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Using UNII-3 Wi-Fi Frequencies to Establish Long Distance Point-to-Point Links: Experimental Validation

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Abstract: This paper demonstrates the use of Unlicensed National Information Infrastructure (UNII-3), 5.725-5.825GHz, Wi-Fi frequencies, in the IEEE802.11a/n standard in setting up long distance point-to-point links, capable of providing broadband internet in rural areas. Although this frequency band was intended for indoor wireless local area networks, its lack of licensing and inexpensive off-shelf networking devices has prompted many researchers and technology enthusiasts to extend its use to outdoor settings. This paper presents a long distance point-to-point test-bed model that uses high-gain directional antennas that may be replicated to provide broadband internet access in rural areas particularly in developing countries. Six long-distance point-to-point links have been set up. A link distance of 24.3kilometers, the longest so far, has been achieved. An average peak throughput of 98.4Mbps has been observed on each of the six links set up, irrespective of its link length. This test-bed model is easy and inexpensive to implement and it may be replicated to provide broadband internet access in the rural areas. The paper shows that using a TDMA based Wi-Fi radio overcomes the fundamental challenges associated with the use of the off-the-shelf Wi-Fi radio whose Media access layer is based on CDMA/CA MAC protocol to implement long distance links. Further, the performance of the long distance links when the channel width is varied is analyzed. This model, therefore, validates the use of these unlicensed frequencies and proves that as long as a clear line of sight between the nodes is achievable, high bandwidth links may be achieved capable of serving one thousand or more simultaneous users each utilizing at least 100kbps.

Keywords- Point-to-point links, long distance Wi-Fi, broadband for rural areas, TDMA MAC protocol

1. Introduction

In the recent past, the information revolution has experienced accelerated growth particularly because of technological advancements in telecommunication industry. These technologies have brought forth what is commonly known as 'global village' because of the ease in which communication takes place between individuals and communities in distant localities. Broadband Internet access has been one of the forces behind the advances in communication technologies currently being enjoyed. The term broadband generally refers to Internet connectivity that is always on and that provides high capacity of data.

Rural areas have hardly experienced the advantages provided by broadband Internet access. This is primarily because; they have economic challenges that make Internet service providers (ISPs) find it unprofitable to put up necessary infrastructure in such areas. Because of these challenges, other approaches have been put forward with an aim of providing broadband Internet access to rural areas. Such approaches include mobile broadband access (3G, LTE, 4G), WiMAX, DSL, broadband over power lines, VSAT among others. As things stand, only wireless-based solutions have the potential of making any tangible progress because of their generic low cost and ease of deployment.

Surprisingly, even the mobile broadband Internet access provided by mobile telephone service providers hardly meets the demands for rural population in terms of throughput requirements per user. This is particularly because, the ISPs concentrate more on providing basic telephony services such as 2G technologies and forsake the broadband solution that rural areas can afford leaving them under-served. This situation means that only the urban populaces fully enjoy the benefits associated with the information revolution being enjoyed today.

In the view of the foregoing, the rural population needs a viable alternative to meet their broad access requirements. The IEEE-802.11 (Wi-Fi) family of wireless technologies has shown tremendous acceptance as well as growth since its inception. While it was designed for indoor use or for short-range access and primarily as a last-hop wireless access, its wide acceptance has motivated its use beyond its typical use. The range of indoor Wi-Fi spans up to a hundred meters from the access point. Because of its numerous advantages such as open standard and interoperability, it has enjoyed competitive mass production and thereby widespread acceptance. IEEE-802.11 (Wi-Fi) has been anticipated as being affordable and acceptable alternative to provide broadband access to rural areas[1]. It is capable of providing a ubiquitous and cost effective broadband access alternative, which if properly planned, may be a viable solution to the rural broadband requirements.

1.1. Proposed Design

The design proposed makes use of the unlicensed U-NII-3 frequencies to establish long distance point-to-point link. These links are then used to extend the Internet ‘hotspot’ from urban localities to the distant rural areas. Most of the rural areas are often a few kilometers to a few tens of kilometers (5-30km) from the urban areas. This means that, a broadband Internet access can be tapped from an urban area, distributed to the neighboring rural areas using few point-to-point links, and then distributed to the entire area using Wi-Fi technologies as depicted in Fig. 1 below.

