A Study of Radio Signal Behaviors in Complex Environments

Lee, Ee Foong   Chen Wang   Li Xiao
Computer Science Department, Michigan State University
Michigan, MI
Email: {leeee}@msu.edu

***Abstract*—This paper presents a study of how radio signal behaves in complex environments where the effects of reflections and obstructions are taken into consideration. We collect the RSSI data of each environment and use an objective metric to evaluate the experimental result. The base metric that is used for evaluations is the radio signal strength behavior in an open flat area that is free from reflections and obstructions. We reveal that radio signal strength does not work well in all indoor and complex outdoor environments that are selected for experiment purposes, due to the effects of reflections and obstructions. Radio signal strength only correlates with distance in unobstructed outdoor environment. We also demonstrate that the elevation of sensor nodes can reduces the reflections and obstructions effects, both indoors and outdoors.**

1 Introduction

Many applications of military and robotics use radio signal strength (RSS) for range estimation. To estimate the distance between a pair of sensor nodes, we measure the received signal strength from the sender and find the corresponding distance from a pre-defined RSSI model, in which it has a defined rate of signal strength attenuation over distance. RSSI is defined to be the voltage in the received signal strength indicator (RSSI) pin on our radio signal [1]. Several RSSI models have been developed for range estimation such as the linear and theoretical models. These models do not usually provide accurate distance estimation because signal strength does not correlate linearly with distance [1]. However, this methodology is an attractive alternative because it is costless and easy to implement. The main problem of RSS-based ranging is its high sensitivity to environmental changes. This ranging system has long been known to be difficult to use for range estimation because it is too "unpredictable" to use for ranging [1,14]. The effects of the environment on RSS can be significant, especially in more complex environments where reflections and obstructions occurred continuously. In this paper, we present some of the RSSI models that contradict to the previous defined RSSI models. Radio signal strength does not always fall off linearly or theoretically with distance.

In this paper, we collect the RSSI data that can be used for range estimation in more complex environments. The degree of complexity depends on the amount of reflections and obstructions that are present in the environment. Unlike the signal strength behavior in an open space in which there are no reflections and obstructions, the signal strength performs much more unpredictable with increasingly complicated environment. The purpose is to show how great the effects of reflections and obstructions on RSSI characteristics. We demonstrate our methodology in a natural forest with highly dense of tall trees and bushes with only 2 sensor nodes, one is intended for transmitting signals and the other one is for receiving and measuring signal strengths. We then repeat the experiment in an obstructed basketball court and classrooms. We also configure the positions of the sensor nodes in some of the previous environments in order to show how signal strength changes at different elevations. It has been known that small changes in the height of the sensors from the ground can have a large impact on signal strength [1]. We show that the higher the sensor nodes, the stronger the signal strength since there is less obstructions at higher position.

Section 2 discusses previous studies that have used RSS for distance estimation. Section 3 describes the implementation of our RSS-based ranging system and our technique to collect the signal strength readings. Section 4 illustrates the differences in signal strength behavior between indoor and outdoor environments. Section 5 focuses on the factors that may influence the signal strength behavior such as the elevation of the sensor nodes, the effect of obstructions, and reflections.

2 Related Work

Radio Signal Strength (RSS) has evolved as a common technique used for ranging. Ranging is the process of estimating the distance between two nodes [1]. Many studies on RSS have been carried

Environment characteristics	Height of node	Height of grass	Transmission power
Large room with cluster of chairs	Higher position leads to lower attenuation rate and higher range	-	Higher transmission power yields lower attenuation rate and higher range
Open field with low grass (8cm), but with tall trees and buildings	Higher position leads to lower attenuation rate and higher range	Short grass yields lower attenuation rate and higher range	Higher transmission power yields lower attenuation rate and higher range
Open field with tall grass (30cm)	Higher position leads to lower attenuation rate and higher range	Tall grass yields higher attenuation rate and lower range	Higher transmission power yields lower attenuation rate and higher range

Table A: Summary of the factors that have effects on radio signal strength.

on recently to determine its accuracy and consistency for ranging. Most of the studies are majoring into the factors that may influence signal strength behavior in different environments. For example, obstructions, reflections, interference, and sensor nodes variability, can influence greatly the signal strength behavior. Table A summarize how the height of nodes, grass, and the different level of transmission powers affect radio signal strength. Three different environments have been chosen for the experiment purposes. First, the data collections took place in a large room indoor that is filled with chairs and other items. Then, the experiment is moved to a small field with low grass, but with several tall trees and buildings around. Lastly, a slightly different environment is selected, that is in a large open field with tall grass for the same experiment objectives. The results show that the height of nodes, height of grass, and transmission power, all yield the same effects on RSS characteristics. Furthermore, there are other factors that have significant impact on signal strength.

