Among those the directivity of the circular patch was the highest while, the maximum return loss was found for the rectangular patch antenna.

Double layer rectangular microstrip patch antenna of operating frequency of 2.45 GHz which was achieved by using H-slot [8]. The return loss of this configuration was 19.69 dB. Higher bandwidth has been observed in their work and it is about 110 MHz while the simulation showed only 88.56 MHz. The size of this design is suitable for using as RFID in smaller devices.

1.3.2. Omnidirectional Antennas

An omnidirectional antenna can radiate the radio waves uniformly in all direction of a certain plane. Decreasing tendency of radiation power is observed with the elevation angle above and below the plane. The radiation pattern is thus like doughnut shaped. This type of radiation characteristic is suitable as receiving antenna radio broadcasting, cell phones, wireless computer network and many more. An image of outdoor omnidirectional antenna is given in Figure 2.

Figure 2. Outdoor omnidirectional (monopole) antenna.

Omnidirectional antennas can be categorized into two groups, high gain and low gain antennas. Among the low gain antennas there are dipole antennas, discone antennas, mast radiator, horizontal loop antennas, halo antennas etc. Array of the above antennas can be used to achieve the higher gain by combining the radiated field in a certain direction. Besides microstrip antenna this type of antenna is also considered in the group of high gain antenna. There are some recent work on the omnidirectional antenna has been discussed shortly below.

Multiband dual-polarized omnidirectional antenna has been proposed in a study of Da Guo et al [9]. Here horizontal polarization and vertical polarization both were used by introducing different structures of the printed circular antennas. The overall frequency bands were quite vast e.g. from 690 MHz to 1.03 GHz and 1.67 GHz to 3.21 GHz. Because of the wider range of bands this can be used in MIMO communication for indoor operation.

Using circularly polarized array a metamaterial-based omnidirectional antenna has been proposed for WLAN application [10]. The radiation pattern was quite uniformly distributed in x-y plane. The advantage of circularly polarized antenna is the suppression properties of multipath reflections of waves caused by surroundings. The radiators were designed by using Rogers RO4003C substrate. Return loss on the 2.4 GHz was more than 30 dB.

For multiband operational purpose a small planar monopole antenna with a short parasitic inverted L shaped wire fed microstrip fed line has been studied by Jen-Yea Jan et al [11]. The proposed antenna is small and easy to construct. In PCB board along with other circuit this antenna can be printable on the same board. It has a high impedance bandwidth of 188 MHz which is very suitable for WLAN band.

Saou-Wen Su et al have conducted a study of monopole and dipole antennas for WLAN access point [12]. Two antennas are arranged in collinear structure to achieve the 2.4 GHz monopole and 5 GHz dipole antenna for access point application. This antenna was designed for industrial usages and that is why the dimension is optimized to fit into those devices like laptop. The radiation efficiency for both cases is around 80%.

Another microstrip T-shaped monopole antenna with gain more than 4 dB has been proposed by Yogesh Kumar Choukiker et al [13]. The design was very simple but good return loss was achieved which is more than 30 dB. In the simulation, the return loss value is higher. The radiation pattern found omnidirectional. Most importantly the bandwidth found for this design is quite wide and it is 431 MHz.

Switchable polarization for a single fed printed monopole antenna was developed by M.H. Amini et al [14]. There are two radiating element in the form of two monopole rectangular patches which are fed by a single microstrip line. The dimension of the total design is $26\times19\ mm^2$. A pin diode has been introduced between the two L shaped slots to make confirm dual polarization. The return loss and bandwidth both are satisfactory for WLAN operation.

1.3.3. Coaxial Cable

For the purpose of radio frequency transmission, coaxial cables are used, e.g. in antenna, computer network, cable television signals and digital audio. It is made with the purpose of not being interrupted by external electromagnetic signals. As the purpose of this thesis is to setup passive repeater using back-to-back antenna, this cable will be useful to guide the receive signal from receiving end to the transmitting end and vice versa, and the main concern is to keep those signals uninterrupted as much as possible as there is no active element to amplify the signal. The details of this cable with their construction and characteristics will be discussed in the theory part.

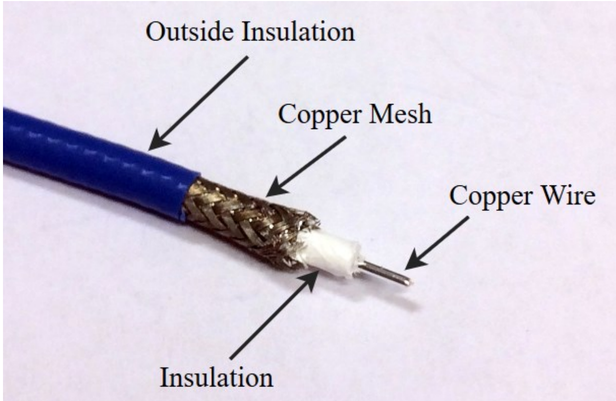


Figure 3. Structure of Coaxial cable.

In Figure 3 the structure of typical coaxial cable is shown. This cable helps to keep the carrying electromagnetic field in the space between the inner and outer conductors. It also provides the protection of the signal from the external electromagnetic interference.

1.3.4. Earlier works on passive signal repeating

Passive repeating system is being used in many places but mostly in outdoor operation. Low maintenance, no power requirements, installation ability in remote area has increased the popularity of it. Mostly in the rural area it is used where the users are less but somehow required to reach the signals. To keep this communication flawless inside the big buildings it is necessary to spread the radio signals in every corner of that building. As power consumption is also a big issue to establish such kind of environment, passive repeater can be the solution for this scenario. For indoor signal improvement purpose some research work will be discussed here.

In 2014 a passive system was tested for cellular coverage within energy efficient buildings by J.M. Rigelsford et al [15]. In energy efficient building the radio frequency is attenuated by the materials used in the buildings. For example, in their case the attenuation for the external wall is 20 dB and for the internal wall 3 dB. After implementing the passive system the comparison was done and they found that the total signal coverage was increased by 30 dB. As an external antenna they used a directional antenna of 20 dBi and for the internal usage an isotropic antenna of 0 dBi were used.

Through-wall passive repeater is another option for increasing the indoor signal. Hristo D. Hristov et al [16] has numerically showed the possible improvement of the indoor signal after using the passive repeaters. It was totally theoretical approach and the authors claimed that by this setup improvement of signal strength is possible but not for wide range. In case of practical implementation the overall cost would be less than installing any active elements for the same purpose.

Using multiple through-wall repeater similar idea was proposed by Yi Huang et al in 2004 [17]. Their proposal showed that by their repeater implementation MIMO systems get more efficient because of antenna diversity.

2. THEORETICAL BACKGROUND

2.1. Definitions and Concepts

Designing a passive repeating system requires the use of various components. In this paper some elements are designed according to the well-established theories and formulas. To understand the procedure, some theoretical explanations are perquisite. In this section some basic components and theories are described.

2.1.1. Antennas

The transmission of electrical signals can happen in two different ways, either through the conductors or via the empty space. Transmission lines are made of electrical conductors so the electrical signals can travel from a higher potential region to the lower potential area. Any electrical signal within a circuit works by this principal that the signals are confined within the transmission line and the circuit as well. When the electrical signals are required to transfer information to a distant location through an empty space then a metallic device is required to produce the electromagnetic wave, which can propagate without any medium, like the sun radiates light to earth at a distance of 150 million of kilometers. An antenna generates power densities that can be detected from a greater distance. In general, the Webster's dictionary defines the antenna as "*a usually metallic device (as a rod of wire) for radiating or receiving radio waves*". By the definition of IEEE an antenna is "*that part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves*" [18].

An antenna generates electromagnetic waves where the electrical and magnetic waves propagate with the same frequency and amplitude, but their orientation is perpendicular to each other. In the next subsection the mechanism of radiation will be discussed briefly.

The propagation velocity of radio waves is equal to the speed of light, both being electromagnetic waves. When an electrical signal needs to be transferred from one place to another it is required to be analyzed many variables like the frequency of the signal, distance of the transmitted and received signals, losses of signals, expenses, mobility issues of the transmitter and receivers, etc. For the lower frequency of signals it is convenient to transmit through solid transmission line. On the other hand the higher frequency has a wider bandwidth but the total cost increases through the solid transmission medium because of the distance and transmission loss.

2.1.2. Radiation Properties

An antenna is designed in a way that the source of the time varying current of an antenna makes the disturbance of electromagnetic field. Because of this disturbance the electromagnetic field can propagate away from the source by the principle of keeping the total power constant [19]. This phenomenon can be understood by explaining some basic sources of radiation; the radiation of single wire, two wire and dipole will be discussed in this section for better understanding the mechanism of radiation.

In single conducting wire the current flow is the motion of electric charges. The density of electric volume charge is expressed by coulombs per cubic meter and denoted by q_v. The cross sectional area of a circular-shaped wire is denoted by using A and volume V. If the total charge of the wire is Q with the moving velocity v_z (m/s) then the density of current is $I_z = q_v v_z$. For thin wire where the radius is considered zero then the equation becomes $I_z = q_l v_z$, where the charge of the thin wire per unit length is q_l. So the derivative of the current can be written as [21]

$$\frac{dI_z}{dt} = q_l \frac{dv_z}{dt} = q_l a_z \tag{2.1}$$

where a_z is the acceleration of the current. For the total length of the wire l, the equation 2.1 can be written as

$$l\frac{dI_z}{dt} = lq_l \frac{dv_z}{dt} = lq_l a_z \tag{2.2}$$

Equation 2.2 is a basic relation of current and charge which is the major relation of electromagnetic radiation. The equation says that for creating radiation a time varying current is needed. In other words acceleration or deceleration of the charge is necessary for the radiation of the energy.

From the above mathematical explanation, it can be concluded that if the charge in a conductor is steady or moving with a certain velocity there will be no electromagnetic radiation. Although with a constant velocity of charges, the radiation can be created if the wire is curved, bent, terminated or discontinuous in shape. If there are any oscillations of charges then there will be no need of shape distortion of the wire [21].

Now we will consider a voltage source applied between two conductors with alternating current and an antenna is attached to the end of the wires, the figure is depicted in Figure 4. Due to the existing voltage difference, two conductors will create the electric field, which starts from positive charge and ends to negative charge. According to the Maxwell's electromagnetic equation the applied alternating current creates the magnetic field. As there is no such thing as magnetic charges, the magnetic field lines form closed loops of magnetic waves encircling the conductors.

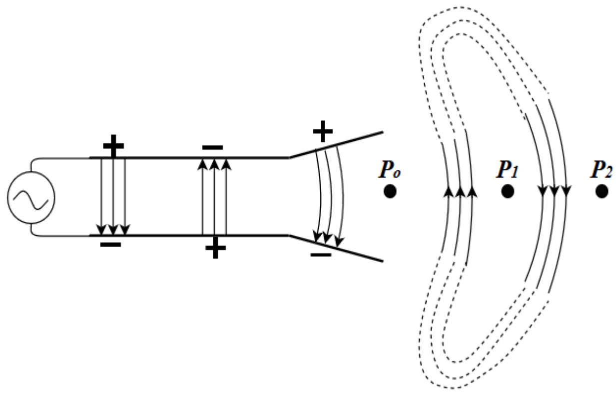
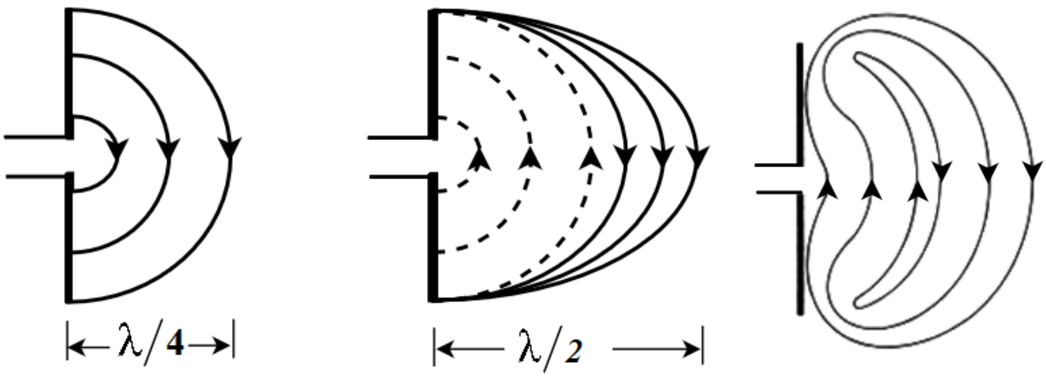


Figure 4. Electromagnetic wave generation in two wires [19].

In Figure 4, the straight line represents the electric filed with its respective direction, and the dotted line represents the magnetic field. The time varying electromagnetic wave enters the antenna from the wire, and the end of the antenna it begins radiating. These free space magnetic waves maintain the constant phase. The first phase is represented as P_0, which continues to move every half wave length as P_1, then P_2, and so on. The generation of electromagnetic waves continues as long as there is the variation in the velocity of electric charges in the wires.



(a) (b) (c)

Figure 5. Radiation of Dipole [19].

The radiation mechanism can be easily understood from the type of dipole antennas. If a small dipole antenna attached to an electrical source of alternating current with the time period of T, it is known that the maximum amplitude of current is found in $P/4$ and $3T/4$. In Figure 5 three different stages of charges and their corresponding free space waves are illustrated. During the first $T/4$ the charge has reached its maximum. Then the free space wave travel through the positive charges to the negative charges of the dipole. Here the radial distance is covered by the wave is λ/4, shown in (a). In (b) when the time period of the signal is from $T/4$ to $T/2$ opposite line of free space wave is generated with the same distance covering λ/4 and counting the previous distance the total distance of the generated electromagnetic waves become λ/2. Then due to the equal but opposite charges than the previous time period the total density of charges diminish which leads to the neutralization. At the time period $T/2$ there is no charge exists on the antenna. In that situation those lines created up to the period $T/2$ are forced to detach themselves from the conductors. Because of the opposite direction of the waves in two different time period those form a closed loops forms to unite them together, as shown in (c), and they are able to travel at the speed of light in free space. This process continues even after $T/2$.

2.1.3. Near Field and Far Field

The field surrounding the antenna is divided into near-filed and far-field. The near-field is categorized in reactive near-field and radiating near-field regions. These regions help to understand the field structure of different antennas. Although these different boundaries vary for different cases but there are some common established criteria to identify the boundaries.

Reactive near-field: It exists very close to the antenna. The calculation of electric field (E) and magnetic field (H) is complex in this area. One of those E and H field dominates one after another in that region. That is why the power density measurement is problematic, because for calculating the total power, the phase relationship between E and H field and the angle between those field vectors which are not possible to measure because of their inconsistency [20]. For most of the antennas, the boundary of this region is measured at a distance $R < 0.62\sqrt{D^3/\lambda}$ from the surface of the antenna. D represents the largest dimension of the antenna and λ is the wavelength [21].

Radiative near-field: The region between the reactive near-field and the far field is called radiative near-field which is also sometimes referred as Fresnel region. In this region the radiation fields start to dominate and unlike the reactive near-field the angular field distribution can be determined based on the distance from the antenna. This region is valid if the maximum dimension of the antenna is less than the operating wavelength. The inner boundary which is just beyond the reactive near-field is

$R \geq 0.62\sqrt{D^3/\lambda}$ to the distance $R < 2D^2/\lambda$ [21].

Far-field: The radiation pattern remains constant in this region unlike the near-filed region. It does not change the shape of radiation with the distance. Far field region started after the distance of $2D^2/\lambda$ to the infinity where D is the overall dimension and λ being the wavelength. The E-fields and H-fields remain orthogonal to each other. The far-field region can be calculated by the distance $|\gamma|D^2/2$ from the antenna, where γ is the propagation constant of the medium. The far-field of antenna focusing in infinity is also known as Fraunhofer region.

