An Investigation of Vegetation Effect on the Performance of IEEE 802.11n Technology at 5.18 GHz

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Abstract

In this paper, the performance of IEEE 802.11n Wi-Fi technology at 5.18 GHz frequency in one of the rural areas in Malaysia, which is typically covered by dense tropical foliage, is evaluated and analyzed. To our best knowledge, studies on the performance of the IEEE 802.11n technology in foliage area have not been fully explored. We have conducted line-of-sight and non-line-of-sight measurements through the tropical foliage using directional high gain antennas to determine the throughput and other well-known performance metrics. It is observed that by utilizing the key features of 802.11n such as channel bonding and short guard interval, superior performance results can be achieved for both aforementioned situations. Precise correlation of utilized hardware specification and acquired results in different points is another aspect of this work. The findings are useful for future rural wireless deployment particularly with low height antenna using IEEE 802.11n technology.

1 Introduction

Nowadays, deployment of Internet and multimedia services in rural areas is one of the main concerns of communication service providers. Rural populations are deprived from information access due to lack of proper communication infrastructures in such areas. In recent years, Wi-Fi based networks have become a popular option as a reliable solution for Internet access in rural areas. Examples of such deployments include Digital Gangetic Plains (DGP) in India [1], CRCNet in New Zealand [2] and Djursland in Denmark [3]. The popularity arises mainly due to the low cost Wi-Fi based equipment and its operation in the unlicensed spectrum. Furthermore, the IEEE 802.11 standard offers the possibility of reaching relatively high broadband speed in its latest evolutions. The latest IEEE 802.11n amendment which is already available in the market offers physical data rate up to 600 Mbps using 40 MHz bandwidth. The IEEE 802.11n based products have incorporated various medium access control (MAC) and physical (PHY) layer enhancements to support higher data rates and better coverage while ensuring backward compatibility with previous 802.11 variants such as IEEE 802.11a, b and g. To significantly increase the physical rate in IEEE 802.11n, Multiple Input Multiple Output (MIMO) technology and increased channel bandwidth size from 20 MHz to 40 MHz are employed.

In addition, the reduction of the guard interval, PDU and SDU frame aggregation and block acknowledgement in the MAC layer procures further improvements in this aspect [4]. Over recent years, investigation on the performance of the newly released IEEE 802.11n has attracted a lot of interest. Independent field measurement results that have been presented are essential and useful for understanding the performance of the 802.11n wireless devices in realistic environment. However, the studies of the performance of IEEE 802.11n in rain forest foliage environment have not been fully investigated.

The main contribution of this paper is a field study on IEEE 802.11n links at 5.18 GHz as well as the investigation of link length effect through the foliage areas using well known performance metrics. The findings can be used as a general reference for the deployment of IEEE 802.11n networks in rural areas which mainly consists of foliage coverage. The remainder of this paper proceeds as follows. In the next section, related works about the evaluation of IEEE 802.11n and the investigation of Wi-Fi characteristics through the foliage districts are discussed. Then in section 3 the measurement setup procedure is delineated in detail and in the succeeding section all collected values are analyzed and correlated to the test bed setup. Finally, concluding statements and future plans are presented in section 5.

2 Related Works

So far, a number of research works have been conducted on the investigation of IEEE 802.11n technology in indoor and open environments. Also, a lot of papers have been published about features and capabilities of this standard in comparison with the former IEEE 802.11 technologies. For instance, [5] has investigated new aspects of IEEE 802.11n through running a test-bed experiment and also it has revealed a drastic effect of IEEE 802.11g links which lead to the throughput degradation of IEEE 802.11n networks. Another empirical study was performed in [6] on UDP/TCP
performance of IEEE802.11n in comparison with IEEE 802.11g. The result has given insights on the achievable UDP/TCP throughput values for both IEEE 802.11g/n standards. Similar study was conducted in Bradford University on the throughput analysis of IEEE 802.11n MIMO dual band system in indoor areas [7]. Another work in [8] focuses on practical link performance evaluation for IEEE 802.11a/b/g/n standards in outdoor environment. Various configurations of physical and MAC layers’ settings and their impact on link throughput have been presented. The paper also reported that high throughput communication can be attained using IEEE 802.11n in long distance line-of-sight links. Although a wide range of research works on different aspects of this standard has been undertaken, the effects of vegetation and foliage on 802.11n technology remain an open research question.

One of the main concerns of wireless network implementation in foliage sites is the determination of maximum distance for which the wireless equipment is going to operate without any disruption. There is no definite answer for this question, but many papers have been published on the prediction of the wave propagation loss in open environments. For instance, ITU-R 883.6 [9] has reported that the key factors of radio attenuation in vegetation areas are plant species, densities and its water content. Also a simple analytical model was elaborated in [10] to explain the foliage effects on the propagation loss in wireless communication systems. According to the authors, the amount of attenuation in a tree canopy is determined by different variables such as frequency, polarization, biophysical factors of trees and the statistical distribution of branches.

