Basic Antenna Theory and Application

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Abstract

Currently highly directive antennas on the market can range from as little as fifty dollars to a couple of hundreds of dollars. The gain of these antennas is between the ranges between 8dBi to 20dBi. A cheaper alternative with a similar gain characteristic can be developed to appeal to the consumers on the market. This project involves the designing, building, and testing of a highly directional antenna that can be manufactured cheaply and be sold at a price that would be appeal to customers.

Acknowledgement

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Table of Contents

Table of Figures

Table of Tables

Table of Equations

Introduction

With an ever advancing society, technology plays an important role in everyday life. In September of 2009, there was an estimated 1.73 billion internet users worldwide, approximately 26% of the world population [1]. In the United States, as of 2008, there were approximately 270 million cell phones in use [2]. Compared to the country's population of 306 million, there are almost as many cellphones in use as individuals living in the United States. Internet and mobile cellular rely heavily on wireless interfaces to provide services to their customers due to a lower cost of implementation and maintenance compared to wired alternative. Antennas are important part of this experience in that they allow users to receive and transmit data to communicate with the infrastructure.

In President Obama's State of the Union address in January of 2011, the president set a goal to have reach 98% of all Americans to be able to access to wireless internet , with the hope of bringing every part of America into the digital age by 2016 [3]. In addition, he believes that the increased availability of high speed internet will help business owners sell their products, provide instantaneous access of resources to students, and improve the way Americans currently conduct business. An efficient way to increase Wi-Fi availability is to use a directional antenna that provides a direct signal in densely populated areas.

Currently most routers for Wi-Fi come with omnidirectional antennas which propagate signal radiation in all directions with approximately equal radiation strength. Depending on the location of the router, an omnidirectional antenna may not be the best type of antenna. By having a highly directional antenna, users can place the router at one end of a given space and aim the antenna to provide signal to a desired area. This would increase the maximum coverage distance away from the router, allowing users to access internet from farther away than with tradition omnidirectional antennas. The directional antenna can be used to provide stronger signals over densely populated areas such as city streets and

9

office buildings. Similarly, the highly directional antennas can be used provide rural areas, which have more sparsely populated neighborhoods, with cost effective wireless internet access by strategically aiming the highly directional antenna.

Currently, high gain Wi-Fi antennas are available through many online and retail stores. However, some models are costly, priced around $150. While cheaper antenna models are available but they do not perform as well in terms of gain and can be bulky, making it difficult to mount on flat surfaces such as a wall or side of a building.. Although many companies have produced high gain Wi-Fi antennas, a lower cost, similar gain, light weight antenna can be produced to attract more consumers.

The goal of this project is to design and build high gain, low cost, low profile antenna that can be used for Wi-Fi applications that can compete with current high gain antennas already in the market. In order to accomplish this goal, we first review current high gain antennas available on the market to access and determine both the competitive production cost and gain performance of an antenna that would be able to compete with other high gain antennas. We investigate the Wi-Fi 802.11 standard to determine the operation frequency of our antenna and determine the antenna configuration will used to meet our gain, low cost, and low profile standards. Once an antenna design is chosen, we design our antenna using a simulation program. Following, we build the design and test our antenna to compare simulated results with experimental results to evaluate whether or not the designs goals were met.

Background

  Almost everyone in a modernize country uses wireless internet on a daily basis. We use the internet to access information instantaneously. Some common uses of the internet include to checking email, shopping for merchandise, communicating with friends and family through social networking or instant messaging system, and keeping up with current news. Internet is an integral part of our daily lives. Because of this, we must develop a way to provide internet to as many people as possible while reducing the cost. Developing a low cost high gain antenna can increase the wireless coverage.

  We will start off by investigating Wi-Fi IEEE 802.11 by discussing the 2.4GHz and the 5GHz frequency band used for 802.11. This allows us to understand at the operating frequencies our antenna in order to comply with the 802.11 standard. Next we will discuss various types of antenna configurations and its characteristics. We will discuss the design parameters for each type of antenna describe and also define several antenna measurements to help determine how well our antenna is working.

IEEE 802.11

  IEEE 802.11 is the current standard for wireless local area networks (WLAN). Most people refer to WLAN as Wi-Fi. 802.11 have four popular protocols: 802.11a, 802.11b, 802.11g, and 802.11n. 802.11b/g/n all operate at the 2.4GHz industrial, scientific and medical(ISM) band. 802.11a operates at the 5GHz while 802.11n operates at both 2.4GHz and 5GHz band. The 2.4GHz band is divided up into 14 channels which have bandwidth of 22MHz. Figure 1 illustrated the center frequency of each channel and how they overall with each other.
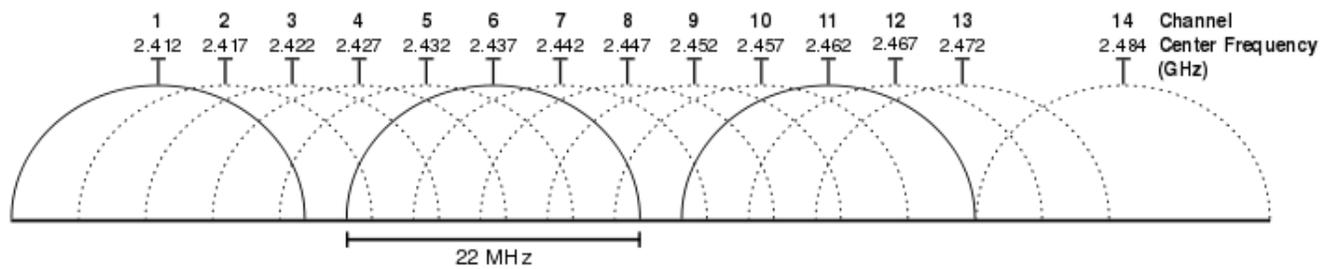
Figure 1 2.4GHz Channel Frequency and Channel Overlap [4]

The figure illustrates that only 4 channels can be operated at the same time without interference from other channels. Those channels are 1, 6, and 11, and 14. This 2.4GHz band ranges from 2.4GHz to 2.5GHz, approximately 4.1% bandwidth. The United States only permits the use of channel one through 11 from 2.4GHz to 2.472GHz leaving only 3 channels can be used simultaneously without overlap.

2.4GHz vs. 5GHz

The 2.4GHz band is more popularly used than the 5GHz band. The 5GHz band operates between the frequencies of 5.1 to 5.8 GHz. The 2.4GHz has long been a standard around the work while the 5GHz band is prohibited in the use in Wi-Fi in some countries, i.e. China. One reason to use the lower frequency band is because the 2.4GHz band can propagate better through objects such as walls than that of the 5GHz band and provides better coverage. The 5GHz band is not used as widely as the 2.4GHz band so there is less interference from neighboring Wi-Fi signal. In addition, cordless phones and other house hold appliances uses the 2.4GHz which can provide interference with the signal. Most computers are not equipped to operate at the 5GHz band. There are dual band wireless cards on the market consumers that operate at both the 2.4GHz and 5GHz band for 802.11n.

Radiation Efficiency

Radiation efficiency is the "ratio of total power radiate by an antenna to the net power accepted by the antenna from the connected transmitter. [5]" Only 50% of the power supplied through the TX network is used to transmit. In the best case scenario, the maximum power accepted by the

transmitting antenna is 50% of the total power supplied and occurs when the generator impedance and

the antenna are matched, usually to 50Ω. The efficiency of an antenna is given by Equation 1.

$$E = \frac{P_{\text{radiated}}}{P_a} = \frac{R_r I^2}{(R_r + R_L)I^2} = \frac{R_r}{(R_r + R_L)} = \frac{1}{1 + R_L / R_r}$$

<div align="center">Equation 1 Antenna Radiation Efficiency [6]</div>

R_L is your loss resistance which corresponds to the loss of your antenna and R_r is the radiation

resistance. In practice, you want your radiation resistance to be big and the loss resistance to be as

small as possible.

Directivity and Gain

Directivity is defined as "the ratio of radiation intensity, in a given direction, to the radiation

intensity that would be obtained if the power accepted by the antenna where radiating isotropic ally"

[5]. In other words it's the ratio of the radiation intensity of an antenna to one that radiates equally in

all direction. This is similar to that of antenna gain but antenna gain takes into account the efficiency of

the antenna while directivity is the losses gain of an antenna.   Directivity can be calculated using the

Poynting Vector, P, which tells you the average real power per unit area radiated by an antenna in free

space [6].   The equation for the directivity of an antenna is given by Equation 2.

$$D = \frac{P}{P_0}, \quad D\big|_{\text{dB}} = 10\log_{10}\frac{P}{P_0}, \quad P_0 = \frac{P_a}{4\pi r^2}$$

<div align="center">Equation 2 Directivity [6]</div>

P_a is the total power radiated by the antenna and r is the distance between the two antennas.

The antenna gain takes into account loss so the gain of an antenna will always be less than the

directivity. Knowing the directivity of the antenna, the total power radiated by the antenna, and the

received power which takes into account loss, you can calculate the antenna gain using Equation 3.

$$G = D \frac{P_a}{P_{\text{accepted by the antenna}}} \leq D$$

Equation 3 Gain in Relation to Directivity [6]

In other words the gain is the efficiency multiplied by the directivity of the antenna, the maximum possible gain of an antenna.

Antenna Bandwidth

Antenna bandwidth is "the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard" [5]. The bandwidth can be viewed as the frequencies left and right of the center frequency (usually the resonant frequency) in which the antenna performance meets the specified values. The impedance bandwidth of an antenna is commonly agreed upon as the power delivered to the antenna greater than or equal to 90% of the available power [6]. Another way to interpret the antenna bandwidth is in terms of the reflection coefficient Γ. Γ is usually plotted in as the power reflection coefficient by using Equation 4.

$$|\Gamma|_{\text{dB}} = 20 \log_{10}|\Gamma| = 10 \log_{10}|\Gamma|^2 \qquad \Gamma = \frac{Z_a - Z_0}{Z_a + Z_0}$$

Equation 4 Power Reflection Coefficient [6]

Z_0 is the line impedance and is typical equal to the generator resistance, usually 50Ω. Z_a is the antenna radiation resistance. When the power reflection coefficient is -10dB, it represents 90% of the available power to the antenna is being sent to antenna. Figure 2 displays an example of a power reflection coefficient graphed in terms of frequency.
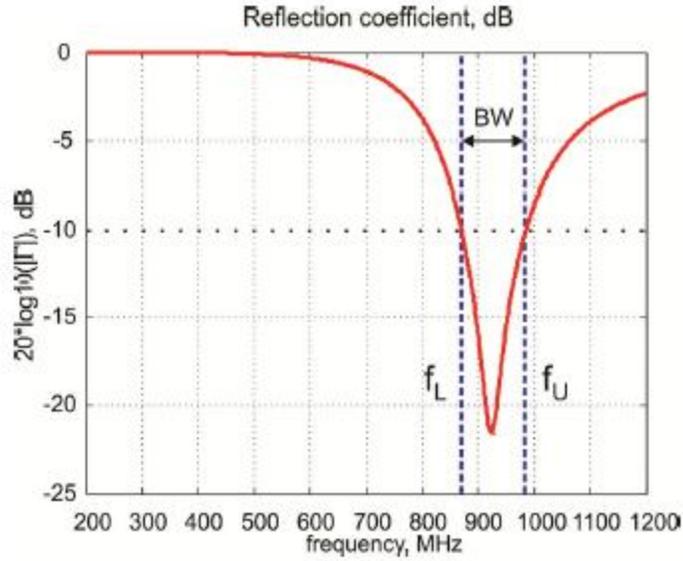
f_L represents the lowest frequency that satisfies the 90% power, and f_U represents the highest frequency that follows the criteria.   The average of f_L and f_U will give you the center frequency f_c and the bandwidth or commonly referred to as fractional bandwidth is determined by Equation 1.

$$Fractional\ Bandwidth = \frac{f_u - f_L}{f_c} \times 100\%$$

The equation is used for antennas with a bandwidth less than 100%. For antennas that exceed 100% bandwidth, the impedance bandwidth is then commonly defined as the ratio of the upper frequency to lower frequency.

$$Fractional\ Bandwidth = \frac{f_u}{f_L}$$

Broadband antennas are defined as antennas that have a bandwidth greater than 2:1. Some common types of broadband antennas are bowtie, biconical, and blade dipole antennas.