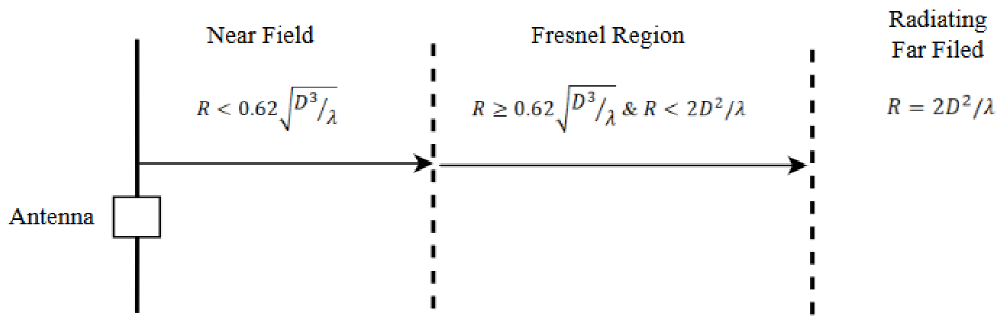


Figure 6. Antenna amplitude pattern in different regions [21].

In Figure 6, the different amplitude pattern of those fields is depicted. Due to the variation of phase and magnitude those fields shows different amplitude patterns with distance. For a typical shape of an antenna with largest dimension D, the reactive near-field amplitude pattern is spread with slight variation which is nearly uniform. In the Fresnel region the pattern started being smooth and also started to form lobes. In the far-field or Fraunhofer region the well-formed amplitude pattern is seen which has one major lobe and might have few minor lobes. Lobes are discussed in details in the section of beam-width.

2.1.4. Path Loss

Path loss is an important element for designing any radio communications system. It determines the transmitter power, antenna gain, height and location of the antennas in the radio communications system. Path loss is used to calculate the signal strength in different locations. In case of installing the wireless local area network (WLAN) systems in the large indoor area e.g. office, university, shopping mall etc. the path loss is vital due to the presence of signal obstacles and complex design of the buildings.

Path loss is the reduction of signal strength as it travels through the space or any other medium. There are several reasons for this loss. Those reasons and the calculation of path loss will be discussed in this section.

Free space loss: Due to the spreading of the signals in the open space the power density reduced for increased distance from the source or transmitter. If we consider the signals are spreading in an increasing sphere then by the law of conservation of energy it is clear that energy of the signal will be reduced for an increased area or in other words with increased distances.

Absorption loss: When the radio signals penetrate through different medium other than free space then the signal power is absorbed with a quantity depending on the strength of the signal and also the material the radio wave passing through.

Multipath: The radio signals can reach a certain destination using multiple paths. As the radio waves have their different phases, it causes addition or subtraction of signals due to the presence of multiple signals in a certain position. It causes loss of the signal.

Diffraction: The radio signals are diffracted by the objects of its propagation path. The rounded objects cause more diffraction of signals than the sharp edged objects.

Buildings and vegetation: Buildings are constructed with different materials which causes absorption of signals depending on the material and the complexity of the design. Also the trees between the line of sight of radio transmitter and the receiver cause attenuation of the signals.

Atmosphere: The layers of gases are surrounding the earth which causes the reflection of the radio signals. Depending on the frequency range of the radio waves, those are reflected or refracted by different layers of gas sphere which causes multipath and losses of signals.

The attenuation or path loss amount varies materials to materials. Here the calculation of free space path loss will be discussed. When the radio wave propagates through the air without being diffracted then this calculation is valid. The free-space path loss depends on the distance between the transmitter and the receiver [22]. If the receiver is d meters apart from the transmitter which has frequency of f hertz and corresponding wavelength λ then the equation of free-space path loss (FSPL) is as follow.

$$FSPL = ({}^{4\pi d}/_{\lambda})^2 \tag{2.3}$$

As $\lambda = c/f$ where c is the velocity of light the equation can also be written in logarithmic scale (in terms of decibels, dB) as

$$FSPL = 10\log_{10}\left(\left({}^{4\pi df}/_{c}\right)^{2}\right) \tag{2.4}$$

Simplified equation $FSPL = 20\log_{10}(d) + 20\log_{10}(f) - 147.55$ (2.5)

The path loss is usually calculated in decibels along with the gain of transmitter and receiver to ease the total calculation process. In the next section it will be discussed briefly.

2.1.5. Link Budget

Link budget is a method of theoretical assessment of radio link's visibility. Here the calculations provide the theoretical approximation only, and those are not accountable for the real world variables that can affect system performance. To avoid the difference between the theoretical and observed measurements, all the link budgets should be verified before installing the communication systems.

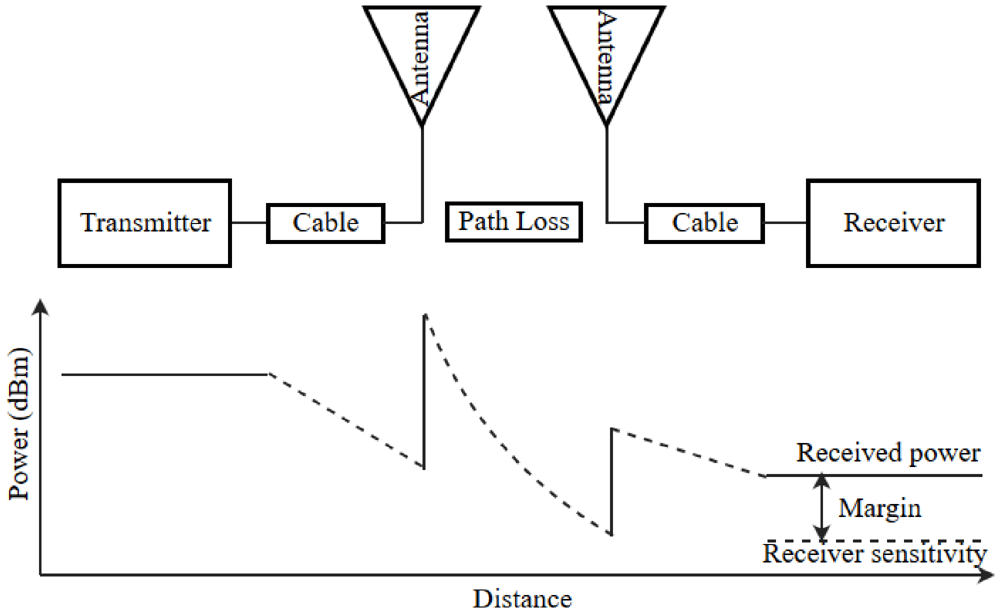


Figure 7. Link budget calculations.

In Figure 7, a typical link budget for WLAN communication system has been showed. The received power of 802.11 or WLAN link is determined by three factors. Those are transmitting power and gain of antenna. The straight lines represent the stable or increment of signal power where the dotted lines represent the loss due to various cases. This scenario is applicable when both the transmitter and the receiver are active. In the passive signal strengthening system there are no input and output power, so no antenna gain will be taken into calculation. At the receiver end the received power must be above the minimum sensitivity level of the receiver. This is known as margin. Usually the margin is kept at least 10 dB or more. In this way the specification of the transmitter, receiver and the system is designed. It gives us the overall idea about the probable power usages in the both ends of communication link.

2.1.6. Link budget equation

Link budget is the calculation of all the gains and losses from the transmitter and propagation medium to the receiver in a communication system. It takes consideration of attenuation of the transmitted signal, antenna gains, feeding losses of the components. The basic form of link budget calculation can be written as follows

Received power (dBm) = Transmitted power (dBm) + Gains (dB) – Losses (dB).

This calculation is quite straight forward where it is a matter of accounting for all the different losses and gains between the receiver and the transmitter. After considering all the probable losses and gains of each link the typical link budget equation is given on equation (2.6).

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} - L_{TX} - L_{FS} - L_p - L_{RX} \tag{2.6}$$

Where,

P_{RX} = Received power (dBm)
P_{TX} = Transmitted power (dBm)
G_{TX} = Transmitter antenna gain (dBi)
G_{RX} = Receiver antenna gain (dBi)
L_{TX} = Transmitter feeder and associated loss (dB)
L_{FS} = Free space path loss (dB)
L_p = Miscellaneous signal propagation losses (dB)
L_{RX} = Receiver feeder and associated loss (dB)

In the basic link budget equation, there is no consideration of antenna gain, as it is assumed that the power spreads out equally in all directions from the source. It is considered that the antenna is an isotropic source, radiating equally in all directions.

This assumption is good for theoretical calculations, but in reality all antennas radiate more in some directions rather than in all direction. In addition to this it is often necessary to use antennas with gain to enable interference from other directions to be reduced at the receiver, and at the transmitter to focus the available transmitter power in the required direction. As our system is passive, the gain of the antennas will be omitted [23].

Link budget calculations are an essential step in the design of a radio communications system. The link budget calculation enables the losses and gains to be seen, and devising a link budget enables the apportionment of losses, gains and power levels. Only by performing a link budget analysis this is possible.

2.2. Parameters of Antennas

As there are no active elements present in the passive system, the designing of antenna is that's why very important to get the highest performance from the system. This section describes the parameters of antenna. For designing the antenna and the purpose of usages these parameters must be considered beforehand.

2.2.1. Radiation Pattern

Radiation pattern of an antenna is the graphical representation or mathematical function in three dimensional space coordinates. It is usually measured in far-field region. This radiation property is consisted of directivity D and intensity U which is measured in watts/units solid angle. In Figure 8, the spherical coordinates are illustrated [21]. Power and field patterns are used to characterize the radiated power in the far-field region. The antenna's field pattern is plotted in electric and magnetic field which is a function of angle at a fixed distance. The power pattern of the antenna is plotted by the square of electric field which is also a function of angle at a constant radius [21] [24].

Based on radiation pattern, the antennas are grouped into three major sections. Those are isotropic, directional and omnidirectional antennas. Isotropic antenna exists theoretically where it can radiate power uniformly in all direction. It is used to make reference for other antennas so the radiation in a particular direction of that antenna can be compared. For the directional antenna it is beneficial if the radiation pattern is directed through a certain direction rather than in every direction. In the omni-directional cases, those have the radiation pattern in the vertical and horizontal plane.

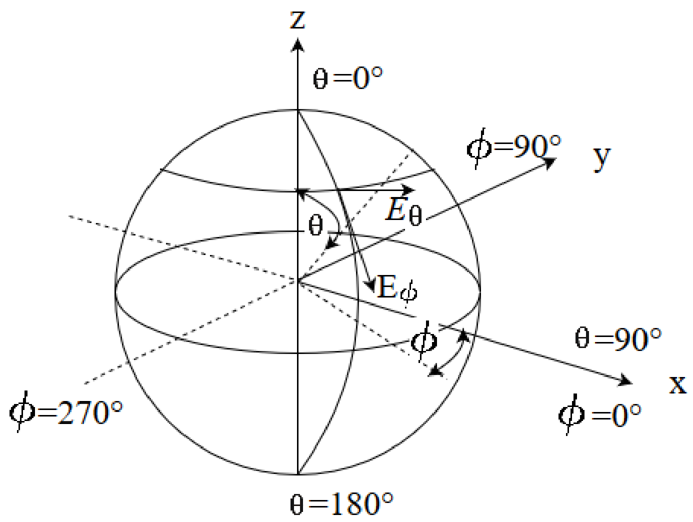


Figure 8. Radiation pattern coordinate system [21][24].

In this spherical coordinates system there are two principal planes known as azimuth plane and elevation plane. In Figure 8, the x-y plane where $\theta = 90°$ is the azimuth plane or sometimes mentioned as '*the horizon*' and the y-z (or x-z) plane where $\phi = 90°$ (or $\phi = 0°$) is called elevation plane also known as '*the vertical*' plane. The pattern of azimuth plane is measured when the measurement is done traversing the entire x-y plane around the antenna. On the other hand the elevation plane is orthogonal to the azimuth plane and made traversing the entire y-z plane. This radiation pattern provides an illustration to visualize the radiation direction in three dimension space [25].

The portions of the radiation patterns are called lobes. Depending on the level of power of those lobes, those are categorized as main lobe, side lobes and back lobe. The main lobe has the greatest field strength. The side lobes are the unwanted result of radiation mechanism. The lobe which is totally opposite of the main lobe is the back lobe. For the directional antennas, the objective is to emit the radio waves in a certain direction. The lobe of that direction is designed to have maximum field strength than the other lobes.

2.2.2. Beam width

Beam width is the aperture angle from where an antenna can radiate most of its power. There are two main considerations of beam width. Those are Half Power Beam Width (HPBW) and Full Null Beam width (FNBW).

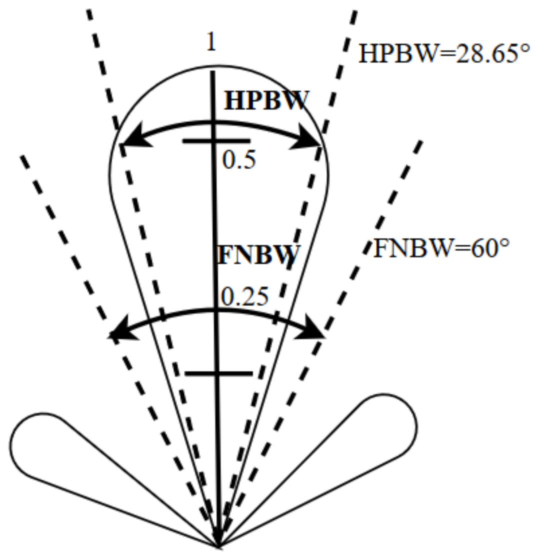


Figure 9. Two dimensional power pattern [26].

Figure 9 demonstrates the various points of main lobe. HPBW is the angle where the relative power of effective radiated are is than half of the peak power. The HPBW is defined as the angular separation where the magnitude of the radiation pattern decreased by 50% or -3 dB from the peak of the main beam. The angular separation between the first nulls of the pattern is referred as FNBW. The beam width determines the merit and trade-off between the main lobe and the side lobes. It is because when the main lobe decreases the side lobes are increased and vice versa. The determination capacity of an antenna is to recognize two sources equal to half of the FNBW, which is approximately equal to HPBW [26].

2.2.3. Radiation Intensity

Radiation intensity is measured in a given direction, which is the power radiated from an antenna corresponding unit solid angle. It is dependent on the radiation density and the square of the distance from the antenna. The mathematical equation of radiation intensity (U) is, $U = r^2 W_{rad}$, where r is the distance from the antenna and W_{rad} is the radiation density. The radiation density is defined as the multiplication of electric field and magnetic field vector $E \times H$. It is measured in watt per square meter.

The total radiating power (P_{rad}) can be obtained by integrating the radiation intensity over the entire solid angle 4π.

$$P_{rad} = \int_0^{2\pi} \int_0^{\pi} U \sin\theta \, d\theta d\phi \tag{2.6}$$

If the source is considered isotropic (theoretically) then the radiation intensity will not depend on the azimuth and elevation angles θ and ϕ. So then the total radiated power will be as follows.

$$P_{rad} = \oiint_{0\,0}^{2\pi\,\pi} U_0 \sin\theta \, d\theta d\phi = 4\pi U_0 \tag{2.7}$$

U_0 is used for isotropic case.

By the radiation intensity it is possible to realize how much power is being radiated in a specific far-field direction, because the radiated power varies in magnitude. This variation depends on the direction of observation and also the distance from the antenna in far-field. To get the distance independent radiation intensity it is required to normalize the electromagnetic power in calculation [26].

2.2.4. Directivity

Directivity of an antenna makes the realization of radiation intensity compared to the radiation intensity of an isotropic antenna. So the ratio of radiation intensity of an antenna to a particular direction and the radiation intensity of an isotropic antenna is defined as the directivity of that antenna. The higher the ratio, the more directive the antenna is. The directivity (D) is thus,

$$D = {}^{U}/_{U_0} \tag{2.8}$$

By replacing the value of U_0 in eq. (2.8) from eq. (2.7) we get,

$$D = {}^{4\pi U}/_{P_{rad}} \tag{2.9}$$

Sometimes the direction of the antenna is not specified and, in that case, the dimensionless directivity is measured considering the maximum radiation intensity (U_{max}) and then it is called maximum directivity (D_{max}).

$$D_{max} = {}^{U_{max}}/_{U_0} \qquad (dimensionless) \tag{2.10}$$

Polarization of antenna affects the calculation of the directivity. Polarization has been discussed in section 2.2.6. In case of orthogonal polarization the directivity measured partially and by combining those, the total directivity is found. For example the partial directivity of θ and ϕ direction is expressed as D_θ and D_ϕ respectively. And the total directivity equation becomes $D_0 = D_\theta + D_\phi$, where D_0 represent the total directivity [21]. Also the partial directivity is dependent on the partial radiation intensities of the corresponding field component (azimuth and elevation angles).