In Fig. 1, the typical design scenario is represented by the following:

- Internet Backbone provided by ISP in an urban area
- ISP access point
- A high directional antenna to establish point-to-point link in urban area
- A high directional antenna to establish point-to-point link in a rural area
- An antenna mast in a rural or remote area from which the Internet is distributed as point to multi point broadband access
- A corporate building in a remote or rural area
- A house in a remote or rural area
- A business in a remote or rural area

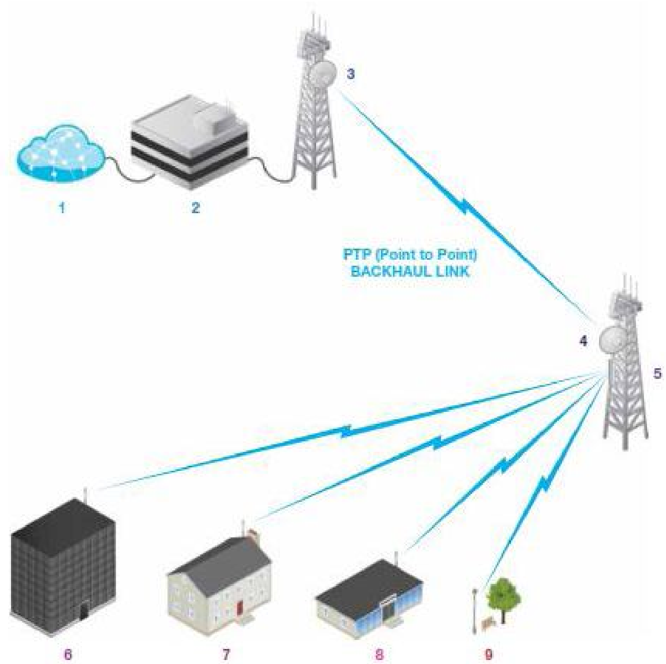

Fig. 1. Typical point-to-point and point-to-multi point Broadband access

- A small village mast with omni-directional antenna acting as a wireless hotspot

There is evidence of ongoing research on the feasibility of using Wi-Fi over long distance point to point links; the Ashwani, the Ak-shaya, Aravind Eye Care System (www.aravind.org) and Digital Gangetic Plains (DGP) projects all in India [1] [2]. Long-distance Wi-Fi based links are being used in the above-mentioned projects to realize long distance point-to-point network deployments ranging up to one hundred kilometers. Most of these studies and implementations of Wi-Fi based long distance point-to-point links are based on the ISM band centered at 2.4 GHz frequency. The standard in use is the IEEE 802.11b/g whose data link layer been modified from the CSMA/CA based MAC protocol to the TDMA based protocols. The performance of the 2.4GHz based long distance point-to-point links has extensively been studied, results documented and characterized [3] [4] [5]. Since the 802.11b based Wi-Fi has lower transmit speeds capped at 11Mbps, the maximum achievable throughput recorded by [3] was 7.63Mbps at the maximum transmit speeds of 11Mbps.

To the best of the authors' knowledge, no consistent and systematic study has been done in regard to the use of IEEE802.11a/n standards in establishing long distance point-to-point links nor their performance analyzed when used to provide broadband Internet access in rural areas. In this regard, the objectives of this research are two-fold:

- To investigate the feasibility of using the unlicensed 5GHz (U-NII-3) frequencies to establish long distance point-to-point links capable of providing broadband Internet access to rural areas
- To evaluate the performance of such links and show their performance characteristics under different channel widths, such that a predictive model is developed that may be used to enable the planning of such links in future with some degree of certainty and accuracy.

1.2. Related Work

Some research efforts have been advanced in this area. The earliest of works that attempted the use of Wi-Fi beyond its typical range was called Roofnet Project and was carried out by a group of Massachusetts Institute of Technology (MIT) students to form an unplanned wireless mesh network nodes that served a large area with broadband access [6]. The mesh network comprised of individual outdoor point-to-multipoint links that extended the Wi-Fi range to a few kilometers using omni-directional antennas [19]. Their objectives were limited to the use of omni-directional antennas and multiple hops mechanism to extend the range of the Wi-Fi links. They did not to utilize the capacity of single-hop point-to-point links that have the potential of reducing the routing challenges that accompanies multi-hop settings. This paper attempts to explore the feasibility of filling in this gap.

Reference [7] conducted further experiments on the performance of Wi-Fi based long distance links, still using IEEE802.11b/g standards and their observations were rather disappointing. The studied links exhibited very high and variable packet losses, resulting in very poor usability of the high throughput along the links. Further tests indicated that when higher transmit power (23dBm) and higher sensitivity Wi-Fi radios were used, longer links in the range of a hundred kilometers could be achieved. These two apparently contradictory results were analyzed to reveal that the cause of high packet losses was the insufficiency the existing carrier-sensing IEEE802.11 MAC protocol in long distance links [8] [3] [1].