15

What is an Antenna?

An antenna is defined by the IEEE as a "transmitting or receiving system that is designed to radiate or receive electromagnetic waves" [5]. An antenna can be any shape or size. A list of some common types of antennas is wire, aperture, microstrip, reflector, and arrays. Each antenna configuration has a radiation pattern and design parameters, in addition to their benefits and drawbacks. In this section we will describe common antenna types and their benefits and drawbacks. In addition, we will discuss fundamental parameters of each antenna configuration.

Types of Antennas

The "IEEE Standard of Terms for Antennas" has not been updated since 1983 and the terms/definitions do not describe many of the new antennas discovered since, according to David V. Thiel of the Griffith University [7]. He proposes antennas should be grouped by categories. The following are the proposed grouping: wire antennas (e.g., dipoles and loops), aperture antennas (e.g., pyramidal horns), reflector antennas (e.g., parabolic dish antennas), microstrip antennas (e.g., patches), dielectric antennas (e.g., dielectric resonant antennas), and active integrated antennas, lens antennas (sphere), and antenna arrays. We will briefly describe several of these antenna categories defined by Mr. Thiel.

Wire Antenna

A wire antenna is an antenna that is made of a conductive wire. Wire antennas can come in different configurations and some of these configurations are dipoles, helix, and loop [8]. Wire antennas can be seen everywhere in daily lives. Some examples of wire antennas are on automobiles as radio antennas, and on buildings as transmitting or receiving antennas. Figure 3 shows an example of a wire antenna of a car.

Figure 3 Example of Wire Antenna [9]

Wired antennas have an omni-directional radiation pattern and the monopole antenna, a type

of wire antenna, comes standard with wireless routers.

Dipole Antenna

A dipole defined by the Merriam Webster Diction is "a pair of equal and opposite electric

charges or magnetic poles of opposite signs separated especially by a small distance" [10]. A simple

design and radiation pattern of a dipole antenna can be seen in Figure 4.
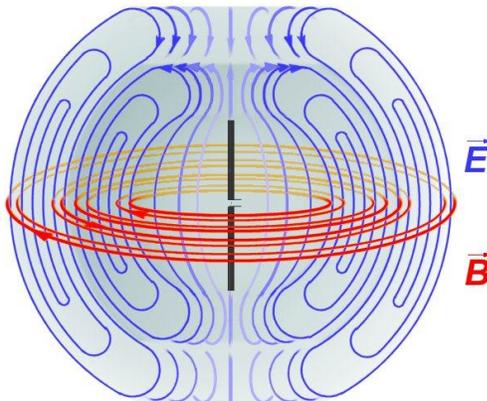
Figure 4 Dipole Antenna and Radiation Pattern [11]

A simple design of a dipole antenna is to make the length of the antenna λ/2, where wavelength λ is equal to the speed of light over the center frequency the antenna is mean to operate at. At the feed of a center fed dipole, the current is at its peak and lowest at the ends of conductors, or wings. Table 1 shows as the length of the dipoles in terms of λ, the directivity of the antenna corresponding to the length.

Length of Dipole	Directivity
.5λ	1.64
1.0λ	1.80
1.5λ	2.00
2λ	2.30
3 λ	2.80

Table 1 Length of Dipole and Resulting Gain

There is an increase in gain with each increase in length. In order to achieve a significant gain, the dipole length must be large in compared to the wavelength. Trying to achieve high gain at lower frequencies is an issue because the antenna can be massive, heavy, and costly. The radiation pattern of a typical dipole can be seen in Figure 5.
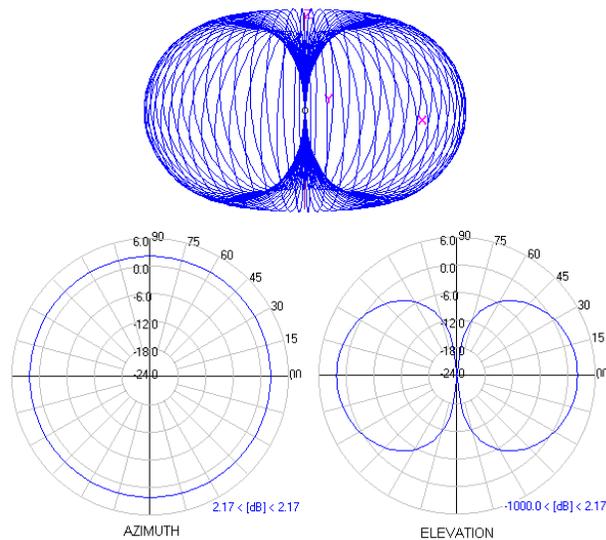
Figure 5 Dipole Radiation Pattern [12]

The radiation pattern of a dipole is in all directions. In addition, the radiation pattern looks similar to that of a donut. There are many different variations of dipole antennas and some common types are biconical, bowtie, and blade dipoles.

Biconical Dipoles

Biconical dipoles are defined as two conical conductors that have are symmetrical about an axis and vertex [5]. An example of a biconical dipole can be seen in Figure 6.
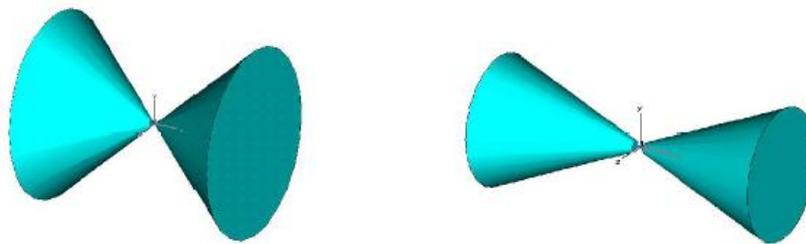
Figure 6 Biconical Dipole [13]

Biconical dipoles are considered part of the broadband dipole, being able to operate at a wide range of frequencies. The dipole feed is located at the center where both the cones meet. The antenna radiation pattern is similar to that of a regular dipole and the only real difference is the allowable bandwidth of this antenna is considerably higher than the dipole and can commonly achieve bandwidths of four to one [14]. Sometimes these cones are made out of a solid metal conductor which can be heavy and costly.

Bowtie Antennas

Bowtie Antenna is another broadband antenna. It also has a similar omnidirectional radiation pattern compared to the traditional dipole. A design of a bowtie antenna is seen in Figure 7.
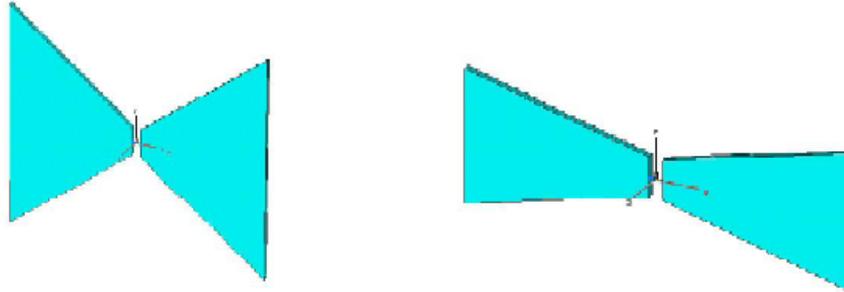
Instead of being constructed with a conductor sheet, bowtie antenna can constructed using a

wire to form the same shape. This is beneficial because it is lower in because less is being used metal

and decreases wind resistances. The bow tie antenna is center fed like a dipole. Figure 8 shows an

illustration of a wire bowtie antenna.
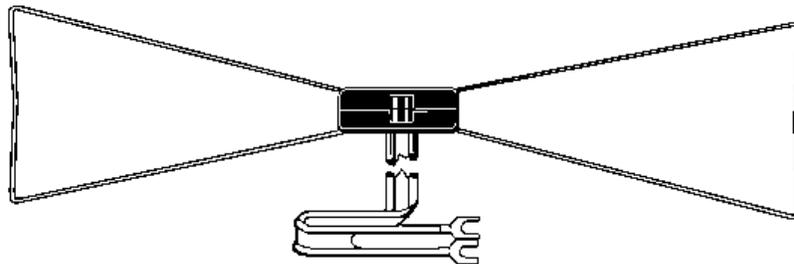
Figure 8 Wire Bowtie Antenna [15]

As you can see, the metal used to construct this dipole is significantly less than a tradition

bowtie antenna constructed from sheet metal. This method will lower production cost and decrease the

weight of antenna.

Helix Antenna

A helix antenna is defined as an antenna whose configuration relates to a helix [5]. The helix

antenna is relatively light weight because it is constructed using a metal conductor wire, a center

support the helix structure, and is usually attached to a ground plane at the base. An example of a helix

antenna is seen in Figure 9/
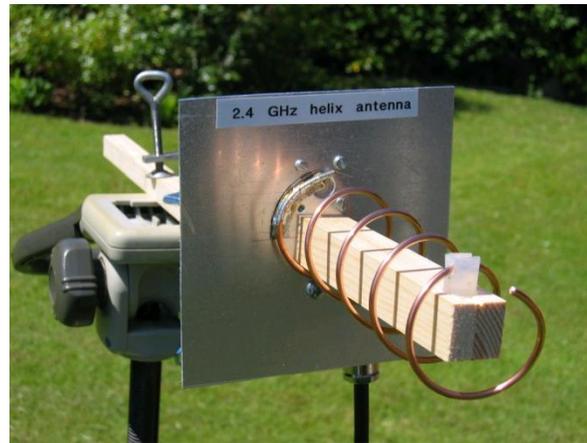
Figure 9 Basic Helix Antenna Configuration

The lossless gain of a Helix Antenna is given by N= Number of turns
C= Circumference of Helix
S = spacing between turns

Equation 7.

$$G = 15N \left(\frac{C}{\lambda} \right)^2 \left(\frac{S}{\lambda} \right)^2$$

N= Number of turns
C= Circumference of Helix
S = spacing between turns

Equation 7 Gain of Helix Antenna [16]

The gain is dependent of the number of turns, the circumference of the helix, the spacing

between turns, and the wavelength. Designers can increase the gain of the antenna by adding

additional turns which will increase the length of the antenna. Another key characteristic is the input

impedance of the antenna. This can be obtained using Equation 8.

$$R = 140 \frac{C}{\lambda}$$

C =Circumference of helix

Equation 8 Input Impedance of Helix Antenna [16]