For the isotropic antenna the directivity is unity as it radiates in all direction equally, but for all other antennas the directivity is greater than unity. It gives the idea about the amount of directivity of an antenna. While designing an antenna considering the directivity, it can be controlled by varying the size of the radiating source. For example the antennas small in size (from quarter wavelength to half wavelength) are poorly directive. If the antenna is several wavelengths long then it shows more directivity. That is why the dish antenna is more directional compared to the half wavelength dipole antenna.

2.2.5. Antenna Efficiency and Gain

Antenna efficiency indicates the difference between the supplied power to the antenna and radiated power from the antenna. For calculating the total efficiency, it is required to consider all kinds of losses of the input terminals and within the structure of the antenna. So in considering the design procedure, it is required to make sure that the antenna will transmit the input power efficiently.

The total efficiency of an antenna is consisted of two types of efficiency. One is reflection efficiency, which is also known as matching efficiency and another is radiation efficiency. Radiation efficiency is the ratio of total received power to the total transmitted power of the antenna [18]. It takes account of structural losses for both conducting and dielectric part of the antenna.

$$e_{rad} = {}^{P_r}/_{P_{in}} = {}^{R_r}/_{R_{in}} = {}^{R_r}/_{R_r + R_L} \qquad (2.11)$$

e_{rad} = Radiation efficiency
P_r = Radiated power
P_{in} = Input power of antenna
R_r = Radiation resistance
R_L = Internal resistance of antenna

The equation of reflection efficiency as follows.

$$e_{ref} = (1 - |\Gamma|^2) \qquad (2.12)$$

Thus the total efficiency becomes $e = e_{rad} e_{ref}$ (2.13)

The ratio of radiation intensity in a particular direction of an antenna to the radiation intensity of isotropic antenna at some constant distance from the radiation point is known as Gain. Higher gain of an antenna is comparatively more directive. In general the equation of gain is expressed as

$$Gain = 4\pi \frac{Radiation\ intensity}{Total\ input\ power} \qquad (2.14)$$

The total efficiency is also related to the gain and written as $G = eD$. Here D is the directivity. The amount of input power conversion into radio waves and vice versa is determined by the gain of an antenna.

2.2.6. Polarization

Polarization of antenna is the polarization of the radiated wave. It is measured in the line of propagation. In the far field of the antenna, the electric and magnetic components are perpendicular to each other. The phase of those two components might vary for different types of antenna. Depending on the phase, the antennas are mainly categorized into three polarization classes. These are Linear, Circular and Elliptical polarization illustrated on Figure 10.

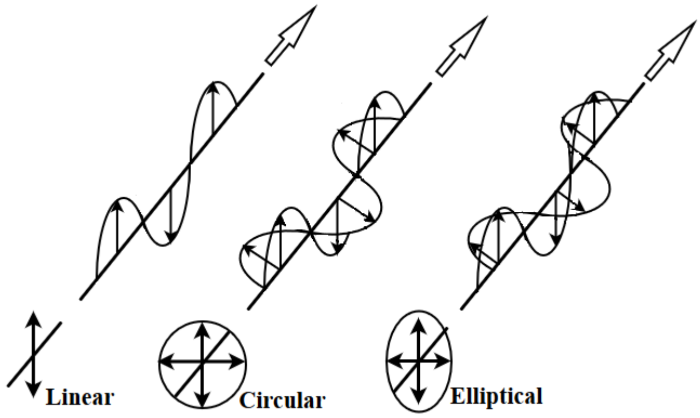


Figure 10. Different classes of polarizations [28].

As the electromagnetic wave is the resultant wave of the both E and H component, the propagation of that electromagnetic wave changes because of phase variation or no phase difference. Linear polarization happens when there is no phase difference between the E and H fields, then the electromagnetic wave propagates in same straight line, although the magnitude of that wave varies within that line of propagation. It is because when the both electric and magnetic component has zero magnitude then the resultant electromagnetic wave also has zero value. In case of maximum magnitude of those two components the resultant wave reaches to the maximum which is shown in the first picture of Figure 10. The linear polarization is subcategorized into vertical and horizontal linear polarization. It depends on the orientation of the radiating elements. In horizontal polarization the electric field's traces follows a horizontal line while it is vertical for vertical linear polarization [28].

If any of the E and H component has a 90° phase shift, then the resultant electromagnetic wave gets constant amplitude but rotating around the line of propagation. On the second part of the Figure 10 causes circular polarization because of their 90 degree phase difference between the electric and magnetic component. It is also separated into two classes, right hand and left hand circular polarization. If the rotation of the constant magnitude electromagnetic wave is clock-wise in the direction of propagation then it is defined as right hand circular polarization (RHCP). For anti-clock-wise case it is left hand circular polarization (LHCP) [24].

The elliptical polarization occurs when there will be a phase difference but which is not a quarter wave or 90 degree. In this case the resultant electromagnetic wave propagates in elliptical orientation. By varying the phase of E and H component different shapes of ellipses can be made. It has been showed in the third part of the Figure 10. The right and left hand elliptical polarization happens according to the clock-wise and anti-clock-wise rules as before [24].

In practical application for non-identical polarization in transmitting and receiving ends, there will be loss of signal strength. For example linearly and circular polarized antenna can work on the two ends of the communication systems but there will be at least 3 dB signal strength loss compared to the same polarized antennas [28].

2.2.7. Bandwidth

In general bandwidth means the ranges of frequencies used. For an antenna, bandwidth indicates the frequency ranges of transmitting and receiving energy. According to the ranges the antennas are classified into broadband and narrowband antennas. Broadband antennas have wider ranges of operating frequencies where the narrowband antennas have lower ranges. In both cases the upper frequency (F_U) is the end most operating frequency and the lower frequency (F_L) is the minimum operating frequency. As the difference between the F_U and F_L is higher in case of broadband, the ratio of those two frequencies is represented, example is shown in Figure 11. For example 10:1 broadband antenna means the higher frequency is 10 times than the lower frequency. On the other hand the bandwidth of narrowband antennas is represented in the percentage form of $(F_L - F_U)/F_C \times 100$ where F_C is the center frequency [21].

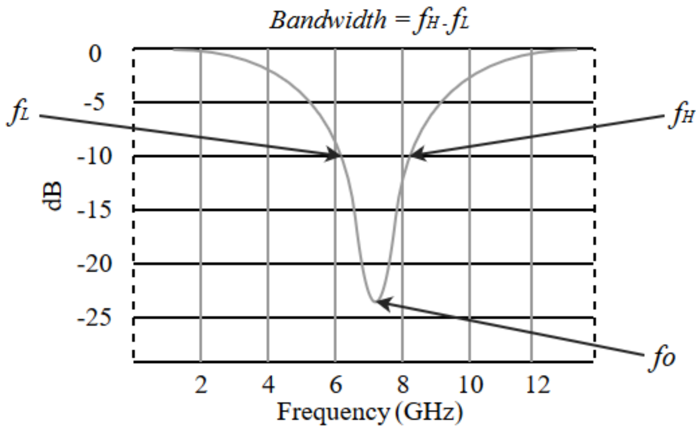


Figure 11. Antenna bandwidth [21].

The bandwidth of an antenna can be found by measuring the S-parameter curve. S-parameter curve depicts the reflected power from the antenna input port because of the impedance mismatching. In general, the return loss of 10 dB is the threshold point of measuring the operating bandwidth. For example, in WLAN operation the 10 dB impedance bandwidth should be 40 MHz, keeping the center frequency at 2.43 GHz [29].

2.2.8. Antenna Input Impedance

Input impedance of an antenna is the ratio of voltage to current in the input terminal of the antenna [21]. The value of input impedance of the antenna indicates the amount of power accepted from the transmitter or delivered to the receiver. In design consideration this parameter has great impact as the antenna is operated along with the other circuits and transmission line. So the maximum performance from that antenna can be found only when the impedance is well matched with the other parts of the main circuit.

$$Z_a(\omega) = {V_{in}}/{I_{in}} = R_a(\omega) + JX_a(\omega) \tag{2.15}$$

The equation 2.14 represents the mathematical expression of input impedance. Here V_{in} and I_{in} are the voltage and current respectively, provided to the input terminal of the antenna. R_a is the total resistance of the of the antenna which is frequency dependent. X_a is the frequency dependent reactance. ω is the angular frequency which is equivalent to $2\pi f$ where f is the operating frequency of the antenna. The equivalent circuit of the antenna can be drawn as Figure 12.

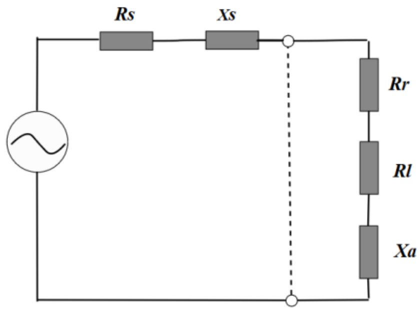


Figure 12. Equivalent circuit of an antenna [30].

R_a is the combination of radiation resistance R_r and loss resistance R_l or can be written as $R_a(\omega) = R_a(\omega) \ +R_l(\omega)$. The radiation resistance is measured by calculating the total height of the antenna where the loss resistance is dependent on the dielectric and conductive characteristics of the material of the antenna [30].

2.2.9. Reflection Coefficient

Reflection coefficient of an antenna is an important parameter for quantitative evaluation of the performance of that antenna. The value of reflection coefficient shows the effectiveness of a load for instance antenna is matched with the transmission line. The calculation of input impedance is as equation (2.16).

$$\Gamma = |S_{11}| = {Z_a - Z_0}/{Z_a + z_0} \tag{2.16}$$

Γ = Voltage reflection coefficient.
S_{11} = Single element obtained from scattering parameter matrix of single port network.

Z_a = Impedance of the antenna.
Z_0 = Characteristic impedance of the transmission line.

An important goal of antenna designing is to minimize the reflection coefficient as much as possible to the antenna port, at the desired operating frequency. The value of reflection coefficient zero means the antenna is matched perfectly which also indicates that the impedance of the antenna and the characteristic impedance of transmission line are matched equally. The value of Γ varies from -1 to +1 in different cases. The value -1 represents complete negative reflection in short-circuited line case and +1 is for positive reflection. It happens when the line is open-circuited [30].

3. STUDY OF USED WLAN ANTENNA TYPES

3.1. Patch Antennas

Patch antenna is a low profile radio antenna which can be easily mounted on a flat surface. When a flat metal sheet which is known as patch is placed over another larger metal sheet which works as ground and there is a layer of dielectric materials then it is called a patch antenna. The main advantage of patch antenna is the directivity properties and it costs low for fabrication, forming array of antennas is easier and light weight. Although there are few disadvantages like it has limited relative bandwidth for instance 1% to 5% with low power handling capability [31].

The size of the patch antenna is frequency dependent. The size of the patch is inversely proportional to its frequency and thus why it is not suitable for low frequency radio communication. For example for frequency modulation (FM) radio communication if a patch antenna is used then the size of the patch would be 1 meter long, which is not feasible for practical usages. So for high frequency application like WLAN in 2.4 GHz or 5 GHz the size of the antenna becomes very small [32].

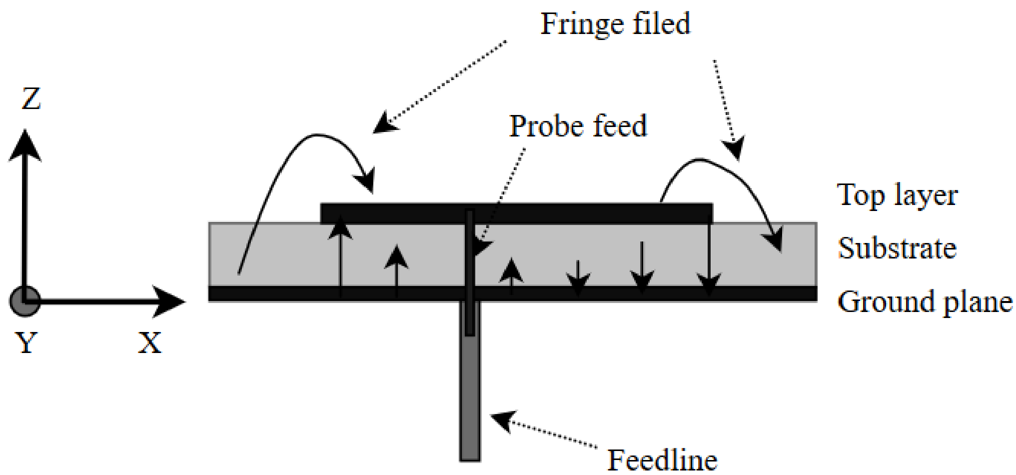
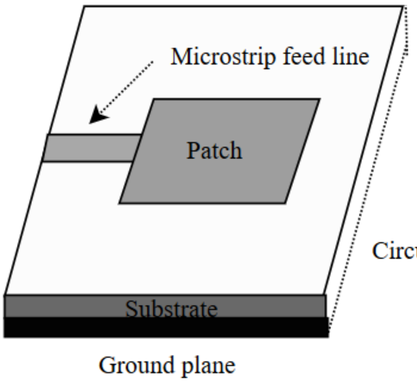


Figure 13. Cross section of the patch antenna [31].

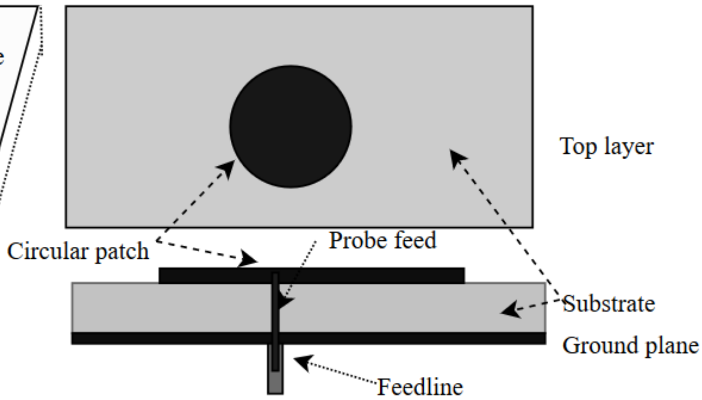
The cross section of a typical patch antenna is shown in the Figure 13. The center conductor of a coaxial cable serves as the feed probe. It couples the electromagnetic energy in and out of the patch. The feed can also be made by mictostrip line which is convenient for installing the antenna along the printed circuit board with other RF parts of the device [31].

3.1.1. Feeding techniques

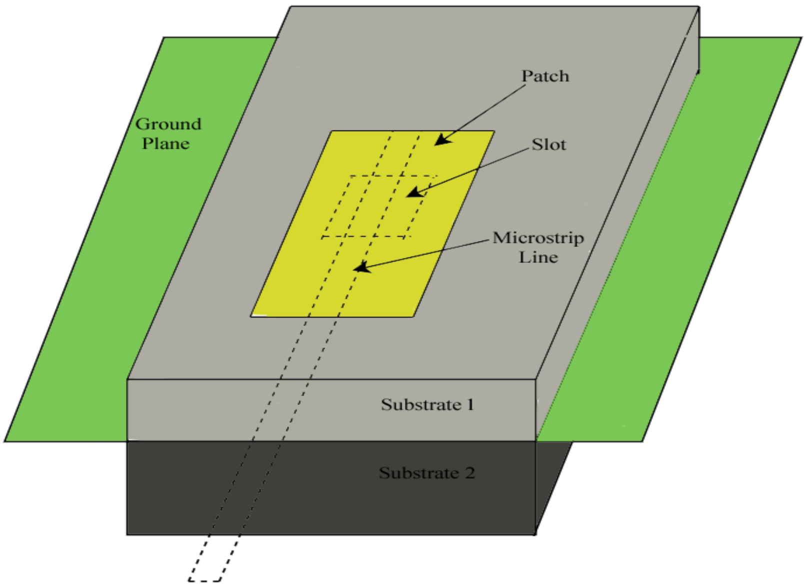
There are mainly four methods practiced to feed the patch antenna. Those are coaxial probe, microstrip line, aperture coupling and proximity coupling. Figure 14 shows different feeding techniques.