Some further work in this field was advanced by TIER group in University of California Berkeley [5]. They used high-gain directional antennas to boost the link length. This allowed them to achieve link distance spanning up to a few tens of kilometers [7]. Flickenger et al [4] records to have achieved 6Mbps over a 382km link. Their findings were based on a TDMA enhanced MAC protocol modifications on IEEE802.11b/g standard that are necessary for a long distance links, as described by [8] [5]. Since the IEEE802.11g standard has highest data rates capped at 54Mbps, that explains why their highest observable throughput was relatively low. However, IEEE802.11n standard has since dominated the Wi-Fi markets. Tests on its capacity, when deployed over long distance outdoor Wi-Fi links, is worth investigating. It is expected that links based on 802.11n are likely to give better speeds particularly because of the superior features applied by the 802.11n standard such as MIMO technology. This justifies the attempts in using of the 5 GHz frequencies to establish long-range point-to-point links to provide broadband access to rural areas.

Since the introduction of TDMA based MAC protocol for long distance Wi-Fi links, increased interest was observed among many technology enthusiasts and manufacturers. Raman [1] describes two projects in India in which they have used IEEE 802.11 b/g (Wi-Fi) as a cost-effective technology to provide wireless access to rural areas i.e. Digital Gangetic Plains (DGP), and Ashwini. The DGP project was initiated in 2002 at the Indian Institute of Technology, Kanpur (IITK), Uttar Pradesh, to explore the technical feasibility of establishing long-distance 802.11g – based link. The Ashwani Project is a network deployment effort by the Byrraju Foundation, to provide broadband access and services to a collection of villages in the West Godavari district of Andhra Pradesh, India. The authors claim to have achieved 364 Kbps throughput capable of supporting an interactive video-based applications such as distance-education and telemedicine, on the network.

2. Methodology

2.1. Design Considerations

When setting up the Wi-Fi based long-distance links, several factors were addressed. These considerations include site selection, terrain and elevation profile, tower heights, choice of antenna, link budget, Fresnel zone clearance, antenna polarization, earth grounding and effects of earth's curvature among others. Each of these considerations was factored for a successful link establishment. The following six links were established as shown in the Fig. 2 below

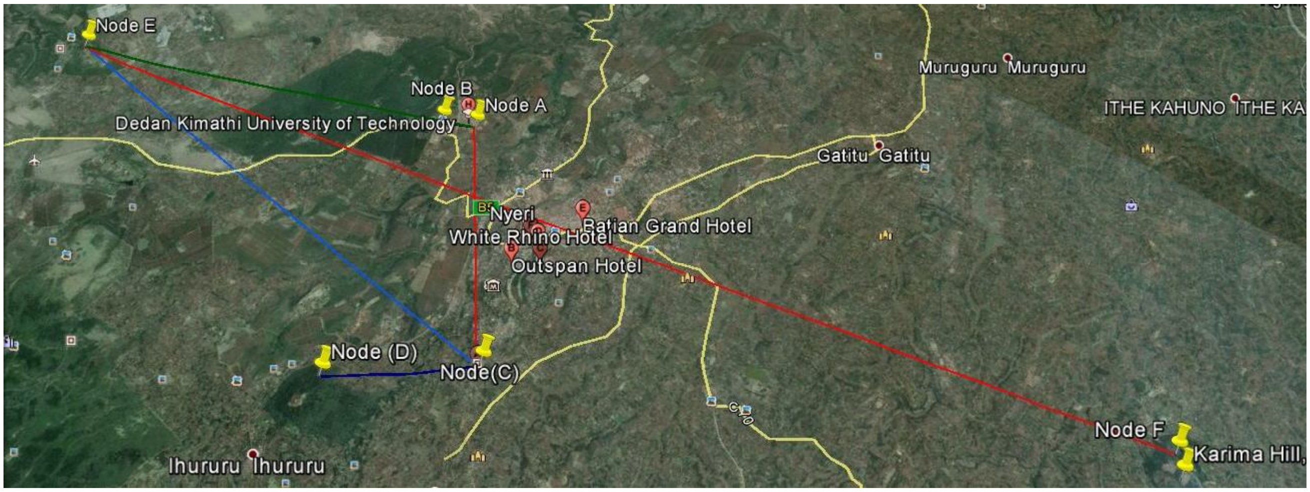

Fig. 2. Satellite view of six nodes used as test beds

2.2. Basic requirements

The basic Wi-Fi based long-distance link required two Wi-Fi radios fixed at the focal point of the parabolic dish antenna. Each pair was located at each of the two nodes, one connected to the wired backhaul broadband access and serving as the access point while the other on the remote site. Two teams each with laptops was stationed at the two nodes and an additional wireless router were used to extend wireless LAN to unlimited number of computers, at the remote site. A pair of binoculars was used to obtain a general view of either nodes and ensure that a line-of-site (LOS) was achieved.

