Fairfield Osborn Preserve Outdoor Autonomous Wireless Network Design and Implementation

Final Project Report

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Submitted in partial fulfillment of the requirements for the Master of Science Degree
Aug 15, 2012

Fairfield Osborn Preserver Outdoor Autonomous Wireless Network

Design and Implementation for FOP

by Sen Guan

A thesis (project) submitted to

Sonoma State University

In partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

in

Computer and Engineering Science

Dr. Farid Farahmand, Chair

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Date

Acknowledgement

First and foremost, I would like to express my deep sense of gratitude to the invaluable contributions of Dr. Farid Farahmand, my project advisor. I feel motivated and encouraged every time I meet him. I would not complete this project without his abundant help and invaluable assistance, support and guidance. Deepest gratitude is also due to the members of the supervisory committee, Dr. Ali Kujoory and Dr. Jack Ou, without their assistance this study would not have been successful. I also wish to express my gratitude to Mr. Shahram Marivani, the network analyst and adjunct professor of Engineering Department of SSU, who rendered help during the period of my project work. My special thanks to Centre of Community Engagement of SSU. Without their generous funding, this project would not have been materialized. I would also like to acknowledge the work done by Shivam Aditya. His thinking and contributions helped me to develop the solar power system of this project. Last but not least I wish to avail myself of this opportunity, express a sense of gratitude and love to my friends and my beloved parents for their manual support, Strength and help and for everything.

Abstract

Global climate change exerts a great influence to environment. The costs of unmitigated climate change are potentially enormous. The environment impacts also cause harm to wildlife. Therefore, collecting weather information and monitoring wildlife becomes a major object to many researches and studies. Many weather stations and sensors have been set in Fairfield Osborn Preserver (FOP). However, people have to collect data manually. The proposed Fairfield Osborn Preserver WLAN (FOPW) project designs and implements an outdoor autonomous Wireless Local Area Network (WLAN) located in FOP. The FOPW covers certain areas where weather stations and sensors exist. By connecting to the FOPW, weather stations and sensors are able to upload data automatically. The system comprises three types of nodes: controller node, intermediate node, and end node. The Controller Node has a wired Internet access and is in charge of data roaming. The other two nodes will be set in the field to extend the wireless signal coverage. There is no AC power resource outside the building of FOP and the intermediate and end nodes are powered by the same solar power system. Besides the hardware design, this paper also introduces some fundamental theories for the WLAN characterizations, radio wave propagation, antenna principle, environmental impacts of signal attenuation, and the solar power system. The last part of the paper includes some experimental testing results and analysis. Through experimental measurements, we demonstrate that the modified indoor network devices can be effective alternatives for the expensive outdoor devices in an outdoor WLAN design. By increasing the transmit power and antenna height, the FOPW design overcomes the huge path loss due to foliage. We also evaluate the performance of FOPW in different weathers.

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List of Abbreviations

AP - Access Points
ART- Average of Response Time
dBi - states the gain of an antenna in decibel as referenced to an isotropic source
DHCP -Dynamic Hosting Configuring Protocol
DIY - Do It Yourself
EIRP - Effective Isotropic Radiated Power
FCC - Federal Communication Committee
FSPL- Free Space Path Loss
FOP - Fairfield Osborn Preserve
FOPW - Fairfield Osborn Preserve WLAN
GPS - Global Positioning System
LOS - Line of Sight
MIMO- Multiple in & Multiple Out
MPP - Maximum Power Point
OFDM - Orthogonal frequency-division multiplexing
PLR - Packet Lost Rate
POE - Power Over Ethernet
RF - Radio Frequency
RSSI - Receive Signal Strength Indication
SSID - Service Set Identifier
SSU - Sonoma State University
VSWR-Voltage Standing Wave Ratio
WDS - Wireless Distribution System
Wi-Fi -Wireless Fidelity
WLAN - Wireless Local Area Network

1. Introduction

Since last century, Earth's average surface temperature has increased more than one degree Fahrenheit and the rate of warming is nearly three times. Most of scientists believe global warming becomes the major issue of climate change. Global warming generates a series of consequences, such as the retreat of glaciers, rising sea level, desertification and so on. It also brings some serious damages to ecosystem and agricultural. Especially, it has a significant impact to wildlife. It even accelerates the extinction of some species. However, people know very little about the changes between biological diversity and climate. Therefore, monitoring environment and wildlife becomes a very important object to sciences and researchers.

As a multidisciplinary university, Sonoma State University (SSU) has been committed to the research of protecting ecological environment and wildlife. The SSU Field Stations & Nature Preserves provide lands, facilities, databases and programs that inspire participation, collaboration and innovation in education and research at their preserves. Fairfield Osborn Preserve (FOP) was one of it that managed by the SSU Field Stations & Nature Preserves department. The 411-acre Osborn Preserve lies on the northwest flank of Sonoma Mountain, predominantly in the Russian River watershed at the dry southern end of the North Coast Range of the northern California. The Nature Conservancy established Fairfield Osborn Preserve in 1972 through the generosity of William and Joan Roth in honor of Joan’s father, Fairfield Osborn. The Preserve was donated to SSU in 1997. The Preserve is dedicated to protecting and restoring natural communities and to fostering ecological understanding through education and research. Figure 1 shows a snapshot of the FOP map on Google Earth [1] . In the figure, the green line shows the boundary of the Preserve. The blue line shows the areas where are the weather stations are located.

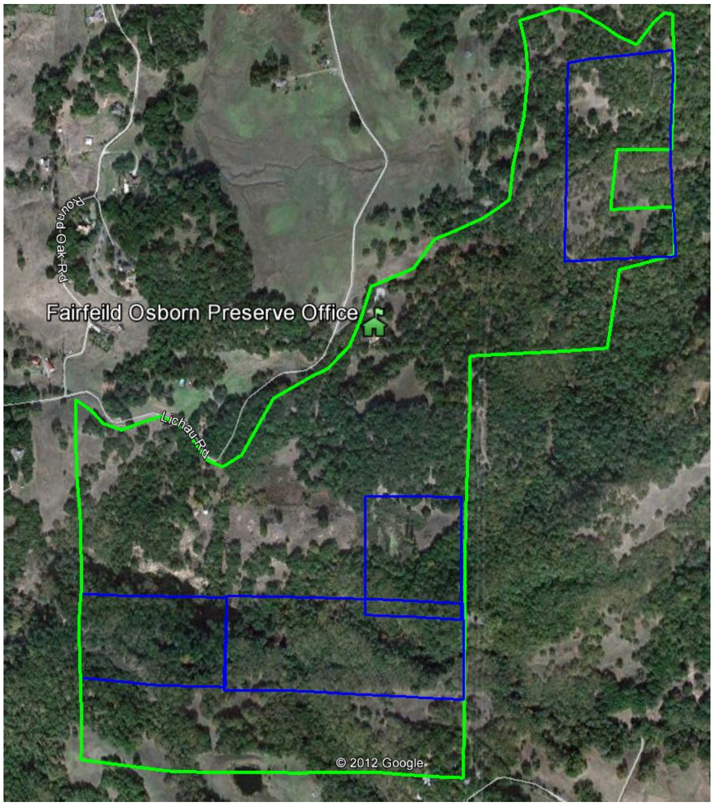

Figure 1 - Fairfield Osborn Preserve on Google Earth

Because of the impact of the Global Warming, more and more researches and studies are concentrated in environment monitoring. Several weather stations have been set in the preserve. They are used to record different parameters of climate such like temperature and humility. Electronic sensors are wildly used in these weather stations to accomplish the goal. So far as the sensors receive enough power, they can capture accurate data continuously under different weather conditions. Besides that, sensors are capable to save the weather information automatically without any manual operation until researchers walk to the locations of the weather stations and collect those data. Figure 2 shows a typical weather station settled in FOP.

Figure 2 - Weather Station Settled in Osborn Fairfield Preserve

Even though these weather stations have so many benefits, the users of these weather stations still have difficulty on collecting the data. They have to spend considerable amount of time on hiking because some of the weather stations are set in the middle of the forest where one needs a lot of time and energy to reach. In order to save time, the purposed project, Fairfield Osborn Preserve WLAN (FOPW), provides a wireless network to cover the areas between the weather stations and sensors. The FOPW offers Wi-Fi signal that can be used to upload the data. The researchers do not have to come to the Preserve physically but sit in their offices to control the sensors and collect climate information remotely. They can save a lot time and energy. Besides that, it provides other opportunities and feature such as using wireless camera to monitor wild life and having Internet access in the preserve. By knowing the motivation of the FOPW project, the next section introduces some background information.

2. Background

In section 2, we introduce four similar outdoor WLAN designs. Two of them are "Do-It-Yourself" (DIY) projects, and the other two require professional solutions. Then, I will compare them to our proposed FOPW design. After the comparison, we can find out the uniqueness of the FOPW design.

In chapter 9 of "Wi-Fi Toys" [2], the author, Mike Outmesguine introduced a DIY project to build up an outdoor wireless repeater node by using indoor devices and solar power system. He used two wireless access points operating in bridge mode. One access point (AP) is used for broadcasting the signal and the other one is used for backhaul downlink. He claims in the beginning of chapter 9 in his book that by using signal booster and high gain antenna, “the system can be located out as far as the eye can see”,. A solar power system also embedded with his repeater node. By collecting energy directly from the Sun with a 70W solar panel, the repeater node becomes a standalone system on the top of a hill where there is no AC power resource to access. All communication devices and two lead-acid batteries are put in an 18*18*6 inch waterproof steel box. Even though the repeater node has an outstanding performance, it is very heavy to carry on up a hill and attach to a steel pole. Denny Mavromatis [3] did another DIY project that modified a Linksys router to work as a bridge. He puts the router in a waterproof enclosure with an 8dBi Omni directional antenna. So that, he was able to pass the Wi-Fi signal from his parents house 200 meters away. He did not have a solar power system to power up his system but used AC power from his house. Due to the limitation of hardware, the modified repeater did not work reliably. He says he had to reboot the repeater once a while and lost connection in rainy days. One common problem in these projects is the modifying indoor routers to work as outdoor APs or repeaters. The reason for modifying the indoor products instead of buying outdoor products is to reduce cost. Without solar power system, the average cost of each node is about $200 to $300. However, indoor APs are not designed for outdoor environment. Compared to the outdoor products, the indoor products are difficult to keep in stable status beyond room temperature. Besides that, the indoor products usually have lower transmit power than the outdoor products, which will give the indoor devices shorter signal range. Typically, an indoor router has a 300-metersignal range if there is no obstacle on the signal propagation path.

Other than the mentioned DIY projects, Meraki [4] and Trango [5] are two companies that manufacture high performance outdoor devices and offer professional solutions for outdoor WLAN design. Their expertise is to design and implement a reliable WLAN with high performance. Meraki uses four high-performance outdoor APs to establish a roughly pentagonal-shaped wireless mesh network with over 500 meter across, straight through the heart of the Jefferson National Forest in University of Virginia. Each AP costs more than $2000. Trango System provides another outdoor solution. Because 900MHz system offers excellent receiver sensitivity and penetrability in a forest environment, their subscriber unit can expect no line-of-sight (NLOS) performance of up to 6 miles or beyond. Each node costs over $1300on average. The advantage of the professional solutions is all the devices having high performance in areas with different weather and they are easy to operate. However, the cost is unaffordable. It costs easily over $4000 on a point-to-point WLAN design. The budget of the FOPW design does not allow us to choose the commercial devices.

Table 1 - The Comparison of Similar Outdoor WLAN Designs

Outdoor WLAN Design	Frequency	Distance	LOS	Cost	Antenna
DIY: How to create an outdoor wireless repeater[2]	2.4GHz	Up to 3,200m	Yes	$800 (With Solar Power System)	16dBi Grid Antenna
DIY: Outdoor Wireless Access Point/Signal Repeater [3]	2.4GHz	200m	Yes	$200/Node	8dBi Omni Antenna
Meraki: University of Virginia [4]	2.4/5GHz	152m	No	$2096 +Tax/ Node	11/14dB Sector Antenna
Trango System: 900 MHz wireless radio, NLOS Broadband Wireless Network [5]	900MHz	9656m or beyond	No	AP: $1993+Tax Subscribe unit: $713 + Tax	10dB Panel Antenna

The FOPW design tries to find a balance between performance and cost. Different from other people's projects and professional solutions, it has to deal with more complicated environmental impacts than DIY projects and to have a lower cost than commercial solutions. As we know, the signal will attenuate very quickly when there are obstacles between the transmitter and the receiver. The attenuation rate is from 0.2dB/m to 0.5dB/m inside the forest canopy, said Chymitdorzhiev, T.N [6]. With big attenuation rate, users can lose connection even less than a few meters away from a regular indoor router. However, there is no way to have a clear wave propagation path because there are too many trees in the FOP. Therefore, the FOPW design has to overcome huge signal attenuation and obtain a stable performance. In the meantime, the budget of the FOPW design does not allow us to choose professional outdoor wireless products. As it was mentioned in the previous paragraph, there are some commercial products in the market that can overcome the difficulty of signal attenuation but they can cost over $2,000 for each node. In order to reduce cost, I needed to build an outdoor access point by modifying some indoor devices and put them in a waterproof enclosure. The total cost of each node is much lower than the cost of a commercial outdoor product but with compactable performance.

Besides keeping balance between performance and cost, to locate a position that can satisfy both the solar power availability and the signal strength requirements is another issue. In the middle of FOP, there is no AC power resource to use and hard to find open areas for solar panels to absorb maximum sun light during daytime because of the shade of trees. We need to find out a place for the solar panels to obtain as much solar power as possible. In the meantime, the location has to avoid as many trees as possible to reduce signal attenuation on the propagation path.

3. Design Architecture & Fundamental Theories

This chapter has three sections. First section describes the design challenges. The second section introduces the network architecture of FOPW. The last section summarizes five fundamental theories to help understanding the challenges of designing a WLAN in a forest environment.

3.1 Design Challenges

The goal of the purposed FOPW design is to create a self-sufficient outdoor WLAN and evaluate the network performance in different weathers. In order to achieve the goal, there are two critical challenges to resolve: the power consumption and the coverage.

Coverage: The FOPW extends Wi-Fi coverage from the FOP office building to the area around Turtle Pond. There is a hill on the radio wave propagation path. Therefore, an intermediate node sets up on the top of the hill to pass the signal from the office building to the End Node. Then, the End Node rebroadcast the signal to cover the area around the Turtle Pond. Shown as Figure 3, the total distance from the office building of FOP to the End Node is 371m. There are many trees grown on the hill that are over 20 meters high and also it is impossible to put antennas over the height. Therefore there is no line of sight (LOS) between the adjacent nodes. The signal attenuation, multipath fading, and various interferences caused by trees all become issues to affect communications between the nodes. When the connections become unreliable, packets are dropped during transmission, which means the data captured by the weather stations will be lost. Increasing the total system gain and the antenna height and avoiding the obstacles can help transmitters to send stable signals over the path. In addition, The End Node has to cover an area of 37370m² (185m*202m). Sensors and weather stations are set up in the covered area. However, the sensors and weather stations usually have a low transmitting power. Even if they have a good reception, their signals cannot reach the End Node. In order to obtain an appropriate communications, the End Node of the FOPW cannot use high transmit power; however we can increase antenna height to extend the coverage.