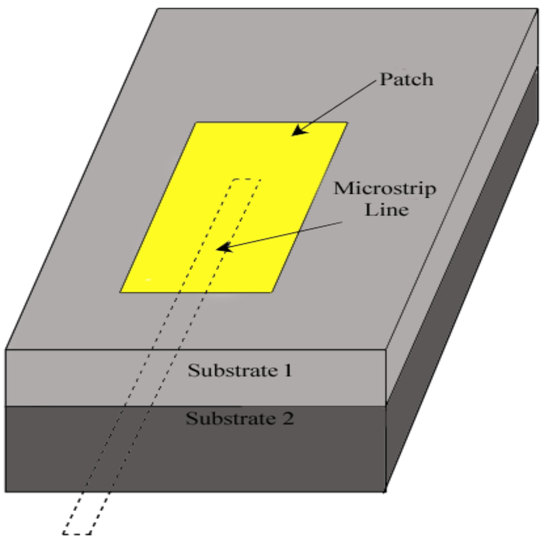
(a) Microstrip line feed



(b) Probe feed



(c) Aperture-coupled feed



(d) Proximity-coupled feed

Figure 14. Different feeding methods of patch antenna [21].

In coaxial fed patch, the inner conductor is connected to the radiating patch and the outer conductor to the ground plane. The good spurious response and easier matching are the brighter side of this modeling, where the disadvantage is narrow bandwidth. It is also difficult to model with thin substrate height [21].

The fabrication of microstrip line fed patch is comparatively easier, also matching with other component can be found easily by varying the inset position of the microstrip line. The limitations of this feeding method are the increment of spurious feed radiation and surface waves. This limits the bandwidth to 2% to 5% [21].

In aperture coupling method there are two substrate layers separated by the ground plane where typically a higher dielectric material is used for bottom substrate and the lower dielectric material on the upper substrate. In the bottom substrate layer there is a microstrip feed line from where the energy is coupled through a slot on the ground plane which separates the two substrates. The matching is done by controlling the width of the feed line and by varying the length of the slot [19] [21].

The proximity-coupled fed patch antenna higher bandwidth compared to the other feeding methods. Here multiple substrate layers are also used and the microstrip line is used for feeding which is inserted between the two substrate layers. There is no slot like aperture coupling method. The modelling of proximity-coupled feed patch antenna is easier but difficult to fabricate. The width and feeding stub is used to control the matching characteristics.

3.1.2. Circular patch antenna

The circular patch is one of the most popular configurations of the patch antennas. This configuration works on both for single and array operation. The degree of freedom for designing the circular patch antenna is the radius of the patch only. By varying the radius of the patch, the resonant frequency of the antenna can be achieved. The calculation of radius can be found by the following formula [33].

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi \epsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}} \tag{3.1}$$

where

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\epsilon_r}} \tag{3.2}$$

Where

a = Patch radius (cm)
F = Operating frequency (Hz)
h = Substrate height (cm)
ϵ_r = Dielectric constant
f_r = Resonance frequency (Hz)

At the edge of the patch antenna the electric flux line bends, which is shown in Figure 13. This is known as fringing effect. Due to this bending of the electric flux, electrically the patch becomes larger. So the effective radius is slightly different from the theoretical one, and the formula for the effective radius is given in equation 3.3.

$$a_e = a\left\{1 + \frac{2h}{\pi\epsilon_r F}\left[\ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2} \tag{3.3}$$

where a_e represents the effective radius of the patch and hence the resonant frequency (f_r) equation changes accordingly. The equation 3.4 shows the dominant transverse magnetic mode where v_0 is the velocity of light in free space [33].

$$f_r = \frac{1.8412 v_0}{2\pi a_e \sqrt{\epsilon_r}} \tag{3.4}$$

These are basic design formulas for the circular patch antenna.

3.1.3. Circular patch modeling

Due to relatively good directional capabilities, the circular patch antenna has been chosen for the receiving purpose on the passive system. The connection between the two antennas is made by the coaxial cable, so the patch antenna is chosen as pin fed circular patch [32].

According to the calculation represented on section 3.1.2 the theoretical operating frequency of the patch antenna is

$$F = \frac{8.791 \times 10^9}{2.4 \times 10^9 \sqrt{4.3}} = 1.7664$$

The radius can be found by using the equation 3.1 which is 1.6959 cm.

$$a = \frac{1.7664}{\left\{1 + \frac{2 \times 0.24}{\pi \times 4.3 \times 1.7664}\left[\ln\left(\frac{\pi \times 1.7664}{2 \times 0.24}\right) + 1.7726\right]\right\}^{1/2}}$$

$$= 1.6959\ cm$$

Due to the fringing effect the effective radius is increased and by the equation 3.3, it is found that for the WLAN operation, the effective radius of the patch will be 1.77 cm.

$$a_e = 1.6959\left\{1 + \frac{2 \times 0.24}{\pi \times 4.3 \times 1.7664}\left[\ln\left(\frac{\pi \times 1.6959}{2 \times 0.24}\right) + 1.7726\right]\right\}^{1/2}$$

$$= 1.7658\ cm$$

In the above calculation, the substrate height $h = 2.4\ mm$ has been used of FR-4 substrate which dielectric constant, $\epsilon_r = 4.3$. So the theoretical diameter of the patch will be 3.5316 cm or 35.316 mm, and the diameter used in the prototype antenna is 33 mm.

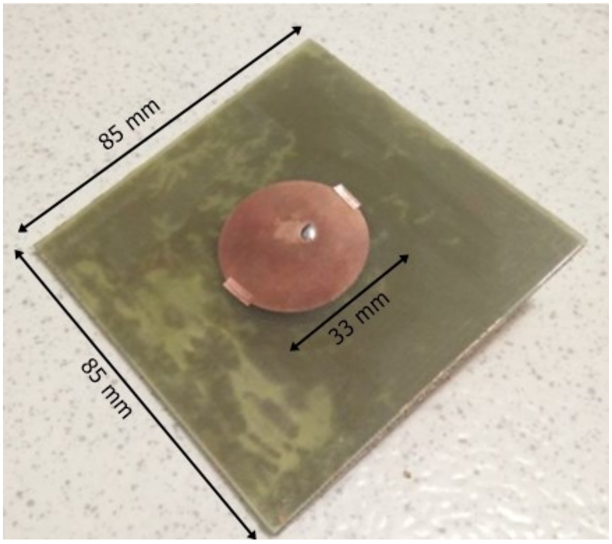


Figure 15. Fabricated patch antenna.

According to the equation presented above and considering the simulation model the fabricated patch antenna was built which is presented in the Figure 15.

3.2. Dipole Antennas

In telecommunications a dipole antenna is the most widely used antenna. It is built by using two identical conductive elements. For a dipole antenna of length L centered along with the z-axis the current flows according to the following functions.

$$I(z) = \begin{cases} I_0 \sin\left[k\left(\frac{L}{2} - z\right)\right], & 0 \leq z \leq \frac{L}{2} \\ I_0 \sin\left[k\left(\frac{L}{2} + z\right)\right], & -\frac{L}{2} \leq z \leq 0 \end{cases}$$

This current oscillates in the time domain at frequency f sinusoidally. For the quarter wave and full wavelength, the current distribution is shown in Figure 16.

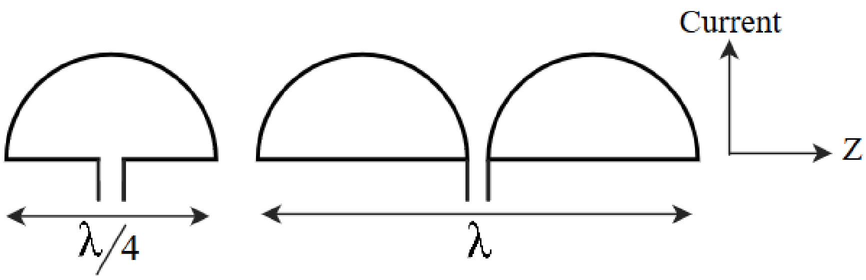


Figure 16. Current distribution for finite length dipole antennas [23][24].

The far field of the dipole antenna can be constructed by the equation 3.5 and 3.6.

$$E_\theta = \frac{j\eta I_0 e^{-jkr}}{2\pi r}\left[\frac{\cos\left(\frac{kL}{2}\cos\theta\right) - \cos\left(\frac{kL}{2}\right)}{\sin\theta}\right] \tag{3.5}$$

$$H_\phi = \frac{E_\theta}{\eta} \tag{3.6}$$

In case of directivity, the full-wavelength dipole antennas are more directional than the shorter wavelength antennas. The radiation pattern is symmetrical while it is viewed azimuthally. It is not dependent on the azimuth angle ϕ. This characteristic made the dipole antenna omnidirectional. Two dimensional radiation pattern of the half-wavelength dipole antenna is illustrated on Figure 17 [21][24].

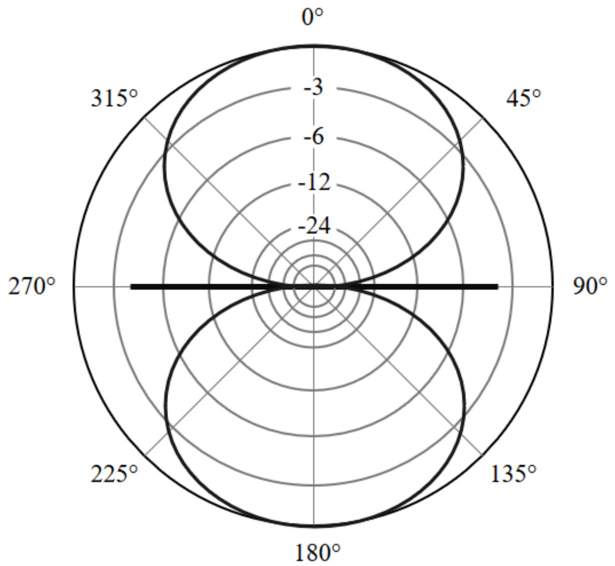


Figure 17. Horizontal (E-field) radiation pattern of half a wavelength dipole antenna [24].

3.2.1. Dipole model

In this study an omnidirectional rubber duck antenna has been used. Figure 15 depicts the outlook of that antenna. The length of thin wire whip protruding from the top of the metal casing is approximately 26 mm, and the length of the metal casing is approximately 24 mm, with a total length of 50 mm. The rubber ducky antenna is also commonly referred to as a rubber duck antenna, or a rubber ducky antenna [34].

Figure 18. Dipole omnidirectional rubber duck antenna [34].

The inside of these antenna elements with a balun is presented on the Figure 18. The cutaway view reveals that it is just a half-wave dipole antenna, with one half of the dipole comprising of the metal casing, and the other half comprising the whip extending from the top of the casing.

The bottom end of this antenna contains a plastic spacer, and its sole purpose is to keep the coax centrally located inside the metal casing. The coax extends from the rpTNC (Threaded Neill–Concelman) connector at the base of the antenna, up through the metal casing, and the top end of the casing has been crimped onto the coax braid, to provide a solid electrical and mechanical join. The center core of the coax extends through this crimped join, and becomes the whip at the top of the antenna [34].

Each half of the dipole is a 1/4 wavelength, with the length corrected based on the velocity of the coax being used. For the center frequency for 802.11b of 2.44 GHz, a 1/4 wavelength in free space is 30.7 mm.

3.2.2. Study of Repeaters

A repeater is simply a device that receives incoming signal and retransmits the signal either adding power or around an obstruction. Unlike a mobile phone tower, a repeater does not interpret the signal in any way and hence any incoming signal on the repeaters frequency will also be retransmitted for instance, noise.

According to the signal amplification characteristics the repeaters are divided into two categories. If there is any signal amplification is done by using electrical power and other components then it is called active repeater. When the repeater does not consume any electrical power, it is known as passive repeater. More details will be discussed on the following sections [35].

3.3. Active Repeaters

Using an active wireless repeater provides the most effective solution for non-line-of-sight cases. When two microwave radio units are directly connected back-to-back, there is minimal signal loss and almost no additional latency added to the network. An example of this would be to have a wireless point to point link from a building to a rooftop of another building (whether a building used by a client's organization or a leased rooftop access) and then another point to point wireless link from that rooftop to the other building needing wireless connectivity [35].

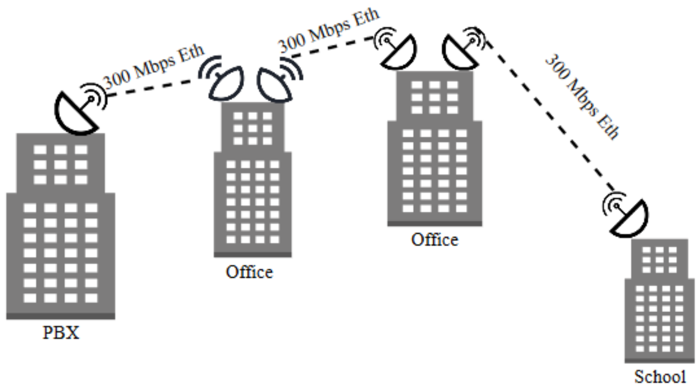


Figure 19. Roof top active repeating system [35].

In Figure 19 a system has been shown where for covering the greater region of communication, the roof top active repeating system is built. The distance of a point to point microwave link depends on the wireless frequency, antenna size, and output power used. In general point to point microwave communication can go upwards of 50 miles. In some cases a client may need to create a wireless backhaul greater than that. In this case using an active wireless repeater will allow a wireless link to be expanded over large distances. In a typical example of this solution is using microwave communication towers as a wireless repeater site. There are thousands of wireless communication towers that allow for clients to lease space off of completing their wireless backhaul networks.

3.4. Passive Repeaters

Passive repeating systems do not need any on-site electric power. In these types of systems therefore, less maintenance is required to keep the system working. It is also very simple compared to the active repeater, for instance there is no need to occupy space for any other equipment, for instance, no power supply unit or remote monitoring devices. This is environment friendly and also no regular road access is required.

A passive site can also be used to simplify the active repeater requirements. In other words, instead of building a tall tower with a long access road, a passive site can be used to redirect the signal to a more practical site with a short tower and short access road. This reduces the cost and improves the environmental impact of the site. Since passive repeaters can be built in high areas not normally suitable for an active site, there is more flexibility to get the site to blend in with the environment [35].

According to the used component, the passive repeater is divided in to two categories. One is reflector type and another is antenna to antenna connected with coaxial cable. Those will be described on the next subsections.

3.4.1. Plane Reflector

Plane reflectors essentially consist of a large, flat "drive-in screen" type aluminum plate that serves to reflect the signal and redirect it around the offending obstruction. This results in no signal distortion, because a flat conductive surface is linear. It can also support any frequency band because it is a wideband device. Being flat, large, and highly conductive also means it is 100% efficient compared to parabolic dishes that are typically only 55% efficient. They can achieve impressive gain figures due to their efficiency and the fact that they can be built to huge dimensions. Reflectors which are big as 12m by 18m are readily available. The gain of passive repeaters increases with the size of it. The larger the reflector plane is, the greater the capture area and the greater the gain (or the less the real passive insertion loss). In order to determine the size of the reflector it is required to work on path power budget and determine the required fade margin. The required system gain should be obtained by a combination of increasing passive gain and the gain of the two antennas at the end of the link, until the fade margin objective is met. Practical considerations and cost should balance an increase of antenna size and passive reflector size [35]. The insertion loss can be calculated as

$$IL = FSL - (FSL_1 + FSL_2) + G \tag{4.1}$$

here FSL denotes the total free space loss, where FSL_1 is the free space loss of the distance from site 1 to the passive site and FSL_2 is the free space loss of the passive site to the site 2, shown in Figure 20. G is the reflector gain in dBi. It is expressed as

$$G = 42.8 + 40 \log f\ (GHz) + 20 \log A_a\ (m^2) + 20 \log(\cos\theta/2) \tag{4.2}$$

where θ is the true angle between the paths.

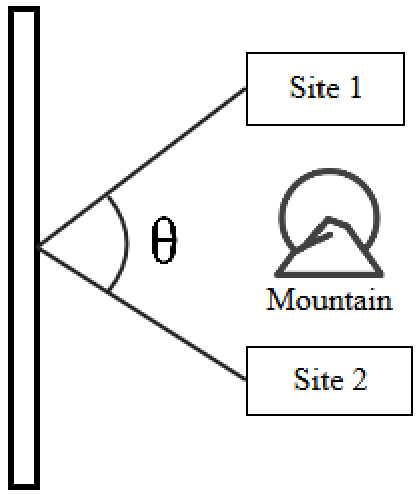


Figure 20. Reflector geometry is showing how two NLOS site are transmitting and receiving the signal by using a reflector [35].

