The Performance of IEEE 802.11b in an Outside Environment

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Abstract

In this paper we discuss the observed performance of the wireless data communication IEEE 802.11b protocol in an outside environment with no obstacles. We compare the general results to a specific experiment in which the signal was directed through a window. There was a significantly lower performance observed in the experiment with the window. We conclude that obstacles, including the ground, the window, and the building, are significant inhibitors in the performance of 802.11b signals.

Five different combinations of heights were experimented with to test the performance over increasing distance. The heights were achieved by utilizing both a six and a ten-foot ladder. The Fresnel zone phenomenon, a radius that can be calculated to avoid interference, was observed through the performance of these combinations. Finally, we conclude that the performance of wireless data communications contains variability and unexpected results even when in an open environment with no ground interference.

Introduction

During the fall of 2003, experiments were conducted to observe the performance of the wireless data communication protocol IEEE 802.11b in an open environment. These experiments involved different combinations of heights for the access point (AP) and the receiver or client. The AP is the sender or the transmitter of the wireless signal. The client is the receiver or the laptop with a wireless network card. The effect of the ground was observed through these different height combinations. The effect of increasing distance was also observed for all experiments. The outside experiment was then compared to another with a window obstacle to determine the effect of obstacles.

In this paper we are discussing the experiments that focused on an outside environment. These experiments were done using commercially available equipment. Experiment one consisted of outside tests with a straight line of sight involving no obstacles and recording the results every five yards. This experiment set involved the different height combinations. Another experiment was also conducted in the same area, but with static heights of both the AP and receiver. The access point was inside, pointing out a window on the second floor of the science building. This was then compared to experiment one as a whole. The results of both show variability and some unexpected results, similar to experiments conducted by colleagues in the spring of 2003 [4].

It is helpful to first explain the Fresnel zone and other possible inhibitors to the wireless signal. The Fresnel zone designates the radius of space needed to avoid obstacle interference to the signal. This radius, existing in the signal path between the AP and the client, can be calculated. In experiment one, Fresnel zone calculation was important to compare ground interference in order to avoid the ground interference. The results of the experiments will be discussed after the explanations.

Signal Interfering Factors

The Fresnel Zone

The 802.11b protocol runs on the 2.4 GHz frequency where obstacles are a definite inhibitor. One way of determining the effect of these obstacles, specifically the ground, is by the Fresnel zone. The Fresnel zone is a calculated radius in which a wireless signal can be affected by an object. The first Fresnel zone is the radius in which an obstacle has the highest negative effect on the signal. Obstacles must only be in 55% of the first Fresnel zone radius to cause a negative affect to the signal performance [5]. Many different items can be inhibitors, if within the first zone. One main obstacle is the ground. The ground soaks up the signal and causes definite performance loss. This is observed from the results of our experiments. Other obstacles include trees, buildings, towers, etc.

The picture below displays the theory of the Fresnel zone. The trees represent a possible obstruction to the wireless signal. r stands for the calculated radius of the first Fresnel zone in feet, d is the distance between the access point and the receiver (also in feet), and f is the frequency of the signal.

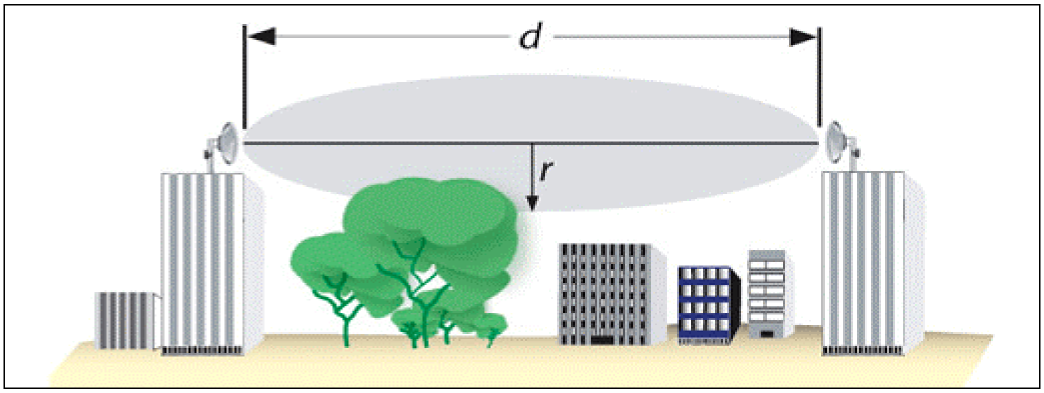

Figure 1: picture of Fresnel Zone [1]

As stated earlier, the radius of the first Fresnel zone can be calculated. We derived the formula below from the textbook Wireless Networking [5] and modified it to work with feet. The variables are the same as described above and the 0.992 (basically 1) is for the conversion from the original meters to feet.

$$r = 0.992\sqrt{4f}$$

The values in the table below were calculated using this formula. The radius calculated is the midpoint between the access point and the receiver where the Fresnel zone is the largest. The formula assumes same height for both receiver and access point. This means that the calculations may not correlate exactly to all of the height combinations in our experiments. However, the principle and calculations will still hold true with slightly different angles. The table clearly shows that for distances of ten to sixty yards (the distances tested in the experiments) the AP and receiver need to be at least .9645 feet in order to completely avoid the first Fresnel zone and interference of the ground (see table 1 below).