The special attention that was placed on the study of the path loss modelling facilitates the deployment of wireless systems for different applications in foliage environment. In [11] a research was done on radio wave propagation to setup a wireless sensor network in a potato field. It was shown that in a flowering potato field, the magnitude of signal strength among wireless sensors for certain distances has been degraded dramatically in comparison with non-flourished field. Also, this phenomenon causes reduction in radio coverage area to less than 50% of non-flowering state. Similar research activities have been directed to path loss prediction in forest areas at different frequency bands. For example, a study of the propagation loss at VHF and UHF frequency bands has been performed in forest environment to analyze foliage and ground effects by Meng et al. [12]. Also, a comprehensive comparison of various well known empirical path loss models in foliage areas has been presented in [13]. Other similar researches have been conducted in [14, 15] to explore path loss at regular wireless frequency bands consist of 2.4, 3.6 and 5.8 GHz in open rural areas. A huge number of RSSI patterns were collected at a deciduous oak tree forest to produce an approximation for the best range coverage and minimum network equipment to cover a specific region of a foliage environment. Moreover, as mentioned earlier, there are different kinds of deployment projects for wireless communication in rural areas of different countries. For instance, in [16] two projects that used 802.11 technologies as a cost effective and reliable solution to provide Internet connectivity for rural areas in India have been explained. Some practical examples for building wireless mesh networks in forest areas are provided in [17]. The impacts of various parameters such as antenna directivity and gain, transmission power and vegetation effects on network performance are also reported in the paper.

In this paper, a preliminary investigation on 802.11n characteristics in a foliage environment is conducted. The results provide the fundamental understanding for the design and implementation of various IEEE 802.11n applications in villages and rural areas.

### 3 Experimental Setup

#### 3.1 Hardware and Software Setup

We conducted our experiment in a rural area covered with tropical trees near Jelebu, Negeri Sembilan, Malaysia [18]. System characteristics and well known metrics for IEEE 802.11n technology in 5.18 GHz frequency band were investigated in multiple points with regard to line-of-sight and vegetation effect. Different metrics such as throughput, jitter, packet loss ratio, Received Signal Strength Indication (RSSI) and bit rate were measured in various locations. The setup and measurement procedure of each experiment steps and key characteristics of equipment used are mentioned in the following section. Before embarking on the measurement procedures, to increase the reliability of obtained results in the chosen location, the area was probed to ensure about the lack of any kind of interference in the selected frequency.

The experiment was conducted in the fixed points as shown in Fig. 1. The point A was considered as the base point in which one access point was configured and the aforementioned metrics were measured in the other points as the wireless client nodes with different link distances. Fig. 2 demonstrates the setup for one wireless end point in line-of-sight condition. As shown, high gain directional antennas were utilized to establish reliable wireless links. To reach high throughput by means of 802.11n standard, 2x2 MIMO high gain antenna was used at the two ends of each link. It provides Spatial Division Multiplexing (SDM) to transfer independent data streams simultaneously to increase data rate between two nodes. The gain of the dual polarization antenna was 19 dBi.

The antenna placement is one of the main concerns of the experiment. The minimum roof height of most rural houses in the area in which the experiment was conducted is around 3 m above the ground. Thus, we considered this height as a fixed parameter during the whole measurement. As shown in Fig. 2 the antenna was assembled at height of 3 m on the top of a tripod. The acceptable Fresnel clearance level [19] for 5.18 GHz frequency in the line-of-sight measurement (A to B) is 74 cm whereas the antenna height in our experiments is much higher than this value.
The PC Engines Alix system board [20] was selected as the embedded system to provide adequate hardware resources during the experiment. The selected board is compatible with wireless adapter cards which support latest ath5k and ath9k drivers for Atheros chipsets [21]. Fig. 3 exhibits our hardware setup and its antenna radiation patterns given by the technical datasheets. In our setup, we used the Compex wireless adapter card come with Atheros AR9220 chipset in 5 GHz unlicensed band for IEEE 802.11a/n technologies [22]. The Power over Ethernet (PoE) support of the Alix board not only allows the device to draw power, but also to control the board firmware through the Ethernet link. It should be noted that the necessary power supply was provided through the external battery modules for each wireless node during the experiment. Besides hardware setup, another major decision is concerning the selection of a reliable and efficient firmware. We chose OpenWrt [23] as it is one of the highly extensible Open source software and Linux distributions for embedded systems, especially for wireless applications. This firmware is supported by the wide availability of the organized documentations, user communities, different packages and compatibility with wide range of hardware products. The firmware was flashed inside 8GB storage which is connected to the board through a compact flash socket. All the required packages and scripts to run the measurement procedure and also acquired results have been placed within the mentioned compact flash. Table 1 summarizes the device and firmware configurations for both end point nodes. The same configuration was maintained in all the experiments in all selected points.