The resistance of the antenna is dependent of the circumference of the helix and the wavelength. By making the circumference smaller and closer to the wavelength, the antenna will have a smaller input resistance but a smaller achievable gain. By changing the circumference, designers can match the impedance of the transmitter to the generator resistance. Figure 10 shows a basic configuration of a helix antenna.
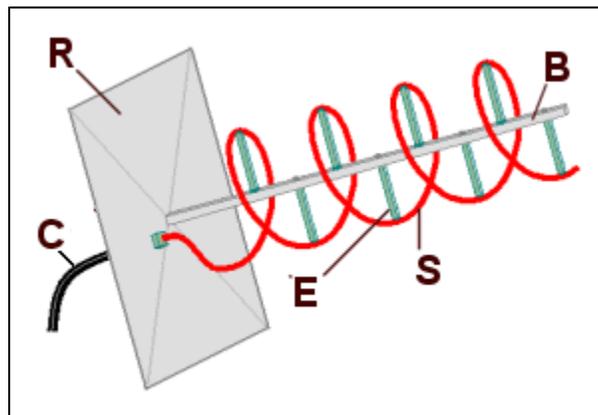
Figure 10 Basic Helix Antenna Configuration [17]

The coaxial cable is connected to the feed is label as C, R is the reflector base, B is the center support, E is the support for the helix, and S is the wire of the helix antenna that is radiating or receiving electromagnetic waves.   Other design parameters that needs to be consider when designing a helix antenna are the pitch angle (arctan (S/ pi*D)), the total length of the antenna (NS), and total length of wire (N*Length of one turn)

There are two operational modes for a helix antenna: axial mode, and normal mode. In normal mode the spacing between helixes and the diameter of the helixes are small in comparison with the wavelength. The radiation pattern is along the helical direction and it is similar to that of a dipole. In axial mode, the antenna functions like a directional antenna and the spacing between elements is $\lambda/4$. The antenna radiates at the top of the helix along the axis of the antenna. The radiation pattern of both operation modes can be seen in

22

Antenna Type	Radiation Pattern
AXIAL MODE HELIX	Elevation & Azimuth
NORMAL MODE HELIX	Elevation: / Azimuth:
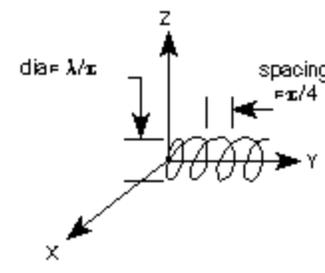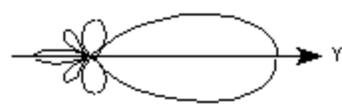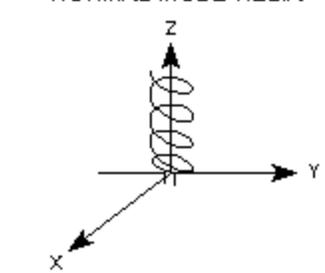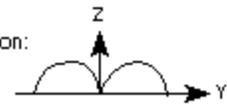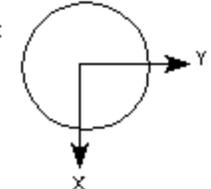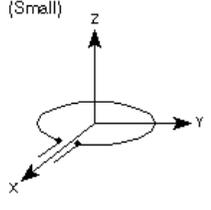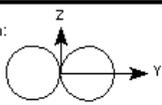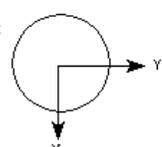
Figure 11 Radiation Pattern of Helix Antenna [18]

Loop Antenna

The "IEEE Standard Definitions of Terms for Antennas" defines a loop antenna as "an antenna whose configuration is that of a loop" [5]. This loop can be in the shape of a square, rectangle, circle trip, and many other geometric shapes. There are two different categories to loop antennas: electrically small or electrically large [8]. Electrically small antennas are defined as antennas that loop length is less than one-tenth of wavelength. Wavelength, λ, is the ratio of the speed of light over the frequency at which the antenna is designed to operate at. Small loop antennas are sometimes called the magnetic loop because it acts like an inductor. Electrically large loop antennas are defined as antennas that have a loop length of approximately λ. Figure 12 shows examples of loop antennas.

Figure 12 Loop Antenna Example [19]

The radiation pattern of a loop antenna is omnidirectional which is similar to the dipole. Figure

13 shows the radiation pattern of small circular and rectangular loop antenna.

Figure 13 Radiation Pattern of a Small Circular and Rectangular Antenna [20]

Aperture antennas

An aperture antenna is an antenna that contains an opening in which electromagnetic waves are transmitted or received through [21]. Aperture antennas can be many different shapes. Popular configurations of an aperture antenna are waveguides and horns [8]. Aperture antennas are used widely in aircrafts because the can be covered with a dielectric. This dielectric protects the antenna from the environments that an aircraft is exposed to. A waveguide is an antenna that guides an electromagnetic wave. It consists of a conductive wall that is hollow in the inside for the wave to travel. A horn antenna is "an antenna consisting of a waveguide section in which the cross-sectional area increases towards an open end which is the aperture" [5]. A typical horn antenna is in Figure 14.
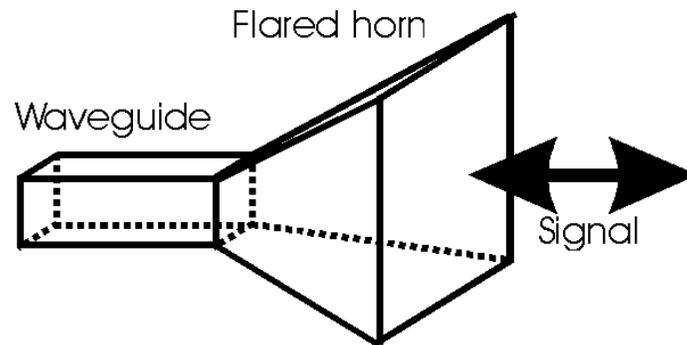
Figure 14 Example of a Horn Antenna [22]

There are three types of horn antennas: 1) E-plane sectoral horn, 2) H-plane sectoral horn, and 3) pyramidal horn [23]. H-Plane Sectoral horn has a wider width to of the aperture while E-Plane Sectoral horn has a wider height. The pyramidal horn has approximately equal width and height.
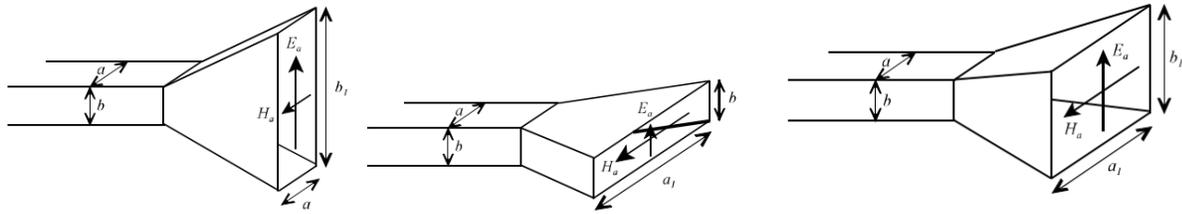
Figure 15 E-Plane Horn (Left), H-Plane Horn (Middle), Pyramidal Horn (Right) [23]

Reflector Antenna

Reflector antennas redirect electromagnetics and refocus it in a certain direction. This type of antenna is commonly used for space crafts for long distance communication [8]. Several common types of reflector antennas are the plane reflector, the corner reflector, and the parabolic reflector. A plane reflector is flat reflector made of a conductor. The electromagnetic waves redirects concept can be compared to sunlight hitting a mirror.

A corner reflector usually consists of two plane reflectors joined together at an angle. Typically these two plane reflector joins together to form a 90 degree angle. Figure 16 shows the concept of a 90 degree corner reflector.
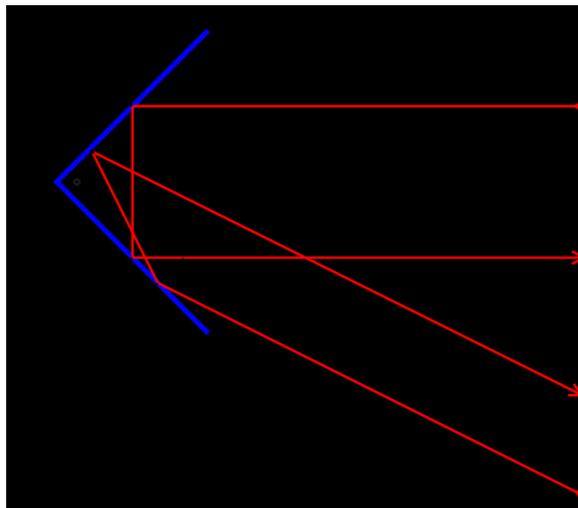
Figure 16 Concept of Corner Reflector [24]

Parabolic reflectors are shaped like a parabola. Electromagnetic waves can be focused into a beam and aimed at locations with accuracies. Because of this characteristic, parabolic are commonly used by dish TV companies, and satellite communication. Figure 17 shows an example of a parabolic antenna.
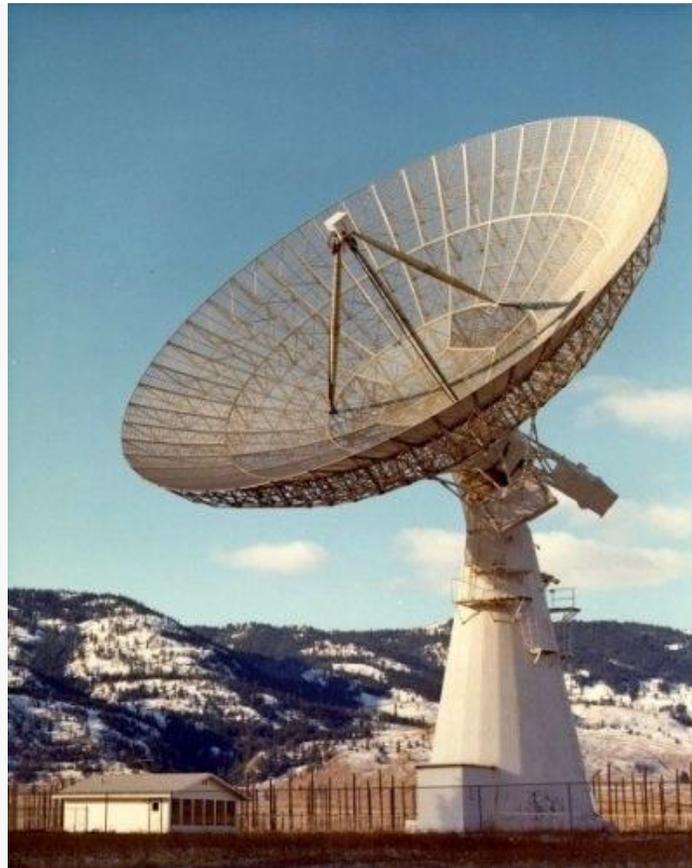
Figure 17 Example of a Parabolic Reflector [25]

The losses gain or directivity of a reflector antenna can be found know the wavelength and the cross-sectional aperture. Equation 9 is the equation for the directive for a reflector antenna.

$$G_{\mathrm{max}} = D_u = \frac{4\pi}{\lambda^2} A_p$$

Equation 9 Directivity of a reflector antenna [26]

The true gain of a reflector antenna takes into account radiation, aperture taper, spillover, and achievement losses. Taking those factors into consideration, the gain of a reflector antenna can be found using Equation 10.