Table 1: Fresnel zone calculations

Distance in feet (Yards in parentheses)	The first Fresnel Zone radius in feet	55 percent of the first Fresnel zone in feet
30 (10)	1.7536	.9645
90 (30)	3.0374	1.6706
150 (50)	3.9212	2.1567
180 (60)	4.2955	2.3625

Other Obstacles

In addition to the Fresnel zone phenomena there are other obstructions that negatively affect the signal propagation. These obstructions can be within the 55% of the first Fresnel zone or directly in the signal's path.

The following chart from Intel's website shows the relative degree of attenuation of obstacles such as a window, concrete, and metal. All of these were observed to be factors in the experiment involving the window. The other obstacles listed show the relation between each obstacle [2].

Table 2: List of Obstacles [2].

Obstruction	**Degree of Attenuation**	**Example**
Open space	None	Outside
Wood	Low	door, floor
Plaster	Low	Inner wall
Cinder block	Low	Walls
Glass	Low	Non-tinted window
Wire mesh in glass	Medium	Door, partition
Metal tinted glass	Low *	Tinted window
Human body	Medium	Groups of people
Obstruction	**Degree of Attenuation**	**Example**
Bricks	Medium	wall, floor
Ceramic (metal content or backing)	High	Ceramic tile, ceiling
Paper	High	Roll or stack of paper
Concrete	High	outer wall, support
Silvering	Very High	Mirror
Metal	Very High	reinforced concrete, ventilator

(Note: This chart has been narrowed down for space purposes.)

* -- this is a different observation then what other experiences have shown

The "Outside Experiment"

Description of the Equipment and Setup

The equipment used consisted of a Pentium 4, 1.8 GHz Toshiba Satellite Laptop with 256 MB of RAM, Windows XP Home edition, Orinoco silver 802.11b PCMCIA card, Netgear router, Netgear wireless 802.11b wireless access point, and a Micron desktop server running the Linux 7.0 operating system.

Additional equipment for the outside experiment included two stepladders. One fiberglass six-foot stepladder and one ten-foot ladder with a top metal step were used for the access point. The six-foot ladder was also used for the receiver location. These ladders were used to create the different height combinations. The different placements are explained in table 3.

The environment

The experiments were conducted west of the west wing Science building on the University of Minnesota, Morris campus. The area was a grass field with 60 yards of open space. There were no obstructions in the line of sight, but there were two trees 20 feet apart from each other. These trees had no effect on the results of the experiment. There is a slight slope from 50 to 60 yards. This may have had a small effect on the signal at the higher distances.

About three feet behind the access point (AP), from ground level to six feet, there is a brick wall with windows at five to seven feet. Directly behind the AP at ten feet, the wall becomes a concrete wall with small outcroppings. At this point the AP was six inches out from this outcropping. At the other heights the AP was one foot from the wall. The omni-directionality of the AP may have created different signal bounces at the different heights. This will be discussed later in the paper.

Description of the Experiment

The tests were conducted using a 105-MB file ftp download (using Smart-Ftp) and recording the following information: location, time of download, overall instantaneous minimum and maximum speed, average speed, time for download to complete, and signal strength. Speeds are in kilobytes per second (Kbps). The signal strength is as reported by Windows XP network connection utility, in bars, with 5 being full strength. The time of download and average speed are as reported by Smart-Ftp. Instantaneous minimum and maximum speeds are the lowest/highest speeds observed by the experiment conductor during the course of a download.

There were four different heights for the access point and two different heights for the receiver. These different heights were used to examine the effect of the ground on the signal performance and to investigate the possibility of other inhibitors to the signal performance. The different heights were used to create five different combinations for the access point and receiver. Table three below shows the explanations for each of the heights. The different combinations are shown in the results (tables four and five).