Most systems that use RSS for ranging reported that indoor environment is not appropriate for RSS ranging because there is no correlation between signal strength and distance [3,12,13]. This shows that the reflections and obstructions can make a major impact on signal strength behavior. A study has reported that radio signals can take multiple paths while they transmit and their signal strength changes when they hit an obstacle [7]. The hitting on obstruction will results in two different signals, called the transmitted and reflected signal, respectively. Their report also shows that the strength of the transmitted and reflected signals depends on the angle at which they hit the obstructions [7]. However, there seem to have too many variances in the experiment. One of the problems is that no one can guarantee at which point, the original signal is going to hit on the obstacle even though the degree at which the signal is facing the obstacle is fixed. There is no ways to determine a signal transmission path because a signal can travel in multiple ways to reach the receiver. Therefore, we will only demonstrate how signal strength behaves in both indoor and outdoor environments with the present of reflections and obstructions. The effect of obstructions on RSS is certainly easier to be tested as compared to reflections because ones can manually place an obstacle between the sender and the receiver to see how that obstacle affects signal strength. However, it is difficult to test the reflections effects since reflections can cause by the floors, ceilings, walls, and other materials in the surroundings. In this paper, we have majored the effects of both obstructions and reflections in a more complicated indoor and outdoor environments in order to show that RSS is even worse for range estimation in those environments.

3 An RSS Ranging System

Radio Signal Strength (RSS) ranging system works by measuring the received signal strength. The value of the signal strength can be obtained from the RSSI pin on the radio signal, and the RSSI value is inversely proportional to the signal strength. Greater RSSI value implies weaker signal strength, and vice versa. Throughout this paper, we will use the RSSI value as an indicator for the signal strength. The system is consists of a sender and a receiver. The

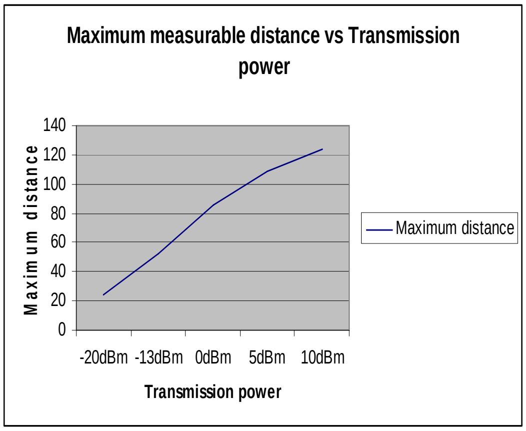

Figure 1: **The transmission power is linearly proportional to distance**. Higher transmission power can be used to measure longer distance between a pair of sensor nodes.


Figure 2: **Outdoor Data** was collected in an open flat parking lot with no obstructions.

sender sets its transmission power to the highest value, 10dBm. The sender sends out messages continuously, and the receiver collects the RSSI value of each message at certain distance from the sender. For each 100 message received, the receiver computes the mean RSSI and output the mean value on the PC through an I/O port. This step is repeated by varying the sender at different locations. By comparing the RSSI value with some pre-defined RSSI models such as the linear RSSI model and the theoretical RSSI model, the distance between the sender and the receiver can be estimated.

Before any RSSI values can be received, we need to know how far that a signal can transmits at different transmission powers. In order to test how transmission power relates to distance, we performed an experiment in which the sender is fixed and programmed with different level of transmission power. For each transmission power level, we measured the maximum distance in which the receiver can receive the signal that is transmitted from the sender. The experiment took place at the hallway on the third floor of the Engineering Building. The result of the experiment is shown in Figure 1.