A cellular phone for each team was necessary for communication purposes, particularly sharing of the setup link parameters and the link performance testing. Google Earth, a topographical software, was used to determine the best locations that were clear of topographical barriers, obstacles or rugged terrain for the LOS establishment.

Fig. 3 shows the elevation and terrain profile of a 24.3km link, the longest achieved distance, within these set of experiments.

Looking at the terrain of link 24.3km link, as shown in Fig. 3, node E has an altitude of 2008 meters above sea level (ASL) whereas node F is at 1942 m ASL altitude. The antennas at each node are hosted on a mast of seven meters ASL. Since the highest midpoint is at 1800m altitude, there is 215 meters difference between the midpoint and node E. Similarly, 149m height difference exists between highest midpoint obstacle and node F. To achieve 100% Fresnel zone clearance, the midpoint Fresnel radius of 17.73m, is required. An additional 8.68m is required to cater for the elevation due to earth's curvature. Assuming that the midpoint has potential obstruction of 15 meters, an approximate average height of a tree, the total antenna elevation, for the link E-F, must be greater than or equal to 41.41metres.

In comparison to the height difference of 149m between the lowest node, F, and this elevation requirement, then, for this link, a 100% Fresnel clearance is achieved. In this case, it is evident that a very clear line of site is established, way above the 60% fresnel zone clearance requirement.

2.3. Choice of Antenna

The deployment of long distance Wi-Fi based links demands use of high gain directional antenna whose characteristics and features have been pre-determined. Most microwave systems utilize parabolic dish antennas because of their high gain advantage. This antenna comprises of a driven element and a passive spherical reflector. The driven element, often called the antenna feed, may be a wire dipole antenna. The reflector size is dictated by the wavelength of the signal to be transmitted or received and is usually in the order of several wavelengths. The driven element must be positioned at the exact focal point of the parabola-shaped reflector. At this position, it receives the converged narrow beam of the electromagnetic waves that bounce off the reflector, which is thereafter fed to the Wi-Fi radio either through a coaxial line feed or the radio is connected at the focal point of the reflector. For this work, Ubiquiti Rocket-dish antenna and MIMO Airmax radio were used.

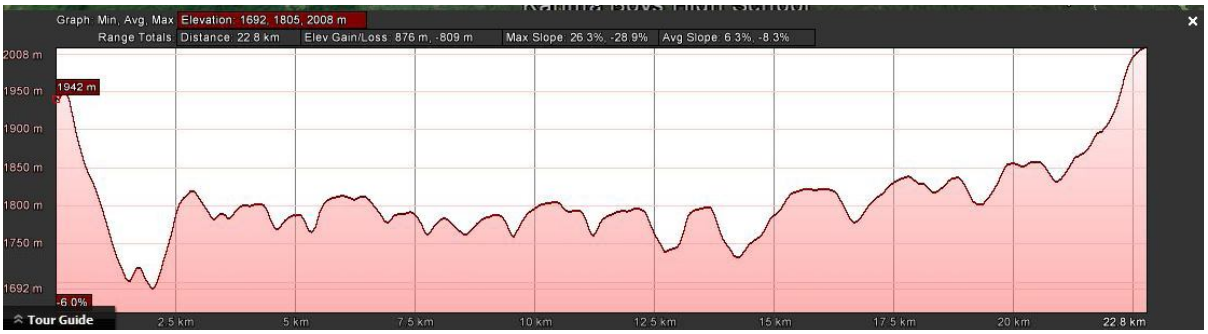

Fig. 3. Terrain profile of nodes E & F, a 24.3KM link, between Aberdare country club and Kiangwaci, Othaya, Nyeri, Kenya

2.4. Antenna height and Fresnel zone clearance

The line of sight path is divided into different regions, called Fresnel zones that accommodate varying velocities of the transmitted signal. Fresnel zone is an elliptical region surrounding the straight path (LOS) between the transmitting and receiving antennas and is caused by diffraction of the signal at a circular aperture [9] as illustrated in Fig below.