The refection geometry of a reflector is represented on Figure 20. Here the two NLOS site communication is enhanced in terms of signal strength where the connecting path is making an angle of θ.

3.4.2. Back-to-back Antenna

Back-to-back antenna systems can be considered for short paths where there is a physical obstruction blocking the LOS. Two antennas connected by a short waveguide connection are positioned at a point where there is full LOS between each passive antenna and the respective end sites. The concept is to capture the microwave energy, concentrate it using the passive antennas, and retransmit it around the obstruction. A fundamental concept to understand when designing these systems is that the insertion loss is huge. Although one speaks of passive gain, the passive site always introduces considerable loss [35].

For the plane reflector passive sites, if the repeater is in the far-field of the two end-site antennas, the FSL is the product of the two FSLs rather than the summation. The two decibel losses must therefore be added together. This results in a very high overall FSL that must be overcome by the two back-to-back antenna gains. This limits the application to very short paths. Back-to-back antenna systems are less effective than plane parabolic passives because they are limited by the physical size of commercially available antennas and, being parabolic, are only 55% efficient. Since the path lengths tend to be very short, the main design consideration is just to achieve a useable receive signal with a minimum fade margin to ensure an adequate residual bit error ratio (RBER), which quantify the accuracy of the received data. The insertion loss (IL) of back-to-back antenna can be calculated by the equation 4.3. Here the gain G is replaced by the antenna gain A_e.

$$IL = FSL - (FSL_1 + FSL_2) + 2A_e \tag{4.3}$$

Where FSL denotes the overall free space loss, FSL_1 is the free space loss of the hop from site A to the passive site, FSL_2 is the free space loss of the hop from the passive site to site B, and A_e is the antenna gain (dBi) of each passive antenna.

4. MEASUREMENTS

The effect of the passive repeating system can be realized by taking the related measurements. To get the full picture from every aspect of the components of the systems, three measurement tools are used and these are Vector Network Analyzer (VNA), SATIMO StarLab and Wi-Fi analyzer. The basic working principle is discussed in this chapter and also those measured data are presented from different perspectives.

4.1. Antenna Measurements

The used antennas for the passive repeating system are firstly measured separately by which the performances parameters are found of each antenna. To get those data both the VNA and SATIMO StarLab were required for different parameters. For VNA measurement, a coaxial cable is needed. Before starting the measurement it needs to be calibrated to get the accurate data. The calibration method is open, short and through method to determine the optimum reference level for that coaxial cable. The commercial VNA of Anritsu is used for this measurement. The VNA used is of two port where only one port is needed to measure the antenna parameters. For SATIMO StarLab measurement, another coaxial cable is used. A horn antenna which is provided by that SATIMO manufacturer is used for the calibration the measurement device. Details of these steps are discussed on the following sections.

4.1.1. Vector Network Analyzing

A vector network analyzer is an instrument which can measure the network parameters of electrical networks for instance S-parameters as in case of high frequency operation the reflection and transmission of electrical network is easier to measure. The characteristic impedance and the position on the smith chart have been observed by this network analyzer. Other important parameters like VSWR, attenuation of the used coaxial cable and dielectric properties has been observed accurately by using this system.

The S-parameters represent the complex number in the form of magnitude and phase of the incident wave changed by the network [36]. In a multiport system the S-parameters are represented in a matrix which is called scattering matrix. For a 2-port network analyzer the scattering matrix can be written as the Figure 21.

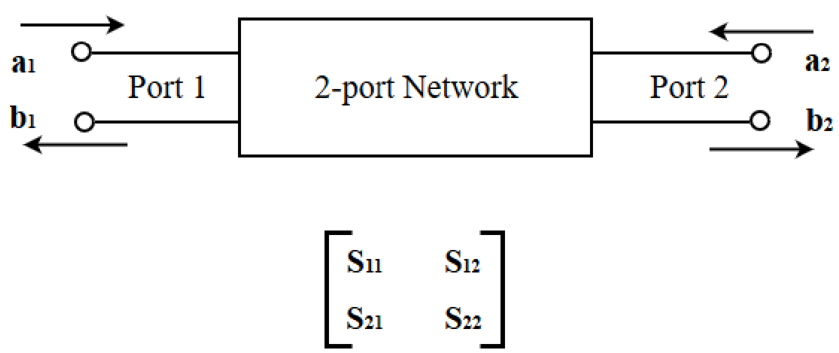


Figure 21. Scattering matrix for 2-port network.

Here 'a' and 'b' is for input and output port respectively, which can be either voltage, current or power travelling from one port to another port. With respect to incoming and outgoing signals the S-parameters can be defined as follows.

$$[b] = [S][a]$$
$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2$$

In general the scattering parameter to a destination port (j) from a source port (i) is written as S_{ij} and expressed as

$$S_{ji} = {b_j}/{a_i}$$

and

$$S_{ij} = {b_i}/{a_j}$$

S_{ii} and S_{jj} is also known as reflection coefficient or return loss. In this study a 2-port VNA is used for the measurement. Thus 2 × 2 S-parameter matrix is obtained where each S-parameter containing amplitude and phase. For an N-port network the scattering matrix is given below.

$$\begin{bmatrix} S_{11} \dots S_{1N} \\ . \quad\quad . \\ . \quad\quad . \\ S_{N1} \dots S_{NN} \end{bmatrix}$$

VNA is useful item of RF test equipment. It enables RF devices and networks to analyze the characteristics of the design and thus why it is being used widely even though they tend to be expensive.

4.1.2. Satimo StarLab Measurements

There are different systems available for measuring the radiation pattern, gain, efficiency and other related parameters. In this study, the measurement of the antennas is done by using the Satimo StarLab systems. The Figure 22 shows the chamber where the antenna is placed, which is surrounded by probe array to measure the radiation from various angles, which gives the idea about the three-dimensional radiation pattern.

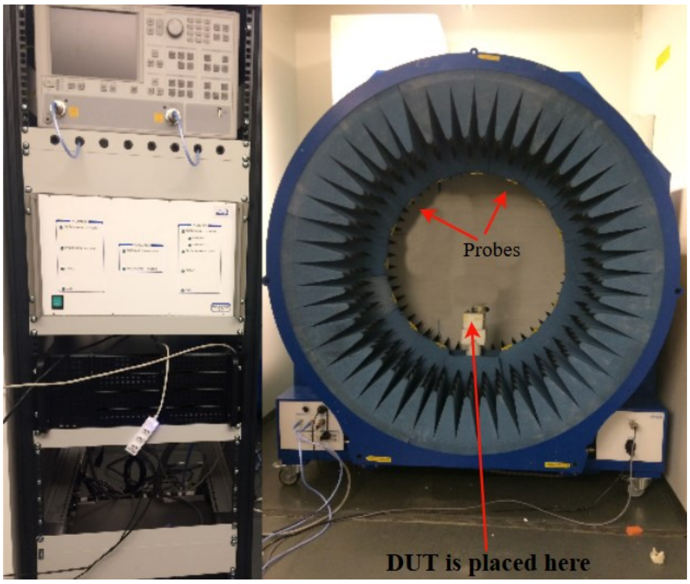


Figure 22. Satimo StarLab measurement system [37].

It is equipped with the vector network analyzer, active switching unit, radio communication tester, amplification unit and a control unit. The function of the switching unit is to switch between the probes. Vector network analyzer performs the antenna measurements. To rotate the antenna during the measurement, the control unit drives the two positioning motors. In case of active measurement, the test needs to be performed through a multi-protocol Radio Communication Tester. There is an amplification unit for both TX and RX chains [37]. A basic functional block diagram of the measurement systems is shown in Figure 23.

The main features of this measurement system are as follows.

- Gain, directivity, 3D radiation pattern, beam-width, cross polar discrimination, side lobes levels measurement.
- Radiation pattern in any polarization, linear or circular and the antenna efficiency.

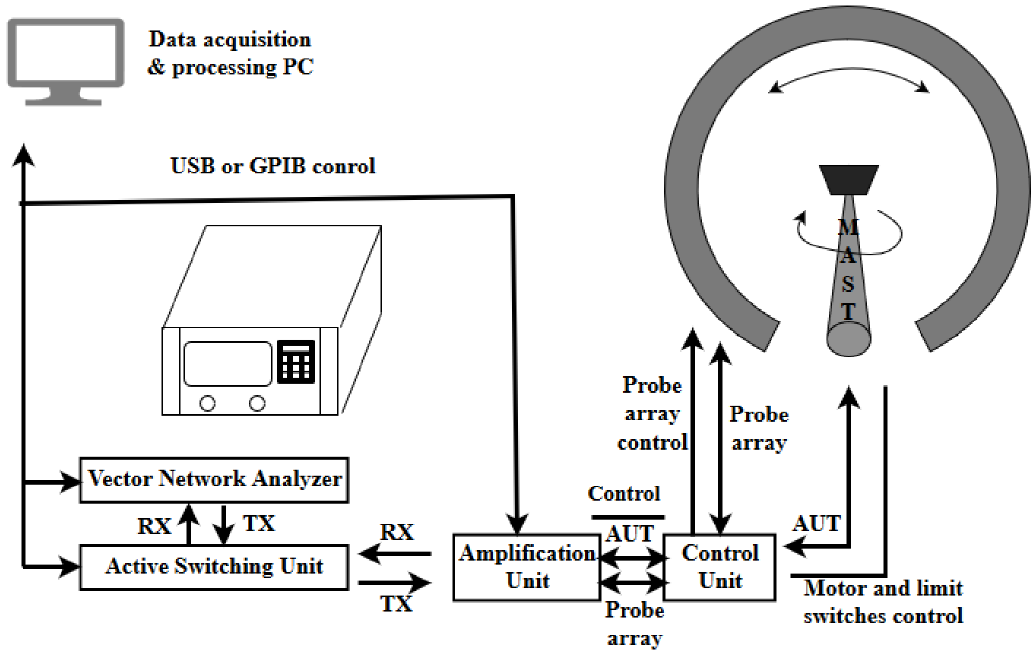


Figure 23. Functional blocks of Satimo StarLab measurement systems [37].

The separation of the probe array is 22.5° from each other and can be reduced to 7.5° by rotating the probe array. This system is designed for measuring the smaller shaped antennas with radius less than 20 cm enclosing the antenna.

4.2. Measuring by Mobile Applications

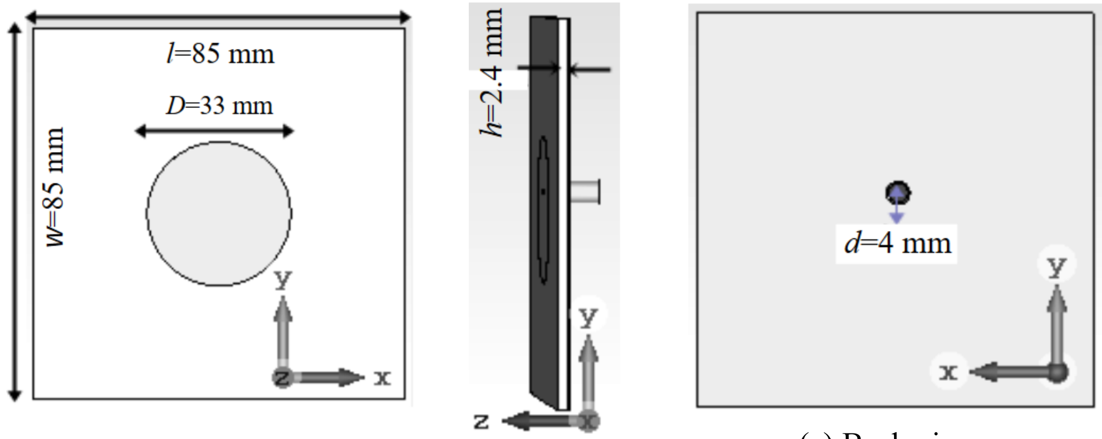
As the operating frequency of this passive repeating system is 2.4 GHz and on the smart phone has the same frequency band transmission and receiving system for WLAN, by using this sensor with the help of mobile application the strength of the signals was measured. This measurement has done for various cases e.g. before and after applying the repeating system and also the strength of different location of the applied area. In this study the android free application named "*WiFi Analyzer*" has been used. There are also other commercial tools available in the market. One of the most popular applications is Nemo Handy by Keysight Technologies. It is suitable for both indoor and outdoor measurement. It also provides the real time visualization of the test area.

Figure 24. Signal strength measurement by mobile application.

In the Figure 24 the sample screen shots showing the strength of the WiFi signal of different available network within the range. The result from a WiFi network might vary over different handset receiving sensitivity but as the study is based on the comparison of the signal strength improvement considering before and after the implementation of the passive repeater, the difference of the values of the decibel of the power is needed.

5. RESULTS

5.1. Simulation results



(a) Front view (b) Side view (c) Back view

Figure 25. Front, side and back view of simulated patch antenna.

Table 1. Physical specification of the patch antenna.

Parameter	Value (mm)
Diameter of the patch (*D*)	33
Fed pin diameter (SMA connector) (*k*)	1.28
Fed pin distance from the center (*d*)	4
Ground plane length (*l*)	85
Ground plane height (*w*)	85
Ground plane width (*h*)	2.4
Thickness of copper of patch (*t*)	0.035

The simulated structure from different angle is represented on Figure 25. According to the equation represented on the section 3.1.2 the theoretical diameter of the patch was around 35 mm but during the simulation of the antenna it was found the maximum return loss and efficiency for the desired frequency is 33 mm. By using this specification, the return loss is found -27.6 dB at 2.43 GHz of frequency, which is shown in Figure 27. The characteristic impedance of the antenna was nicely matched with the 50-ohm system which is around 48.2 ohms, shown in Figure 28.

Radiation pattern of the antenna shows a 6.62 dB gain in Figure 26 which is quite directive

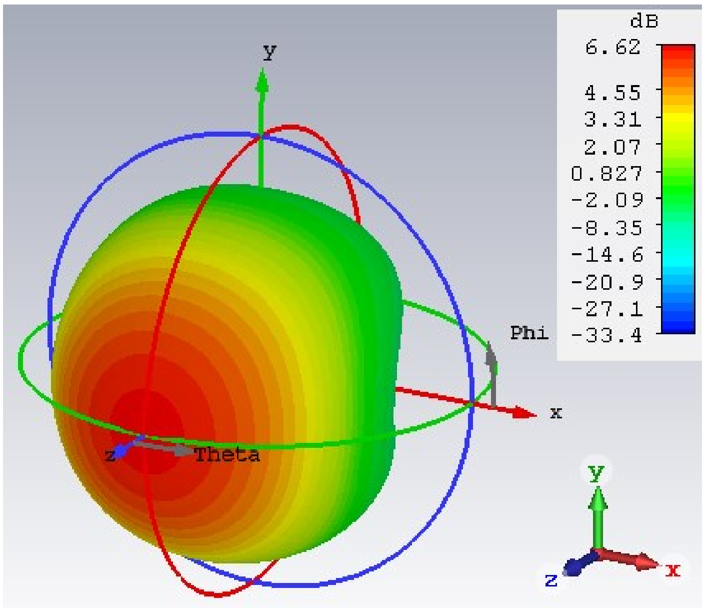


Figure 26. The pattern of radiation with the gain value.

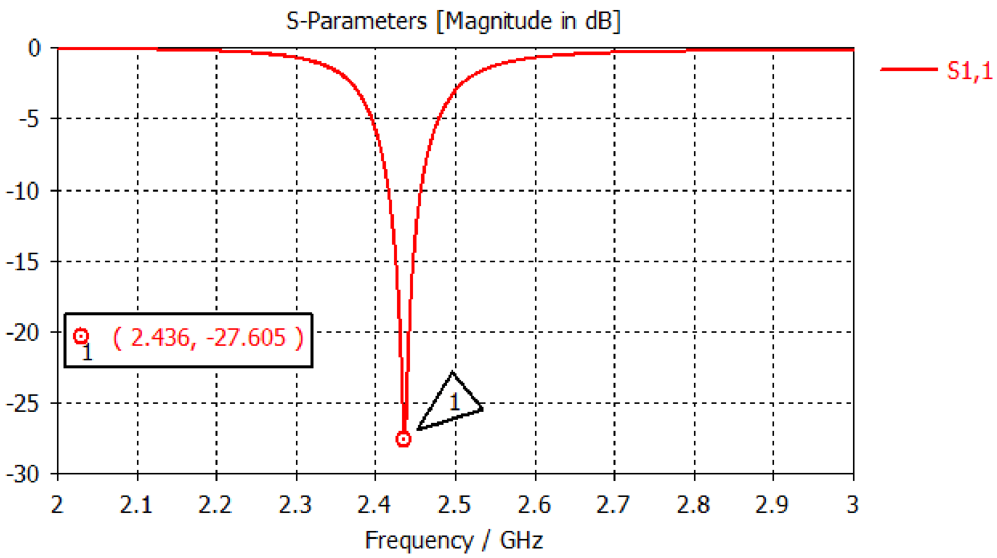


Figure 27. S_{11} of the simulated patch antenna.