$$G = \varepsilon_{ap} D_u = \frac{4\pi}{\lambda^2} \varepsilon_{ap} A_p \quad \varepsilon_{ap} = e_r \varepsilon_t \varepsilon_s \varepsilon_a$$

e_r is the radiation efficiency
ε_t is the aperture taper efficiency
ε_s is the spillover efficiency
ε_a is the achievement efficiency

Equation 10 Gain of Reflector Antenna [26]

Microstrip Antenna

The microstrip antenna, sometimes called a patch antenna, is defined as an antenna which consists of a thin metallic conductor bonded to a thin grounded dielectric substrate [5]. Microstrip antennas are low profile, small in volume, and have low production cost [27]. The feed can be connected directly to the conductor on the same substrate. The antenna design can be printed onto ceramic substrate which eliminates the need for an adhesive to bond the conductor to the substrate. Figure 18 shows a single rectangular patch antenna configuration.
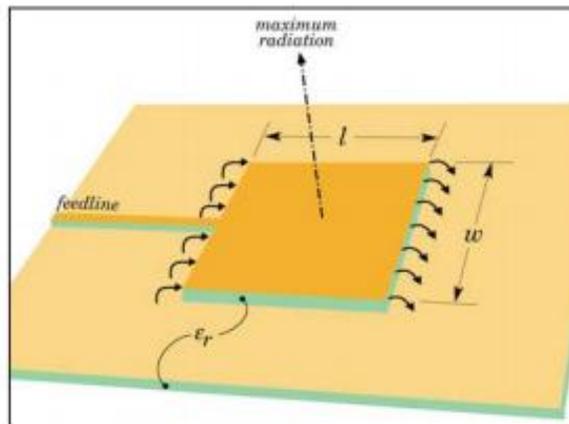
Figure 18 Basic Patch Antenna Design [28]

The patch antenna can operate from the ranges from 1GHz to 6GHz. At lower frequency the antenna can be large in size and may not be practical. To design an antenna to resonance at a desired frequency, Equation 11 can be used.

$$f_{res} = \frac{0.5c_0}{\sqrt{\varepsilon_r}(L + 2\Delta L)} \qquad \Delta L = h\frac{0.412(\varepsilon_{\it eff} + 0.3)\left(\dfrac{W}{h} + 0.264\right)}{(\varepsilon_{\it eff} - 0.258)\left(\dfrac{W}{h} + 0.8\right)} \qquad \varepsilon_{\it eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\frac{1}{\sqrt{1 + 10\dfrac{h}{W}}}$$

h = Height of dielectric substrate
W = the width of the patch
€R = Relative Dielectric of substrate
Equation 11 Resonant Frequency of Single Patch Antenna [6]

There are many different variations of shape for patch antenna's radiating element. Some common shapes are square, circle, ellipses, triangle, circular ring, and dipole. The more commonly used shapes are square, rectangle, dipole, and circle are used because they are easier to analyze than other shapes.

The ground plane of a patch antenna is effective in redirecting radiation in the forward direction. A single microstrip patch antenna has a typical directivity of 8-9 dBi [28]. Multiple microstrip radiating elements can be coupled together to produce a higher gain which can approach 20dBi gain.

Resistance of a Patch Antenna

The patch antenna can be thought of as an open ended microstrip transmission line. Because of this, the voltage and current are 90 degrees out of phase. The current peaks at the center of the patch while the voltage is zero at that location. The magnitude of the voltage is maximized at the edge of the patch. The voltage and current distribution can be seen in Figure 19.

Because the magnitude of the voltage is largest at the edge and the current is the minimum, this causes the resistance of the patch to be greatest at the edges of the patch. The resistance is zero at the center because the voltage is zero while the current is maximized. Typical the edge resistance of the patch antenna is around 200Ω. The impedance at the edge of the antenna can be found using

$$R_{in} = \frac{1}{(2G_e)} \quad G_e = 0.00836 \frac{w}{\lambda_o}$$

G_e = Edge Conductance
W = width of patch
Equation 12 Edge resistance of microstrip patch [30]

To match the patch to a lower resistance, the antenna is fed between the middle and the edge of the antenna.

Substrate of Patch Antenna

The dielectric constant of the substrate affects the size of the microstrip antenna. With a higher dielectric constant, the substrate slows the propagating wave through the substrate making the wave slow. Because of this, radiating elements can be smaller. This means the elements are designed at a higher frequency but because of the dielectric constant, the antenna will be operating at a lower frequency. . A disadvantage to patch antenna is the overall efficiency of the antenna. Losses produced

30

by the feed network and the substrate material decrease the overall efficiency. In addition, patch

antennas can be susceptible to interference at certain frequencies

Feed Technique

The feeding method to the patch antenna can be done in many different ways. Four typical

feeding methods are the microstrip line feed, probe feed, aperture coupled feed, and the proximity –

couple feed [8]. The microstrip line feed is one of the easier feeding techniques to implement. It

consists of a conductive strip connected to the patch. One of the disadvantages to this method is that as

the substrate thickness increases, the bandwidth decreases as a result of surface waves. Figure 20

shows the microstrip line feed method.

Figure 20 Microstrip Line Feed Method [29]

Aperture-Coupled feeding method requires the use of two substrates. In the middle of the

substrates is a ground plane with an aperture. Commonly, the top substrate has a lower dielectric than

that of the lower substrate. The reason for this is to limit undesired radiation from the patch element to

the feed. This feeding method is the hardest to fabricate out of the four types of feeding methods that

are being discussed. Figure 21 demonstrates the aperture-coupled feed method.
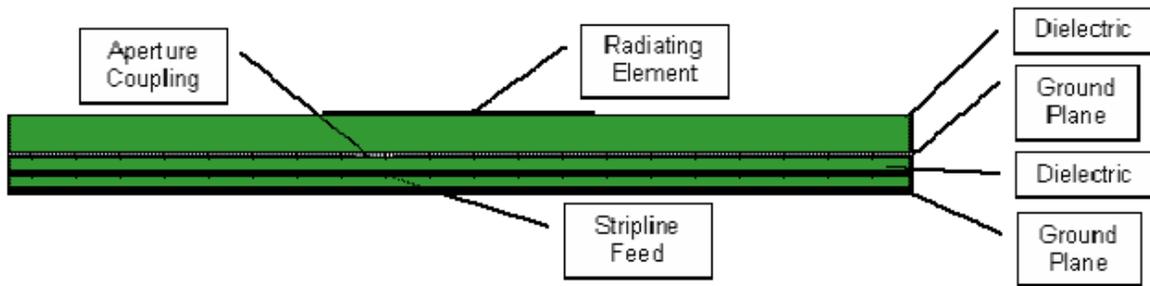
Figure 21 Aperture-Coupled Feed Method [26]

Probe Feeding is a feeding technique where the inner conductor of the coaxial cable is connected to the radiating element and the outer conductor is connected to the ground plane. This type of feed is easy to fabricate but provides a narrow bandwidth and is difficult to model for thick substrates. Figure 22 shows the concept of probe feeding.
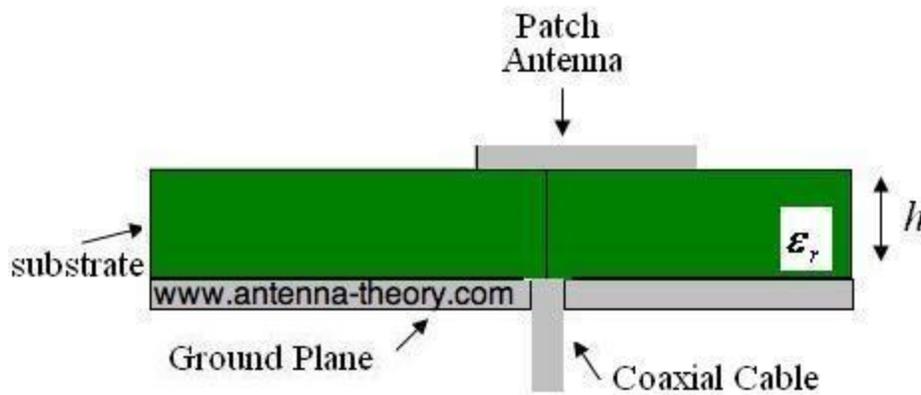
Figure 22 Probe Feed [31]

Proximity-Coupled Feed technique has the highest bandwidth of all four feeding technique. However, fabrication of this feed is difficult. Figure 23 demonstrates the proximity-coupled feed technique.
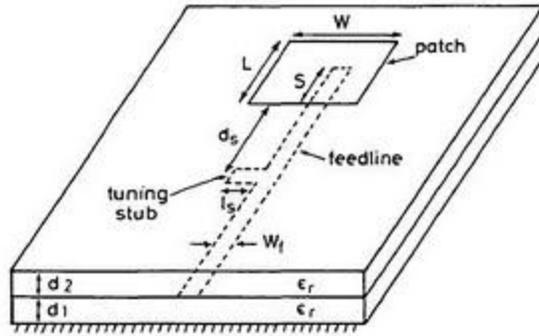
The length of the feeding stub S and the width to line ratio is used to match the impedance. Two layers of substrate are needed for this feeding technique.

Antenna Array

An antenna array is "an antenna comprised of a number of identical radiating elements in a regular arrangement and excited to obtain a prescribed radiation pattern [5]." Antenna arrays can be divided into two divisions: scanning and non- scanning antenna arrays. Scanning arrays are able to move their main beam electronically, usually by changing the phase of the elements. Non-scanning array can only change their main beam lobe by moving the antenna orientation and are used commonly to for directional radiation applications. A common type of scanning array is the phased array. Non-scanning array examples are an array of dipoles, or microstrip antenna.

Phased Array

Phased array antennas are an antenna that has multiple radiating elements each connecting to a phase shifter. The phase shifting allows the radiation pattern to be "steered" towards a certain direction.
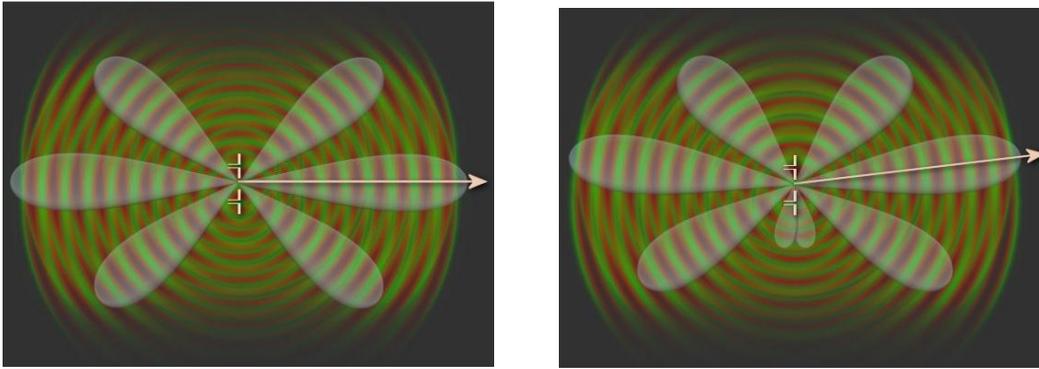
The lobe is increased upward as a result of the phase shift demonstrating by changing the phase one can steer the beam in desired location without actually moving the element. Some benefits and drawbacks to the phased array can be seen in Table 2.