Radio waves travel in a straight line unless obstructed. When there are reflecting surfaces within an even Fresnel zone, the radio waves reflected from these surfaces arrive out of phase with the line of sight signal causing destructive interference and hence signal degradation. When the reflection off a surface is in an odd Fresnel zone, the interference is constructive leading to improved signal quality [10]. A clear first Fresnel zone allows the transmitted signal to travel with very little attenuation. It is free when the midpoint of the ellipse is free and clear of obstruction at least 0.6 of the radius. To achieve best results, the radius of the elliptical shape should be calculated in order to determine the height of the antenna towers.

Fresnel losses may be as high as 20dB if large objects and obstructions are present in the line of sight. However, if at least the first 0.6 Fresnel zone is free of such objects, then Fresnel losses of approximately 6dB can be avoided. Whereas attempts may be made to attain clear line of sight by electing antennas on very high towers, the degradation of microwave frequencies with height, due to ground reflections cancelling out the signal, becomes the drawback that must be contended. The rule of thumb with Fresnel considerations is to keep at least 60% of first Fresnel zone unobstructed to achieve acceptable signal strength and tolerable signal attenuation. A formula to be used in calculating the Fresnel zone radius clearance is shown in equation (0.1)

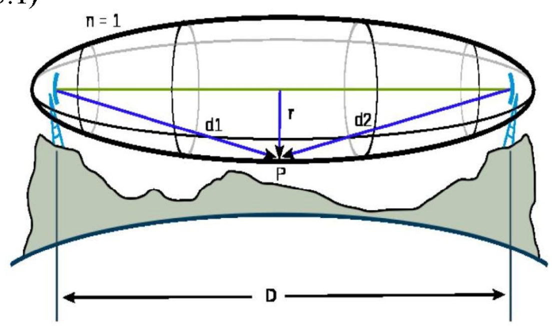

Fig. 4. Detailed illustration of Fresnel zone and associated dimensions [10]

$$h = 17.32\sqrt{\frac{d_1 d_2}{f(d_1 + d_2)}} \quad [11] \qquad (0.1)$$

Where h is the Fresnel radius at a point just above potential obstruction
f is the frequency of the Wi-Fi signal in GHz
d_1 is the distance (km) from transmitting antenna to point just above potential obstruction
d_2 is the distance (km) from receiving antenna to point just above potential obstruction

Considering the 5.3km, Shama Hostels to Resource centre, link and assuming the land is perfectly flat, then the antenna towers height would be calculated as follows:

Given the frequency of operation $f = 5.8$ GHz and the distances d_1 and d_2 are assumed to be equal and the highest potential obstacle is located at the midpoint ($d_1 = d_2 = 2.65\text{km}$), then the antenna tower heights would be given by

$$h = 17.32\sqrt{\frac{2.65 \times 2.65}{5.8(2.65+2.65)}} = 8.27 Meters \quad (0.2)$$

From these calculations, it is clear that a minimum antenna mast height on each side was 8 meters. However, the assumption is obviously inaccurate and the most likely scenario is that the antenna mast is located at an elevated point. This gives the advantage of reduced height requirements. For the work that was carried out, detachable antenna mast of seven to ten meters were used. As shown in Fig. 3 above, the terrain for all of the six[1] links resembled it or varied very insignificantly. This means that the 60% Fresnel zone clearance was met for all the links.

2.5. Link Budget Considerations

Link budget requirements demands proper calculation of the gain of the antennas used as well as the sensitivity of the Wi-Fi radios to achieve required signal strengths. The overall goal is to ensure that the signal strength at the transmitter meets the threshold required by the sensitivity of the receiver.

To meet this goal a terrain based propagation model is employed. Considering the frequency of operation and the range of link distances, the Hata-Okumura model is a good fit. This propagation model is empirically formulated to predict median path loss when the frequency of use is in the range of 150 to 1500MHz. Although UNII-3 frequencies do not lie within this range, this model may serve as a good estimator of the minimum required antenna gains and the respective sensitivities of the receivers.