S_{11} or return loss value indicates the amount of power reflected on a particular frequency. The higher return loss means more power is transmitted.

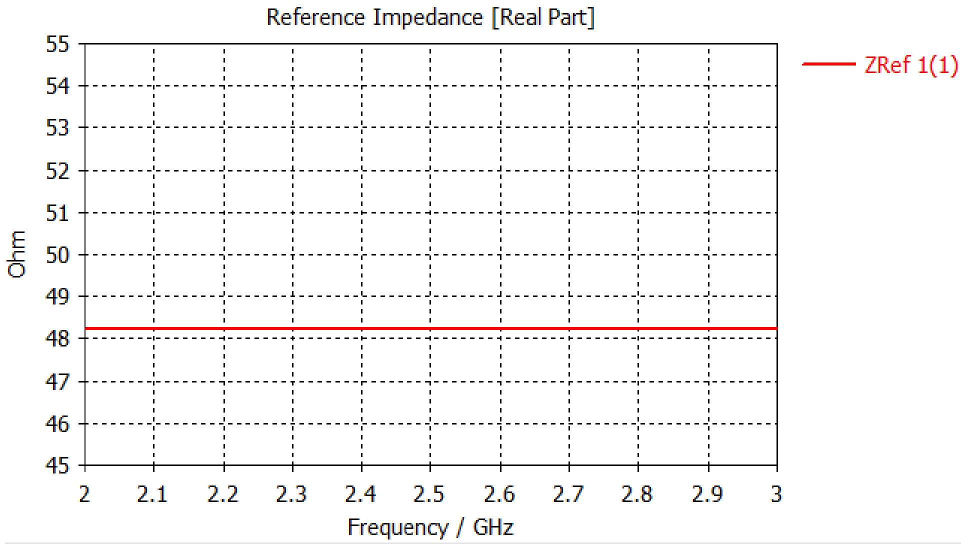


Figure 28. Reference impedance of the simulated patch antenna.

The characteristic impedance or reference impedance is kept close 50-ohm so that it can match with other 50-ohm equipment of the system without using any matching circuit to achieve that. In practice most of the cases; the RF network is designed with this impedance value.

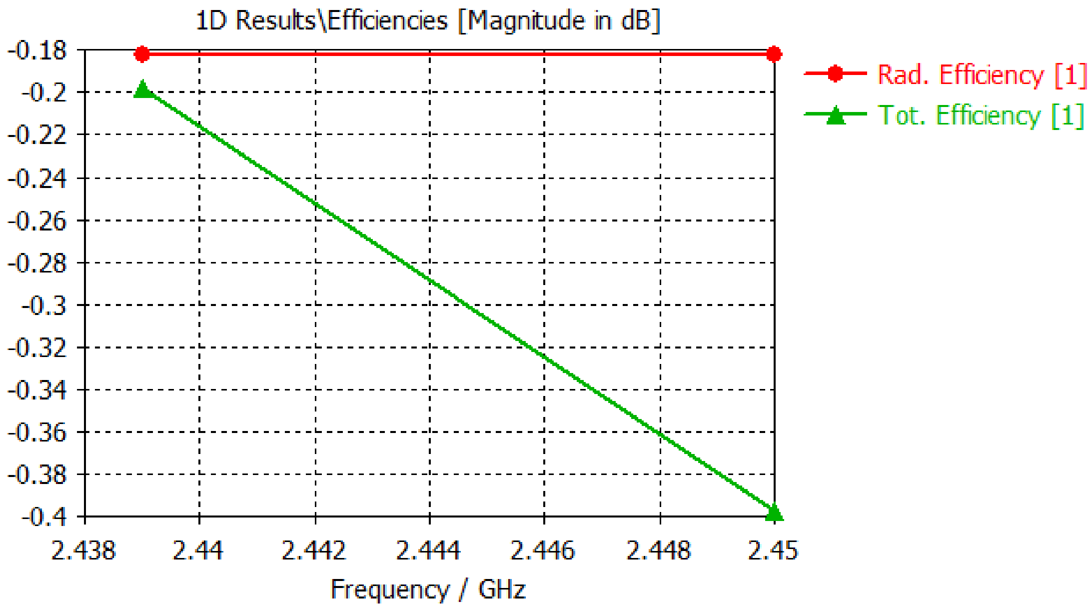


Figure 29. Radiation and total efficiency of the simulated patch antenna.

The importance of efficiency is discussed on the section 2.2.5. It is required to get as much efficiency as possible especially when the system is passive. In this case the total efficiency is found as -0.2 dB which is around 95%. This is quite efficient antenna output.

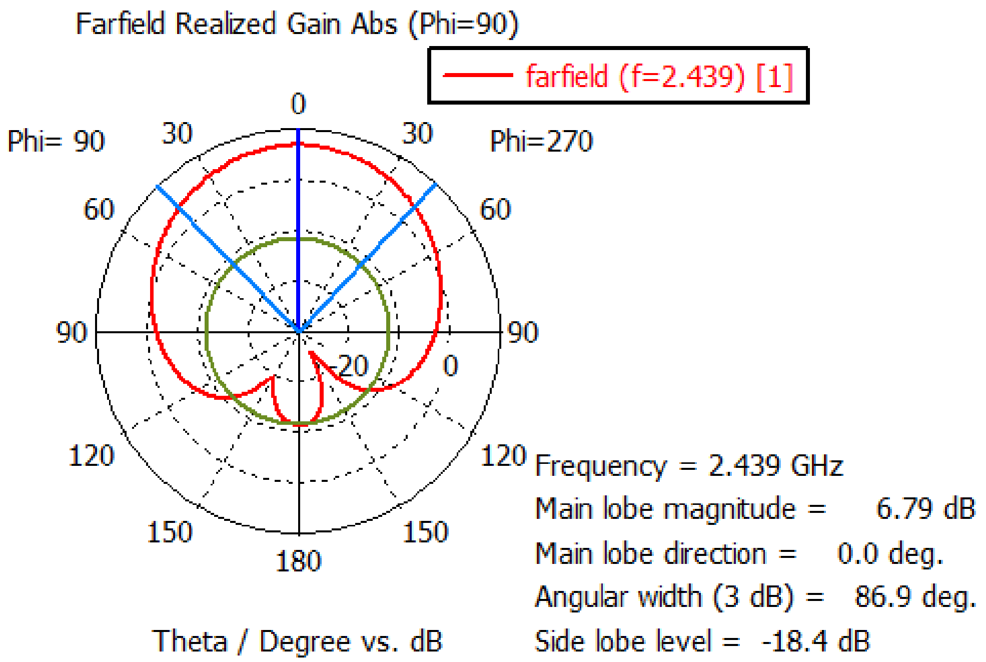


Figure 30. Simulated gain of the patch antenna at 2.439 GHz.

The maximum lobe magnitude is found in the angle 0° with a 3 dB beamwidth of 86.9°. From the radiation pattern shown in the Figure 30, it is seen that there is a main lobe and a small back lobe which ensures that the antenna is directive enough for the desired operation.

5.2. Practical Measurement

Vector network analyzer can measure the port to port isolation, transmission and the return losses of the several ports. As the antenna contains one port only, on this measurement chapter the single port measurement data are shown in this section.

5.2.1. Network Analyzer Measurement

The return loss of the patch antenna is -15.82 dB at the frequency of 2.44 GHz is shown in the Figure 31. The -10 dB impedance bandwidth is found 45.9 MHz.

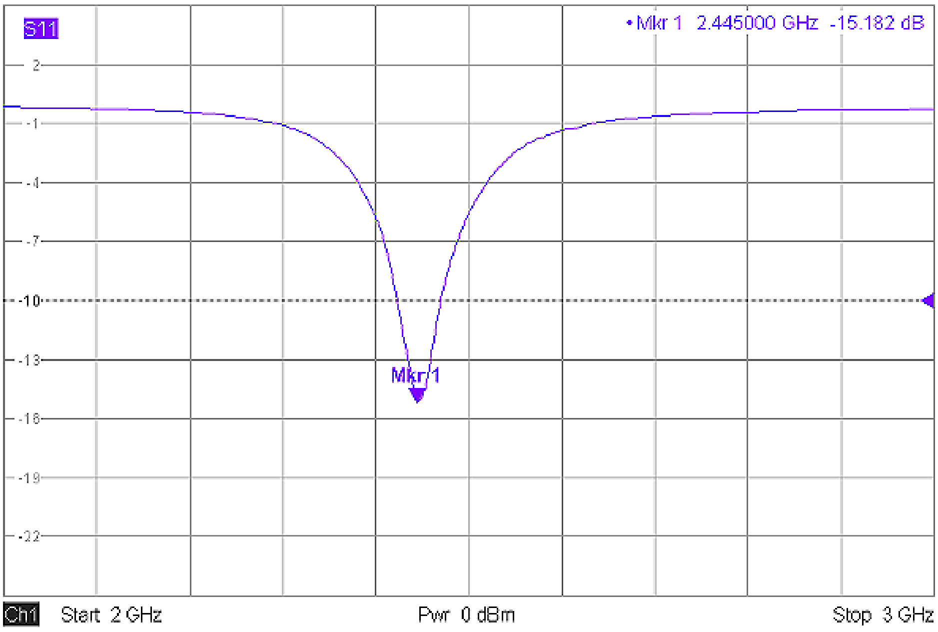


Figure 31. S11 of the fabricated patch antenna at 2.44 GHz.

On the following Figure 32 the dipole antenna return loss is shown where at the -10 dB impedance bandwidth is 209.5 MHz. The resonance frequency is 26 MHz higher than the operating frequency. It shows with the maximum return loss of -32.14 dB.

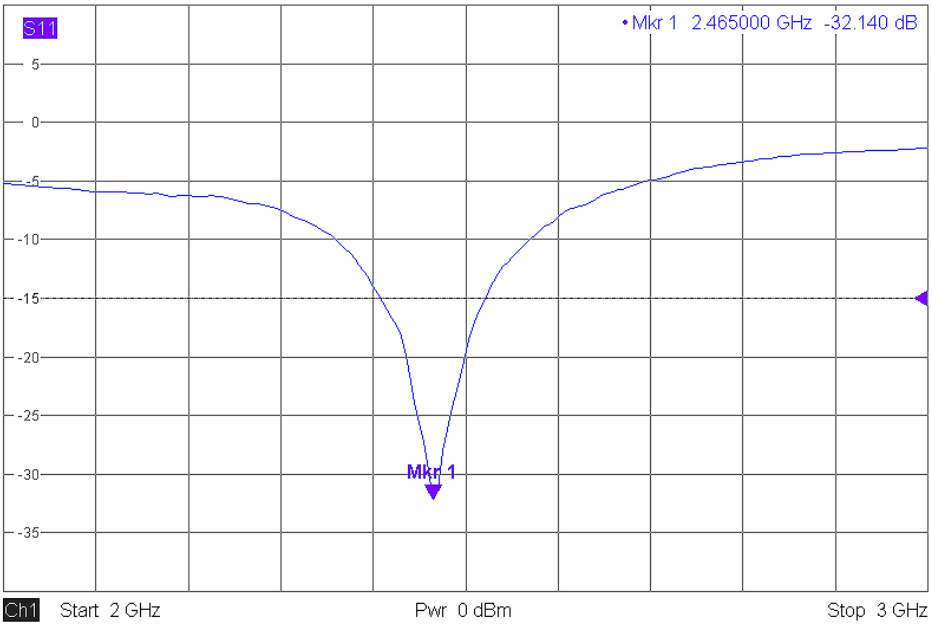


Figure 32. S11 of dipole (rubber ducky) antenna.

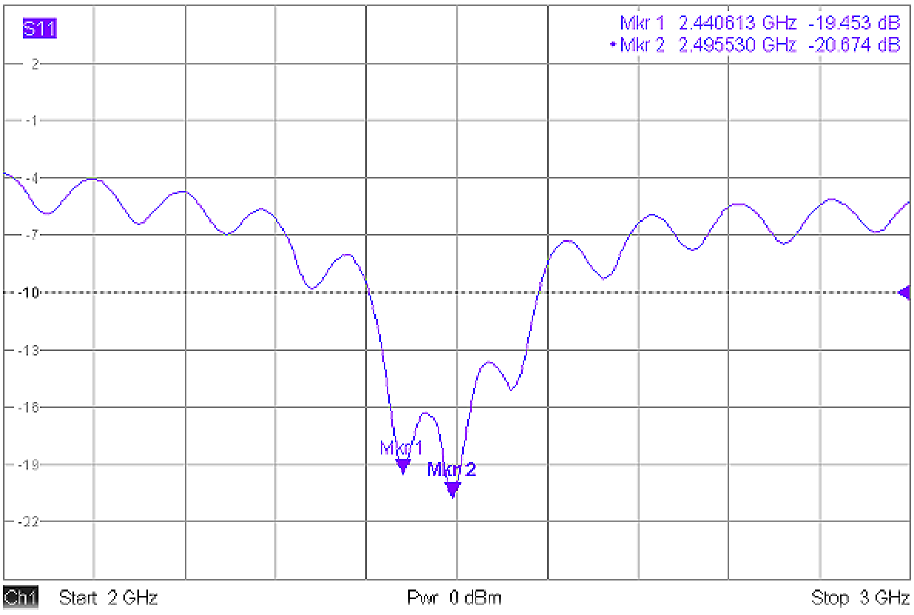


Figure 33. S11 of industrial patch antenna.

Beside the fabricated patch antenna there is another industrially available patch antenna is used in this study to observe some comparison. The return loss of the industrial patch antenna has two notches. One is found in 2.44 GHz and another is at 2.49 GHz. The loss values are under -19 dB. Figure 33 is found from the measurement of that patch antenna.

Compared to the fabricated and commercial patch antenna, it is seen that the commercial antenna has lower bandwidth at 10 dB impedance and which is 187 MHz. Both patch antennas meet this bandwidth specification which is described in the section 2.2.7 of bandwidth requirements.

5.2.2. Radiation Pattern Measurements

In the section 5.1.2 the description of the Satimo StarLAB was presented by which the radiation pattern measurement has been done. In Figure 34 the radiation pattern of the fabricated patch antenna has been shown. The gain at the operating frequency was found 4.63 dB. The radiation pattern is quite similar to the simulated one, although the simulation results show little more gain in this case.

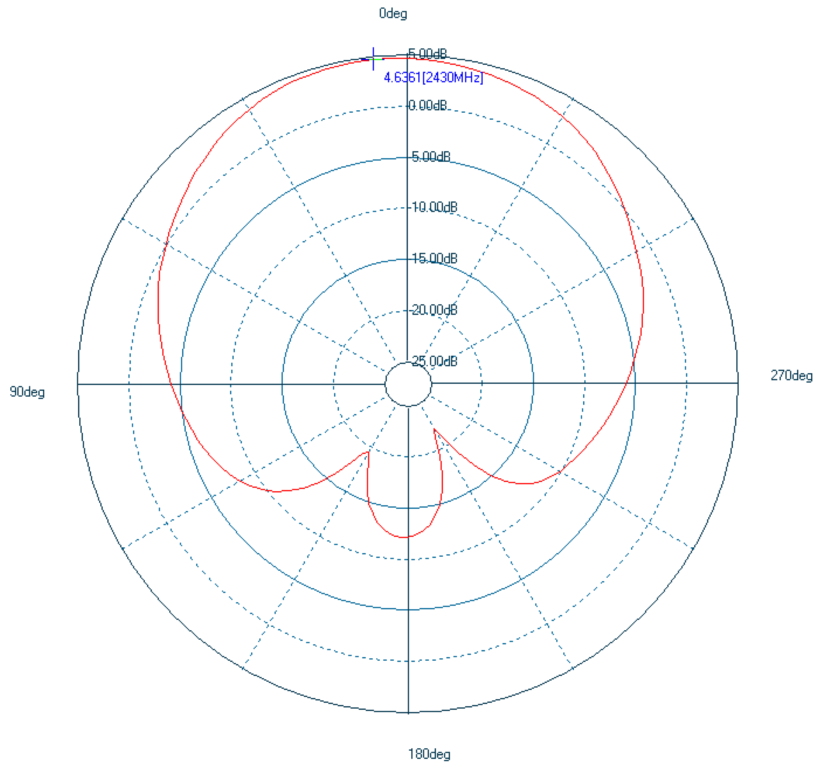


Figure 34. Measured realized gain of fabricated patch antenna at 2.43 GHz.