Table 3: Explanation of the height combinations

Access point	**Explanation**
Ground (1.5 feet)	On top of a desktop computer tower, about 1 foot 6 inches off ground
6 foot	On top of the 6 foot fiberglass ladder
10 foot	On top of the 10 foot ladder
Window	A second story window (Science 2650)
Laptop Location (receiver)	**Explanation**
Ground (6 inches)	In the lap of observer sitting on the ground about six inches off the ground
6 foot	On top of the same 6 foot ladder

Recordings were taken every 5 yards for the available space of 60 yards. The distance was estimated by a pacing method that has a possible error of about 5 yards for the 60 yards. The most any of the experiments differed in distances was 55 yards to 64 yards at the last point. These small differences are deemed to be insignificant to the results of the experiments.

Results of the Experiment Sets

Tables 4 and 5 display the observed results for each of the experiments. Combinations B through F represent the outside experiment. Combination A represents the experiment involving the window. Table 4 displays the average speed and time for each combination. Table 5 displays the resulting standard deviation for the set of distances of the corresponding combination. The combination descriptions are also shown in the second and third columns. The colors correspond to the graphs 1 through 6 to make comparisons more intuitive.

Table 4: The averages for the outside experiment.

Combination	**AP location**	**Laptop Location**	**Average Speed (Kb/s)**	**Average Time for download**
A	Second floor window	Ground (6 inches)	386.89	5:22
B	**Ground (1.6 feet)**	**Ground (6 inches)**	**504.489**	**3:35**
C	**Ground (1.6 feet)**	**6 foot up**	**532.64**	**3:22**
D	**6 foot up**	**Ground (6 inches**	**557.303**	**3:13**
E	**10 foot up**	**Ground (6 inches)**	**505.227**	**3:41**
F	**10 foot up**	**6 foot up**	**501.013**	**3:42**

Table 5: The standard deviation from the experiments.

Combination	**AP location**	**Laptop Location**	**Avg. Speed deviation**	**Avg. Time for download deviation**
A	Second floor window	Ground (6 inches)	146.6215	0.0914
B	**Ground (1.6 feet)**	**Ground (6 inches)**	**44.760**	**0.0142**
C	**Ground (1.6 feet)**	**6 foot up**	**10.4374**	**0.0027**
D	**6 foot up**	**Ground (6 inches)**	**8.6237**	**0.0021**
E	**10 foot up**	**Ground (6 inches)**	**86.2694**	**0.0375**
F	**10 foot up**	**6 foot up**	**68.9740**	**0.0313**

Statistical Analysis of the Outside Experiment

The data was analyzed using Multiple Linear Regression techniques. Average speed was the designated response. The analysis could be repeated with the time for download as the response, but the two are directly related and would have very similar results. The recorded signals, overall maximum, and overall minimum speeds reached are not discussed in the statistical analysis since they are observed along with the response. The predictor is the distance of the receiver from the AP. This analysis finds the best model of average speed as affected by that distance.

The graphs below are representations of the results. The graphs were created using Microsoft Excel. Figure 3 shows 2 points that are noticeably different from the rest of the data points. These were examined to determine if they are outliers and have a high effect on the modeling of the average speed.