By increasing the transmission power, the sender can transmits the radio signal for a longer distance. When the transmission power increases from -20dBm to 10dBm, the maximum measurable distance also increases by up to 99.5ft. This corresponds well with the predicted result [1]. Each increment in the transmission power will increase the strength of the signal, and therefore, the signal can travel in a longer distance.

4 Signal Strength Behaviors in both Indoor and Outdoor Environments

Different environments cause signal strength to act differently. We perform some experiments in both indoor and outdoor environments to illustrate this point. In these experiments, we fixed the receiver in the middle of the selected location and varied the sender at the distances of 10ft, 20ft, 30ft, 40ft, 50ft, 60ft, 70ft, and 80ft from the receiver. For each range, we measured the received signal strength.

4.1 Comparing Indoor with Outdoor Environments

In this section, we compare the signal strength behavior in indoor and outdoor environments. The experiment took place at the third floor of the Engineering Building (indoor) and at the parking lot on Service Road (outdoor). Figure 2 shows the signal strength measurement in the open parking lot. The result of the experiment is shown in Figure 3.
The result shows that signal strength is correlated with distance in the outdoor environment, but not in the indoor environment. In the open outdoor field, as the distance between the sender and the receiver increases, the strength of the signal becomes weaker. However, this is not the case in the open hallway. Signal strength does not correlate with distance. The signal strength fluctuates in an unknown pattern over distance. As shown in Figure 2, the signal

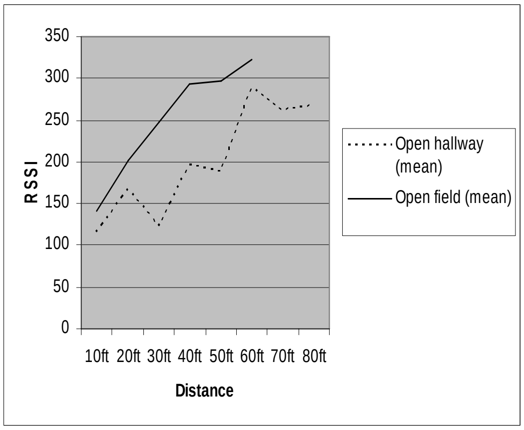

Figure 3: **Signal strength behaves differently in indoor and outdoor environments**. Signal strength does not correlate with distance in the open indoor hallway.

Figure 4: **Signal strength behaves almost similarly in slightly different outdoor environments**. The grassy field is a soccer field with short grasses.

strength at the range of 30ft is even stronger than at the range of 20ft. This makes RSS-based ranging difficult in an indoor environment, even though the environmental factors are often held constantly indoor.

However, the signal strengths appeared to be weaker (indicated by higher RSSI) in an outdoor environment than an indoor environment. Another disadvantage of using RSS ranging system in an outdoor environment is that the maximum range is smaller. As shown in Figure 3, the maximum range is only 60ft in the open field, which is smaller than in the open hallway. As a result, both the indoor and outdoor environments have their own disadvantages in using RSS-based ranging.

4.2 Comparing Different Outdoor Environments

In this section, we compare the signal strength behavior in different outdoor environments. The experiment took place at a small soccer field next to Demonstration Hall and at the parking lot on Service Road as shown Figure 2. The result of the experiment is shown in Figure 4.

No obvious distinction can be obtained from Figure 4. Again, the result shows that signal strength is correlated with distance in different outdoor environments. It shows that the greater the range, the smaller the signal strength. Those short grasses in the soccer field do not have a great impact on the signal strength. Therefore, the effects of short grass on RSS can be ignored. However, tall grass can have large effects on signal strength. The taller grass yields weaker signal strength and affects the range estimation accuracy [1]. Such effects can be minimized as long as the height of the grass is less than the height of the sensors from the ground. On the other hand, there are some other factors that may have a great influence on signal strength. These factors will be analyzed in the following section.

5 Environmental Effects on RSS

In Section 5.1, we will demonstrate the effects of different elevations of sensor nodes on radio signal strength. Then, in Section 5.2 and 5.3, we will show the effect of obstructions and reflections on signal strength, respectively.