### 3.2 Measurement Procedure

Prior to the configuration of the wireless nodes, the installation of kmod-ath9k package to provide the essential Atheros drivers in OpenWrt for the configuration of Compex wireless adapter is an imperative task. After the installation of the required packages, an Access Point (AP) was constructed based on the guidelines in Table 1 to operate in master mode at point A. During the experiment, wireless client node was located at points B, C and D. At each point, wireless client established a wireless connection to the AP and acquired an IP address through the configured DHCP server in the master node. Fundamental information about the initiated connection between the client and AP is accessible by means of iwconfig and iw commands in OpenWrt. The experiment procedure for each point was conducted in 2 steps: the measurement of the selected performance metrics and wireless link characteristics. For the first part, iperf 2.0.5 [24] package was
utilized in AP and client sides to quantify UDP throughput, packet loss ratio and jitter values for established wireless link. It is important to note that during the experiment, sufficient system resources consist of CPU and I/O buffer should be available for `iperf` to present precise and reasonable results. To address this limitation, we directed each step of the measurement process separately. Also, Alinx3d3 embedded system as an appropriate board with plenty of hardware resources was selected to conduct the experiment. For the generation of a UDP flow between the client and AP, `iperf` was executed in AP to operate in server mode. The UDP buffer size in AP was set to the default value of 110 Kbytes and the length of UDP datagram packet was 1470 bytes. Also, `iperf` running interval was selected long enough (120 seconds) to ensure the accuracy of acquired results in the client side. During each `iperf` session, client creates huge amount of UDP traffic to the `iperf` server (AP) to quantify the maximum achievable link throughput and other performance metrics.

With regards to the largest possible throughput value for 2x2 MIMO implementation of 802.11n technology [8], 200 Mbps UDP traffic was transmitted from client to AP for 2 minutes. In the second part of the measurement, we gathered 1000 signal samples at each point. To facilitate the data gathering procedure, a small script has been written to capture required data through `iw` command in the client side. At a sampling rate of 22 samples per second, the samples were collected and stored in the wireless client node. Determination of data rate upper limit for 2x2 MIMO 802.11n and received signal strength (RSSI) in the foliage area were the main concerns in the second part of each experiment. Each sample contains information about the established wireless link which the signal strength (RSSI) and data rate (bit rate) are the most important values for our experiment. As an instance, the content of a captured sample is shown in Fig. 4. The represented sample is the output of `iw wlan0 link` command in the client side that shows 300 Mbps bit rate as the maximum physical data rate for 2x2 MIMO 802.11n. Although, in the first step of each experiment we attempted to prevent all processes, except `iperf` from using the system resources, it should be noted that during the sampling procedure, the `iperf` process was running in both end points. This action was taken to attain the highest data rate for the initiated wireless link through occupying the established connection by UDP traffic. In the next sections, the measurement results for the wireless clients at 3 selected points (B, C and D) with the AP at point A are investigated.