Power Consumption: For a standalone system, a solar power system is required to provide enough power to run the system continuously. There are two major challenges for to build a solar power system. The first one is to find a shade-free area in forest to set up the solar panels. The place should satisfy both the solar power and signal strength requirements. The solar panel should be put in an open area to absorb enough sunlight during daytime. In the meantime, the node should receive strong signals at the same place. Another challenge is the solar panel output. Each node would use several hundreds of watt-seconds per day. That will require large enough solar panel within affordable price. The panel output will vary based on factors such as the temperature, panel tilt angle, atmospheric conditions, and how clean is the path. We can adjust the panel tilt angle to improve the output of each solar panel.

Figure 3 - Distances between Each Node & End Node Coverage

3.2 Design Architecture

Shown as Figure 4, the design architecture of the FOPW is divided into three parts: the controller node, the intermediate node, and the end node. The Controller Node has a wired Internet access and it is in charge of routing the data. The Intermediate Node needs to work as a bridge, in order to repeat the signal sending from the Controller Node and extend it to the End Node. The End Node provides Wi-Fi communications to the sensor nodes and the weather stations within its coverage area.

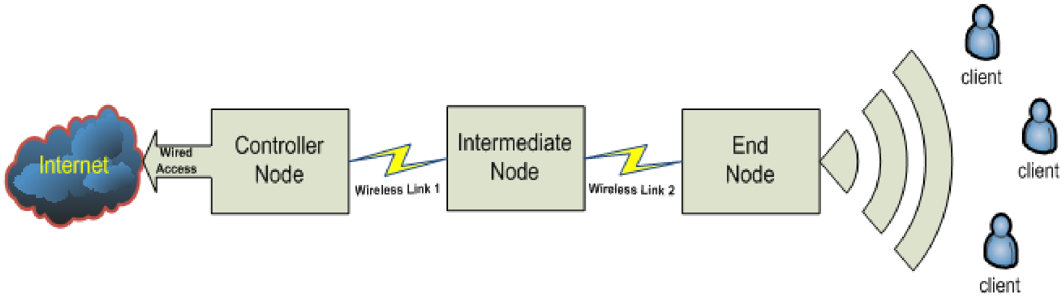

Figure 4 - Design Architecture

3.3 Fundamental Theories

Sub-section 3.3 summarizes five fundamental theories in the following paragraphs to help us understand the design process more clearly. I start with describing the WLAN characterization. Then, I describe the three components of a WLAN: the Router, the Access Point, and the Repeater. The next is the understanding of the radio wave propagation. The third is the antenna principle. Then, I introduce two environmental impacts on signal attenuation. At the end of the sub-section, I present some knowledge of the solar power system.

3.3.1 Wireless LANs and Their Characterizations

The Definition of WLAN is a local area network which uses a high frequency radio signal to transmit and receive data over a distance of a few hundred feet and over the Ethernet protocol. WLAN is used to extend boundaries of the Local Area Network (LAN). There are two basic modes for the WLAN, the Ad-hoc and the infrastructure mode. The architectures of both modes are shown in Figure 5. Whereas the infrastructure mode has a central device to control the communication, the Ad-hoc mode does not. Ad-hoc devices are only able to communicate with another Ad-hoc device in their range including an infrastructure device or any other device connected to a wired network.

Moreover, the security level of the ad-hoc mode is lower compared to an infrastructure mode network. On the other hand, the Infrastructure mode requires an access point as a base station to control communications. Access point of an infrastructure WLAN supports increased levels of security, faster transmission speed and integration with a wired network. The FOPW uses the infrastructure mode.

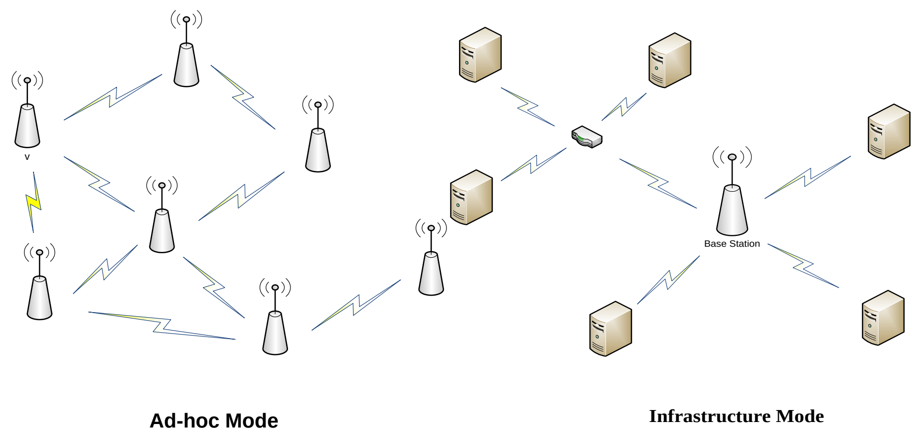

Figure 5 - WLAN Modes

Another concept of a WLAN is the communication protocol. This WLAN combines 802.11g and 802.11n protocols that are created and maintained by the IEEE LAN/MAN standards Committee 802.11 family. It consists of a series of modulation techniques that use the same basic protocol. These two protocols are compared in Table 2: 802.11g and 802.11n. The IEEE 802.11g protocol divides 2.4000-2.4835 GHz band in to 13 channels spaced 5 MHz apart, each channel has a bandwidth of 20MHz. 802.11n protocol has same property, but has a 40MHz-wide channel on 5GHz operating. 802.11n can operate on 4 streams because of adding Multiple-Input Multiple-Output (MIMO) antennas. The MIMO streams have better performance on severing multiple clients. The IEEE 802.11n protocol allows a maximum of four MIMO streams and can achieve a 600 Mbit/s data rate with four spatial streams using on 40 MHz-wide channel. Both of

802.11g and 802.11n protocols use OFDM (Orthogonal Frequency Division Multiplexing) spread spectrum system. They transmit multiple signals over a single path within its own unique frequency range in order to distribute the data over a large number of carriers. The benefit of OFDM modulation method is easily adapted to sever channel conditions and lower multi-path distortions. It has high spectral efficiency and low sensitivity to time synchronization errors.

Table 2 - 802.11 Protocol Comparison

802.11 protocol	Freq (GHz)	Channel Bandwidth (MHz)	Allowable MIMO streams	Maximum Data Rate (Mbit/s)	Modulation
G	2.4	20	1	54	OFDM/DSSS
N	2.4	20	4	72.2 per stream	OFDM
	5	40	4	150 per stream	

3.3.2 Router, Access Point and Repeater

Router: Router is the core device of a network. It forwards data packets between networks, and plays the role of gateway. In a network, router determines the path a data packet shall take. Especially, a router with wireless function can establish a WLAN and distribute the connection without the need of cable. In an infrastructure WLAN, a router is required and works as a base station to control signal communications.

Access Point: Similar to a wireless router, the main purpose of an AP is to allow the wireless devices to connect to a wireless network. AP usually connects to a wired network, and can relay data between the wireless and wired devices on the network. The difference between the router and AP is that the router directs the way of the packets whereas AP performs as an antenna. If a network is geographically too large to be covered by one AP, more APs would be required to make a complete wireless infrastructure.

Repeater: In a wireless communications system, APs can only transmit the data only in a limited distance before the quality of the signal degrades. Repeaters can pick up and amplify the receiving signal to extend the distance over which data can safely travel. When located on top of a hill, a repeater can greatly enhance the coverage of a wireless network by allowing communications from one side of the hill to another side. However, a traditional repeater works in its own subnet with its client devices. The primary router and repeater work in different IP domains. In order to reduce complexity, a Repeater Bridge is introduced to WLAN system. A repeater bridge repeats a wireless signal from primary AP and has all clients on the same network. This feature can greatly benefits the FOPW design. The Office Node and the End Node of FOPW are two cooperating APs set in two opposite sides of a hill. They must establish a wireless connection because pulling a wire is restricted and not cost effective. Middle Node is built up at the top of the hill and performs as a repeater bridge. The node ensures the signal sending from Office Node will reach to End Node. Moreover, all clients connected to the FOPW are in the same IP domain. However, repeater bridges have a disadvantage. The maximum throughput halves after the first retransmission being made because repeater bridges can be considered bridging and accepting wireless clients at the same time.

3.3.3 Radio Wave Propagation

Without doubt, the performance of wireless communication systems depends in a fundamental way on the RF link. As a consequence, predicting the propagation characteristics between two antennas is one of the most important tasks for the design and installation of wireless communication systems [7]. There are five basic phenomena of radio wave propagation. The first one is free space path loss (FSPL), which indicates the loss in signal strength of a radio wave when it is traveling through free space (usually air) with no obstacles nearby to cause reflection or diffraction. The expression of FSPL [8] in terms of dB is:

$$FSPL(dB) = 10\log_{10}\left(\left(\frac{4\pi}{c}df\right)^2\right) = 20\log_{10}(d) + 20\log_{10}(f) - 27.55$$

Where,

c: Speed of light in vacuum

f: Signal frequency (in MHz)

d: Distance from the transmitter (in meters)

Equation 1 - Free Space Path Loss [8]

From Equation 1, we know a fact: the longer the transmit distance and the higher the operation frequency, the bigger would be the attenuation. The second phenomenon is the reflection, which occurs when the radio wave is transmitting in different mediums. Reflection is caused by impedance mismatch, so it is often measured in a dimensionless ratio know as Voltage Standing Wave Ratio (VSWR). In an outdoor environment, reflection would occur of buildings, surface of earth or plants. The reflected waves follow the typical laws of reflection. The incident angle is equal to the angle of reflection and that the wave undergoes a phase change of 180 degrees. The third phenomenon is absorption. When the signal wave is transmitted through a medium, a portion of its energy will be absorbed. Especially in an outdoor environment, complicated weather situations and terrains will cause much more absorption than an indoor environment. The fourth phenomenon is diffraction. Diffraction occurs when the radio is transmitted, it obstructed by a sharp edge [9]. The radio signal impinging on the edge results in secondary waves that propagate in all directions around the edge (including behind the obstacle.) Diffraction is responsible for providing a path between the transmitter and the receiver even when there is no direct or reflected path. The diffraction depends on the geometry of the object, as well as on the amplitude, phase, and polarization of the incident wave at the point of diffraction. The last phenomenon is interference. In physics, interference is the phenomenon in which two waves superpose to form a resultant wave of greater or lower amplitude. In a WLAN, two Radio Frequency (RF) signals performs in a nearly frequency will cause a cross talk or attenuation. Two waves could be from one source or two different sources. All of these phenomena will be considered as a factor to influence WLAN performance.

3.3.4 Antenna Principle

The antenna is a key building block in the construction of wireless communications systems. The purpose of this sub-section is to provide an overview of fundamental antenna properties and performance characteristics. There are four concepts included: passivity, radiation patterns, beamwidth and Fresnel Zone. This knowledge can be used to establish antenna selection criteria for optimum system performance.

First, antennas are passive devices. To operate, they require no supply voltage and they do not amplify RF energy. Antennae convert electrical energy to RF waves in the case of transmitting antennae or convert RF waves into electrical energy in the case of receiving antenna. The physical dimensions (especially length) of an antenna are directly related to the frequency at which the antenna can propagate or receive waves. Total amount of energy emitted by antenna does not increase. It only distributes the energy around the antenna.

The second concept is radiation patterns, which describes how the antenna directs the radiation energy. As stated earlier, an antenna cannot radiate more total energy than is delivered to its input terminals. Radiation patterns are typically presented in the form of a polar plot for a 360-degree angular pattern in both vertical and horizontal planes. Based on pattern ship, antennas can be divided into two categories, which are Omni directional and directional antennas. The Omni directional antennas radiate or receive equally well in all directions. They are used when coverage is required in all directions around the horizontal axis and most effective when large coverage areas are needed around a central point. Commonly used for point-to-multipoint designs. On the other hand, the directional antennas radiate RF energy in one or two directions and are commonly used for a point-to-point connection. Often radiate in a hemispherical or cylindrical coverage pattern. They have back and side lobes and if used effectively, they may further reduce the need for additional access points. Figure 6 [10] simply shows the radiation patterns of a typical directional antenna.

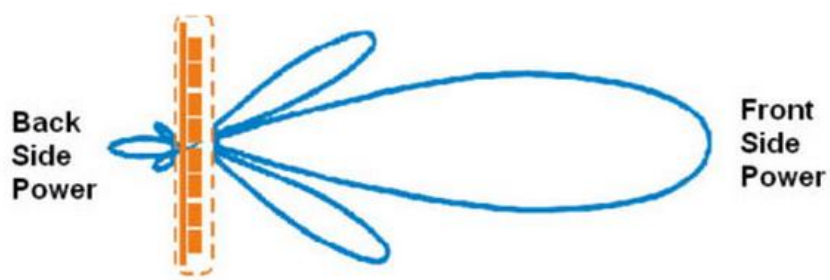

Figure 6 - Panel Antenna Radiation Patterns [10]

The next concept good to know about antenna is the beamwidth. Beamwidth is calculated by measuring the off-axis angle in degrees where beam drops by ½ (-3 dB) of the strength at the 0° position. Horizontal and vertical vectors must be considered when discussing an antenna's beamwidth. Typically, an Omni directional antenna will have

360° beamwidth on horizontal and 7° to 80° on vertical vector. A directional antenna will have 30° to 180° on horizontal vector and 6° to 90° on vertical vector. As seen in Figure 6, a directional antenna may have multiple lobes. The one with highest radiated energy is called the main lobe and the rest is called side lobes. When we are talking about beamwidth of a directional antenna, it means the beamwidth of the main lobe. Figure 7 [10] shows the beamwidth of the main lobe for the directional antenna in Figure 6.