The Hata-Okumura model may be used to approximate median path loss for open areas. Most of the links used in this research are best categorized as lying in open areas. The Hata formulation utilizes the Okumura model as defined in equation (0.3) below.

$$L_{50}(dB) = L_{50}(\text{urban}) - 2\left(\log\left(\frac{f_c}{28}\right)\right)^2 - 5.4 \quad (0.3)$$

Where L_{50} (dB) is the median path loss, L_{50} (urban) is the median path loss if the link is in an urban area defined by equation, and f_c is the frequency of operation.

$$L_{50}(\text{urban}) = 69.55 + 26.16\log(f_c) - 13.82\log(h_t) - a(h_r) + [44.9 - 6.55\log(h_t)]\log(d) \quad (0.4)$$

Where a (h_r) is the receiving antenna correction factor defined in equation(0.5), h_t is the height of the transmit antenna and d is the separation distance in km [12, p. 148].

$$a(h_r) = (1.1\log(f_c) - 0.7)h_r - (1.56\log(f_c) - 0.8), \quad for\ 1 \le h_r \le 10m\ for\ a\ small\ city \quad (0.5)$$

For the 24.3km link, h_r=h_t=7m, f_c=5800MHz, the median path loss is computed from equations(0.3), (0.4) and (0.5) as shown below

$$a(h_r) = (1.1\log(5800) - 0.7)7 - (1.56\log(5800) - 0.8) = 19.01\text{dB} \quad for\ h_r = 7m \quad (0.6)$$

$$L_{50}(\text{urban}) = 69.55 + 26.16\log(5800_c) - 13.82\log(7) - 19.01 + [44.9 - 6.55\log(7)]\log(24.3) = 191.86dB \quad (0.7)$$

$$L_{50}(dB) = 191.86 - 2\left(\log\left(\frac{5800}{28}\right)\right)^2 - 5.4 = 175.73dB \quad (0.8)$$

The equations above, (0.6) (0.7)and(0.8), show that the resulting median path loss is 175.73dBm.

To determine the link budget, the maximum transmit power is set at $P_t = 24\text{dBm}\ (125\text{mW})$ and receive sensitivity at -79dBm. If the cable and connector losses are approximated to be negligible, then the effective transmit power, P_{eff} can be expressed as

$$P_{eff} = P_t - TFL + G_t = 24dBm - 0 + 30dBi = 54dBm \quad (0.9)$$

Where TFL is the transmitter feeder loss and is assumed to be negligible and G_t is the transmit antenna gain.

The effective receiver sensibility S_{eff} is given by

[1]Deployment of one point-to-point link entails a lot of work, and in the definition of the scope of this research, six links were defined as the maximum number of links that would be adequate to serve as proof of concept.

$$S_{eff} = G_r - RFL - S$$
$$= 30dBi - 0dB - -79dBm = 109dBm \quad (0.10)$$

Finally the link budget shows that link margin of -12.73dBm is required as calculated in equation (0.11)

$$P_r = P_{eff} + S_{eff} - pl$$
$$= 54dBm + 109dBm - 175.73dB \quad (0.11)$$
$$= -12.73dBm$$

Although the link budget demands a minimum power margin of 0dB, it is possible to approximate the achieved power margin is close to meeting this requirement.

2.6. Antenna Alignment

While the antenna alignment is an enormous research task by itself [13], way beyond the scope of this research, a simplified approach of antenna alignment was used. Since the link distances were relatively short, the antenna alignment was mainly performed to achieve azimuth plane alignment first and then a little tilting of the antenna masts to achieve elevation plane alignment.

The Ubiquiti antennas have an inbuilt software based frequency spectrum analyzer that was used to perform antenna alignment. It produces different beep sounds depending on the signal strength received. When for instance the antennas are completely out of alignment, the received signal strength was less than -96dBm. As the antenna masts are rotated in the azimuth plane and tilted in elevation plane, the received signal strength rises to the best achievable. For most of the links, the best alignment produced signal strength in the range of -20dBm to -68dBm depending on the link length.

Fig. 2 shows the interface of the software based spectrum analyzer used in the antenna alignment.

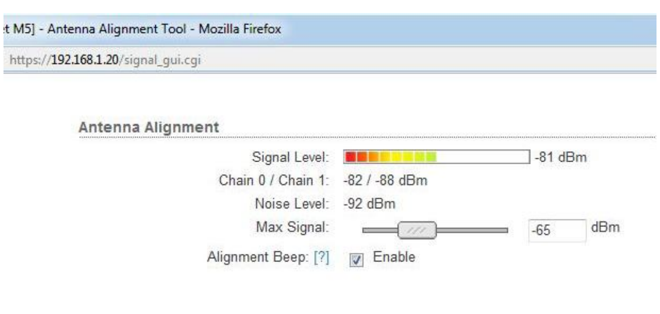

Fig. 4. Software based Spectrum analyzer

2.7. Data Collection

The general objective of this research was to simply validate the usability of the U-NII-3 Wi-Fi frequencies in establishing long distance point-to-point links. Initially, at least six links were to be tested for consistency and proof of variability of the achievable throughput and any possible packet losses or un-anticipated causes of any link performance degradation. Each link was to meet the above mentioned design factors and considerations; each link must have clear line of site, with at least 60% Fresnel clearance, the gains of the antennas must meet the minimum threshold as defined in the link budget calculations.