4 Results and Analysis

One of the crucial criteria for the determination of a wireless link quality in different environments is the received signal level which usually is known as RSSI. Different manufacturers of wireless adapters define specific amount of signal strength for attainable data rate in each wireless technology. This parameter defines the receiver sensitivity as the weakest signal that can be heard reliably in the receiver side of a communication channel. Generally, it is regarded as the function of network speed and data rate for wireless links. To provide a rational explanation about the achieved data rates in different points of experiments, we should refer to the technical specification of the wireless adapter and the receiver sensitivity values for its operation in our experiment [22]. Fig. 5 represents the data rate peaks versus different Modulation and Coding Scheme (MCS) indexes, according to the latest proposed MCS index for IEEE 802.11n in 2009. Each MCS index stands for a specific number of spatial streams, modulation type, coding rate and physical data rate. Also, it should be noted that in default mac80211 which is utilized in ath5/9k drivers, minstrel rate control algorithm is used that supports multiple rate retries and is one of the best rate control algorithms [25]. In Fig. 6 the obtained RSSI and bit rate for 1000 captured samples at point B are shown. The left axis represents the captured RSSI values and the right one demonstrates the maximum attained bit rate versus samples numbers in this point. As shown in the figure, the received signal strength values at point B, in most cases are between -25 and -10 dBm. Regarding the technical specifications which are mentioned in the wireless adapter datasheet, we should be able to achieve the maximum physical bit rate for 2x2 MIMO 802.11n. Fig. 6 confirms that the physical rate for line-of-sight link at point B is 300 Mbps almost for the whole experiment. To reach the maximum data rate for 40 MHz channel, the Short Guard Interval (SGI) of 400 ns was applied through the measurement. Activation of SGI parameter in wireless nodes has a tangible impact in improving of the data rate up to 10% [4]. The attained 300 Mbps data rate in Fig. 6 is due to enabling this parameter in the driver for Atheros 9k chipset. As mentioned in section 3, open source `ath9k` driver has been used in OpenWrt firmware to manage wireless adapter cards. Note that so far, this function is only applicable for 40 MHz channel and it is not plausible to use this feature on 20 MHz channel according to [25]. In other words the largest possible physical data rate for 20 MHz channel in `ath9k` driver with 2 spatial streams is 130 Mbps which is 10% smaller than the 144.4 Mbps for the case of enabling SGI in 20 MHz channel. To investigate this as a special case, we have measured the bit rate for 20 MHz channel in point B with regards to other experiment assumptions. For more than 99% of the captured samples in point B, the bitrates were 130 Mbps which are consistent with forecasted physical data rate. At point C, as the second location of our measurement which is 108 m away from the configured AP, there is significant difference in the acquired results. Fig. 7 demonstrates the obtained RSSI and bit rate quantities at this point. As shown, the RSSI values decrease to less than -70 dBm and the bit rate fluctuates significantly, and on average the physical data rate is found to be around 60 Mbps. The degradation of RSSI and receiver sensitivity at point C has a dramatic effect on the bit rate in comparison to the line-of sight-situation at point B. Also as demonstrated in Fig. 8, similar incident with more drastic reduction in received signal strength has been observed at point D which is 174 m away from point A.
Table 2 shows the receiver sensitivity and their respective data rates in 802.11n 40 MHz channels (HT 40) for the wireless adapter in our experiment [22]. According to Table 2, at point D, the maximum achievable bit rate is equal to MCS index 1. When referring to Fig. 5, the attainable peak physical data rate at this point is only 30 Mbps. Note that the maximum bit rate at point D is in accordance to the specified MCS indexes in Table 2. Together with the iperf outputs, the results of our measurements at different locations can be summarized in Table 3. Due to the existence of various required overheads by 802.11 MAC protocol, the actual throughput in most cases is less than half of physical data rate [26]. As shown in Table 3, at point B, due to the high RSSI value, the average throughput value is 147 Mbps. The consistency of the acquired value and mentioned fact confirms the rightness of the attained throughput at this point.

The other performance metric at this point which has been measured through iperf is packet loss. Packet loss value at point B for 802.11n is higher than packet loss for other Wi-Fi technologies such as 802.11g. One reason for this is the high receiver sensitivity requirement of SDM at high rates, even in the absence of interference. The lack of rich multipath may result in huge packet loss ratio even at high RSSI values for MIMO 802.11n [27]. Also, the low value of jitter indicates that the established connection was stable during the measurement at point B. For the other points, the acquired throughput such as data rate has been declined dramatically. At point C, it was decreased more than 100 Mbps and for point D its degradation was more than 96% of the throughput value at point B. The outcomes demonstrate the destructive impact of foliage on UDP throughput even in short distances (less than 200 m) at mentioned points. Absorption of radio waves through tropical trees and vegetation is the main cause for reduction of received signal level and consequently physical data rate at selected points. The other point is the reduction of packet loss ratio in points C and D in comparison to line-of-sight situation. This event derived from multipath advantage gained by MIMO technology for 802.11n in non-line-of-sight situations [27]. In contrast with packet loss, jitter values for C and D have increased. This implies that the wireless link stability between AP and the selected points is lessened.

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Sensitivity (2 chains)</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 M</td>
<td>-89 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>36 M</td>
<td>-86 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>48 M</td>
<td>-82 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>54 M</td>
<td>-79 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS0</td>
<td>-92 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS1</td>
<td>-90 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS2</td>
<td>-87 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS3</td>
<td>-84 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS4</td>
<td>-81 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS5</td>
<td>-77 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS6</td>
<td>-76 dBm</td>
<td>± 2 dB</td>
</tr>
<tr>
<td>MCS7</td>
<td>-74 dBm</td>
<td>± 2 dB</td>
</tr>
</tbody>
</table>

**Table 2:** Receiver sensitivity values for the wireless adapter
5 Conclusion and Future Works

In this paper, we have analyzed the performance of IEEE 802.11n standard in foliage environments. Devastating impact of vegetation on the throughput of Wi-Fi based networks, even in short ranges (less than 200 m) is one of the main concerns in the deployment of such networks in rural areas. Our work provides preliminary information for future research works regarding the deployment of IEEE 802.11n technology in the foliage districts. Investigation of IEEE 802.11n characteristics with regard to vegetation effect can be considered as an initial step to procure a proper network infrastructure to develop different IT applications in village areas. We are currently planning for implementation of wireless mesh back-haul networks in rural areas by using IEEE 802.11n standard.

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