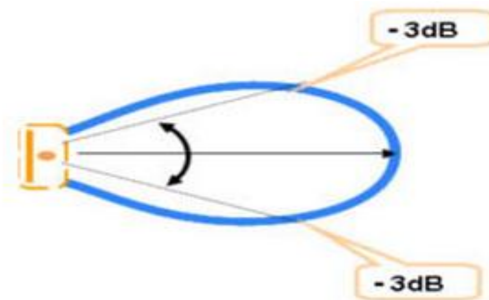

Figure 7 - Directional Antenna Beamwidth [10]

The last important concept is the Fresnel Zone, which is the area centered on the visible Line of Sight (LOS) between the transmitting and receiving antennas. Fresnel Zone defines an area around LOS that can introduce the RF signal interference if blocked. RF waves travel in a straight line from the transmitter to the receiver without any obstruction. However, if there are obstacles along the path, the radio waves reflecting off those objects may arrive out of phase with the signals that travel directly and reduce the power of the received signals. In Figure 8 [11], the green line is the visual line of sight between the wireless signal transmitter and receiver. The black circle is the boundary of the first Fresnel Zone and indicates the wave line of sight. D is the distance between the transmitter and the receiver, r is the radius of the first Fresnel Zone at point P. d1 and d2 are distances from point P to the transmitter and the receiver, respectively.

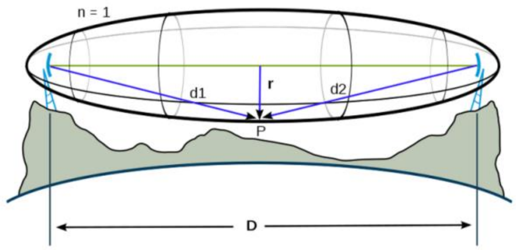

Figure 8 - Fresnel Zone [11]

An accurate calculation of the Fresnel Zone will improve the reliability in the design of a WLAN. Equation 2[11] introduces a general way to calculate the Fresnel Zone radius.

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}}$$

Where,

F_n = The nth Fresnel Zone radius in meters
d_1 = The distance of P from one end in meters
d_2 = The distance of P from the other end in meters
λ= The wavelength of the transmitted signal in meters

Equation 2 - Fresnel Zone Determination [11]

The first zone (n=1) must be kept wildly free without obstructions to avoid radio wave interference. Equation 2[11]can be simplified to Equation 3[11], which gives the radius of the First Fresnel Zone by knowing the frequency of operation and total transmitting distance.

$$r = 8.657\sqrt{\frac{D}{f}}$$

Where,

r = radius in meters
D= total distance in kilometers
f= frequency transmitted in gigahertz.

Equation 3 - 1st Fresnel Zone Radius [11]

3.3.5 Environmental Impacts

Obstacle vegetation causes the first environmental impact. In the FOPW design project, the signal has to pass through much vegetation that may cause a huge loss in the signal strength. In a wired network, signal will be transmitted through cables. We can simply predict the signal loss by the length of the cable. However, it is more complicated to measure the attenuation of outdoor wireless links especially in a forest environment. Many researchers have studied the effect of obstructions on the signal attenuation. Hidayab in his paper "Wi-Fi Signal Propagation in 2.4 GHz" [12] claims that the environmental circumstance is an important thing that needs to be taken into consideration. He shows that the propagations between an indoor environment with no obstruction and an outdoor environment, which has obstruction along the propagation path, are quite different. The path loss of outdoor scenario is much bigger than the indoor scenario. Additionally, vegetations cause multiple path fading and interference that will cause more attenuation. In order to obtain a clear First Fresnel Zone, both the transmitter and the receiver antennas can be erected to high enough location above the obstructions so that the path loss would be negligible. When radio wave travels in a straight line from the transmitter to the receiver without any obstacle, we can simply calculate the signal strength loss by using Equation 1. "However, the antenna height is not the only consideration in engineering design and some fundamental principle must be considered such as communication quality, economical cost and engineering implementation, etc", said Siyu Li [13]. He believes that the speed of signal attenuation is not monotonically decreasing and the transmission range is not monotonically increasing, with the increase of antenna height. If antennas are set above the height of the obstructions, it will be very unfeasible and uneconomic. Therefore, Antennas are not necessarily to be set at a very high position. If a network is set up in a forest environment, it is very difficult to increase the antenna height to obtain a clear Fresnel Zone. Equation 1 is not suitable in this situation. In other words, we need to create a model to predict the signal loss along the propagating path in a forest environment. Many studies have been carried out to characterize and model the effects of vegetation experimentally. Weissberger's Modified Exponential Decay Model [14] is applicable in situations where propagation is likely to occur through a grove of trees rather than by diffraction over the top of the trees. In the FOPW design, the LOS path is blocked by dense, dry and leafy trees. Therefore, we can use Weissberger's model to predict the signal loss. The expression is shown in Equation 4 which claims that the path loss must be calculated with inclusion of the FSPL. Based on this model, the 2.4GHz signal has an additional 0.2dB/m ~ 0.5dB/m in a forest environment.

$$Loss(dB) = \begin{cases} 1.33 * f^{0.284} * d^{0.588} & 14m < d < 400m \\ 0.45 * f^{0.284} * d & 0m < d \leq 14m \end{cases}$$

Where,

$Loss$: Vegetation loss in dB

f: Frequency in GHz

d : Depth of trees in meter

Equation 4 - Weissberger's Modified Exponential Decay Model [14]

Another impact of environment comes from different weather conditions. In different weathers, air will have different intensity and contains impurities such like rainfalls, snow and sands. It can cause more absorption, reflection and diffraction to influence the network performance on Average of Response Time (ART) and Packet Loss Rate (PLR). In Hidayab's also [12] shows two figures of signal strength under windy environment and ideal environment. The difference is minor, but the author believes that, the outdoor environment such as wind and drizzling also caused the path loss during propagation. Especially in a forest environment, rainfall will cover on foliage. From RF point of view, the density of the transmitting medium is changed. It causes more attenuation on the signal propagation path. In the area of FOP, the main weather situation in winter is rainfall and fog. The Weissberger's model does not include the factor caused by humility. Therefore, in the FOPW design, we need to consider the influence of foggy and raining weathers.

3.3.6 Solar Power

The key issue of building a self-sufficient system is the power resource. Typically, there are several ways of drawing power from the nature such like solar power, wind force, and waterpower. Solar power is the most common and efficient resource to be used in a mountainous region. Solar panels, solar controller, and batteries combine to make a stand-alone solar power system. However, solar panels and batteries only provide DC current. In some cases, the loads need to be powered up by AC power supply, so that a DC-AC inverter will be required. Figure 9 shows a typical solar power system.

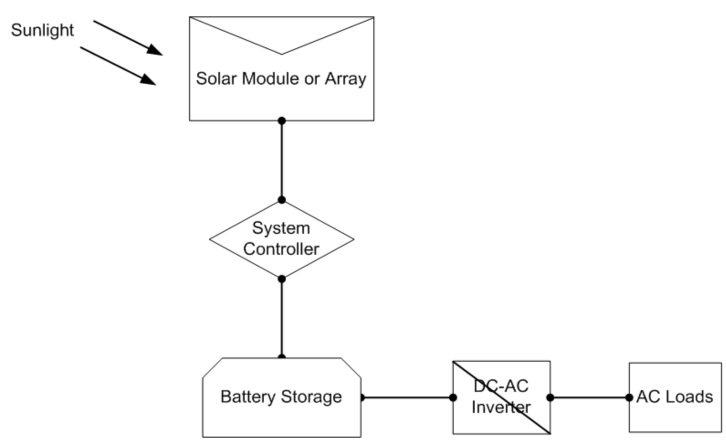

Figure 9 - Typical Solar Power System

The solar panel is the most important part of a solar power system, and the most expensive part. Many pieces of photovoltaic cells assembled to create a solar panel. It absorbs the sunlight and converts the energy directly into electricity by the photovoltaic effect. There are three main types of solar cells, Monocrystallines silicon, Multi-crystalline and orthin-film silicon. Crystalline silicon is the most popular and efficient product as it provides an excellent balance of performance and cost. The solar power ratings assume operation at a Maximum Power Point (MPP), which is generally considered impossible to achieve in the real-world deployments. The solar panel output varies depending on the physical location of the solar power system and the availability of consistent sunlight exposure. The expected output power is somewhere in the 80% to 90% efficiency range during the peak hours of sunlight. As we all know, the sun light is only available in the daytime. Figure 10 [15] shows the FOP area's sunrise, sunset, dawn and dusk times for the whole year. The daytime duration of FOP is from 10 hours to 15 hours due to different season. However, the MPP is assumed to achieve during the peak hours. When the output current is bigger than 80% of the maximum value, we assume the sunlight is in peak hours. By knowing that, we can choose the proper size of the solar panel for both Nodes. Table 3 shows output values of different sizes of solar panel. More power will charge batteries faster, keeping them topped up for cloudy days. Too little power may cause a power outage from drained batteries due to decreased charge capacity.

Table 3 - Solar Panel Power Output

Rate Power	Rated Voltage	Rated Current	Open Circuit Voltage	Dimensions (H*w*d in inches)	Panel Weight
40w	12V	2.41A	22.2V	50.9*13*1.4	22lbs
50w	12V	3.15A	19.8V	48.0*13.0*1.3	17lbs
70w	12V	4.25A	21.4V	47.3*20.8*2.2	23lbs
100w	12V	6.00A	21.0V	56.9*20.8*2.2	26lbs

Once the sunlight is converted into electricity, a controller controls the working state of the entire solar power system to protect the batteries from over being over charged. When the modules generate enough power for the loads, the extra power can be stored in batteries for use in the nighttime and any weather conditions without sunlight. Lead-acid batteries are commonly used for the solar power systems.

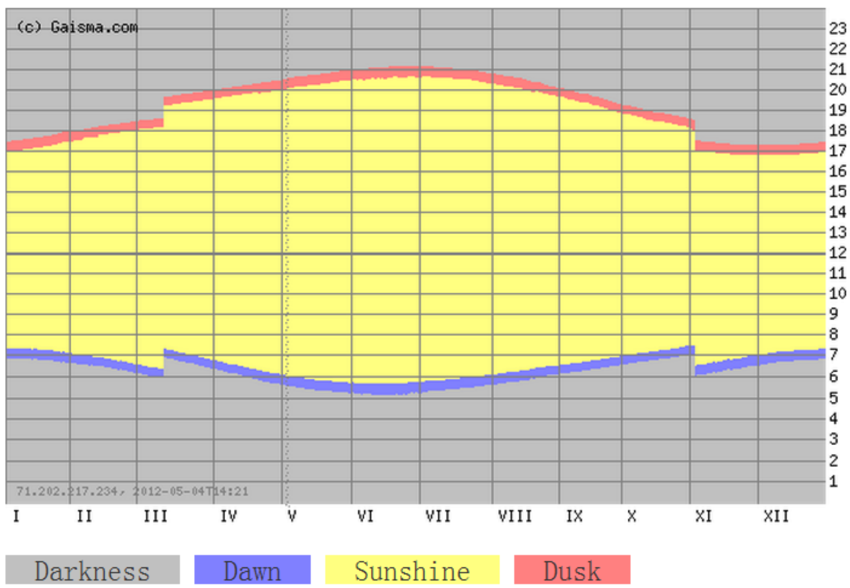

Figure 10 - Sunrise, Sunset, Dawn and Dusk Times in FOP [14]

4. Hardware Design & Implementation of FOPW Design

This section first introduces hardware design and implementation. At end of the section, we introduce an approach for the signal strength measurement and how to use the approach to select the installation location for each node.

4.1 High level Design

Figure 11 shows the location of the FOPW design in a visual way. FOPW uses a point-to-point repeating infrastructure and contains three nodes, which are the Office Node, the Middle Node, and the End node. The Office Node is considered as a controller node that will be set up around the office building of FOP. The facility provides the Internet access and AC power. The Office Node creates a wireless network and transmits2.4GHz signal through a high gain directional antenna. The hill in the area blocks the signal transmission from the Office Node to the End Nodes. A Middle Node is introduced at the top of the hill to perform as a bridge to relay the signal from one side of the hill to the other. The End Node is located beside the Turtle Pond to create Wi-Fi signal coverage around the pond. Two solar power systems provide power for the Middle Node and the End Node.

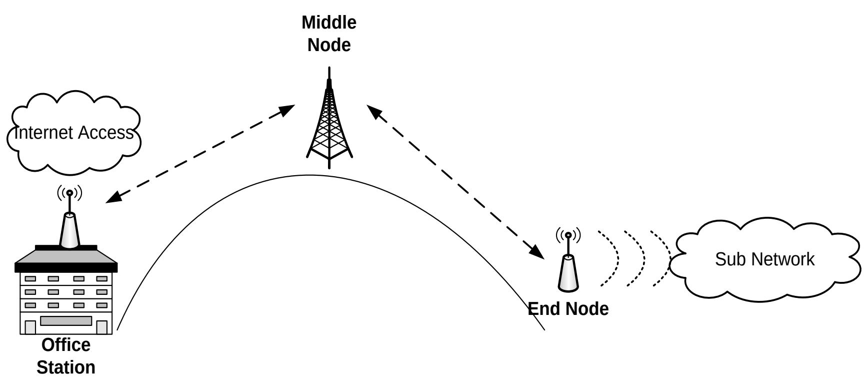

Figure 11 – The High Level Data Communication Design

Figure 12 shows the main components of each node. The Office Node contains one router, one signal booster and a high gain directional antenna. The router connects to a wired network by Ethernet cable and to create a wireless network. As the basic station, the router performs DHCP function that creates an IP domain of 192.168.2.*. The wireless signal is amplified by the signal booster and is transmitted through a high directional antenna. The signal booster is set up at the maximum transmit power level to ensure for the signal to reach the Middle Node. The Middle Node contains a repeater bridge, two signal boosters and two high gain directional antennas. The main function of the Middle Node is to receive the radio wave from the Office Node and relay the signal to the End Node. The End Node is also a repeater that uses Omni antenna to extend the coverage. Two solar power systems are attached to the Middle Node and End Node.