Another design consideration was the source of power for each node. The sources of power options available were either to utilize the mains electricity and for the remote stations, a 12V lead acid battery with an inverter. Each node had a parabolic dish antenna and a Wi-Fi radio. For this work, an off-the-shelf commercial antenna, Ubiquiti Rocket Dish 30dBi antenna was used. This antenna comes with a Wi-Fi radio whose MAC protocol has been modified from the usual CSMA/CA based protocol to a proprietary TDMA based protocol called, Airmax.

Data collection was done for the six links mentioned, all independently of each other. Two independent factors and their effect on the achievable throughput were investigated. These are the channel width and link distance. The objective was to determine how and to what extent each of these affects achievable throughput and their correlation. The research question meant to find out whether the achievable throughput is dependent on the link and whether there is any significant correlation between the link distances and the channel width. Further, whether the effect of channel width is the same for all the link distance or whether there are link lengths when its effect is more or less pronounced was explored.

For each link, a file of 1.17GB was transferred across the link from the access point node to the station node. This was repeated for different parameter values, that is, when channel width was at 40MHz, 20MHz, 10MHz and 5MHz. the observed values of the achievable throughput for each channel width were recorded and tabulated. This was repeated for the six links.

3. Results and Discussions

3.1. Effect of Channel Width on Achievable Throughput

To start with, the first test was to evaluate how channel width affects the achievable throughput. Several tests were conducted initially to determine which parameter, among channel width, packet size, transmit rate and transmit power, had the largest impact on the achievable throughput. It was observed that all of them had some threshold value beyond which the link performance very high degradation but channel width played a very pivotal role.

The effect of channel width was investigated first. For each of the five links, the antenna and radio settings were initially kept at default configurations. The default configuration is a general setting that the off-the-shelf Wi-Fi devices are preset. In this configuration, the Ubiquiti Rocket Dish and radio comes with default channel width as 20MHz, transmit power at maximum (27dBm), packet size at 1500bytes and transmit rate at maximum of MCS 15, which is equivalent to 300Mbps. The object of this section is to compare the performance of the different link lengths when deliberate changes to the default channel width are made to higher (40MHz) or lower values (10MHz & 5MHz).

When the tests were conducted, the widest channel width (40MHz) gave the best and very consistent results. An average achievable throughput values in the range of 96Mbps to 106Mbps were recorded for each of the five links when the channel width was set at 40MHz. this is in contrast to the default 20MHz channel width that comes preconfigured. As indicated in the Fig. 5 the four different channel widths have very distinct performance characteristics.

While the three lower channel widths have a trend that predictably decays with link distance, it is apparent that the 40MHz channel width is unaffected by link distance. On the contrary, its average throughput is relatively capped at 100Mbps mark and does not rise or fall above this value no matter the link distance. A very likely explanation for this is that, although the link capacity exceeds the 100Mbps mark, the Fast Ethernet Standard, where the Ethernet cables interconnecting radios, antennas and the laptops at each node are defined, has speeds of 100Mbps, which in fact becomes the limit of the link.

It is worth noting that channel width has very significant effect on the attainable throughput for any link distance. As observed, there is a negative correlation between achievable throughput and link distance. Short link distances exhibit different peak throughputs at different channel width. It is further noted that for short distance links in the range of 1-25Km, 40MHz channel width exhibits best performance with peak throughput at 100Mbps range. An increase in link distance results in a very consistent decrease in the achievable throughput. An attempt is made to model the interrelationship between achievable throughput and link distance for different channel width using power regression models as shown in equations (0.12) - (0.15).