Benefits	Drawback
Can steer the beam in desired location in a matter of microseconds.	Very complex (requires phase shifters, and processors)
Can combine beams to produce high gain	High Cost
Can produce multiple lobes allowing multiple targeting	Coverage of a maximum of 120 degree sector

Table 2 Benefits and Drawbacks to Phased Arrays [33]

Market Research

In this chapter we will investigate current high gain antennas developed for WLAN. High gain antennas for WLAN application has been produced by many companies such as Hawking, Netgear, Cisco, and many other WLAN companies.   We will investigate different configurations of high gain antennas from different companies and develop a set of criteria the design are set to meet in order to be competitive in the market.

Hawking Technology's HAI15SC, 2.4GHz Hi-Gain Wireless Corner Antenna

Hawking Technology currently has on the market a corner antenna with an advertised with gains from 2dBi to a max of 15dBi. The MFRP for this antenna is $51.99 [34]. The product operates at the

2.4GHz ISM band for 802.11 and is most likely a corner reflector dipole antenna. This product is seen in

Figure 25.

Figure 25 Hawking Technology's HAI15SC, 2.4GHz Hi-Gain Wireless Corner Antenna [35]

The antenna is 10.2 inches by 6.5 inches by 2.5 inches and weighs approximately pound. The

antenna is covered in plastic and is built for indoor application. The benefits of this product are that it's

small and provides high gain. The downside to this product is not suited for outdoor application.

Hawking Technology Hi-Gain™ 14dBi Outdoor Directional Antenna Kit

The Hawking Technology Hi-Gain outdoor antenna provides gain from 2dBi to 14dBi gain. This

product MSRP is $106.99. The antenna operates at the 2.4GHz ISM band for 802.11 and is most likely a

microstrip antenna array. Figure 26 shows an image of the product.

Figure 26 Hawking Technology Hi-Gain™ 14dBi Outdoor Directional Antenna Kit [35]

The antenna includes a mounting kit and is encased with a weatherproof case which protects it from the environment. The antenna is 10 inches by 9 inches by 3.6 inches and weighs approximately 2.8 pounds. This antenna provides high gain and is built for the outdoors. In addition, the antenna can be mounted flush to the side of a house and is low profile.   One downside to this product is it is high in cost.

CISCO AIR-ANT5195P-R Aironet 9.5-dBi Patch Antenna

Cisco's Aironet 9.5-dBi Patch Antenna is a 9.5dBi microstrip antenna that provides omnidirectional gain. This antenna MSRP is $169.99. This antenna operates at the 5GHz 802.11 band. Figure 27 shows the actual antenna and its radiation pattern.
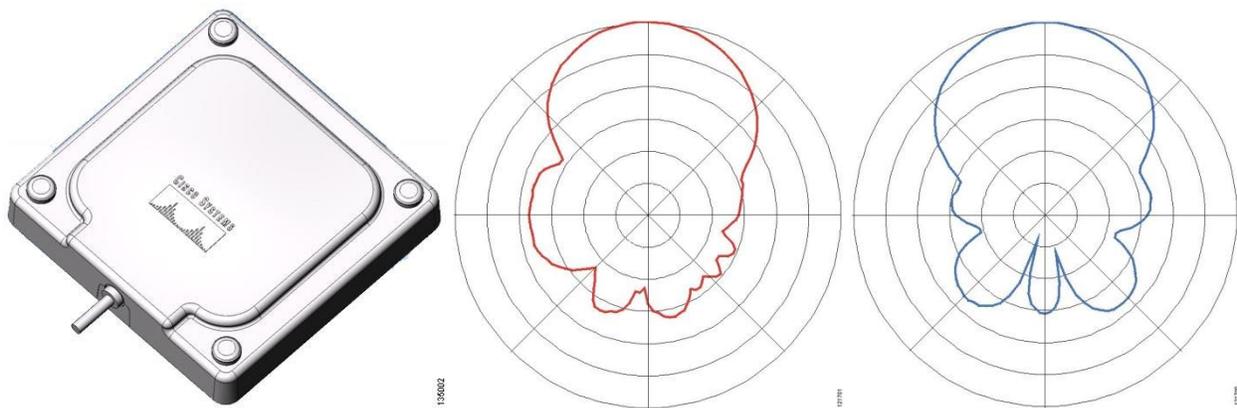
Figure 27 CISCO AIR-ANT5195P-R Aironet 9.5-dBi Patch Antenna and Radiation Patter (Red-Vertical, Blue-horizontal) [36]

The benefits of this product are that it is weatherproof and made for the outdoors. The drawback is the price of the antenna is relatively expensive compared to the other competitive antennas. In addition it operates at the higher frequency band of 5GHz which is not widely used and is not compatible with most computers being used today.

TRENDnet 14dBi Outdoor High Gain Directional Antenna TEW-AO14D

The TRENDnet 14dBi gain antenna is a highly directional antenna.   The antenna's MSRP is

$71.99. The antenna operates at the 2.4GHz 802.11 band. The antenna can be shown in the Figure 28

below.
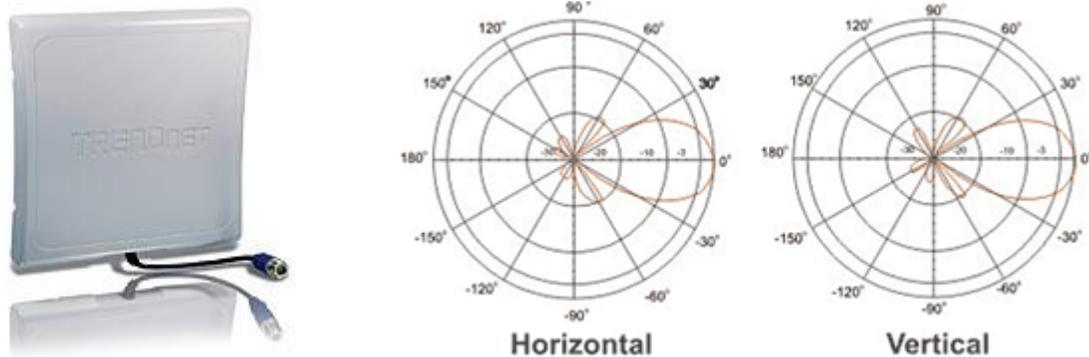
Figure 28 TRENDnet 14dBi Outdoor High Gain Directional Antenna and Radiation Pattern [37]

The antenna comes with a mounting kit and is suited for outdoor use. The antenna is flat and

can be mounted flush to a wall or the siding of a house. The antenna is 8.9 inches by 9 inches by 1.2

inches.

2.4 GHz 24dBi Grid Parabolic Dish Antenna N-Female Die Cast

Liard manufactures a 24dBi grid parabolic dish antenna for the operation of 802.11 at the

2.4GHz band. This antenna MSRP is $66.22. The antenna and radiation pattern and antenna can be

seen in Figure 29.
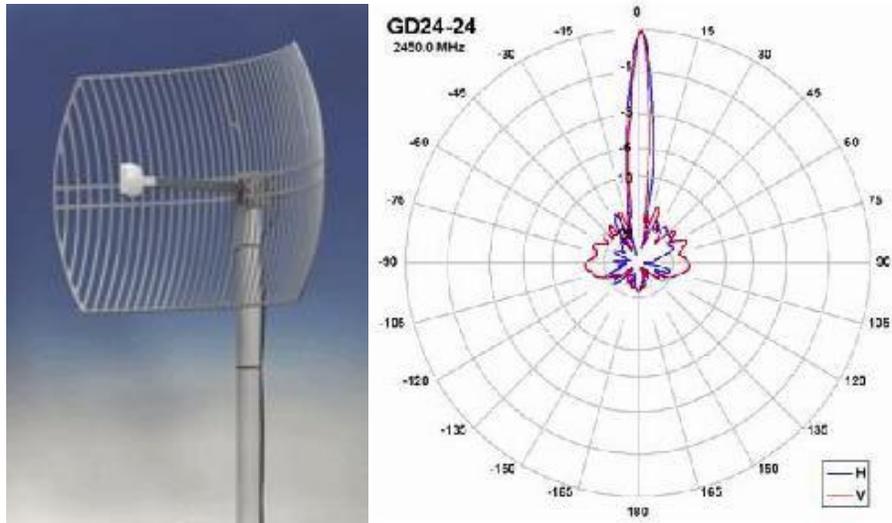
Figure 29 Liard 24dBi Grid Parabolic Dish Antenna and Radiation pattern [38]

The antenna weighs approximately 10 pounds and comes with pole mount. The antenna is powder coated to weatherproof the design. Dimensions are not specified for this product but the reflector is curved.

Market Research Conclusion

There are many types of configurations for a high gain antenna.   The gain of the reviewed antennas approximately average out to be around 14dBi. The parabolic antenna produces high gain but is heavy and requires heavy duty mount. The panel antennas flat antennas and can be mounted flush to buildings which makes them low profile but the cost of these panel antennas are high in cost to the alternatives. The cost of the antennas ranges from around $51.99 to $169.99.

Product Requirement

The purpose of this project is to design a highly directive, low cost, low profile and easily reproducible antenna. This antenna was designed for the use of WLAN 802.11. To achieve this goal we identified 4 main objectives. The antenna must have high gain, low build cost, small and light weight design, and easy to manufacture. In this section we will discuss the design parameters and the importance of them. These parameters will later be used to identify which antenna configuration will use for the project.

Highly Directive

A highly directive antenna will allow the signal from the WLAN router to be aimed at a designed location. By doing this, signal can be directed towards high density location such as busy city streets and provide WLAN to users on an entire street block. This provides a convenient way to provide an extended coverage area of high density of people without the need to install more access points. Also this antenna would be beneficial in rural areas where houses are farther apart. A directional antenna can prove internet access to other houses in the neighborhood.

The radiating power of the directional antenna is used effectively by targeting locations where people are located. In the case of home user, this would provide stronger signal and increased data rates for users at farther distances away from the access point.

Antenna Cost

There are many different types of high gain antennas out on the market. Some of these antennas can go for hundreds of dollars while sum can range from mid to upper $90. In order to compete with the current market, the antenna design must be lower or equal in cost with the same or better performance. By lowering cost, this will draw in consumers to upgrade their wireless antenna. The goal is the design an antenna below $15.

Antenna Dimensions

One of the major criteria to the antenna design was to have the antenna be low profile. Pedestrians do not want to see a large hideous metal mounted near a historical building or an old district which could ruin the scenery. It must be relatively small and fit in almost any space.   The antenna has to be low weight so it can be easily mounted in sides of buildings or on street post without the need of heavy mounts mechanisms which could be ugly and increase the cost. In addition for residential homes, it was essential for the antenna to be easily mountable on walls or locations that are small and tight.

Ease of Production

In order to keep the prices down, the manufacturing process should be ease to limit labor cost. With the increase in production difficult, it will result in more hours needed to produce the desired product quantity. This could result an increase in hourly wages for employees which in turn will result in a higher production cost per unit of merchandise.   In addition, with the increase in production time, fewer products can be produced in a given time frame which can reduce sales of product. The product should require little to no additional customization of components.

Results and Analysis

In order to achieve our goal of building a high gain, low profile, low cost, and easy to manufacture antenna, we conducted research of high gain antennas configurations, the construction cost of these antennas, the material cost, and the man hours to build them. This section will discuss the design steps and the implementation and testing of our design.