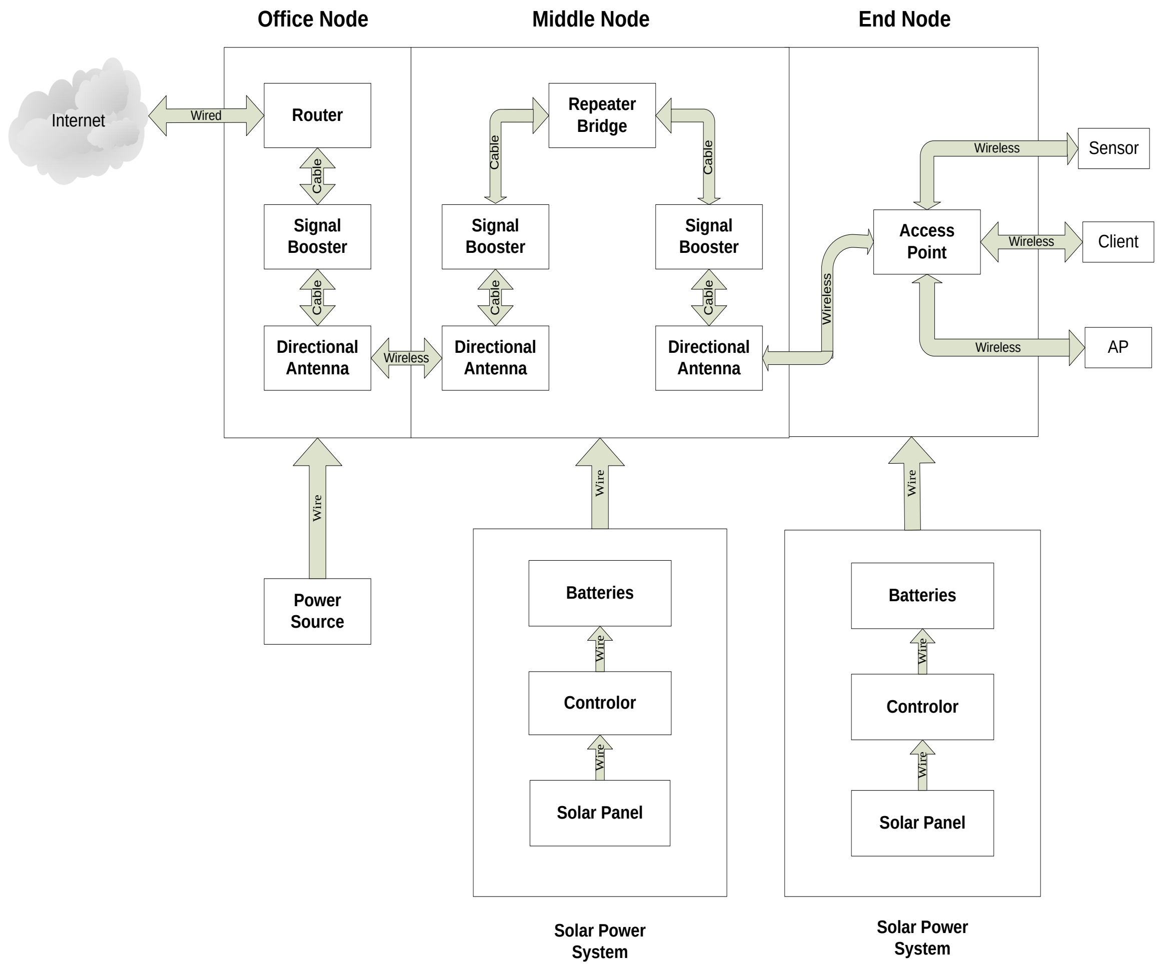

Figure 12 – The FOP Communication System Block Diagram

4.2 Design Details

From the last sub-section, we learned that the FOPW is build up of three nodes and two solar power systems. Each node contains different components and has different power requirements. The following sub-section introduces the details for each node and the solar power system as shown in Figure 12. Table 4 contains the detail specifications of each node. The FOP design uses 2.4GHz radio and 802.11b/g protocol to communicate with adjacent nodes. The End Node uses 5GHz radio and 802.11n protocol to communicate with end users such as sensors and computers. In order to overcome huge propagation attenuation, the FOP design uses 500mW transmit power and high gain directional antennas between adjacent nodes.

Table 4 - Specifications of Each Node

Specifications \ Nodes	Office Node	Middle Node	End Node
Mode	Router	Repeater Bridge	Repeater
Firmware	D-link	DD-WRT	Hawking
SSID	Office Node	Middle Node	End Node
Frequency	2.4G Hz 802.11b/g	2.4G Hz 802.11b/g	Receive: 2.4GHz /802.11b/g Re-transmit: 5GHz/802.11n
Channel	Channel 1	Receive: Channel 1 Re-transmit: Channel 6	Receive: Channel 6 Re-transmit: Channel 183
IP Domain	192.168.2.*	192.168.2.*	192.168.2.*
Transmit Power	500mW	500mW/500mW	200mW/65mW
Antenna Type	Directional	Directional	Directional/ Omni
Antenna Gain	14dBi	14dBi	12dBi/5dBi
Max Throughput	54Mbps	27Mbps	27Mbps

4.2.1 Office Node Design

Figure 13 shows the detail of the Office Node. The Office Node contains a D-link DI-624 wireless router (See Appendix E1), a Hawking HAO14SPD directional antenna (Appendix E4) and a Hawking HSB2 signal booster (See Appendix E5). The directional antenna is mounted at the top of a steel pole. Because the Middle Node has a higher elevation than the Office Node, a tripod is used to hold the steel pole with a tilt angle to make sure the antenna can point to the Middle Node. The router and the signal booster are put in a waterproof enclosure right under the antenna. In order to connect to the Internet, an Ethernet cable is plugged into the WAN port of the router. As the base station of the infrastructure WLAN, the wireless router of the Office Node creates a WLAN and generates the IP domain for IP addresses from 192.168.2.101 to 192.168.2.200 by using DHCP protocol. In the U.S, The maximum Effective Isotropic Radiated Power (EIRP) of a radio wave is regulated by part 15 of the Federal Communications Commission (FCC) rule. The rule governs the maximum transmitter power of 27dBm when the antenna gain is 15dBi. Thus the transmit power of the signal booster is set at 500mw (27dBm) max and the directional antenna used has a 14dBi gain with the output of 25mW. Implementation process is shown in Appendix C1.

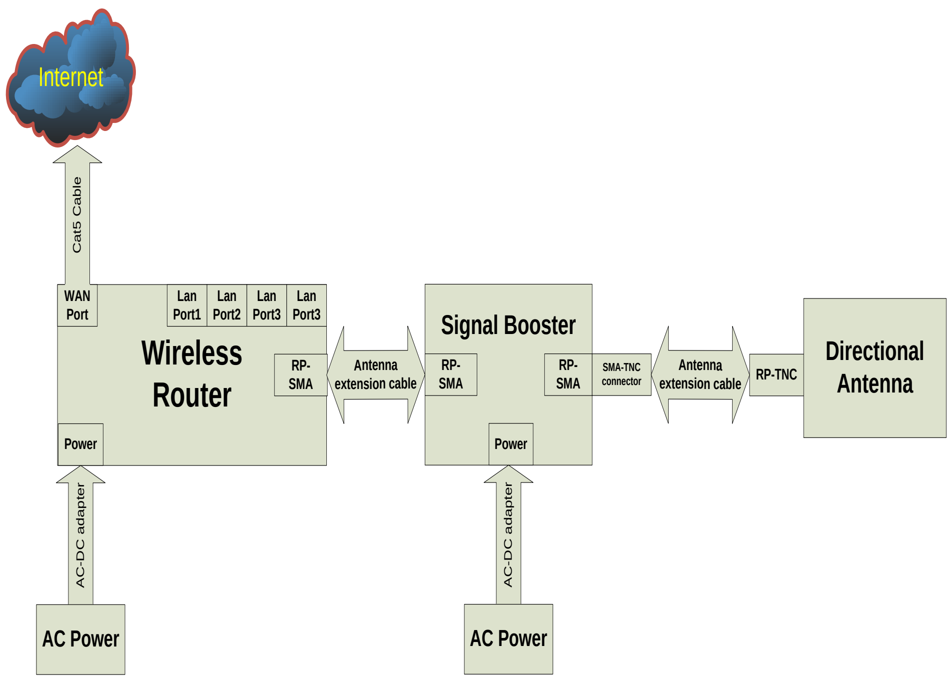

Figure 13 – The Office Node Design

4.2.2 Middle Node Design

Figure 14 shows the components of the Middle Node and the solar power system. The main purpose of the Middle Node is to establish connection between the Office Node and the End Node. The Middle Node contains a Linksys WRT54G router (See Appendix E2), two Hawking HAO14SPD antennas and Hawking HSB2 signal boosters (See

Appendix E5). Same as in the Office Node, the antennas are mounted at the top of a 9 feet high steel pole. One antenna will point to the Office Node and the other points to the End Node. The router and the two signal boosters will be put in a waterproof enclosure under antennas.

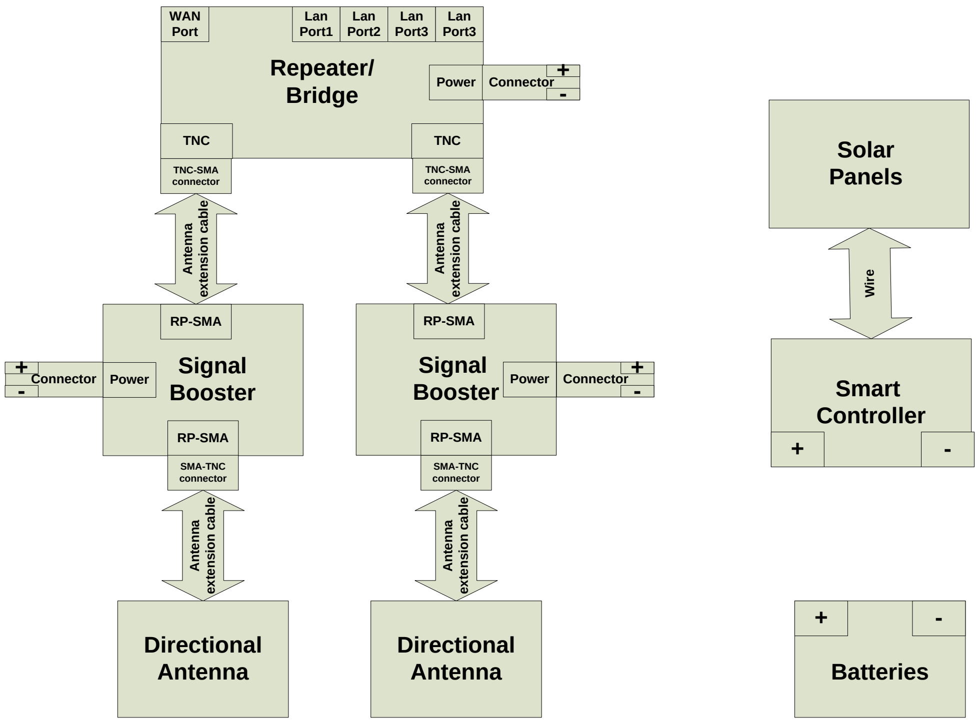

Figure 14 – The Middle Node Design

The critical design of the Middle Node is to modify an indoor router into a compatible outdoor repeater bridge. Table 5 contains the major specifications of a Linksys WRT54G router. The hardware design of Linksys WRT54G router brings 4 major benefits to accomplish the modification. First, the router has a dual attachable antenna design, which allows us to switch the original low gain antennas into high gain antennas. In additional, one antenna can be used to receive RF signal, another antenna can be used to retransmit RF single to another direction. Second, the Linksys router can operate under an outdoor temperature, because, in the area FOP, the average temperature is from 39.0 °F ~ 83.0 °F [16] in the most time of a year.

Table 5 - Linksys WRT54G Specifications

Frequency Band	2.4GHz
Data Transfer Rate	54Mbps
Transmit Power	1mW ~251mW
Antenna Type	Dual attachable Omni antennas
Power Consumption	6W
Operating Temperature	32.0 °F ~ 104.0 °F
Humidity Range Operating	10 - 85%
Dimensions (W*D*H)	7.3inch *6.9inch*1.9inch
Weight	1.1lbs

By changing the firmware into a third party firmware called DD-WRT. An indoor router (Linksys WRT54G) is able to perform as a repeater bridge. The modification procedures are shown in Appendix C2. The firmware adds many useful features such as adjustable transmit power and the scheduled radio time restrictions.

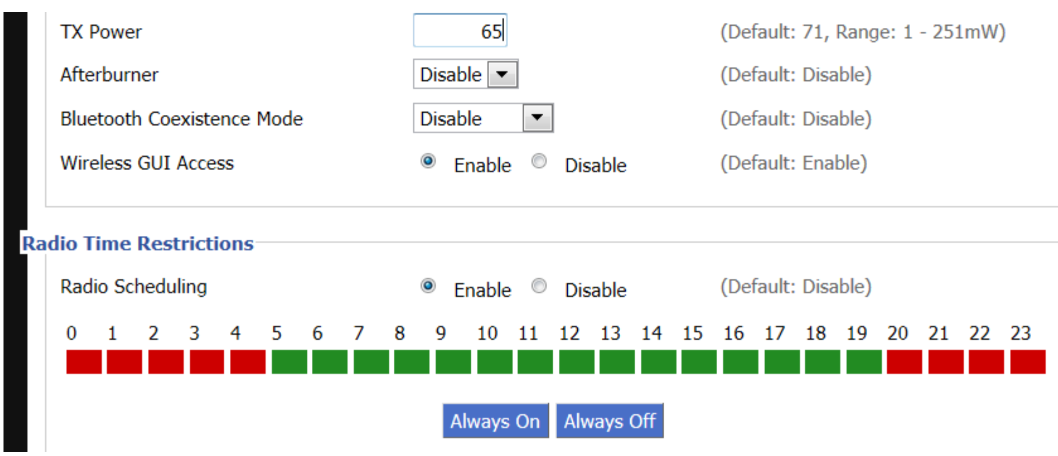

Figure 15 - Linksys WRT54G Configuration

Form Figure 15, the transmit power set up at 65mW (18dBm) because of the signal booster requires input power from 8dBm to 18dBm. In the "Radio Time Restrictions" setup menu, the transmit radio is closed from 20pm to 5am of the next day. By shutting down the radio wave transmission, the Middle node can reduce power consumption in a daily routine. In order to build up a self-sufficient system, the Middle Node requires a solar power system conserve power in different weathers. The solar power system includes the solar panels, the smart controller, and the batteries. The solar power system design is introduced in section 4.2.4. The installation procedures are provided in Appendix C2.

4.2.3 End Node Design

Figure 16 shows the components of the End Node. The End Node picks up the signal sending from the Middle Node and rebroadcasts it to cover the area around the Turtle Pond. The communication unit is a Hawking HOW2R1 Outdoor Smart Repeater (See Appendix E3). The repeater has an internal directional antenna to communicate with the Middle Node and two external Omni directional antennas to create Wi-Fi coverage. Same as the Middle Node, the End Node requires a solar power system as discussed in the next sub-section. The smart repeater uses Power Over Ethernet (POE) technology to pass electrical power safely, along with data over Ethernet cabling. 12V DC power supply cannot power up POE devices. Therefore, the End Node uses a DC-AC inverter to transform 12 DC power into 220V AC power for use by the smart repeater. The installation procedure is of End Node is shown in Appendix C3.