The coordinate system is similar to the simulated Azimuthal diagram shown in the Figure 26 which is $\phi = 90°$.

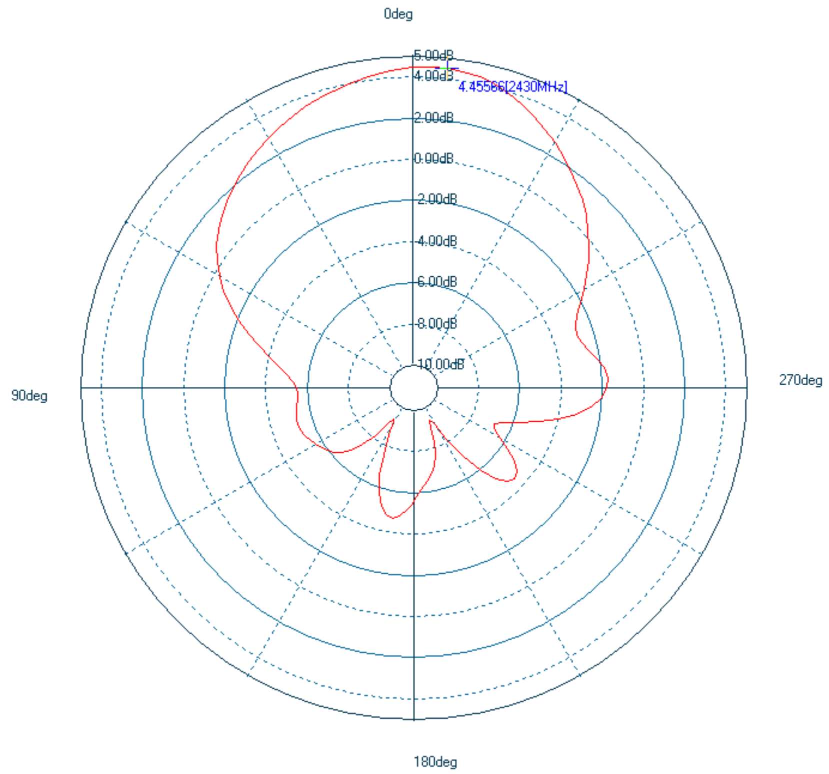


Figure 35. Measured realized gain of industrial patch antenna at 2.43 GHz.

The Figure 35 represents the radiation pattern of the dipole antenna. The gain found for this antenna at 2.43 GHz is 2.04 dB. This figure has also been taken at $\phi = 90°$ angle. The realized gain of main lobe is very close to the operating frequency. There is a difference between the fabricated and commercial patch antenna. It is seen that there are a couple of side lobes and also the number of back lobes is more than one, where in fabricated patch antenna there is no side lobes and only one back lobe. It means most of the power is directed to one direction in case of fabricated patch antenna where some power is dissipated also in the two sides of the antenna in case of commercial patch antenna.

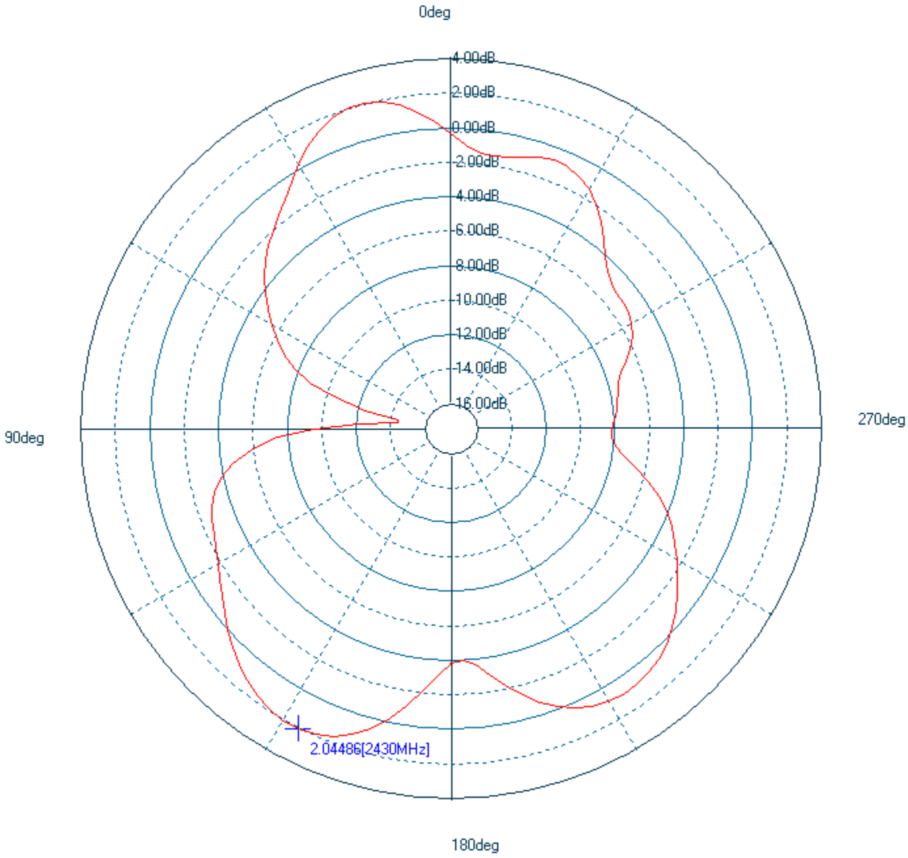


Figure 36. Measured gain of dipole antenna at 2.43 GHz.

Efficiencies have also been measured for the used antennas. The efficiency found for the patch antenna was -2.43 dB in Figure 37 which is 75.59% efficient for WLAN operation. The system is passive and in that sense the efficiency of the used elements needs to be of higher efficiency. The more the efficiency is, the higher performance of the system can be expected.

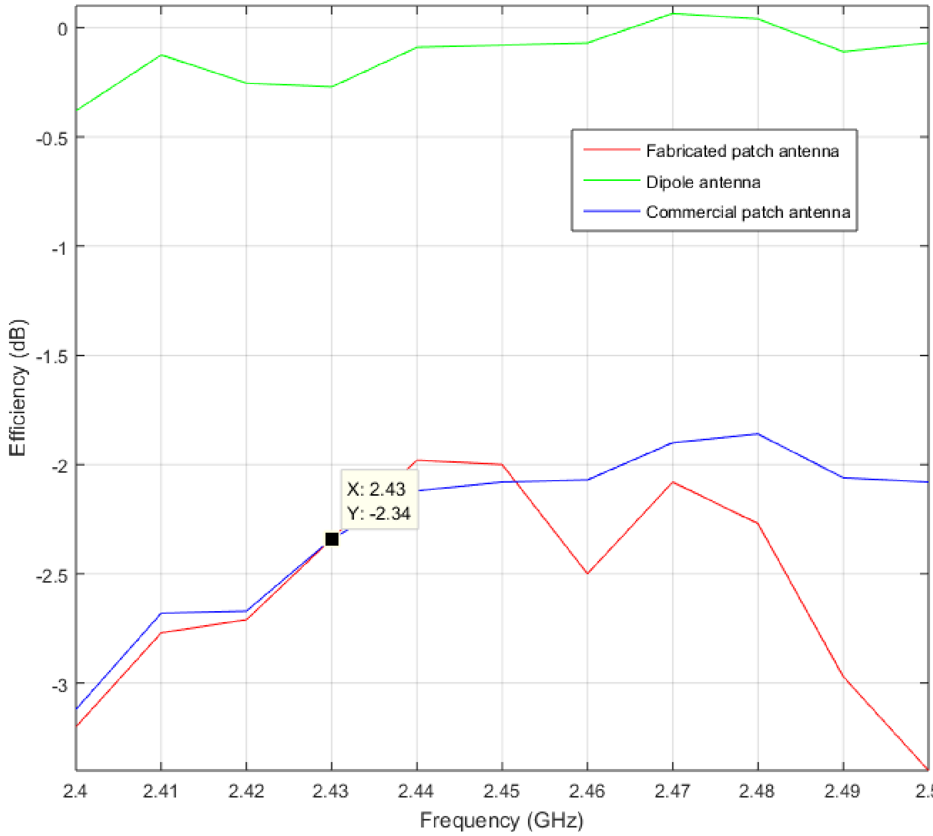


Figure 37. Measured efficiency of the fabricated patch antenna at 2.43 GHz.

For the dipole antenna the measured efficiency was 96.9% which is -0.27 dB shown in by the green color line.

In case of efficiency of the commercial patch antenna, the measured efficiency was almost same compared to the fabricated patch antenna. In this case it was -2.43 dB which is 75.59%. It means that it can radiate 75% of the input power on that 2.43 GHz.

5.3. Full Repeater System Measurements

Three different test environments is considered for performance measurement of the repeating system. Those environments have been considered by the presence of other signal sources and the length of the coaxial cable. Results were varying according to those factors like attenuation of the cable and the noise from other signals. The output from the system has been taken from three different measurement points which are near to the dipole antenna where it was supposed to get the strongest signal, in the middle of the room and in the corner of the room. For final test setup the fabricated patch antenna was used near to the reference base transceiver and the on the other end the dipole antenna was used as its radiation pattern is omni-directional to cover more area. Those results will be discussed on this section.

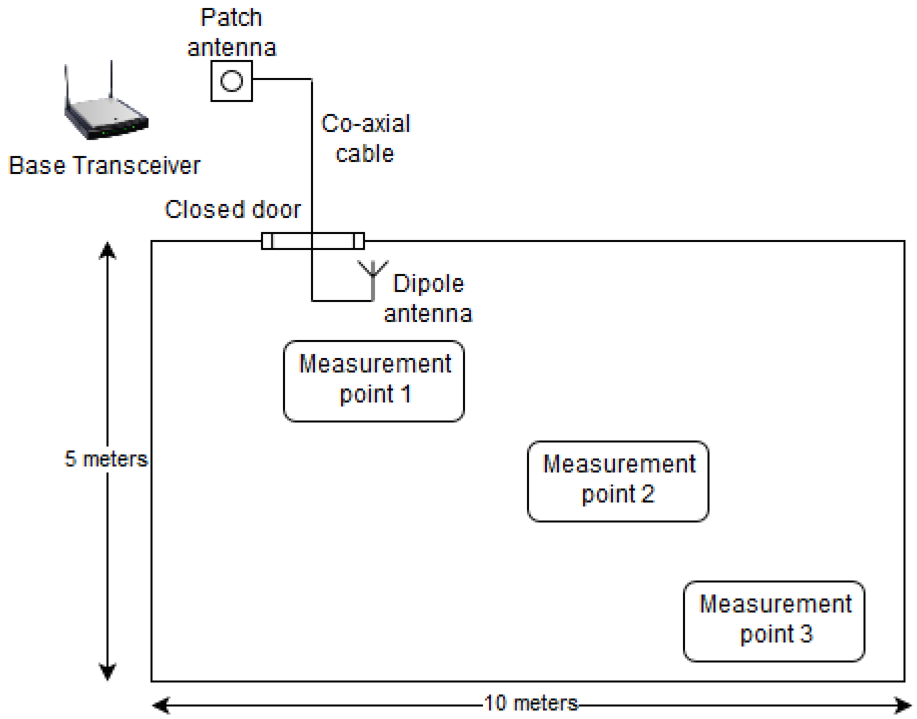


Figure 38. Measurement setup and measurement points for case 1.

The Figure 38 is the illustration of test setup of the repeating system for case 1 and the different measurement point taken into consideration.

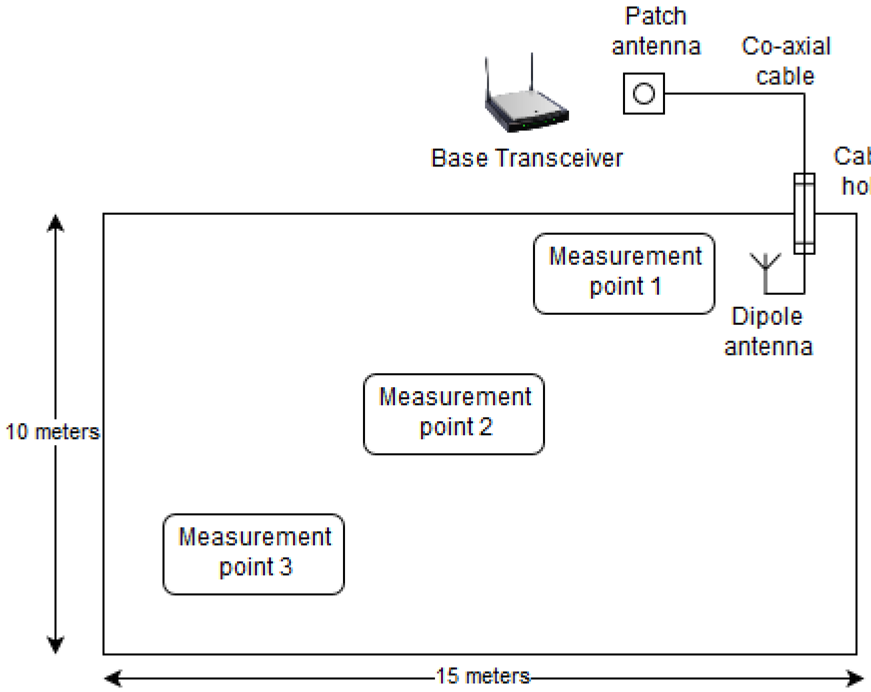


Figure 39. Measurement setup and measurement points for case 2.

The main difference between the test case 1 and the test case 2 is the room size, which is much bigger in case 2 represented on Figure 39.

5.3.1. Case 1

In the first case the fabricated patch antenna was installed near to the transceiver in the second floor of the University of Oulu and by using a long coaxial cable the dipole antenna was attached on the other end of the cable. As the cable was long which is around 6 meters there was a presence of high attenuation of the signal. The attenuation curve is shown on the Figure 40.

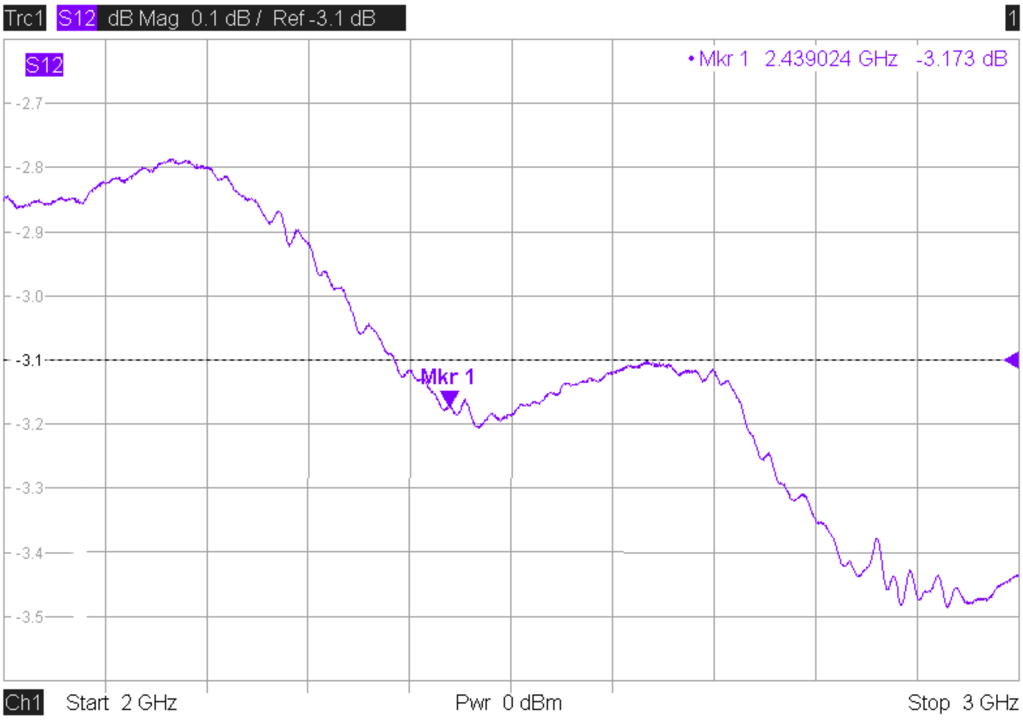


Figure 40. Attenuation of the coaxial cable used in the repeater system.