High Gain Antennas

After reviewing different antenna configurations, a list of high gain antennas were compiled to be considered for our application. The following antenna models were identified as possible antenna designs:

- Reflector
- Aperture
- Microstrip Array
- Phased array
- Helix

Reflector antennas can provide sufficient gain with the use of a plain, parabolic, or corner reflector. Aperture antennas use a waveguide and branch into an aperture which can be designed to achieve a desired high gain. Phased arrays radiation pattern can be changed by varying the phase of each/or certain radiating element. It can provide high gain but also be configured to directional high gain signals to multiple users in various directions. Microstrip antennas can provide directivity in the range of 7-9dBi. An array of microstrip antennas can achieve considerable higher gain. Helix antenna in axial mode can produce directive radiation patterns.

Cost of Production

Phased array antennas are expensive to produce with the cost increases with the more radiating elements. Phase shifters, numerous feeds, and multiple cables are needed. In addition, the building and assemble of a phase array will require more time than other antenna configurations being considered.

Aperture antennas can be pricy depending on what type of material is used. Dimensions of a horn antenna are more complicated and may be hard manufacture. Sheet metal is usually in the production of aperture antennas to maintain a rigid structure. Different sections of the antenna can be produced and then welded together to form a single structure but this will increase the produce time and require additional skilled workers.

Helix antenna requires minimal amount of material. The materials needed would consist of conductive wire and a metal plate that serves as ground plane. The supports for the helix structure could be made out of wood and could be used to support the helical structure. The support mechanism must be installed by hand.

Microstrip antennas can be built at a low cost by using cheaper substrate material, and conductor material for the radiating elements and ground plane. Laser cutters can be used to cut out the shapes of the design and this can be quick and is dependent on the number of elements of the array. Substrate materials can be easily cut with a laser cutter or a mechanical saw. Cheap foil conductor can be used versus metal sheeting.

Reflector antennas can be expensive depending on how the reflector is made. A reflector made out of solid metal will cost more than one made of round bar connected together to form a reflector. In order to form the shape of the reflector, the metal can be pressed into a mold to form the desired shape. This may be higher in cost because of the thicker metal in order to hold its reflector shape.

Low Profile Design

Axial mode helix antennas can be mounted on the wall but the helix structure extends into the horizontal plane. The structure may not withstand high speed wind and maybe a problem in colder weather. Depending on how many turns are needed to achieve the desired gain, the antenna can be extremely long and may require a stronger middle support.

Reflector antennas cannot be mounted flush on the side of buildings so they are considered low profile, especially parabolic reflectors. In addition, reflector made out of metal and is heavier than the microstrip and helix antenna.

Microstrip antennas are light weight because it can be made with a thin substrate and conductive foil. In addition they can be mounted flush to buildings and walls with simple screws. The antenna has a smaller cross-sectional area than reflector antennas achieving the same gain and is overall smaller than the parabolic antenna.

Antenna Design Winner

The microstrip patch array antenna was chosen over the other antenna configurations. The antenna can be mounted using basic screws because it light weight and can have rectangular dimension. The antenna is also low profile and be mounted flush to buildings and can weather proof if a case is used. The cost of building a microstrip antenna can be cheap using cheap substrate material and thin conductive foil

Microstrip Antenna Array Design

This section will discuss the design process of the microstrip patch antenna array chosen to be used for our project design.   The design process discussed in this chapter will include the choosing of the substrate and conductive material, the dimension and number of conductive element, and the microstrip feeding technique for the array.

Step 1: Choosing Substrate Material

FR4 is cheap substrate material that can be bought in sheets. A .032 x12 x 48 inch sheet of FR4 sells for around $20. The thicker the substrate material, the higher it costs. A .125 thickness FR-4 with the same width and length dimension sells for approximately $53. Plexiglass with the dimensions of .0625x 24 x 48 inches sells for around $20. The material is thicker and cost about the same as the FR4. In addition, plexiglass is a less lossy material than FR4 which will increase the overall efficiency.

Teflon sheets are more expensive than FR4 and plexiglass. A vendor sells 0.031 x 12 x48 inch Teflon sheet for approximately $25.14 which is approximately 25% more than FR4 and plexiglass. Table 3 shows characteristics of previously discussed substrate materials.

Material	Cost	Dielectric Constant
FR4	$	4.35 − 4.7
Plexiglass	$	2.6 − 3.5
Teflon	$$$	~2.1

Table 3 Substrate Material Comparison

The dielectric materials discussed is shown in Figure 30.

Figure 30 FR4 (Left) [39], Plexiglass (Middle) [40], Teflon (Far Right) [41]

Plexiglass was picked as the substrate material because of the low cost and lower loss tangent that FR4. FR4 was the runner up because of its low cost. Teflon was more expensive and would increase the manufacturing price of the product.

Step 2: Conductive Material

The conductive material will be used to produce the microstrip arrays elements, the feed network, and the ground plane. The material must be cheap. The materials that were considered are aluminum and copper foil. Aluminum has 61% of the conductivity of copper making copper a better choice of material with lower energy loss. Aluminum and copper are close in price but copper foil was readily available in antenna lab so the material was chosen as the conductive material.

Step 3: Number of Microstrip Elements

To find the gain of the array, the array factor for a 2-D antenna array must be determined. The array factor can be multiplied by element pattern to obtain the theoretical gain. The equation for the array factor can be found using

$$AF(\theta,\varphi)=\left|\sum_{m=1}^{M}\sum_{n=1}^{N}I_{mn}\exp\left(j(md_{rx}\tau_x+nd_{ry}\tau_y)\right)\right|, \quad d_{rx}=\frac{2\pi d_x}{\lambda}, \quad d_{ry}=\frac{2\pi d_y}{\lambda}$$

$$\tau_x=\cos\theta_x-\cos\theta_{xs}, \quad \tau_y=\cos\theta_y-\cos\theta_{ys}$$

$$\cos\theta_{xs}=\frac{\psi_x}{d_{rx}}, \quad \cos\theta_{ys}=\frac{\psi_y}{d_{ry}}$$

I_{mn} = 1 for real excitation
D_x = x dimension of unit cell
D_y = y dimension for unit cell
M = # of elements in column in x plane
N= # of elements in a row in x plane

Equation 13 General Array factor for an array [6]

To determine the maximum gain, we will work in the zenith direction. $\cos\theta_{xs}$ and $\cos\theta_{ys}$ are both

equal to zero in this case. The array factor equation can be further simplified to a summing of an

exponential function multiplied by the element number multiplied by a constant. Using the identities

seen below, the equation can be simplified further.

$$\sum_{n=0}^{N-1}e^{jn\psi}=\frac{1-e^{jN\psi}}{1-e^{j\psi}}$$

$$S=1+x+x^2+x^3+\cdots+x^{N-1}$$
$$xS=\ x+x^2+x^3+\cdots+x^{N-1}+x^N$$
$$(1-x)S=1-x^N \Rightarrow S=(1-x^N)/(1-x)$$

$$1-e^{jN\psi}=e^{jN\psi/2}2j\sin(N\psi/2)$$

Equation 14 Mathematical Identity

The phase can be ignored because there is uniform excitation and the spacing between each element is
equally spaced and the equation can be simplified to Equation 15.

$$AF(\theta,\varphi)=\frac{\sin x}{x}\frac{\sin y}{y}, \quad x=\frac{1}{2}Md_{rx}\tau_x, \quad y=\frac{1}{2}Nd_{ry}\tau_y$$

Equation 15 Simplified Array Factor Equation [6]

τ_y and τ_x are is equal to the directional cosine of Θ_x and Θ_y. The array factor can be can be

multiplied by the element pattern to obtain the directivity of the antenna.

$$D_0 = 10\log_{10}\left[NM\frac{4\pi d_x d_y}{\lambda^2}\left(\frac{\sin x}{x}\frac{\sin y}{y}\right)^2\right] \quad \text{dB,} \qquad x = \frac{1}{2}Md_{rx}\cos\theta_x \quad y = \frac{1}{2}Nd_{ry}\cos\theta_y$$

Equation 16 Directivity of 2-D Array calculated using array factor [6]

Since the antenna is a non- scanning array, the equation can be further simplified to Equation

17.

$$D_0 = 10\log_{10}\left[MN\frac{4\pi d_x d_y}{\lambda_0^2}\right]$$

Equation 17 Directivity of an array [6]

From this equation, the directivity of an array is related to the free space wavelength, the

number of elements, and the unit cell of a single radiating element. A 16 element array with a unit cell

of λ/2 spacing will achieve a directivity of 17.98dB. This directivity is higher than my desired gain

because losses of up to 7dB are possible.

Step 4: Ansoft Design

Since there are multiple radiating elements, they have to connect in some sort of fashion. Two

types of ways to feed these elements are corporate feed and series feed. Corporate parallel feeding

network are used to provide power splits for 2^n elements which can be applied to the 16 elements. The

feeding method can be seen Figure 31.

Figure 31 Corporate Feeding Method for Array

There are four subsectors each subsector feeds four patches. Every two elements in each subsector are in parallel with the other two elements in the subsection. The impedance is matched with a λ/4 transformer between two elements. Every subsection is also in parallel with subsector to the left or right of the sector and each half is in parallel with each other and is also joined by λ/4 transformer. The array is center fed with a coaxial feed.

Ideally the elements should be spaced λ/2 apart but because of the λ/4 transformers the radiating element and the transformer would overlap. The solution was to increase the spacing between elements to 5*λ/8 = 76.5mm. The λ/4 transformers length was 15.60mm. The design of the microstrip array is four two by two arrays connected together. The radiating elements are 30mm x 30mm wide and are center fed by the corporate feed technique. The design is shown in Figure 32.

Figure 32 Schematic of Microstrip Antenna Array

Every two element of a two by two array are joined together using a λ /4 transformer. The microstrip transmission line is approximately 100Ω. The resistance of the transmission line is found by using Equation 18.

$$Z_O = \frac{87.0}{\sqrt{\varepsilon_r + 1.41}} \times \ln\left(\frac{5.98h}{0.8W + t}\right)$$

Each two by two lattice uses three λ/4 transformers and are connected through a common middle transmission line. Simulation was used to find the location for the feed which would allow for maximum power.