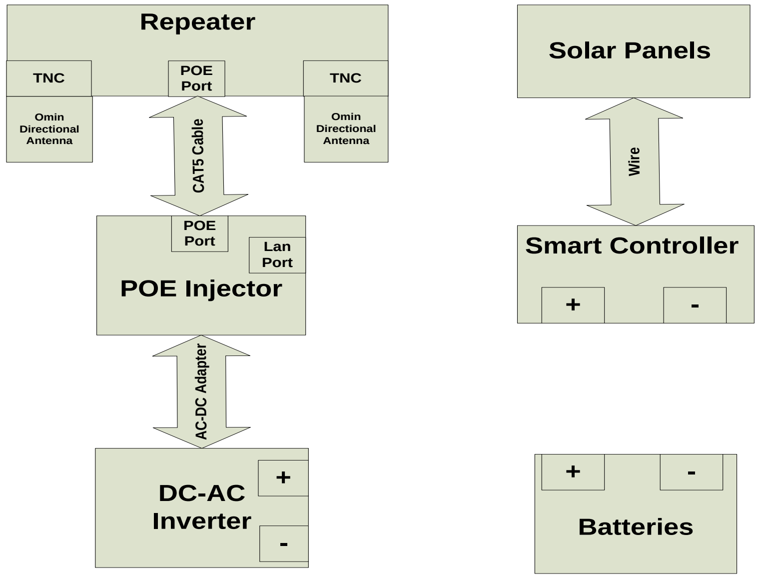

Figure 16 - The End Node Design

4.2.4 Solar Power System Design

In order to build a self-sufficient system, both the Middle Node and the End Node require Solar Power System to generate enough power to use. The Solar Power Systems not only generate power to use in daytime but also conserve power in nighttime and days without any sunlight. The design has to follow four steps: calculate the power requirements, choose the right solar panel, choose the right batteries and build a rugged structure to support equipment.

First step is calculating the power requirements. After measuring the power consumption of every item, we find out the Hawking HSB2 signal boosters and HAO2R1 Smart Repeater have fluctuating value for the power consumption due to varying throughput. The results are listed in Table 6. The measurement procedures are shown in Appendix D1, D2 and D3. We can predict the power consumptions of the Middle Node and the End Node by adding different components. Amp-hour represents the number of hours that a 1-amp current drawing device will be powered by a particular battery before it runs out of energy.

Table 6 - Power Consumption for the Router, the Signal Booster and the Repeater

Load Items	Voltage (V)	Current (A)	Power (W)	Average amp-hour /Day
Linksys WRT54G Router	12	0.45	5.4	10.8
Signal Booster	12	0.01~1.2	0.12~14.4	14.52
Smart Repeater (with AC-DC inverter)	12	0.85~0.91	10.2~10.92	21.12

Once we find out the power consumptions of the Middle Node and the End Node, the solar panel sizing becomes the second step. In the FOPW design, we choose "Sunforce-50048 (12V, 60W)" solar panel sets (See Appendix E7). The set includes four 15W solar modules. The following sizing processes determine how many solar modules are required for the Middle Node and the End Node.

Middle Node:

1. Total average amp hours per day for The Middle Node: 25.32
2. Average sun hours per day in the position of Middle Node: 5
3. Divide line 1 by line 2 for total solar array amps required: 5.064
4. Divide line 3 by 0.85 to compensate for the solar panel efficiency: 5.96
5. Peak Amps of solar module used: 1
6. Total number of solar modules in parallel. Divide line 4 by 5: 5.96

End Node:

1. Total average amp hours per day for The Middle Node: 20.64
2. Average sun hours per day in the position of Middle Node: 6
3. Divide line 1 by line 2 for total solar array amps required: 3.46
4. Divide line 3 by 0.85 to compensate for the solar panel efficiency: 4.07

5. Peak Amps of solar module used: 1

6. Total number of solar modules in parallel. Divide line 4 by 5: 4.07

The power generated by the solar power modules should be bigger than the power used by the nodes. Therefore, the numbers of modules required to provide enough power per day is 6 for the Middle Node and 5 for the End Node.

The third step is to choose the right batteries. The capacity of the batteries decides the expected work duration which means how many hours the system can operate and carry the load without any sunlight. In another word, the solar power system has to offer enough energy in daytime and save in the batteries, so that the system can stay operation and collect data during nighttime until the sunlight comes back. Then, the batteries can be charged again when the sun returns. The Deep-Cycle batteries are like any other batteries - the less they work, the longer they last. Therefore, a bigger bank not only gives a larger reservoir, but also offers longer battery life.

$$Power_B * n_B > Power_L * (24 - h)$$

Where,

$Power_B$: The power conserved in one battery

$Power_L$: The power used by load

h: Average sunlight peak hours

n_B : The number of batteries

Equation 5 – Estimation for the Number of Batteries

According to Table 6, the power used by the Middle Node 12.66W, which is the sum of the power used by the router and the average power used by the signal booster. The average power used by the End Node is 10.56W. The power conserved in one battery is 84W. Based on that, numbers of batteries can be estimated by using Equation 5.

Middle Node: $n_B > \frac{Power_L*(24-h)}{Power_B} = \frac{12.66*(24-5)}{84} \approx 4$

End Node: $n_B > \frac{Power_L*(24-h)}{Power_B} = \frac{10.56*(24-5)}{84} \approx 3$

In order to protect batteries from over discharge, 50% more batteries need to be added to each node. Based on calculation, Middle Node requires six of 12V at 7Amp Lead-Acid batteries. End Node requires five of the same kind of batteries.

The last step is to design a rugged structure to support the equipment. Figure 18 shows the design structure for the idea installation. Solar panels need to be pointed in the direction of the sun to allow the panel to capture the most amount of sunlight. In the FOPW design, the solar panels have to point to the south because the location is in the northern hemisphere. The solar panels are mounted on steel poles with a certain tilt angle. In order to achieve MPP, the tilt angle between a solar panel unit and the holding pole is different in different seasons [17]. The tilt angles between solar panels and holding poles is calculated and summarize in Table 7 and shown in Figure 17.

Table 7 - Solar Panel Angel Calculation [17]

Summary: Solar Panel Angle Calculation for FOP	
SEASON	ANGLE / TILT CALCULATION
Winter	(Latitude * 0.9) + 29 degrees = (38*0.9)+29=**63.2**
Summer	(Latitude * 0.9) - 23.5 degrees = (38*0.9)-23.5=**10.7**
Spring and Fall	Latitude - 2.5 degrees = (38-2.5)=**35.5**

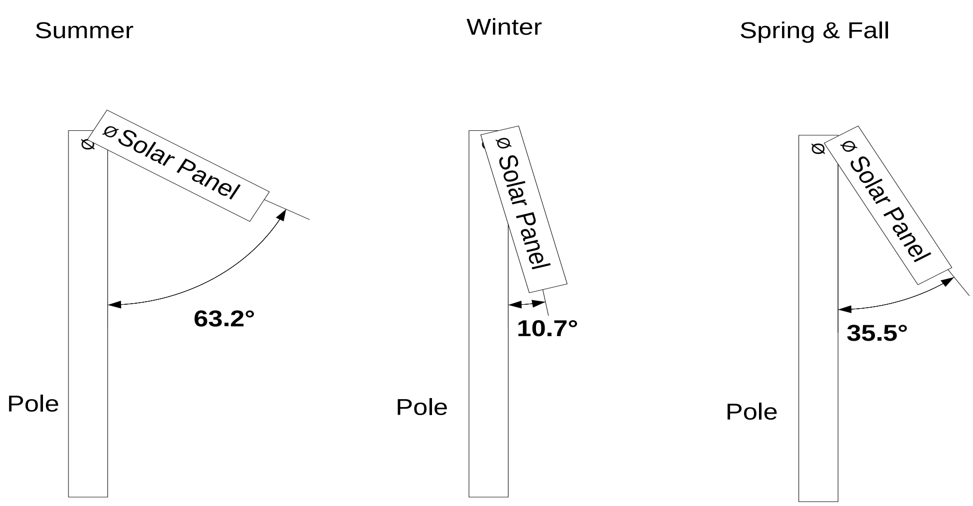

Figure 17 - Solar Panel Tilt Angle

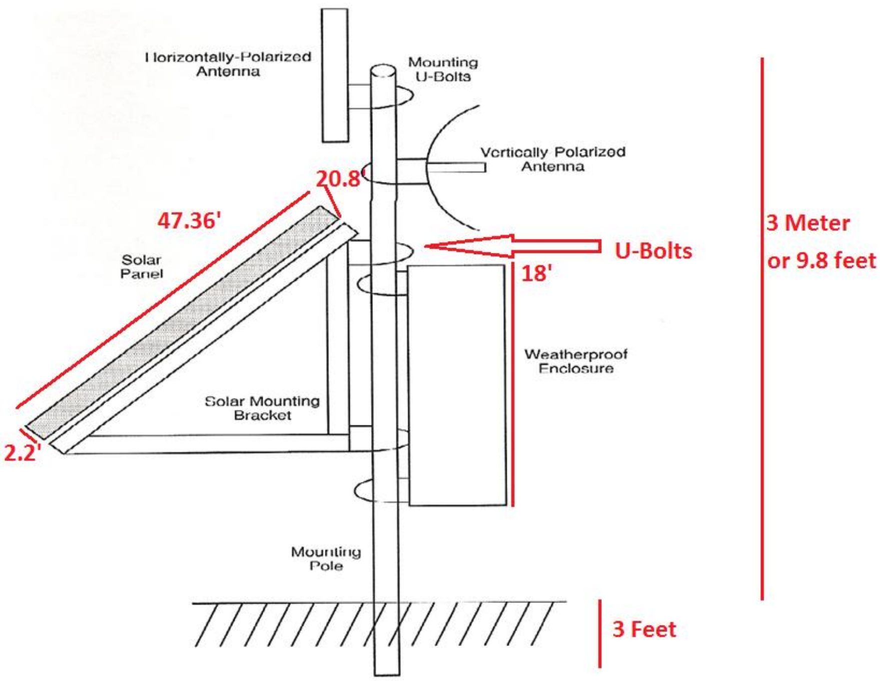

Figure 18 - The Idea Installation [2]

4.3 Signal Strength Measurement & Locations Selection

Stable and strong signal strength ensures a wave link keeping connected and having a good data transmission rate. It is the most important factor to influence the network reliability and performance. By measuring the signal strength in the area with many trees, we can find a location for the Middle Node to have the best reception. In the FOPW design, we introduce one approach to estimate signal strength by using the free Wi-Fi network scanner software called "InSSIDer" [18]. Service Set Identifier (SSID) refers to as a network name or identifier. All devices attempting to connect to a specific WLAN must use the same SSID. By monitoring and analyzing the signals captured by the wireless Network Interface Controlled (NIC) card of any computer, InSSIDer can inspect the surrounding SSIDs and track the received signals strength in dBm over time. The software detected eleven SSIDs as shown in Figure 19. The signals are received with different strength from -37dBm to -79dBm and shown under "RSSI" category. RSSI stands for Received Signal Strength Indication which is an indication of the power level being received by the antenna. In addition, InSSIDer shows all the detected networks are working under different frequency range and channels. In the FOPW design, we can use a laptop installed InSSIDer to simulate the RSSIs of the Middle Node. First, connect a wireless NIC card with 500mw transmit power to the laptop. Then, connect a 14dBi directional antenna to the wireless NIC card. At last, walk around in the FOP and raise the antenna to the same height as the Middle Node would be. In this case, we can use inSSIDer to inspect the surrounding RSSIs to simulate the receptions of each node. Therefore, we can locate the best place to install the Middle Node

Figure 19 – The Wireless SSIDs Captured by InSSIDer [18]

One important feature of InSSIDer is to associate Wi-Fi reception with GPS coordination. By using this feature, the RSSIs are associated with GPS coordination and are able to be displayed on to Google Earth map. It requires a GPS sensor installed on computer to gather the GPS information. In Figure 19, there are two categories on the left side, which are "Latitude" and "Longitude". By recoding the parameters over time and exporting data to Google Earth map, one can collect the capability to measure the signal coverage with meaningful signal strength over time in the area. If there is no GPS sensor configured, the values show all zero. In Figure 35, these two categories show the real time values of latitude and longitude. For example, Figure 20 shows the track when people carry a laptop loaded with InSSIDer and travels in the FOP. Green bubbles indicate the RSSIs captured by InSSIDer on the travel path. The sizes of the bubbles indicate the strength of received signals. The biggest bubble location is assumed to be the location of transmitter.

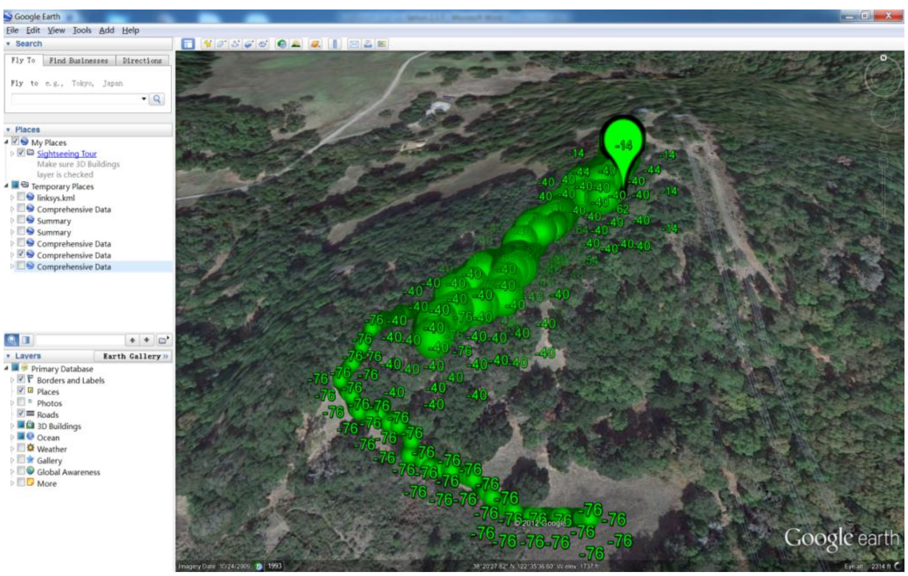

Figure 20 – The Signal Strength Captured by InSSIDer as Shown in Google Earth Map

The location of the Middle Node is not only having good signal reception, but look as good as an open area for the solar power aspect. There are three open areas marked as B1, B2 and B3 shown in Figure 21 that could be used to set up the Middle

Figure 21 - Middle Node and End Node potential locations

Using the approach introduced earlier this sub-section, the RSSIs capture at each locations are shown in Figure 22. The reception at B1 is slightly better than the others.