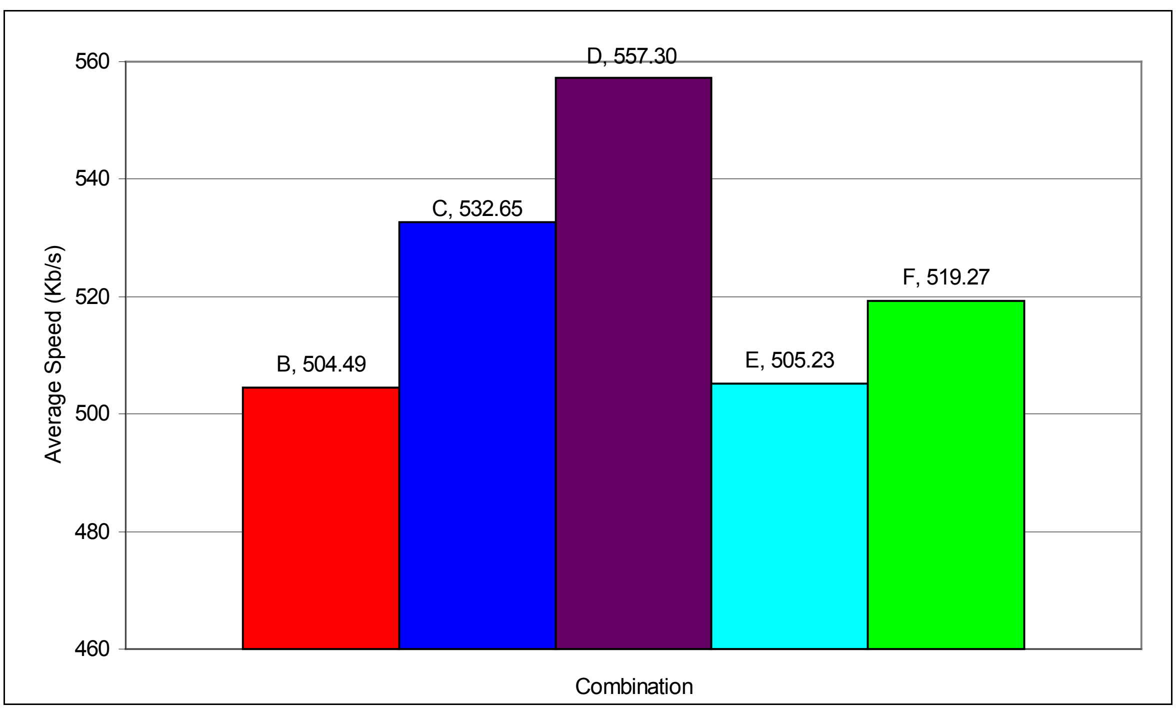

Figure 2: Graph of average speeds for each combination.

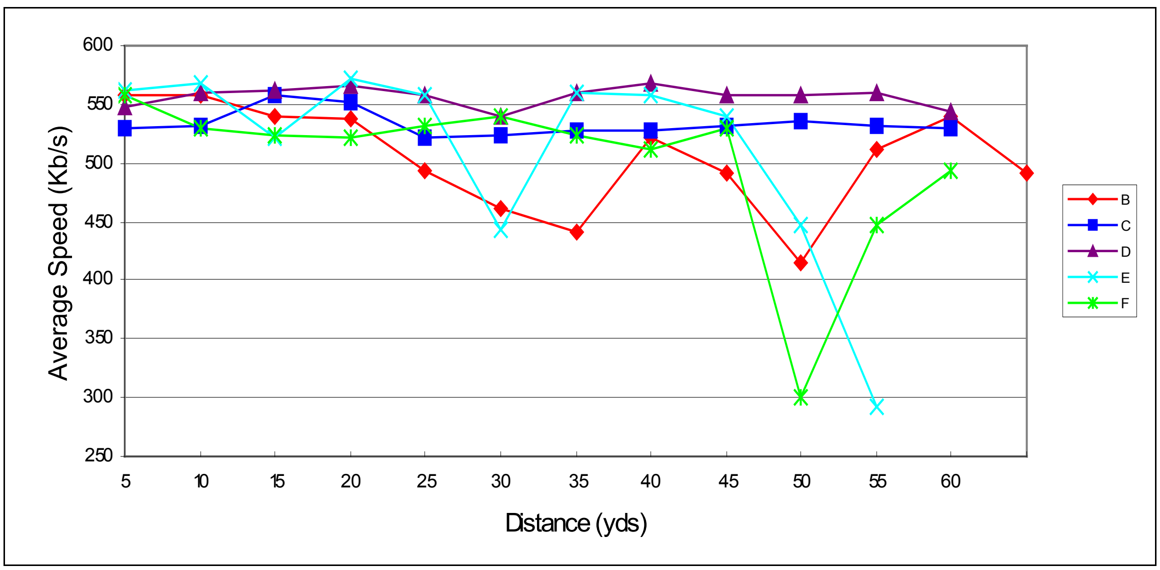

Figure 3: Average speed vs. Location.

Two of the data points were discovered to be outliers. Both had very high Cook's D values (meaning a high impact or influence on the model) [3]. Deleting these outliers prevents "weird" readings from influencing the model. There were no other outliers found in the data set. The first point removed from the data set was from combination E at 55 yards, with an average speed of 291.14 Kb/s, and an average download time of 6 minutes and 11 seconds. With this deletion the average speed for all of combination E increases from 505.227 to 532.87 and average time improves from 3 minutes 41 seconds to 3 minutes and 24 seconds. This is a very significant improvement. The model is a much better representation of the average speed without the outlier point at 55 yards.

The second point removed was from combination F at 50 yards, with an average speed of 300.14 Kb/s, and an average download time of 6 minutes. With this deletion the average speed for all of combination F increases from 501.013 to 530.21 Kb/s and average time decreases from 3 minutes 42 seconds to 3 minutes and 25 seconds. Again this is a significant improvement on modeling the average speed. Figures 4 and 5 below, and Tables 6 and 7 show the data after these outliers have been removed. Notice the much smaller spread of data points for combinations E and F. The data can now be analyzed with confidence that there are now no single abnormal readings that are driving the model.