Once a two by two array lattice was created and joined together, they were replicated three times to create this 16 patch array. The location of the feed is in the center of the symmetrical microstrip patch design. The antenna is on a 306mm by 306mm substrate that is 4.67mm thick. The substrate was set to have a dielectric constant of 3 and the material of the conductor was copper. A radiation box was made to enclose the antenna and PML material was placed around the box. A parameter sweep was used to determine which height should be used to generate a resonant of approximately 2.45GHz. The simulated reflection coefficient can be seen in Figure 33.
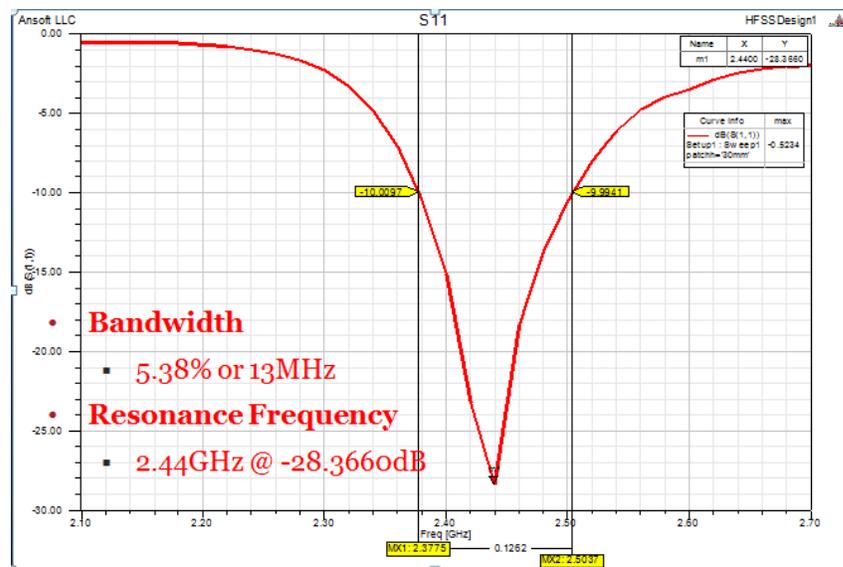
Figure 33 Simulated Reflection Coefficient with 30x30mm Patch

The antenna resonates at 2.44GHz and the -10dB bandwidth encompasses entire span of the ISM 2.4GHz operating band. Another important aspect to our design was the gain of the antenna was to in the range of 12-16dBi. The simulated radiation pattern of the antenna is shown in Figure 34.
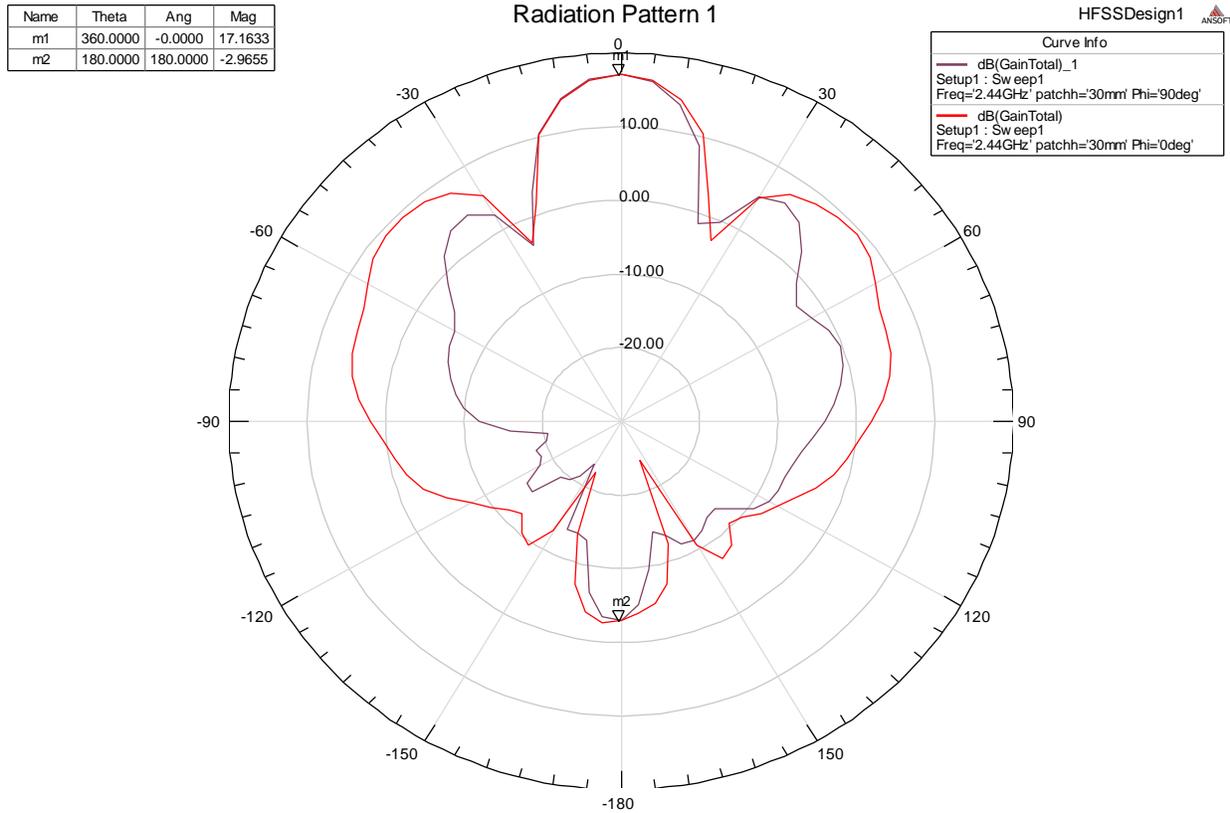
Figure 34 Radiation Pattern of Simulated Patch Antenna Array

The maximum directivity of the antenna is 17.16 dB with losses taking into consider Ansoft simulation predicts the gain with losses to be around 15dB which falls in our desired range.

Step 5 Implementation of Design

One of the main parameters that were out of our control was the dielectric constant of our plexiglass substrate material. The dielectric constant of plexiglass can be as low as 2.6 and as high as 3.5. In our design, we assumed the dielectric constant to be 3.0. Looking at the Equation 11, the resonant frequency is dependent on the relative dielectric, the thickness of the dielectric, and the length of the patch antenna. The width of the patch should be approximately the length of the patch to help avoid parasitic resonance and parasitic

oscillation mode. Plugging in ε_r = 3.0, and thickness of the dielectric, h of 30mm, to be 3/16 inch or 4.67mm, the

approximate length of the patch was approximated to be 31mm. The impedance of the transmission line feeding

network is also affected by the dielectric constant and Equation 18 shows that.

The length of the patches was initially cut to the longer length of 40mm and was shorted to approximately

to 34mm to produce a resonant frequency of 2.41GHz.   This value was very close to our designed center

resonance frequency but as long as the -10dB bandwidth encompassed the frequency between 2.4GHz and

2.5GHz; we were satisfied with the design. The impedance mismatch of the array and the 50Ω varied greatly. As a

result the resonant frequency did not have reflection coefficient below -10dB. To better match the antenna, an

additional copper strip was added at the center of the array to match the impedance. The constructed antenna

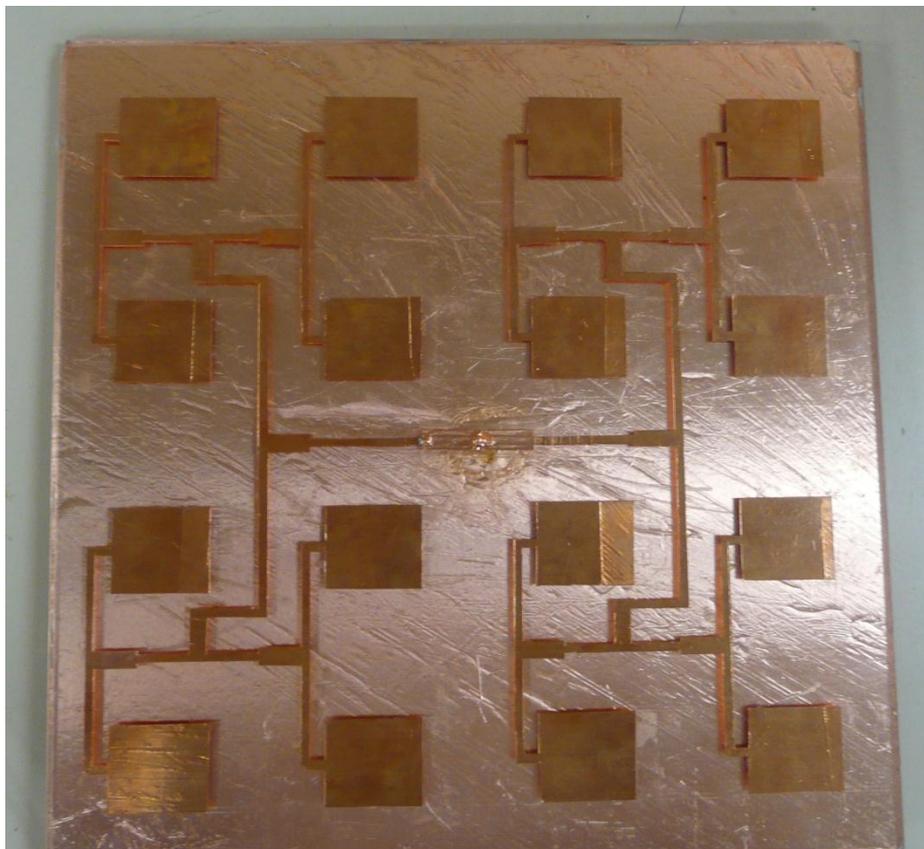array is shown in Figure 35.

Figure 35 Constructed Antenna Array with 30x34mm Rectangular Patches

To approximate the relative dielectric constant of the plexiglass, we ran simulations with Ansoft with the new length radiating elements. By changing the dielectric constant of our material, we can find at what value the antenna is resonating at 2.41 GHz. The completed simulations concluded that the relative dielectric of the plexiglass as approximately 2.7, .3 below the assumed dielectric value.

Another method to determine the dielectric constant of the material would have been to design a single patch antenna using the same substrate material and determine the resonant frequency using the network analyzer. With the known dimensions of the antenna, simple calculations can be done to determine the dielectric constant. This experiment was not done because each batch of plexiglass will produce different dielectric constants. Since the plexiglass was cut exactly to size, there was no extra piece of the dielectric that could be used to conduct the test.

Step 6 Antenna Measurements

Three antenna arrays were constructed. The reflection coefficient S11 was measured using an Agilent E5062A Network Analyzer. Each antenna array was connected to the network analyzer by a coaxial cable.   The cable was first calibrated before testing the reflection coefficient S11. The data was recorded and graphed on the same figure to compare the values of each of the three antennas.
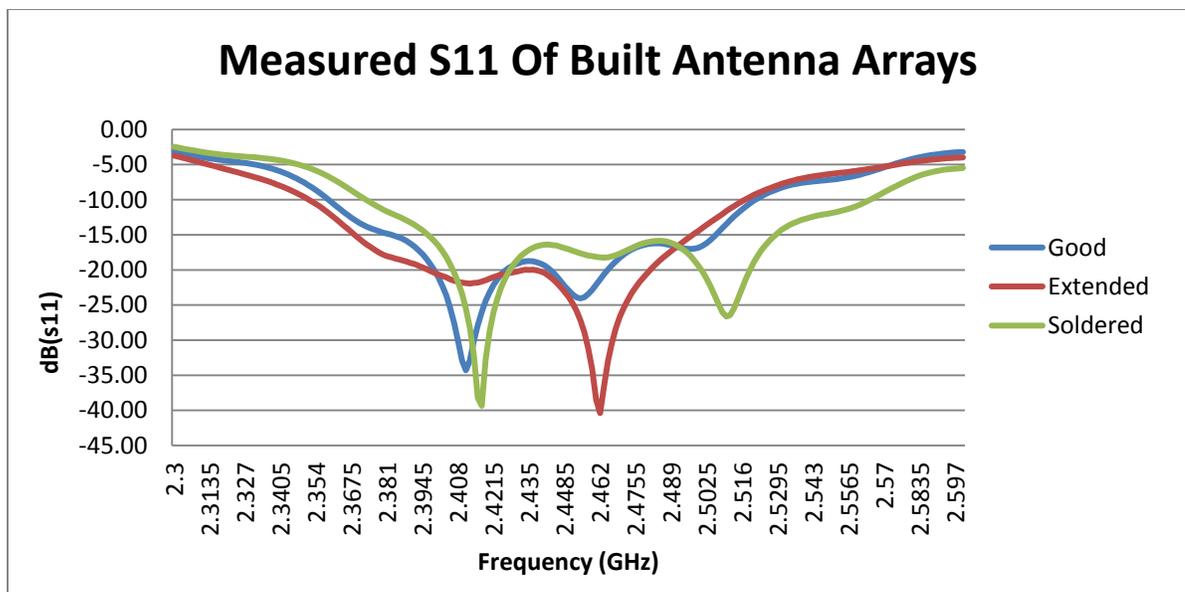

Figure 36 Measured S11 of Antenna Arrays

53

Although the resonant frequency was not exactly at 2.45 GHz, the -10dB bandwidth encompassed the ISM 2.4GHz band from 2.4GHz to 2.5 GHz The -10dB bandwidth and the characteristics is shown in Table 4.