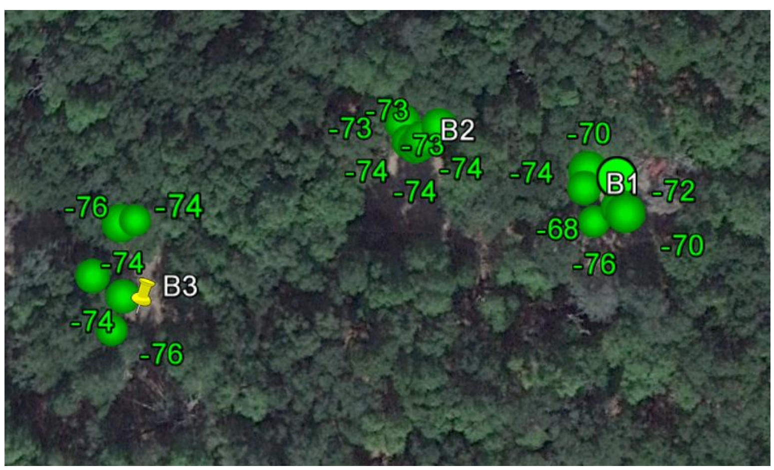

Figure 22 - Middle Node Reception Survey

From Table 8, we also observe that B1 has the best communication link with the End Node. Even though, B1 is not the best locations on solar power aspect, B1 should offer enough energy to run the Middle Node. Therefore, B1 is the best location to set up the Middle Node.

Table 8 - Middle Node Locations Comparison

Locations	RSSIs Received from Office Node	RSSIs Received by End Node	Percentage of Peak Sunlight Hours
B1	-68dBm ~76dBm	-68dBm ~ -76dBm	50%
B2	-73dBm ~-74dBm	No Connection	40%
B3	-74dBm ~-76dBm	-73dBm ~ -80dBm	70%

5. Experiment Results and Analysis

This section includes three parts. In the first sub-section, we compare the theoretical path loss with the realistic path loss of both links. Then, we listed and analyzed three results for the network performance test. The last sub-section is the results of the power consumption measurement of the Middle Node and the End Node.

5.1 Path Loss Measurement

Table 9 contains the path losses of the two wireless links in the FOPW design. One link is between the Office Node and the Middle Node; another one is between the Middle and the End Nodes. The path length of each link is 203m and 171m. By using Equation 1 and Equation 4, the theoretical path loss for the each link is 125dBm and 120dBm. In a wireless system, the total system gain equals to the sum of transmit power (in dBm), transmit antenna gain and receive antenna gain. Received Signal Strength Indication (RSSI) is the relative received signal strength (usually is a negative number in dBm). Therefore, the path loss is the subtraction of the Receiver RSSI and the total system gain. The measured path loss of the first link is from -123dB to -133dB. The second link has a measured path loss in the range of -121dB to -129dB. Both of the theoretical path losses are in the corresponding ranges. The results show that the

Weissberger's Modified Exponential Decay Model is applicable to predict the signal path loss in an environment with much foliage.

Table 9 – The Path Loss Comparison over The Links

Link	TX Antenna Gain (dBi)	RX Antenna Gain (dBi)	TX Power (dBm)	Total System Gain (dB)	RSSI (dB)	**Measured Path Loss (dB)**	**Theoretical Path Loss (dB)**
Office Node to Middle node	14	14	27	55	-68 to -78	**-123 to -133**	**-125**
Middle Node to End Node	14	12	27	53	-68 to -76	**-121 to -129**	**-120**

5.2 The Network Performance Test

According to Table 9, the total system gain is the subtotal of the transmit antenna gain, the receive antenna gain, and the transmit power, which is 55dBm for the link between the Office and the Middle Nodes and 53 dBm for the link between the Middle and the End Node. However, the FOPW system has to deal with an extra huge attenuation, which is about 0.2dBm ~ 0.5dBm/meter caused by forest environment. The signal would drop to an unreliable level in 200 meters. It is very important to optimize the received signal strength to insure the connections between each node and improve the network performance. In sub-section 5.2, we analyzed three experimental results of the signal strength measurement and the networking performance test under different criteria.

5.2.1 Impact of the Antenna Height

For the wireless sensor networks, the antenna height of the transmitter and the receiver should be raised high enough to obtain a clear Fresnel Zone. In that case, the plant impact on path loss could be negligible. However, the antenna height is not the single consideration in engineering design and some other issues such as communication quality, economical cost, and engineering implementation must be considered. In the FOPW project, due to the complicated terrain, it is impossible to make antennas to cover all desired areas. Two different antenna heights (3 feet and 6 feet) were tested at the End Node. One of the impacts of changing antenna height is increasing the receiving signal strength. Figure 23 shows the signal strength captured at different distances from the End Node. From the figure, we observe that the system has higher gain when the height of transmitting antenna is increased. The testing procedures are shown in Appendix D5.1.

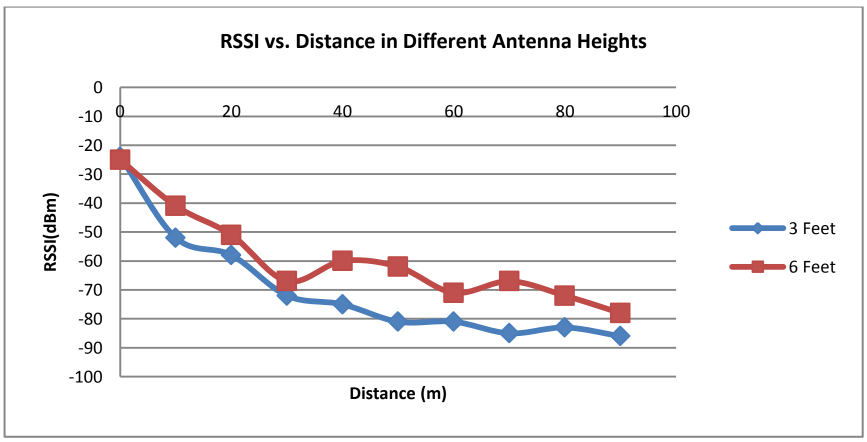

Figure 23 – The Signal Strength for Different Antenna Heights

Another impact of increasing antenna height is increasing network coverage. Figure 24 shows the coverage of the End Node in different antenna heights. When the antenna height of the End Node is 3 feet, the signal barely covers the pond. The receiving signal strength is mostly under -80dB, which is unacceptable. When the antenna height increases to 6 feet, the coverage of the End Node is better near the area around the pond with average signal strength of -70dBm.

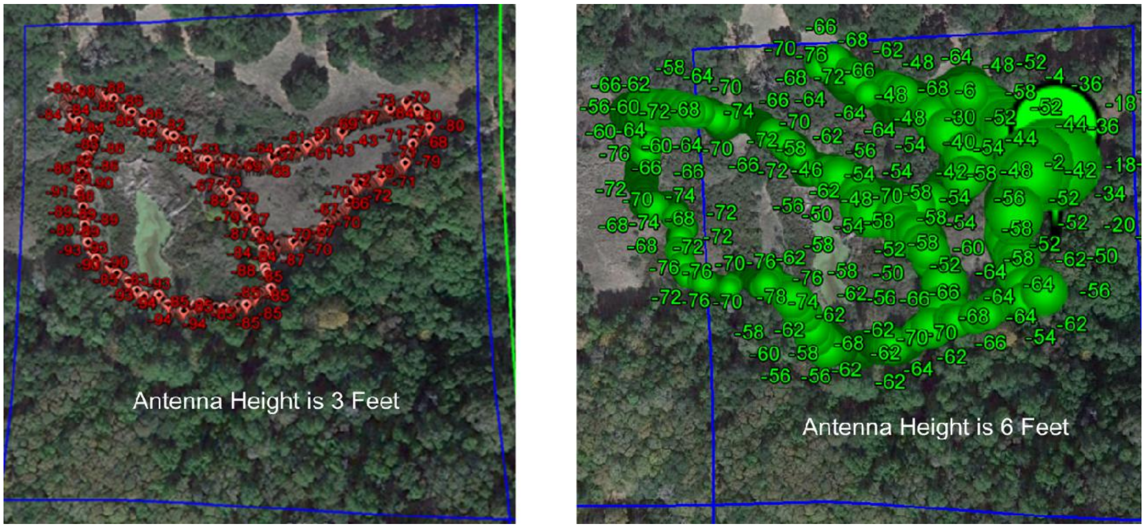

Figure 24 - End Node Coverage in Different Antenna Height

5.2.2 Impact of Different Antenna Propagation Directions

Because of lacking of LOS between each node, the signal attenuation is unpredictable in the aspect of propagation direction. Based on the data sheet of Hawking HAO14SDP panel antenna (See Appendix E4), the beamwidth of using antenna is 30 degree in both the horizontal and vertical directions. The impact of the antenna propagation direction is tested in both the horizontal way and vertical way. The angle between the transmission path and ground is taken to be 30° and 60° (See Figure 25). The antenna rotation angle is taken 0° and ±30° (See Figure 26).

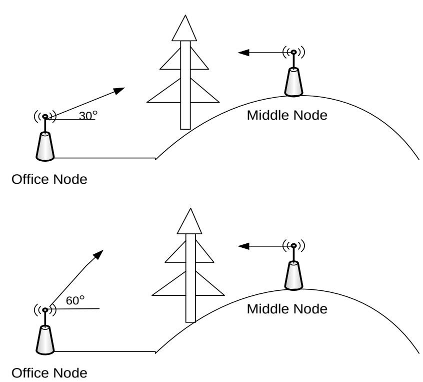

Figure 25 - Signal Propagation in Vertical Directions

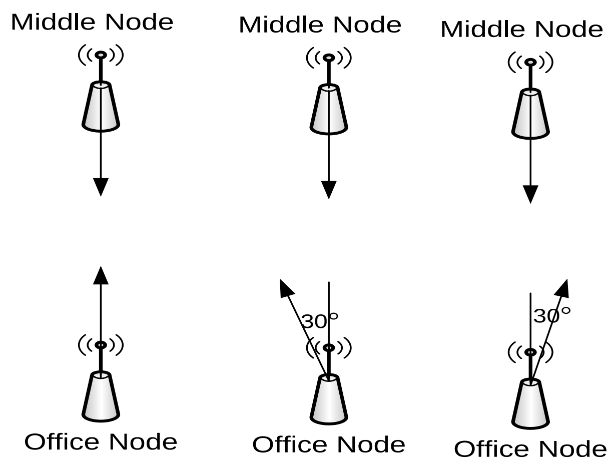

Figure 26 - Signal Propagation in Horizontal Directions

RSSIs in these different propagation directions were obtained, as shown in Table 10. It can be observed that there is no obvious difference in the signal attenuation in both vertical and horizontal directions. In the NLOS case, as far as the directional antenna keeps in its beamwidth, the wireless signal reception does not rely on the directionality. In this NLOS scenario, wireless signal propagation takes on certain homogeneity because of the high density of trees and inter-twisting of foliage.

Table 10 - RSSIs in Different Directions

Horizontal Angle / Vertical Angel	0°	30°	60°
30°	74dB ~ -81dB	-76dB ~ -84dB	-74dB ~ -85dB
60°	-72dB ~ -82dB	-73dB ~ -83dB	-75dB ~ -86dB

5.2.3 Impact of the Weather Condition

In the FOPW project, three tests were taken in a sunny day, a foggy day and a rainy day. The Average of Response Time (ART) and the Packet Lose Rate (PLR) were measured. WinPing is a software application that allows you to test network performance. First, use a laptop and connect to the End Node wirelessly. Then, enter the IP address of the Office Node, which is 192.169.2.1 in WinPing. The button "Options" opens the WinPing options: Infinite Loop allows running pings in an infinite loop and shows the average. However, we can stop the loops at 1000. The "Auto-Save" option allows saving all the pinging information (in Infinite Loop Mode). A Ping Graph allows us easily to view the information for every loop.

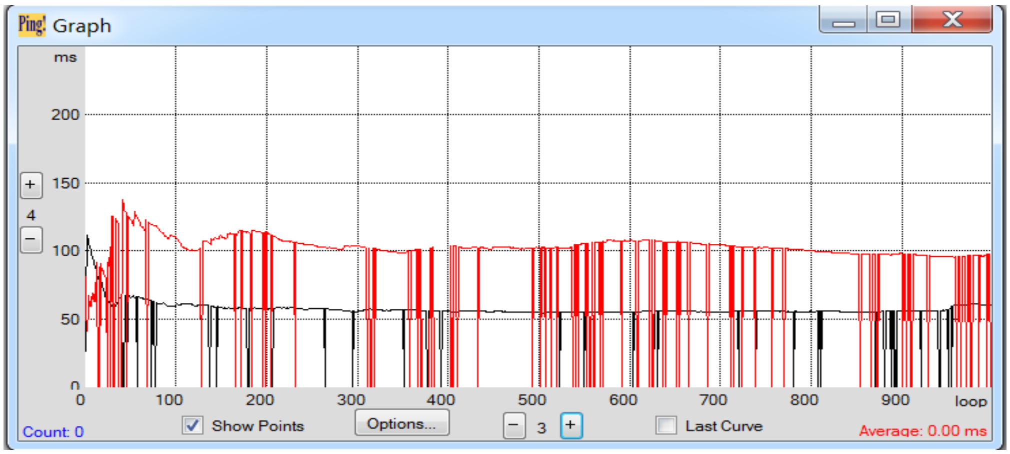

Figure 27 - Network Performance in Different Weather

The results are shown in Figure 27 and summarized in Table 11. In the figure, red lines indicate the response time of the communication between Office Node and End Node in foggy weather and black lines for sunny weather. From the table we can tell that in foggy weather, the ART increased by 50% and more packets dropped. 1000 packets were sent from the End Node to the Office Node. If the Office Node received the sending packet, it sent an acknowledgment back. Otherwise, the packet was considered to be lost during transmission. In 1000 loops, 58 packets are lost in sunny weather and, 108 packets are lost in foggy weather. In rainy weather, there is no connection between each node. From the results, we observe that the 2.4GHz radio wave has a poor penetrability in the forest environment in rainy weather. When it is raining, rainfall sticks on trees and leaves. Water causes more absorption and reflection then dry foliage.

Table 11 - Network Performance in Different Weather

Weather Condition	Average of Response Time	Packet Lost Rate
Sunny	61.38ms	5.8%
Foggy	97.95ms	10.8%
Rainy	Time Out	100%

5.3 Power Consumption

The power consumption is tested after the entire network was set up. The Middle Node uses 5.1W without any traffic. The power consumption jumps to 24.2W When the Middle Node has a large throughput (loading videos). We choose the average value to predict the power consumption of the Middle Node, which is 14.65W. The current of End Node has a slightly difference between staying ideally and working status. We just use 10.32W to estimate the power consumption. Based on testing the results, six modules of solar panels and six 12V*7Amp batteries are capable to offer enough power for the Middle Node operating as a standalone node. Also five modules of solar panels and four12V*7Amp batteries are required for the End Node to operate as a standalone node.

Table 12 - Middle Node & End Node Power Consumption

	Middle Node	End Node
Current (no traffic)	0.425 A	0.86A
Current (with traffic)	0.53A~1.51A	0.89A
Solar Panel Voltage	23.69 V	22.78V
Battery Voltage (fully charged)	12.58V	12.96V
Power Consumption (average)	14.65W	10.32W

5. Future Work

In section 6, we elaborate on some future work that can be done on FOPW to enhance it based on the purposed design.