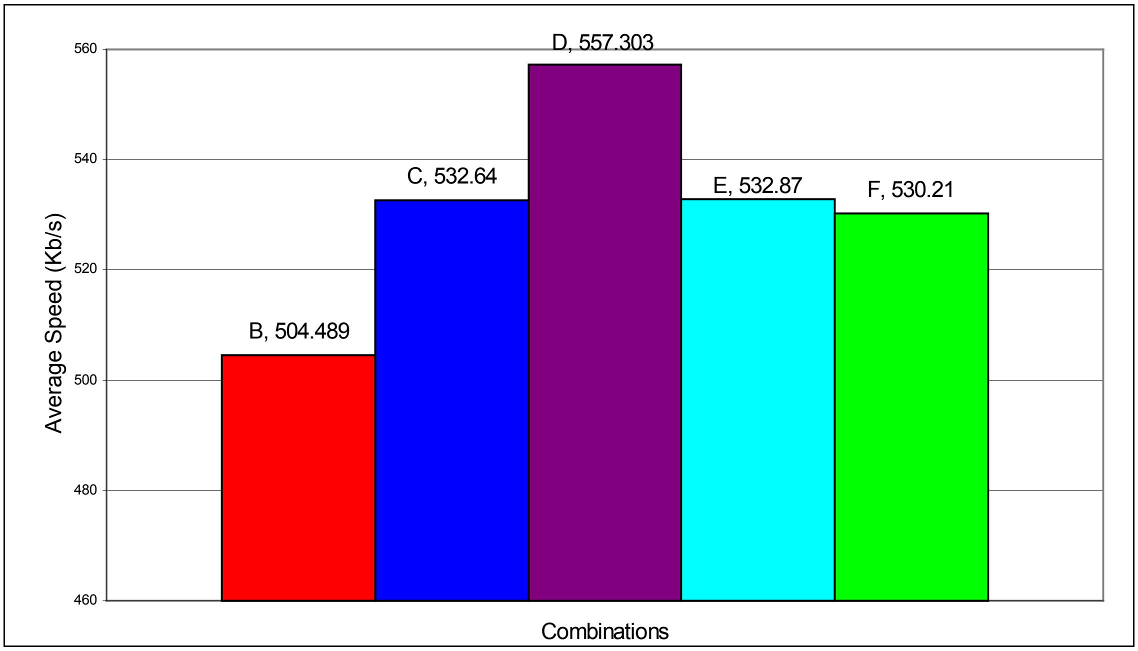

Figure 4: Average speeds after outliers removed

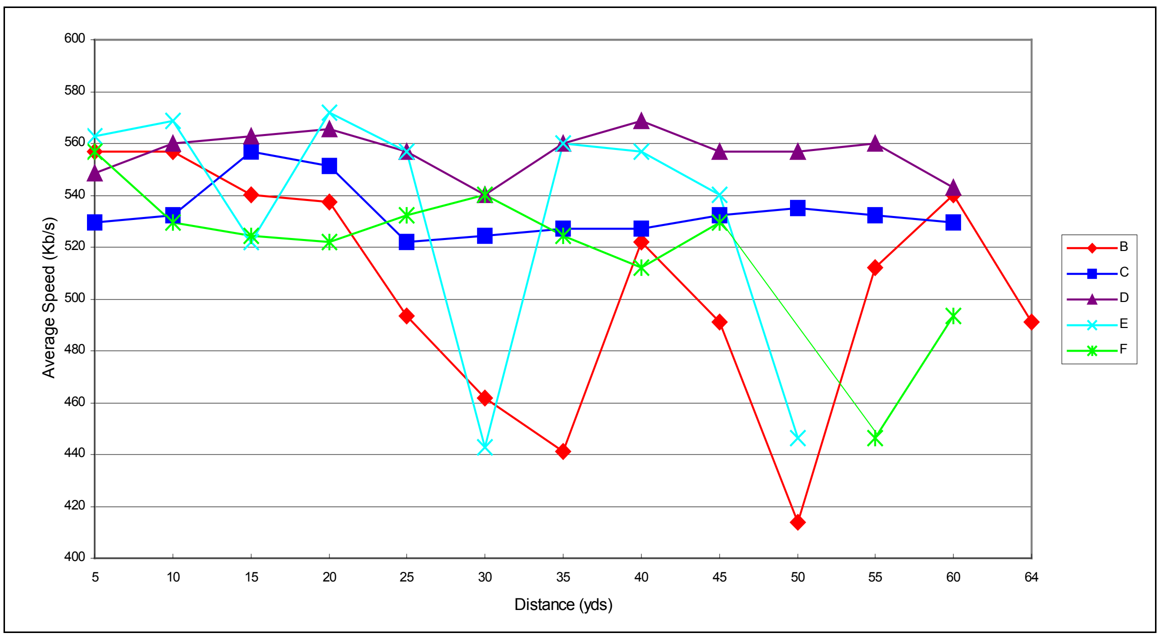

Figure 5: After outliers removed

Table 6: The averages for the outside experiment with outliers removed.