	Simulated Array	Good Array	Soldered Array	Extended Array
F_L	2.3775GHz	2.357GHz	2.37GHz	2.36GHz
F_H	2.5038GHz	2.519GHz	2.56GHz	2.5086GHz
F_{res}	2.44GHz	2.41GHz	2.42GHz	2.462GHz
Bandwidth	5.17% or 126MHz	5.16% or 161MHz	7.7% or 190MHz	6.1% or 148MHz

Table 4 -10dB bandwidth of simulated and measured results

The radiation pattern of the antenna was measured using the network analyzer and two tripods. A reference gain was needed to calculate the gain of the antenna array. First two horn antennas with a gain of 10dB were used to determine a 10 dB reference level. S21 of the horn antenna was measured and recorded to be the -20.6dB reference level. The setup of the S21 measurement can be seen in Figure 37.

Figure 37 Horn to Horn Measurement

The distance between the tripods and evaluations were not changed during the testing. The transmitting horn was then replaced by a patch antenna array and s21 was measured at 10 degree

intervals from 0 to 180 degrees. Ideally the measurements would be done outside or in an anechoic

chamber but because of weather and lack of facilities, the measurements were done in the antenna lab.

The setup of the experiment can be seen in Figure 38.

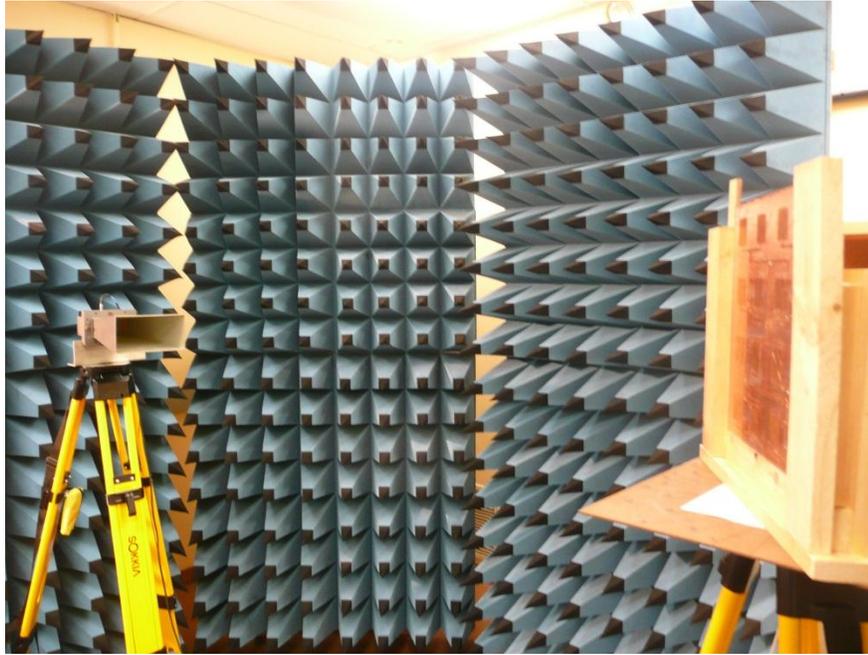

Figure 38 Antenna Radiation Measurement Setup

The measured s21 or received signal strength was recorded at every 10 degree interval and the

gain was calculated by subtracting the received S21 of the horn at the front lobe by S21 of the array at

different degrees then an addition 10dB. The antenna at degrees can be seen in Table 5.

	Perfect	Solder	Extended
180	-8.4	-9.4	-7.4
170	-11.4	-6.1	-7.4
160	-9.4	-7.4	-8.4
150	-18.4	-15.4	-17.4
140	-3	-3.2	-3.7
130	-6.4	-4.8	-3.8
120	-0.7	-2.1	-5.4
110	9.3	9.6	8.2
100	12.8	13.2	12.34
90	13.2	12.9	12.7
80	2.7	6.2	5.9
70	-4.5	-7.6	-14.4
60	-0.7	-0.5	-2.2
50	-5.3	-6.5	-7.9
40	-8.8	-9.8	-10.2
30	-8.1	-8	-8.3
20	-9	-9	-8.5
10	-8.4	-9	-10.4
0	-10.4	-9.4	-9.4
Front to Back Ratio	14.2	14.5	14.1

Table 5 Measured Antenna Gain

The 90 degree angle represents the main lobe gain and the decreasing angles represent the antenna rotating counterclockwise and the increasing angles represent the rotation of the antenna clockwise. The gains versus angle were plotted on a polar plot with simulated radiation pattern and are shown in Figure 39.

Radiation Pattern (total gain, dB)

Ansoft Simulation
Extended Patch
Solder Patch
Perfect Patch
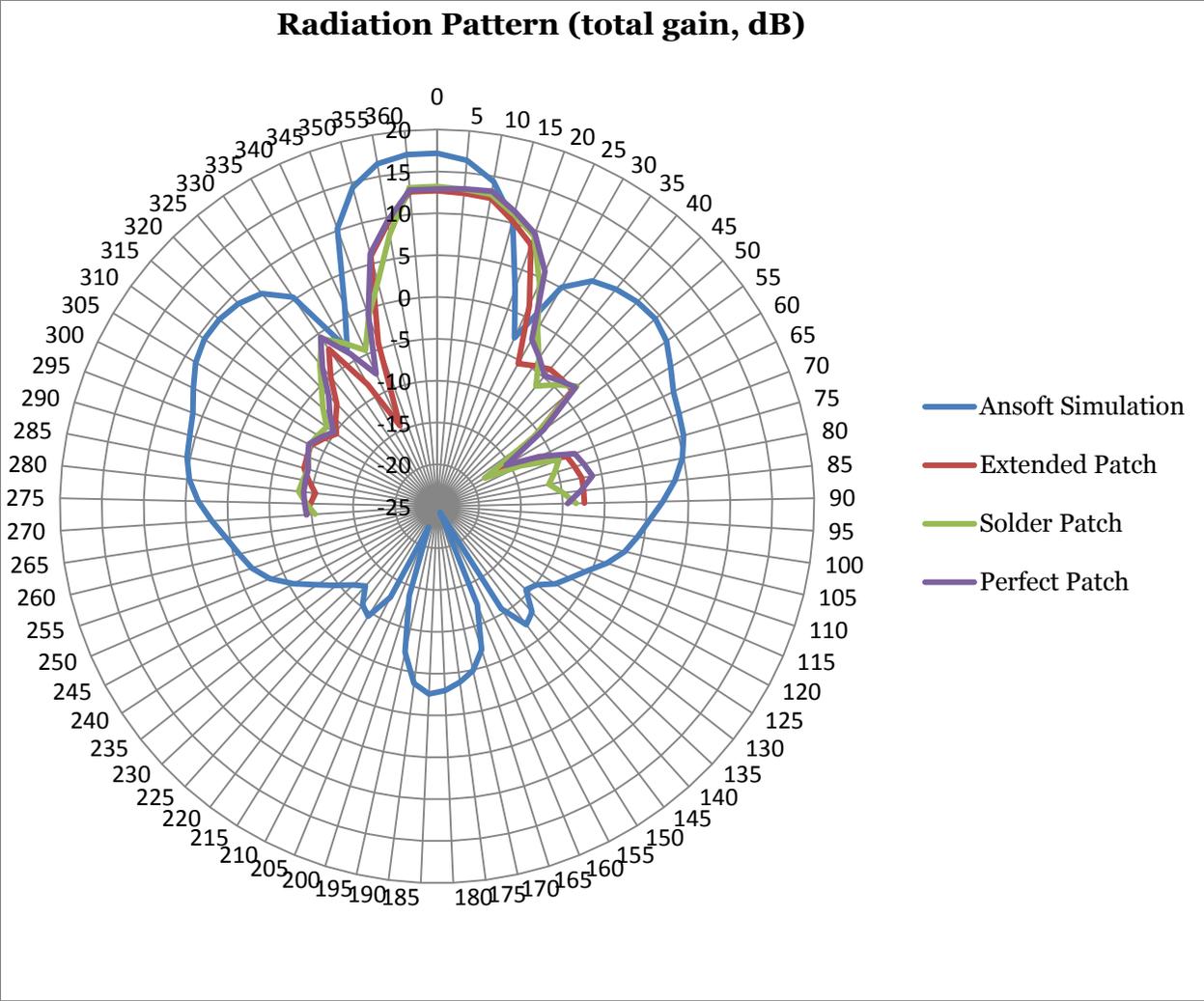
Figure 39 Radiations Pattern of Measured Arrays and Simulated Data

The antenna has losses that are a result of conductive, dielectric, and surface wave losses. As a result the maximum gain and the directivity show a difference of 3.9dB. The efficiency can be calculated by finding the ratio of power gain with losses over the power gain without losses. The radiation efficiency of the antenna is approximately 40.38%. Table 6 shows a comparison between the Ansoft simulated parameters and the best produced antenna array.

57

	Simulated	Measured Best Array
Gain	17.16 dBi	13.2dBi
Bandwidth	5.17% or 126MHz	5.16% or 161MHz
Bandwidth Range	2.3775-2.5038 GHz	2.3572-2.519 GHz
Resonance Freq.	2.44GHz	2.41GHz
Patch Dimensions	30x30 mm	30 x 34mm
Front to Back Ratio	22.118 dB	14.2 dB

Table 6 Comparison of simulation and best performing antenna array

There most noticeable difference between the antennas is the main lobe gain. This can be reduced by using low loss substrate material with printed radiating elements but this would not allow us to meet our $15 goal. The total cost of the antenna array was $14 dollars. The coaxial connected was $4, the plexiglass substrate cost $5, and the copper foil was bought in a large roll and it was assumed $5 worth of copper was used.

Conclusion

The goal of this project was to design a low cost, highly directional antenna that was low profile and easy to manufacture. Current high gain antennas on the market that meet these specifications are expensive. The development of a lower cost supplement with similar performance would attract consumers.

The use of a directional antenna allows the electromagnetic waves to be focus towards a specific section. This allows wireless connections at greater distance from the router than a traditional omnidirectional antenna. In addition, higher data rate can be achieved at greater distances. This antenna would be beneficial in both rural and urban environments.

The overall design meets all of our design criteria developed during market research. The antenna array is 306mm by 306mm with a thickness of 4.76mmm, approximately 13inches by 13inches by 3/16 inch.   It is flat and light weight and can be mount flush to buildings and walls. The gain of the antenna was measured to be 13.2dBi and falls between the range of 12-16dBi. The material cost of the antenna was less than the desired $15 which allows the product to be sold at a lower cost than current directional antenna with similar performance.

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