Larger Backbone: At beginning of Chapter 1, Figure 1 shows that the areas (circled by yellow the lines) needed to be covered by wireless signal. However, the

FOPW presented in this project only covers one of areas. In the future, a larger backbone is needed to cover the whole preserve. For that the repeaters that are similar to the Middle Node can be added to the existing network. When more nodes are added to the FOPW design, some problem may arise. One problem is the network frame. The Office Node is not only going to communicate with one Middle Node, but multiple nodes. Then the Router used in the Office Node has to be capable of handling multiple communications links. Another problem is the network performance. Data packets will hop multiple times to arriver the destination. This will cause longer delay and more chances of dropping packets.

Improve Reception: In order to improve the signal reception, there are three alternative designs that can be used. One is to use the 900MHz radio frequency to establish the links between each node instead of the 2.4GHz radio frequency. With the 900MHz frequency, signal can easily go through the forest and reach 1 mile away in any weather. The disadvantage is that the cost of the 900MHz components is higher than that of the 2.4GHz. Another potential solution is to add more nodes on the propagation path so that fewer trees would obstruct the link. The reliability of each link will be improved. However, more nodes require more power and higher cost. Another solution is to increase the antenna height by hanging it under a balloon for clear LOS. Clear Fresnel Zone will make sure that the signal can be sent from the Office Node to the End Node in any weathers.

Applications: Using wireless IP cameras to monitor the wildlife and the environment is a very helpful application. The higher transmission speed and power consumption requirements would be two challenges for this application. In order to monitor the wildlife, the remote IP cameras would be hidden in the forest and far away objects. Higher resolution requirement of imaging or videos requires higher performance to upload data in real time. Due to the environmental impacts, the PLR is more than 5%. It causes noticeable performance issues such like jitter with VOIP and video streams. This application would require more power and in turn bigger solar panels and more budgets.

Alterative Power Source: The climate of FOP is typical Mediterranean regions. It is often raining in winter. Fog inlands frequently cover along the valley bottoms, leaving the upper slopes of the mountain exposed. There is not much sunlight in most areas. Solar power is quite unreliable in winter. Trees also cause a lot of shade blocking the sunlight in daytime. Having an alternative power source will help the required power availability for extended time when enough sunlight is not available. Wind power could be the best option to combine with the solar power.

6. Conclusion

After all, the proposed FOPW design creates a WLAN network, which covers the area around the Turtle Pond and a strip area among the signal transmission path from the Office Node to the End Node. By increasing transmit power and using high gain directional antennas, the FOPW design overcome the huge attenuation on the propagation path, which caused by trees and other vegetations. The FOPW design offers the Internet access under its coverage. We have been successful to check our emails and load YouTube videos within the coverage areas. By increasing the height of antennas, the FOPW design can cover the major area around the Turtle Pond.

By measuring the path loss between each link, we know that the Weissberger's model is accurate enough to account for the signal loss. However, the Weissberger's model does not include any factor for the weather impacts. We can only predict the path loss when the signal propagation path is blocked by dense, dry and leafy trees. When the entire system is completely installed and configured, the performance test shows the weather has a great impact on the signal propagation. By evaluating the performance of the FOPW design, we know that, the weather significantly affects the propagation of the radio signals in the forest environment. The Wi-Fi signal is not stable in foggy weather in terms of ART and PLR increasing. The whole network cannot function during a rainy weather. From the study, we know that the 2.4GHz radio wave is badly attenuated in the forest environments. The penetrability is very poor even when high gain directional antenna with high transmitting power is used. Trees cause a lot of reflection, absorption and multi-path fading. Moreover, poor weather condition can significantly influence the signal attenuation. When it is foggy or rainy, the rainfalls paste on trees and the leaves for sometimes that can attenuate the RF signal. Water absorbs and reflects the RF signal and the penetrability of RF signal decreases. Antenna height is another factor to influence the signal strength. Increasing the antenna height can improve the signal reception and coverage. Antenna directionality has a small influence on the signal penetrability in forest environments because of high density of trees and inter-twisting of branches and leaves.

The total cost of the FOPW design is $2170.17, including the three nodes and two solar power systems (See Appendix B). The costs of the installation such as the tripod and the installation kits are unexpected. Referring to Figure 18, the original design requires digging a 3 feet deep hole in the ground and inserting the mounting pole in it.

However, this structure is not stable to stand. Therefore, we need to purchase a stronger tripod to hold the mounting pole. In that case, the total cost of ROPW design would be over the budget (See Appendix A). From Figure 28, the total cost of the three nodes is $1340.31. The average cost per node is $446.77. Compare to the two professional solutions mentioned in Table 1, the cost per node of the FOPW design is much lower than theirs.

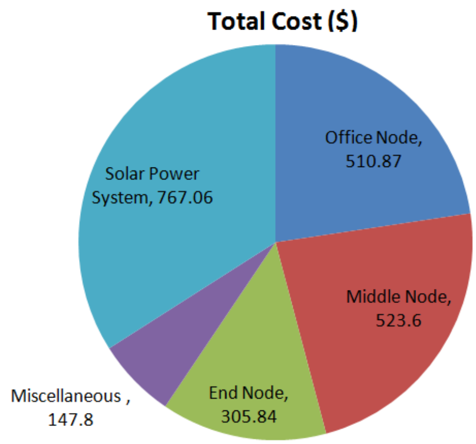

Figure 28 - Total Cost of FOPW Design

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Appendix A – Detailed Budget

Table 13 - Detailed Budget

Item	Projected Cost($)
Communication Units	
Router	50
Bridge	50
Access Point	200
Signal Booster	150
Antenna	300
Enclosure	20
Installation Kits	50
Solar Power System	
Solar Power Sets	500
Battery	100
AC-DC Inverter	30
Testing Item	
GPS Sensor	30
USB Wireless Adapter	20
Omni-Directional Antenna	50
Yagi Antenna	50
Total	1600

Appendix B – Bill of Materials

Table 14 - Bill of Materials

Item	Description	QTY	Price	Total
1	Hawking HAO14SPD Signal Booster	3	80	240
2	D-link DI-624 Router	1	30	30
3	Linksys WRT54G Router	1	50	50
4	Hawking HOW2R1 Smart Repeater	1	239	239
5	Panel Antenna	3	85	255
6	Omni-Directional Antenna	2	30	60
7	Yagi Antenna	1	29.95	32.8
8	Basket	2	1.69	3.68
9	Cement	2	20	40
10	Solar Power kits	2	279.95	559.90
11	Battery	8	14	112
12	AC-DC Inverter	1	35	35
13	GPS Sensor	1	25	25
14	USB Wireless Adapter	1	30	30
15	Tri Pod 1	1	275	275
16	Tri Pod 2	1	39	39
17	PVC pipe	2	5	10
18	Coaxial Power Plug	2	1.49	3.97
19	XL Clip Box	2	6.99	15.16
20	Enclosure	2	5	10
21	Installation Kit	3	30	90
22	Pipe Connector	5	2.69	14.66
			Total	2170.17

Appendix C – Nodes Installation & Configuration

C1 - Office Node

Installation Procedures:

1. Put D-link DI-624 router and Hawking HSB2 signal booster in a waterproof plastic enclosure.

2. Drill two big holes on the top of the enclosure and insert two pipe connectors for wiring antenna cable, power cord and Ethernet cable. Drill some small holes on the bottom to radiate heat.

3. Wrap the enclosure with tinfoil paper to avoid sunlight heating up the devices. Seal the two pipe connectors on the top.

4. Mount the enclosure and antennas on the top of a steal pole.

5. Hold the pole with a tripod.

6. Adjust the direction and tilt angel of antenna.

Figure 29 - Office Node Installation

C2 - Middle Node

Installation Procedures:

1. Put a Linksys WRT54G router and two of Hawking HSB2 signal boosters in a waterproof plastic enclosure.

2. Drill two big holes on the top and one big hole on the bottom of the enclosure. Insert two pipe connectors for wiring antenna cable, power cord and Ethernet cable. Drill some small holes on the bottom to radiate heat.

3. Wrap the enclosure with tinfoil paper to avoid sunlight heating up Middle Node. Seal three pipe connectors. Mount the enclosure and two Hawking HAO14SPD Panel Antennas on the top of a steal pole.

4. Adjust the directions of both antennas. Make sure one antenna point to Office Node, another one point to End Node

4. Put 25 pounds cement in a basket to act as a basement. Insert the steal pole into the basement and use a tripod to make it solid.

5. Put solar panels on the ground. Adjust the direction to south and tile angel to corresponding seasons.

6. Connect solar panels, batteries and electronics devices with a smart controller.

Configurations:

1. Open browser to http://192.168.1.1. Change Wireless Mode to Repeater Bridge. Change Wireless Network Name (SSID) to Office Node.

2. In Wireless-Advanced Setting page set TX Power to 65. In Radio Time Restrictions, we can schedule to shown down the radio in a daily routine. For example, shows the radio will shut down from 0am to 5am and from 20 pm to 24pm every day.

Figure 30 - Middle Node Installation

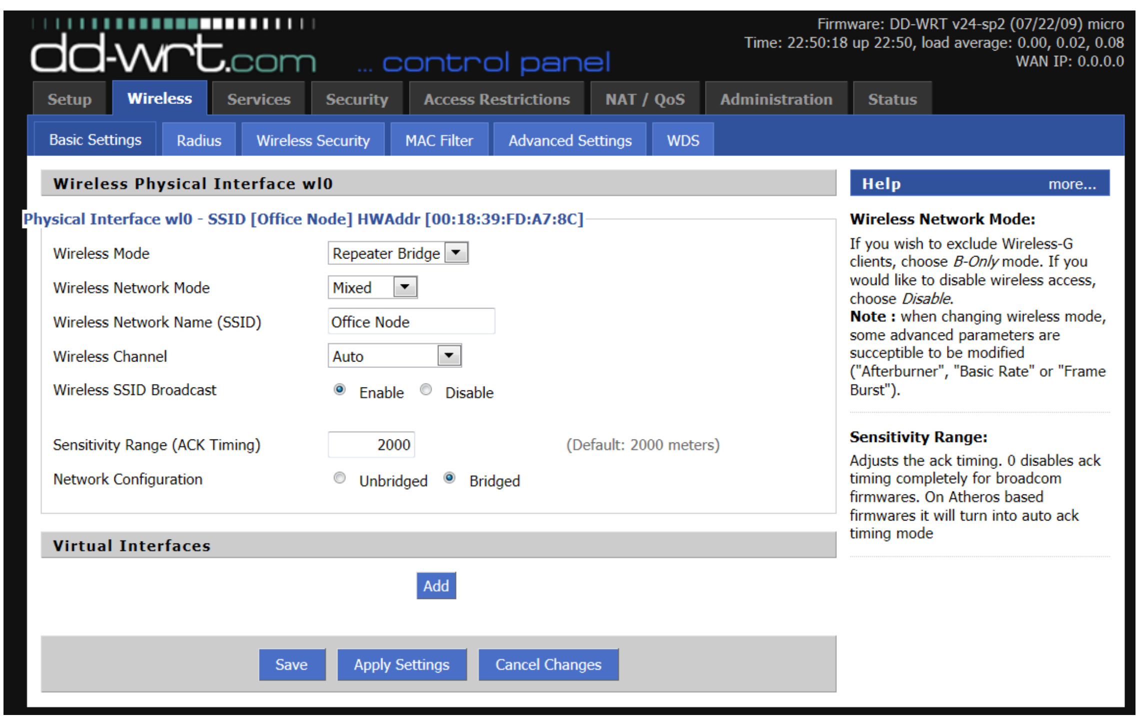

Figure 31 - Linksys WRT54G Configuration

Modification Procedures:

1. Download vxworkskiller Gv8-v3.bin and dd-wrt.v24_micro_generic.bin. Install TFTP.

2. Configure computer's local Ethernet IP address to 192.168.1.100, subnet 255.255.255.0 and gateway 192.16.1.1.

3. Power cycle Linksys router

4. Open browser to http://192.168.1.1

5. Use the firmware upgrade dialog to flash vxworkskiller Gv8-v3.bin.

6. Wait five minutes and power cycle the router.

7. Flash the DD-WRT firmware using TFTP. Enter command line "tftp -i 192.168.1.1"

8. Upgrade firmware of using wrt.24v_micro_generic.bin

C3 - End Node Installation Procedures

Installation Procedures:

1. Mount Hawking HOW2R1 Smart Repeater on top of a PVC pipe

2. Adjust the direction of the repeater to point to Middle Node

3. Similar as Middle Node, a basket with cement is using as a basement to hold the repeater.

4. Use an Ethernet cable to connect the repeater to a POE injector. Then connect the injector to a DC-AC inverter, which connect to batteries. Connect batteries and solar panel with a smart controller

Figure 32 - End Node Installation

Appendix D – Test Plan, Procedures& Results

D1 - Linksys 54G Router Power Consumption Measurement

Equipment:

Agilent E3631 Power Supply, Linksys WRT54G router

Procedures:

1. Connect Linksys WRT54G Router to Agilent E3631 Power Supply.

2. Adjust power from 3.3V to 12V and record current

3. Calculate power consumption by multiplex voltage and corresponding current

Result:

Table 15 - Linksys WRT54G Router Power Consumption

Voltage(V)	Current(Amp)	Power(W)
<3.3	0	0
3.3	0.76	2.508
5	0.65	3.25
12	0.43	5.4

D2 - Signal Booster Power Consumption Measurement

Equipment:

Agilent E3631 Power Supply, Linksys WRT54G Router, Hawking HSB2 Signal Booster, HP DV4 Laptop

Procedures:

1. Connect HSB2 Signal Booster to Linksys WRT54G router
2. Power up HSB2 Signal Booster by Agilent E3631 Power Supply
3. Adjust power from 3.3V to 12 V. In the meantime, record current drawing by HSB2
4. Set output power at 12V level. Let the router access to the Internet, and connect to laptop wirelessly. Make a stream go through signal booster. For example, load YouTube videos on the laptop. Then, monitor the change of current.

Result:

When signal booster stay ideal, it only use very little amount of power, the current is 0.01A. When signals keep sending through booster, it becomes very hard to monitoring the current. The maximum reading of captured current is 1.12A. The most common reading is from 0.4A to 0.8A.