Experiment	**AP location**	**Laptop Location**	**Average Speed (Kb/s)**	**Average Time for download**
A	Second floor window	Ground (6 inches)	386.89	5:22
B	**Ground (1.6 feet)**	**Ground (6 inches)**	**504.489**	**3:35**
C	**Ground (1.6 feet)**	**6 foot up**	**532.64**	**3:22**
D	**6 foot up**	**Ground (6 inches)**	**557.303**	**3:13**
E	**10 foot up**	**Ground**	**532.87**	**3:24**

		(6 inches)		
F	10 foot up	6 foot up	530.21	3:25

Table 7: The standard deviation from the experiments with outliers removed.

Experiment	AP location	Laptop Location	Avg. Speed deviation	Avg. Time for download deviation
A	Second floor window	Ground (6 inches)	146.6215	0.0914
B	Ground (1.6 feet)	Ground (6 inches)	44.760	0.0142
C	Ground (1.6 feet)	6 foot up	10.4374	0.0027
D	6 foot up	Ground (6 inches	8.6237	0.0021
E	10 foot up	Ground (6 inches)	48.7043	0.0146
F	10 foot up	6 foot up	28.8327	0.0089

Once the outliers are removed the results show what may be expected with the different combinations of heights. All of the combinations involving a ladder outperformed the tests with both AP and receiver on the ground. However, there still exists an unexpected result. The variability of the signal for the tests involving the 6-foot ladder is much less then the tests involving the 10-foot ladder. The combination D (6-foot to ground) outperforms all the other combination. Since the ground was thought to be the most inhibitive obstacle involved in the experiment, combination F (10-foot to 6-foot), which avoided any ground interference, was expected to have the best results.

The outlier occurrences indicate an abnormal occurrence at 50 and 55 yards using the ten-foot stepladder in our environment. The outliers where observed at the same time of day, but one week apart with similar weather conditions. It is hypothesized that the ten-foot ladder or any of the factors of the metal top step, the backdrop from this position, the angle of the signal to the receiver, a different signal bounce off of objects may have caused the unusual readings at these distances. We retested these locations with the same setup on a later date. The occurrence of a major drop in speed could not be duplicated at 50 or 55 yards. The variation from test to test leads to our conclusion that wireless signal performance is variable and cannot always be predicted.

Observances from the Outside Experiment

The outside experiment shows the effects of the Fresnel Zone in relation to the ground. Notice the combination B in tables 6 and 7 above. This experiment was done with both the access point and the receiver very close to the ground. This is within the first Fresnel Zone for most of the distances. The higher speeds at the smaller distances show that the ground did not significantly affect the signal. Notice the mostly decreasing pattern in Figure 6 below. It also exhibits the expected result of performance at closer distances. The higher readings at 55 and 60 yards are deemed to be from the slight uphill slope at those distances. The signal performance observed for B is much slower on average and had a higher standard deviation than the experiments with a higher access point or receiver location. This is due in part to the signal being lost in the ground. With both of the heights being less than the calculated Fresnel zones, the ground is determined to be a major inhibitor to the performance of the signal.