At 2.43 GHz the loss is found 3.17 dB, which is quite high, especially any passive repeating operation. This is the path loss of the system from the receiving end to the transmitting end.

The results of Wi-Fi signal strength is presented on the Table 2. This is done by the mobile application Wi-Fi analyzer.

Table 2. Case 1 results.

Measurement points	**Without repeater**	**With repeater**	**Improvement**
Close to the dipole antenna	-74 dBm	-68 dBm	6 dB
Middle of the room	-82 dBm	-77 dBm	5 dB
Corner of the room	-86 dBm	-86 dBm	0 dB

From the Table 2 it is clear that there were improvement of signals near to the antenna and also in the second measurement point which is in the middle of the room. Even the size of the room was not big enough and also the room was not fully noise free from the other sources and reference, the base transceiver system still shows 6 dB improvements of the received signals. It decreased in the middle of the room and no improvement found on the corner end or third measurement point.

5.3.2. Case 2

In the second case the receiving end environment was noise free which means there were no incoming signals from any other sources. Also the coaxial cable was short in length with less attenuation characteristics. For example the used cable was around 1 meter long with the attenuation to the operation frequency was only 0.13 dB. So the gain found on the transmitting was comparatively higher than the previous case. Figure 41 represents the attenuation curve of the used coaxial cable.

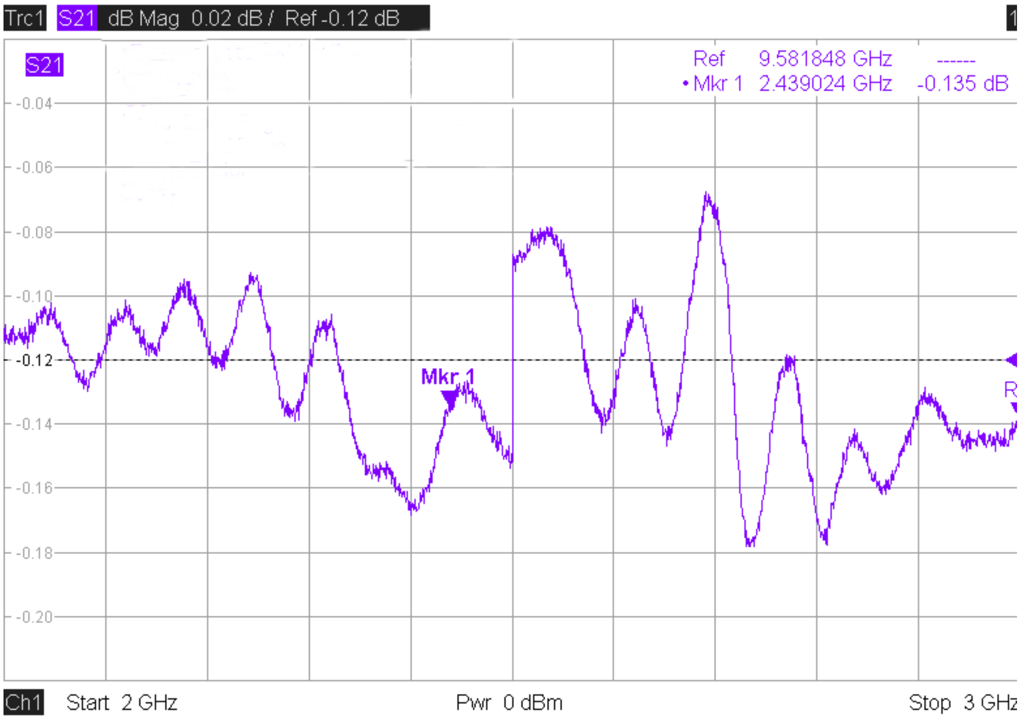


Figure 41. Attenuation of coaxial cable for case 2.

Table 3. Case 2 results.

Measurement points	Without repeater	With repeater	Improvement
Close to the dipole antenna	-80 dBm	-75 dBm	5 dB
Middle of the room	-86 dBm	-83 dBm	3 dB
Corner of the room	-94 dBm	-92 dBm	2 dB

The results of case 2 measurement are presented on Table 3. In this test case the improvements were little bit lower than the test case 1. As the room was completely noise proof it is seen that from the first measurement point is much lower than the first measurement point of the test case 1. Another significant thing is that on the third measurement point there was also improvement of signals which is around 2 dB although the distance of this measurement point was higher compared to the test case 1.

6. DISCUSSION

WLAN is one of the most popular data transmission systems, which is being used worldwide. Compared to data transmission speed it is faster than the 3^{rd} generation cellular network. The cost of the system setup is also cheaper. Due to the modern building structure and materials used for decoration cause huge amount of signal attenuation and thus why the actual range of the transceiver cannot be achieved sometimes. To mitigate this problem the easiest solution is to use redundant amount of base transceiver indoor. This solution is costly in terms of power usages. This study is based on a possible solution which is cost effective and maintenance free. This goal can be achieved by designing highly efficient antennas to build a passive repeating system. It will have no power consumption at all and so there will be no chances of interferences with other active devices.

Designing the antenna for this passive operation was the main goal of this thesis. To achieve the secondary goal which was to set up the whole repeating system and measuring the variation of signal strength before and after using the repeating system. In the designing part, CST Microwave Studio simulation software was used for analyzing various antennas considering the radiation pattern, return loss, efficiency, characteristic impedance etc. It's very user friendly software which is helpful for getting the idea of electromagnetic output of the designed item. It is easy to define the ports as required for the antenna. It is possible to use any kind of materials which are generally used for designing. To change those materials from the various parts of the device is easier to make sure about the best component for specific purpose.

To get the results of the primary goal the vector network analyzer (VNA) and Satimo StarLab were used. Here a two port network analyzer was used. As the antenna has only one port, one port measurement was done for finding out the parameters of those used antennas. In case of finding out the attenuation of the used coaxial cable the two ports has to be used. Usually the network analyzer contains minimum of two ports.

A free version mobile application was used to find out the signal strength variation. There are many applications available for different operating systems of mobile phones. In this part an android operating system mobile device was used. The application which is used is named 'WiFi Analyzer'. It can detect the signal strength and displays the results in dBm for a particular active WiFi channel.

For the secondary goal it was needed to make the prototype and also collecting some industry built antennas which are used in practical operations. The prototype of the patch antenna was built in the fabrication lab of the university. As it was a circular patch antenna, there were several attempts taken to get the cut off frequency desired for the WLAN operation.

After testing several antennas in total two antennas were primarily chosen for real time measurement. The simulated and real time measured data were analyzed. There were deviations among the results found during the simulations and real measurements. It happened because the simulation software does not take consideration of all the factors like surface roughness of the copper and purity of the dielectric materials of the antenna.

In the final measurement the whole passive repeating system was set up in two different environments. Both of those cases in one end, the fabricated patch antenna was used as a directive antenna for receiving the signal purpose and on the other end industry standard dipole antenna was used for its bi-directional radiation pattern to cover more area for transmitting the data. The result found before and after the system is presented on Chapter 6. In both cases there was improvement of signal after using the repeating system. The variation found on the signal strength is not so high, but it is clear that the signal level can be increased significantly if more loss free coaxial cable and more efficient antenna could be used. Further study can be done for designing the directive antenna with higher efficiency for this passive system.

7. SUMMARY

This thesis focused on the improvement of indoor WLAN signal by using the passive repeating system. The system requirements have been studied on the first chapter. There are many researches around the world which are focused on the individual element improvement for this system, and those were presented in the literature review. One of the probable solutions which are used in this thesis is to use a directional antenna and an omnidirectional or bi-directional antenna to build this simple but effective passive repeating system. Those elements were scrutinized on this literature review section to get the idea of efficient elements for the system. Summary of several scientific papers has been done.

Theoretical background studies which are required to understand for the implementation of the system have been provided in Chapter 1. It contains the details of technical terms with basic figures and equations. Those descriptions have been taken after studying several relevant books and references. Chapter 2 started from the definition of antenna, their radiation pattern, beam width, radiation intensity, and efficiency of those antennas, polarization and other behavior to make the theoretical concept crystallize.

Chapter 3 is about the antenna part of the repeating system. Here more detail mathematical equation for the selected antennas and their characteristics has been provided. More specifically the patch antenna and the dipole antenna model has been shown on this section. Couple of industrial standard antennas and a fabricated antenna has been discussed as examples.

Different types of repeating system is included on Chapter 4. Here the idea how the repeating system works, their advantages and drawbacks. After discussing those different systems the back-to-back antenna model is selected for the further analysis.

The measurement procedure and the required equipment has been described on Chapter 5. The vector network analyzer and the basic in electromagnetic measurement have been presented. These were required to measure the characteristics described on the theoretical chapter for the antenna. Another part of the measurements chapter is the procedure of measuring the whole repeating system by using a mobile application.

The Chapter 6 is the core of this thesis where the result found from both the simulation part and the actual measurement part has been shown for the elements used in the system. Chapter 6 also contains the two different types of case studies where the back-to-back antenna repeating system was installed. The test scenario for both cases along with the outcome of the actual improvement found by the whole repeating system is presented.

Based on these studies it can be concluded that as there is a clear improvement found from the repeating system, the efficiency can be improved by further studies focusing on the highly efficient antenna. This is discussed in Chapter 7. The bandwidth on -10 dB for the directive antenna can be improved to get the better results by the system. Another approach can be tested by combining the methods of plane reflector and the passive repeater by considering the structural area of indoor coverage.

8. REFERENCES

[1] "Celotex Saint-Gobain," Saint-Gobain, [Online]. Available: http://www.celotex.co.uk/ . [Accessed 06 01 2016].

[2] L. Guo, M.-C. Tang and H. Xion, "A dual-frequency, frequency tunable patch antenna based on printed superstrate layer," in *IEEE*, Chengdu, China, 2016.

[3] G. M. Aji, M. A. Wibiono and A. Munir, "High gain 2.4 GHz patch antenna array for rural area application," in *IEEE*, Yogyakarta, Indonesia, 2016.

[4] P. S. R. Patre, S. Singh and S. Singh, "Triple-band microstrip patch antenna with improved gain," in *IEEE*, Sultanpur, India, 2016.

[5] F. Yu, Y. Xie and L. Zhang, "Single patch antenna with monopulse patterns," *IEEE Microwave and wireless components letters,* vol. 10, no. November 10, 2016, p. 762, 2016.

[6] H. Hadzic, V. Wally, Z. Blazevic and M. Skiljo, "2.4 GHz micro-strip patch antenna array with suppressed sidelobes," in *IEEE*, China, 2014.

[7] R. Fotedar, P. S. Garia, R. Saini, A. Vidyarthi and R. Gowri, "Performance analysis of microstrip antennas using different shapes of patch at 2.4 GHz," in *IEEE*, Dehradun, India, 2015.

[8] H. Nomikman, F. Malek and N. Saudin, "Dual layer rectangular microstrip patch antenna with H-slot for 2.4 GHz range application," in *IEEE*, West Java, Indonesia, 2013.

[9] G. Duo, K. He, Y. Zhang and M. Song, "A multiband dual-polarized omnidirectional antenna for indoor wireless communication systems," in *IEEE*, China, 2016.

[10] X. Qint, J. Shi and Z. N. Chen, "Metamaterial-based omnidirectional circularly polarized antenna array for 2.4 GHz WLAN application," in *IEEE*, Davos, Switzerland, 2015.

[11] J.-Y. Jan and L.-C. Tseng, "Small planar monopole antenna with a shorted parasitic inverted-L wire for wireless communications in the 2.4, 5.2, 5.8 GHz bands," in *IEEE*, China, 2004.

[12] S.-W. Su and J.-H. Chou, "Hybrid of monopole and dipole antennas for concurrent 2.4 and 5 GHz access point," in *IEEE*, Berlin, Germany, 2009.

[13] Y. Kumar and S. K. Behera, "Design of planar monopole antenna for 2.4 GHz WLAN," in *IEEE*, Bhopal, India, 2010.

[14] M. H. Amini and H. R. Hassani, "Compact polarization reconfigurable printed monopole antenna at 2.4 GHz," *Electronics Letters,* vol. 49, no. 17, p. 1044, 2009.

[15] J. M. Rigelsford, K. L. Ford and L. Subrt, "A passive system for increasing cellular coverage within energy efficient buildings," in *IEEE*, Hague, Netherlands, 2014.

[16] H. D. Hristoz, R. Feik and W. Grote, "Improving indoor signal coverage by use of through-wall passive repeaters," *IEEE Antenna and Propagation Society,* 2001.

[17] Y. Huang, N. Yi and X. Zhu, "Investigation of using passive repeaters for indoor radio coverage improvement," in *IEEE*, China, 2004.

[18] I. S. Association, "145-2013 - IEEE Standard for Definitions of Terms for Antennas," 6 3 2014. [Online]. Available:

http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6758443. [Accessed 26 12 2016].

[19] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, Wiley, 2012.

[20] O. S. a. H. Administration, "Electromagnetic Radiation: Field Memo," U.S. Dept of Labor, Cincinnati, Ohio, May 20, 1990.

[21] C. A. Balanis, Antenna Theory, Analysis and Desing, Wiley, 2005.

[22] B. Sklar, Digital Communications: Fundamentals & Applications, Second Edition, University of California, Los Angeles: Prentice Hall, December, 2005.

[23] I. Poole, "Radio-Electronics.com," Adrio Communications Ltd, [Online]. Available: http://www.radio-electronics.com/info/propagation/path-loss/link-budget-calculation-formula-equation.php. [Accessed 30 8 2017].

[24] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design 2nd edition, United States of America: John Wiley & Son Ltd, 1998.

[25] CISCO, "Antenna Patterns and Their Meaning," CISCO, 07 August 2007. [Online]. Available: http://www.cisco.com/c/en/us/products/collateral/wireless/aironet-antennas-accessories/prod_white_paper0900aecd806a1a3e.html. [Accessed 04 01 2017].

[26] J. D. Kraus, Radio Astronomy, New York, USA: McGraw-Hill Book Co., 1966.

[27] R. S. Elliott, Antenna Parameters, Arizona: Wiley, 1981.

[28] J. H. Reisert, "Antenna Polarization," Astron wireless technologies, [Online]. Available: http://www.astronwireless.com/topic-archives-antennas-polarization.asp. [Accessed 12 01 2017].

[29] I. S. 8. 2009, "IEEE Standard for Information technology- Telecommunications and information exchange between systems- Local and metropolitan area networks- Specific requirements," IEEE Standard Bodies, New York, USA, 2009.

[30] Y. Huang and K. Boyle, Antennas: From Theory to Practice, United Kingdom: Wiley, 2008.

[31] D. O. a. G. Moernaut, "The Basics of Patch Antennas," *RF Globalnet,* 2009.

[32] Microwave101.com “Microwave patch antennas”, [Online]. Available: https://www.microwaves101.com/encyclopedias/microstrip-patch-antennas. [Accessed 18 03 2018].

[33] O. N. I. P. A. B. J. Kwaha, "The circular microstrip patch antenna – design and implementation," *IJRRAS,* 2011.

[34] http://martybugs.net, "Anatomy of a 2.4GHz Rubber Ducky Antenna," Wireless Networking Info, 09 2005. [Online]. Available: http://martybugs.net/wireless/rubberducky.cgi. [Accessed 31 05 2017].

[35] T. Manning, Microwave Radio Transmission Design Guide, Boston, London: Artech House, 2009.

[36] "Microwaves101 S-parameters," [Online]. Available: https://www.microwaves101.com/encyclopedias/438-s-parameters-microwave-encyclopedia-microwaves101-com. [Accessed 20 05 2017].

[37] SATIMO, "Antenna Measurement Systems | Multi-probe systems," Telemeter Electronics.