D3 - Hawking HOW2R1 Smart Repeater Power Consumption Measurement

Equipment:

Agilent E3631 Power Supply, Hawking HOW2R1 Smart Repeater, Power Bright PW400-12 Power Inverter, HP DV4 Laptop

Procedures:

1. Use Ethernet cable connect Hawking HOW2R1 Smart Repeater to POE injector

2. Connect POE injector to Power Bright PW400-12 Power Inverter

3. Use Agilent E3631 Power Supply to generate 12V DC power.

4. Observe current value on Agilent E 3631 Power Supply.

5. Connect Power Bright Pw400-12 Power Inverter to Agilent E3631 Power Supply. Observe current value

6. Connect HP DV4 Laptop to Hawking HOW2R1 Smart Repeater wirelessly

7. Load YouTube video on HP DV4 Laptop. Observe the change of current value.

Result:

Table 16 - Smart Repeater Power Consumption Measurement

Items	Voltage (V)	Min Current (A)	Max Current (A)	Average Current (A)	Power (W)
Power Inverter	12V	0.388	0.389	0.389	4.668
Power Inverter + Smart Repeater (No Traffic)	12V	0.796	0.895	0.853	10.236
Power Inverter + Smart Repeater (Traffic)	12V	0.901	0.912	0.907	10.884

D4 - Middle Node & End Node Power Consumption Measurement

Equipment:

Fluke-179 Multimeter, Laptop

Procedures:

1. Use Fluke-179 multimeter to observe the current of the Middle Node when there is no data being transferred. Record the minimum and maximum value.

2. Connect Laptop to the Middle Node. Start loading YouTube video. Observe the current of the Middle Node and record the value.

3. Repeat step1 and step 2 by connecting multimeter and laptop to the End Node

Result:

Table 17 - Middle Node and End Node Power Consumption Measurement

Node	Voltage (V)	No Traffic		Loading Videos		Average Power (W)
		Minimum Current (A)	Maximum Current (A)	Minimum Current (A)	Maximum Current (A)	
Middle Node	12.58	0.425	0.425	0.53	1.51	14.65
End Node	12.96	0.86	0.86	0.89	0.89	10.32

D5 - Environmental Impacts

D5.1 - Different Antenna Heights vs. Signal Strength

Test Procedures:

1. Use the same set up of End Node to broadcast signal

2. Holding a laptop walk away from the router

3. Record RSSIs along the walking path

4. Display RSSI data in to Google Earth, shown in Figure 33

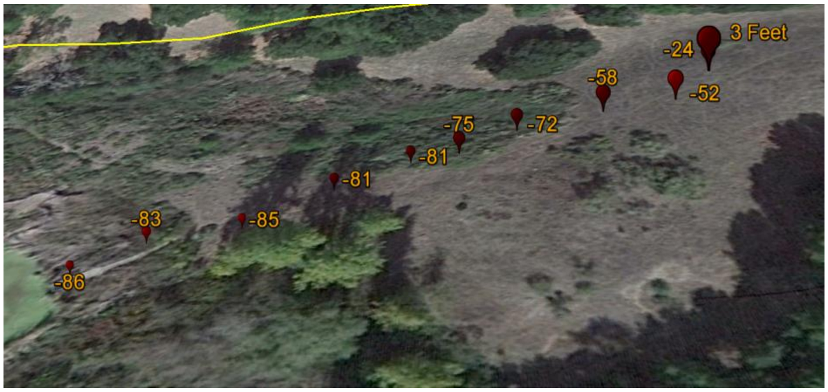

Figure 33 - RSSI vs. Distance (Antenna Height is 3 feet)

5. Repeat step 1 to step 4 by increasing the height of PVC pipe to 6 feet. Result is shown in Figure 34

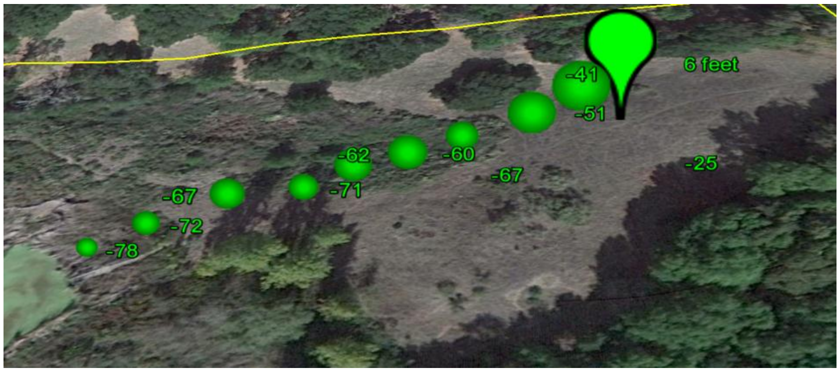

Figure 34 - RSSI vs. Distance (Antenna Height is 6 feet)

D5.2 - Signal Strength vs. Different Weathers

Test Procedures:

1. Set the angle between the transmission path and ground of Office Node transmitter antenna to 30°. Keep the horizontal angle at 0°. The weather is sunny.

2. Walk from Office Node to End Node and record RSSIs along the path,

3. Walk to End Node; connect laptop to End Node wireless.

4. Use WinPing to ping Office Node by IP address of 192.168.2.1.

5. Repeat step 1 to step 4 in foggy weather.

Result:

1. Figure 35 shows the RSSI captured on the path from the Office Node to the Middle Node when it is sunny.

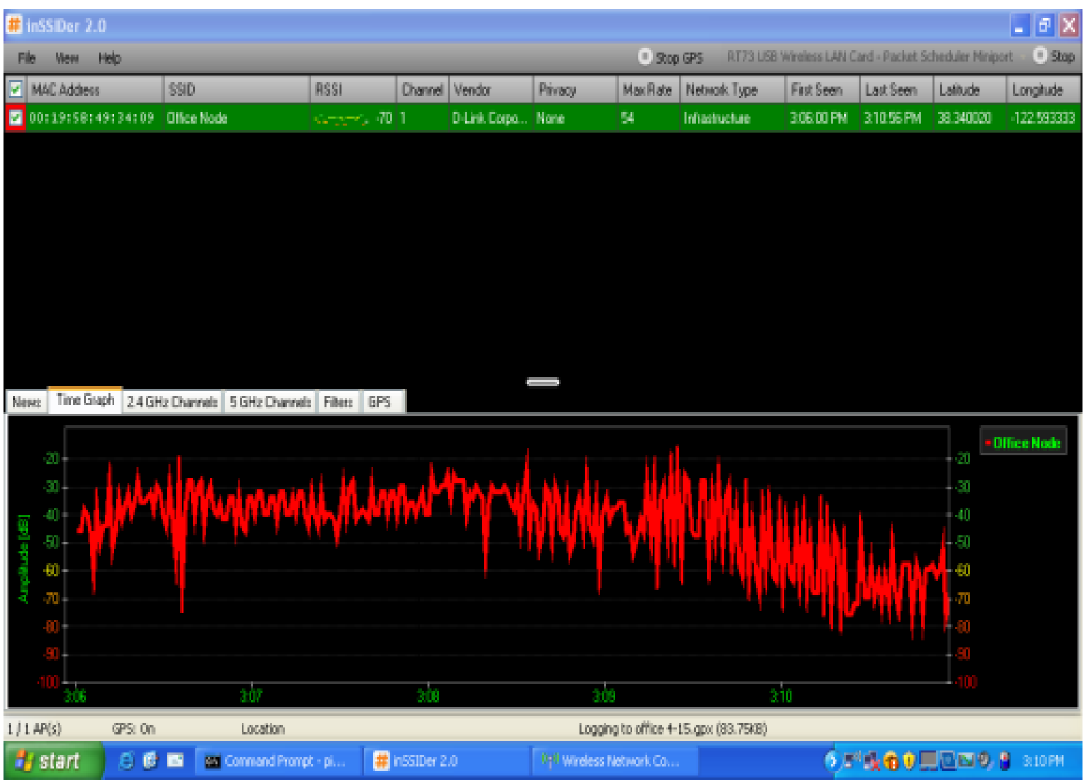

Figure 35 - Signal Strength from Office Node to Middle Node in Sunny Weather

2. Figure 36 shows the RSSI captured on the path from the Office Node to the Middle Node when it is foggy weather

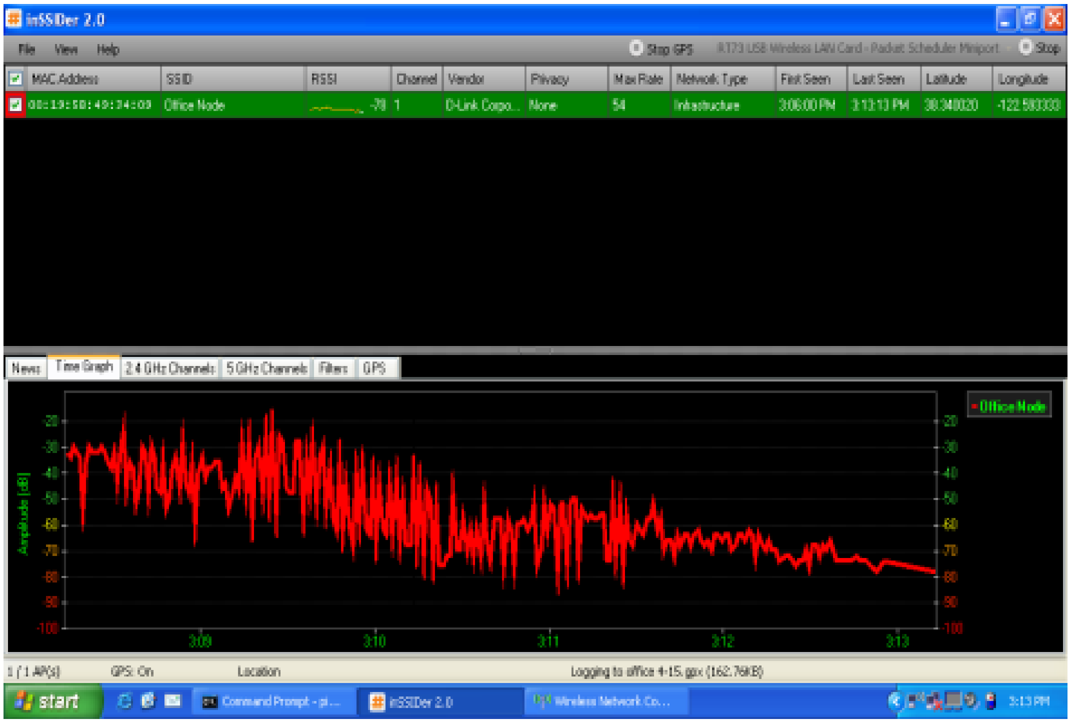

Figure 36 - Signal Strength from Office Node to Middle Node in Foggy Weather

D6 - Coverage Survey

Survey Procedures:

1. Holding a laptop installed InSSIDer, walk along the red lines shown in Figure 37.

2. Record RSSIs and export data into *.kml files.

3. Display the*.kml files on Google Earth, shown in Figure 38.

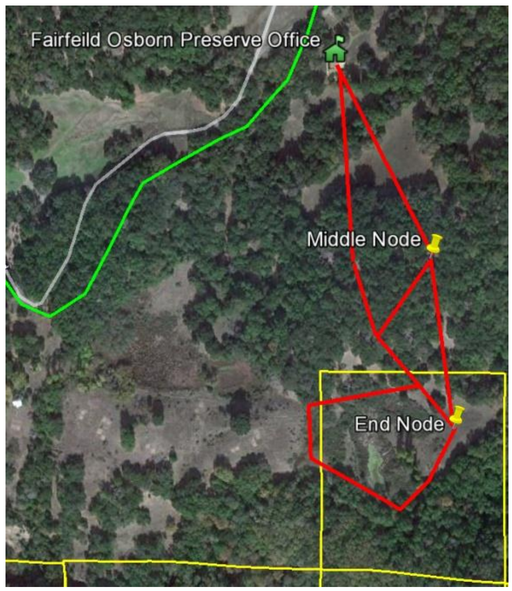

Figure 37 - Coverage Survey Route

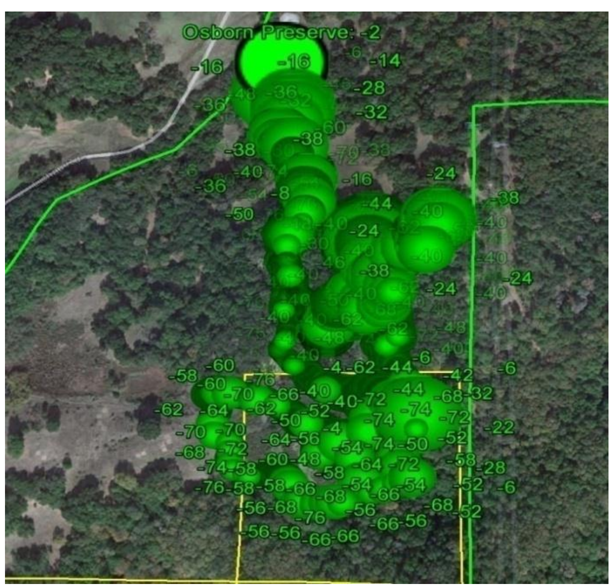

Figure 38 - RSSI from Office Node to End Node

D7 - Received Signal Strength Survey

Survey Procedures:

1. Walk to the location of the Middle Node. Use InSSIDer to capture RSSI of the SSID named "Office Node". Observe the minimum value and the maximum value of the RSSIs.

2. Walk to the location of the End Node. Use InSSIDer to capture RSSI of the SSID named "Middle Node". Observe the minimum value and the maximum value of the RSSIs.

3. Export the capture data into Google Earth.

Result:

As shown in Figure 39, the minimum RSSI captured at the Middle Node is -68dBm and maximum value is -78dBm. The minimum RSSI captured at the End Node is -68dBm and maximum value is -76dBm.

Figure 39 - Middle Node & End Node RSSI Survey

Appendix E – Data Sheet

E1 - D-link DI-624 Router
Data Sheet: ftp://ftp10.dlink.com/pdfs/products/DI-624/DI-624_ds.pdf

E2 - Linksys 54G Router
Data Sheet: http://homedownloads.cisco.com/downloads/datasheet/wrt54gv8-ds.pdf

E3 - Hawking HOW2R1 Smart Repeater
Data Sheet: http://hawkingtech.com/index.php/products/downloadfile/36.html

E4 - Hawking HAO14SPD Panel Antenna
User's Manual: http://hawkingtech.com/index.php/products/downloadfile/134.html

E5 - HawkingHSB2 Signal Booster
Data Sheet: http://hawkingtech.com/index.php/products/downloadfile/37.html

E6 - USB Wireless Adapter
Data Sheet:
http://www.alfa.com.tw/in/front/bin/ptdetail.phtml?Part=AWUS036EH&Category=0

E7 - Sunforce 50048 Solar Panel Kits
User's Manual:
http://sunforceproducts.com/prodinfo/fr_vend_lit/(50048)60W%20kit%20SF.pdf

E8 - Power Bright PW400-12 Power Inverter
Specification Sheet: http://www.powerbright.com/pdf/PW400_spec_sheet.pdf

E9 - GPS Sensor
Data Sheet : http://www.usglobalsat.com/store/download/62/bu353_ds_ug.pdf