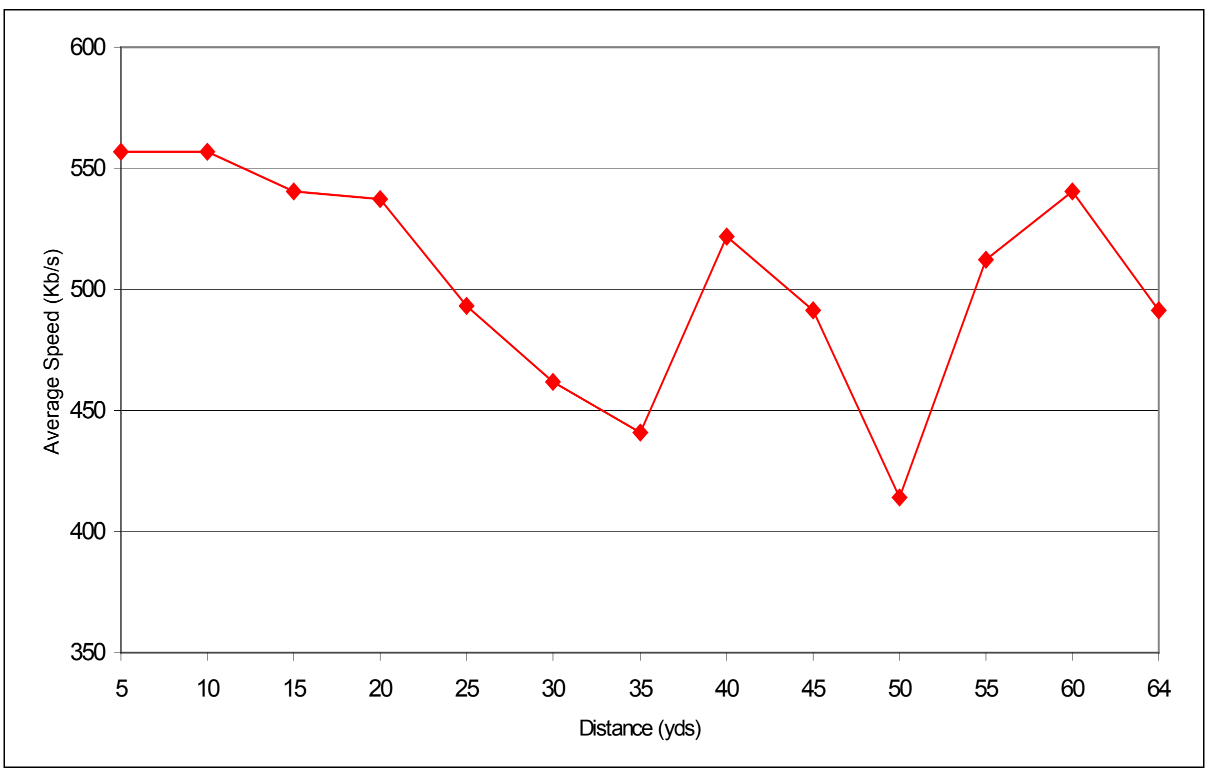

Figure 6: Combination B (ground to ground)

The box plot (created in ARC, a statistical software package) below in Figure 7 displays that the observed results of the average speed are higher for combinations C, D, E, and F than for combination B. Combination B contains a wider range of variables because the ground causes more of the signal to be lost as distance increases. This can be explained by the theory of the Fresnel zone. The outside experiment reinforces the Fresnel Zone's assumptions and shows that more variability in the signal performance will occur.

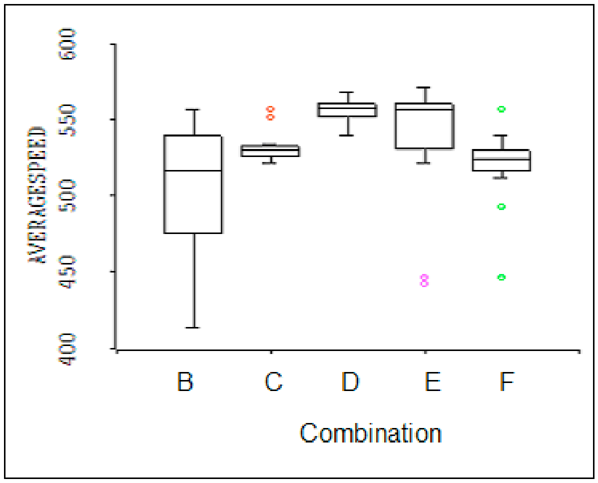

Figure 7: Box plot of the Average Speed per Combination

There is an interesting relationship between experiment C and D (involving the 6 foot ladder) and experiments E and F (involving the 10 foot ladder). This is intuitive since the respective combinations used the same ladders. The average speed was expected to decrease as location (distance from the access point) increased. This is shown in experiments B, E, and F. However, experiments C and D have an almost flat and linear occurrence. These also have a very small standard deviation and have very clustered data around the average speed. An exact explanation for these observations is not known. The Fresnel zone may have less of an effect on the signal with the smaller angle from ground to six feet up. Or the different factors involving the ten-foot ladder may have caused interference lowering the normal performance for that height combination.

The full statistical analysis and the steps taken can be found at:
http://csci.mrs.umn.edu/twiki/view/Main/KLOutsideExperiments

Additional experiment: Effect of a Structure

The additional experiment is designated as combination A in Tables 6 & 7. The additional experiment shows the effect of a structure surrounding the access point. The access point was placed in a second story windowsill, overlooking the same environment as the other experiment. This window had a metal frame and is part of the outside, concrete, wall of the science building. The effects of the windowsill, building wall, and restraint of the AP located inside are highly noticeable in these results. The tables above show much lower speeds and much higher deviation in all of the categories. This combination performed at an average speed of 386.89 Kb/s and an average download time of 5 minutes 11 seconds. This performance is 117.599 Kb/s lower then the next lowest performance, the ground-to-ground combination B. The windowsill combination also caused large variability in the average speed with a standard deviation of 146.62 compared to 44.760 for combination B. In addition, demonstrating the high effect of the windowsill, signal was completely lost at just 45 yards from the building. This was much less than the rest of the outside experiment that showed range with good signal strength and performance at 60-plus yards.