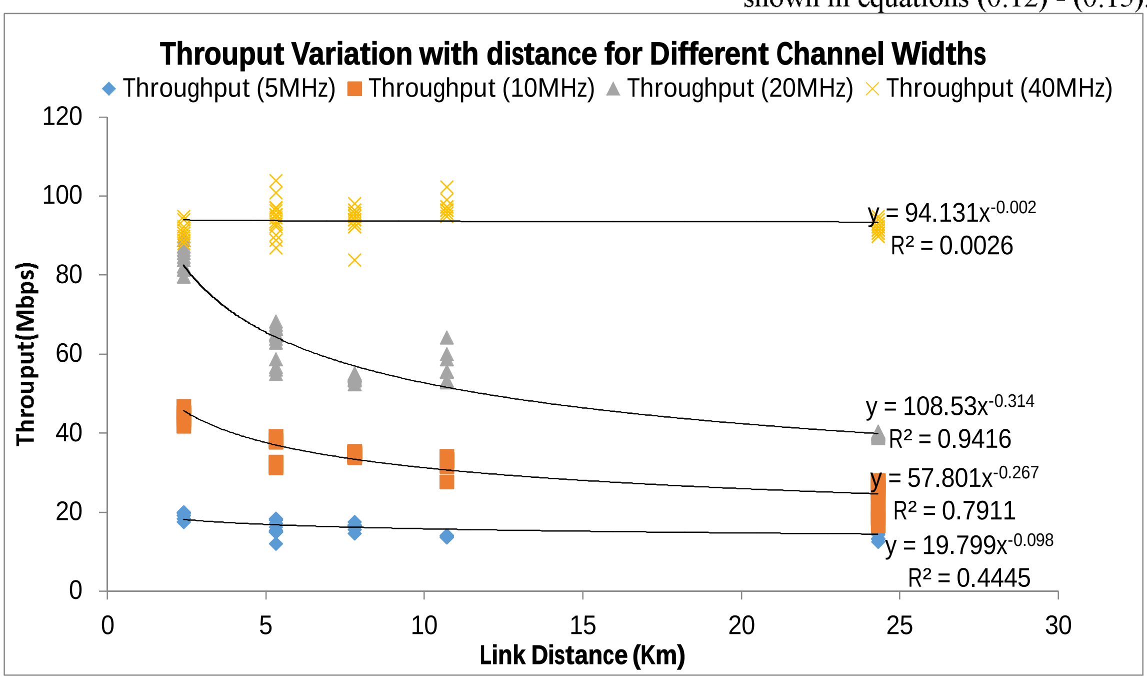

Fig. 5. Throughput Variation with distance for Different Channel Widths

A comparison on the four model equations with their associated R-Squared values shows that the three lower channel widths (5MHz, 10MHz and 20MHz) have a very consistent trend; a negative correlation of throughput vis-à-vis distance exists. It is further evident, from the coefficient of determination, R^2, that the three lower channel widths have considerably high goodness of fits to equations (0.13),(0.14) and (0.15) with 94%, 79% and 44% throughput variation being explained by each equation respectively. However, the 40MHz channel width shows inconsistency with the proposed power regression model since only 0.2% of the variation may be explained by equation(0.12) as indicated by the coefficient of determination.

$$y = 94.13x^{-0.00} \quad R^2 = 0.002 \tag{0.12}$$

$$y = 108.5x^{-0.31} \quad R^2 = 0.941 \tag{0.13}$$

$$y = 57.80x^{-0.26} \quad R^2 = 0.791 \tag{0.14}$$

$$y = 19.79x^{-0.09} \quad R^2 = 0.444 \tag{0.15}$$

In line with the first objective, there is clear significance effect of channel width and link distance on the achievable throughput. Wider channel are seen to give superior performance to short distance links when compared to narrower channels. As the link distances increase, the achievable throughput decays as a power series whose base is the link distance. The wider channels have larger exponent of decay which simply indicates that as link distance increase, the narrower channels are preferable. The effect due to channel width is more pronounced than that of link distance. Justifiably, it is now possible to predict the performance of the Wi-Fi based long distance point to point links form the graph shown in Fig. 5 and equations (0.12) - (0.15).

4. Conclusions

It was observed that as long as the basic requirements for setting up Wi-Fi based long distance point to point links were met, and then link establishment was straightforward. These basic requirements were clear line of sight with at least 60% first Fresnel zone clearance, the link budget requirements of antenna gain and Wi-Fi radio sensitivity Simplified antenna alignment is achievable with minor vertical tilting and horizontal rotation of the antenna masts. This was possible with the use of software-based frequency spectrum analyzer that comes integrated with the Ubiquiti Wi-Fi radios.

This paper has demonstrated a simplified model of a test-bed that may be used to provide broadband internet in rural areas. The observed peak throughput values of 90Mbps and above can meet the demands of an entire village of one thousand simultaneous users assuming 256kbps bandwidth may be utilized by 2-5 users at any given time. This is true since most users in the village will use the bandwidth to primarily access web pages, access emails, visit and share in social sites and rarely download one or two files in a day. This justifies the bandwidth requirement of 100kbps per an average user in a rural area of a developing country.

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