The signal was also inhibited at closer locations such as 5 and 10 yards from the building. This is a direct result of the outside ledge. Because of this ledge a direct line of sight was not achieved resulting in lower performance. The graph below shows the average speed per distance of combination A.

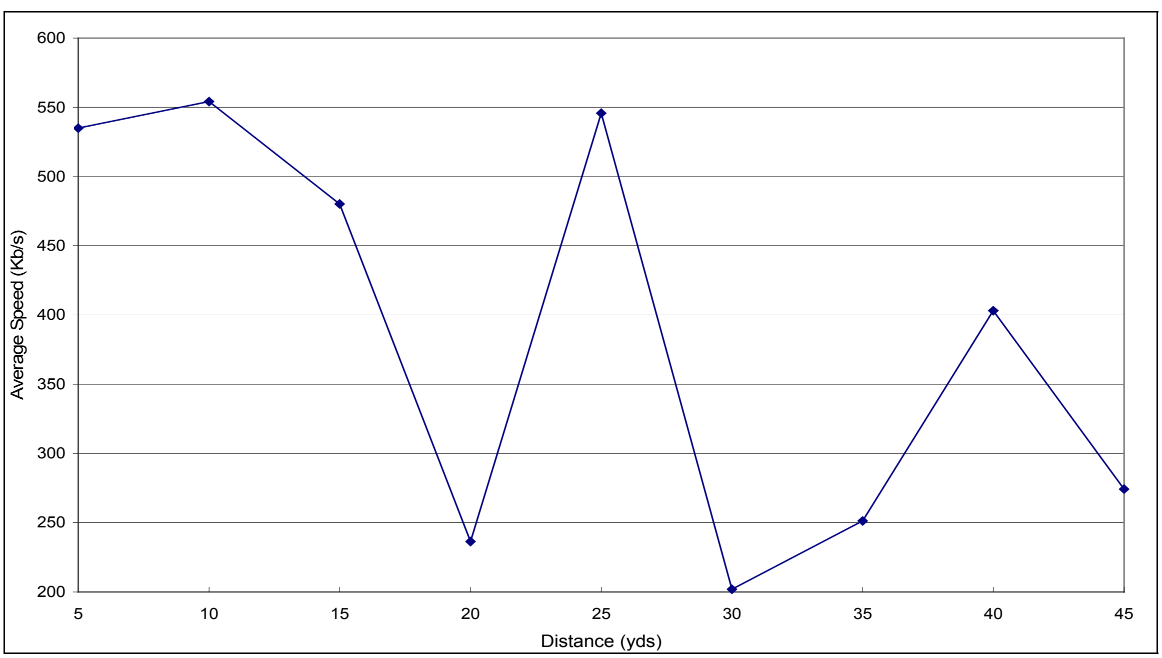

Figure 9: Combination A (from inside to outside)

Conclusion

The experiments conducted in an open environment display the unpredictability of the IEEE 802.11b wireless data communication protocol. The performance of the wireless signal did not always follow the expected behavior of decreasing signal performance to increasing distance. The outliers found in the data shows that there can be abnormal performance that may or may not be repeatable. The variables of an “open” environment are too numerous to account for all of them. Some of the variables may include: backdrop, ladder material, objects surrounding the open environment, height of AP and receiver, and weather. These variables will be different for each environment and may be the explanation for the weird observation points and some of the unexpected results in these experiments.

It is also shown that different combinations of heights between an access point and a receiver will have an effect on download speeds. This can be partially explained by the Fresnel zone phenomena. The experiments, in which the ground was inside the first Fresnel zone, showed a decreased performance. However, the height combination that achieved the best average performance was 6 foot to ground. This combination showed very little variation and a steady performance over the whole environment when compared to the other combinations. In addition, the upward slope of the ground may be a factor in the higher performance observed at the distances between 50 and 60 yards. The slope may have created an ideal angle. More research and experiments are needed to explain the observed occurrence. Finally, obstacles were observed to cause much lower performance in the IEEE 802.11b communication protocol.

Questions arise about manufacturers performance claims of their 802.11b equipment from the results of the experiments conducted. Many of the companies will advertise and document performance throughput and range for their individual products. These claims, performances, and conditions, as seen in this paper, may not always be reproduced or experienced in a consumer environment or even the same environment. We have seen that throughput, signal, and range are not only affected by obstacles, but also by height from the ground and other less obvious variables. Even if all variables are accounted for, the performance of the IEEE 802.11b wireless data communication protocol may not perform as expected.

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