5.1 Height of the Sensor Nodes from the Ground

In this section, we will demonstrate how the position of sensor nodes from the ground affects the radio signal strength. In order to show this, we performed the experiment in which both the sender and the receiver are placed on the ground at first, and then, we lifted them up to 2.5ft, 3ft, 3.5ft, and 4ft from the ground using two tripods for elevation, one for each sensor. The receiver is fixed and the sender is varied at the distances of 10ft, 20ft, 30ft, 40ft, 50ft, 60ft, 70ft, and 80ft from the receiver. The experiment took place at the open parking lot on Service Road as shown in Figure 2. The experiment setting is shown in Figure 5. Figure 6 shows the result of this.

For the same experimental objective, we performed another experiment at two classrooms on

Figure 5: **Outdoor Data** was collected in an open flat parking lot with two tripods to raise the sensor nodes.

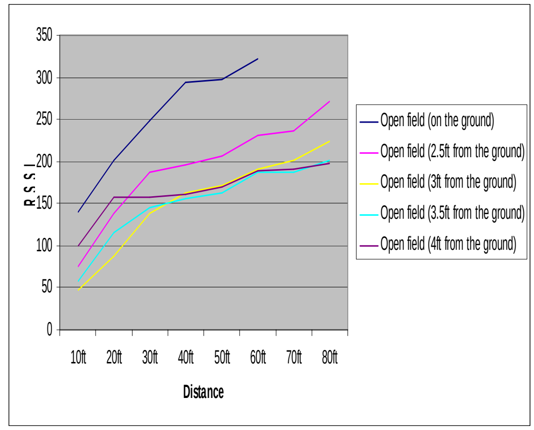

Figure 6: **The effects of elevation of sensor nodes** on signal strength in the outdoor environment. We use the tripods in order to raise both the sensor nodes.

the first floor of the Engineering Building. Similarly, both the sender and the receiver are placed on the ground at first, and then, we lifted both sensors from the ground using desks. We placed the sender in one classroom and the receiver in the other classroom. We then varied both the sender and the receiver at the same distance from the wall that separated the two classrooms. The setting is shown in Figure 7. Figure 8 shows the result of this experiment.

Both the sensor nodes in the previous two experiments are positioned on the same height. However, we are interested in determining how likely signal strength behavior changes if both the sender and the receiver are of different height from the ground. To show that, we performed an experiment in which we placed the sender on the ground and varied the receiver at the heights of 2ft, 2.5ft, 3ft, 3.5ft, and 4ft from the ground. In the experiment, we fixed the distance of 20ft between the sender and the receiver. We then repeated the experiment by changing the distance between the sender and the receiver to 40ft and 60ft. The experiment took place in the same location as shown in Figure 2. Figure 9 displays the experimental result. We later repeat the same experiment with slightly different settings, in which the receiver is placed on the ground and the sender is varied at different heights from the ground. Figure 10 shows the result of this experiment.

Both Figure 6 and 8 showed that the height of the sensors from the ground can have a great effect on signal strength. It shows that the higher the position of the sensor from the ground, the stronger the signal strength. This conclusion holds for both outdoor and indoor environments. This corresponds well with the predicted result. The idea is that a signal can possibly get rid of most of the obstructions (eg. pedestrian, moving vehicle, and etc) if the sensors are positioned higher from the ground. How obstructions affect the signal strength behavior will be discussed in the Section 5.2. However, there is a difference between indoor and outdoor environment. There is a linear correlation between signal strength and distance in outdoor field, but not in indoor field. The results for indoor environment seem to be unpredictable due to the effects of obstructions and reflections. In the indoor environment, there are more obstructions such as walls. When a signal path is blocked, it can either passes through the obstacle and has weaker signal strength after passing it, or reflected from the obstructions. The effects of obstructions and reflections will be discussed in the following sections. On the other hand, there are less obstructions and reflection effects in the outdoor environment. The signals are not easily reflected by obstructions because the area of an outdoor environment is larger than an indoor environment. As a result, the RSS range estimation is believed to be more accurate if the sensor nodes are positioned higher from the ground.

However, this result is not necessarily true if both the sensor nodes are positioned at different elevations. This can be seen from Figure 9 and 10 in which only one of the sensors is placed on the ground and the other one varied at various heights. Both figures show that signal strength does not rise linearly with height. One possible reason is that the scale that is being used for the height is too small (eg. 0.5ft). The difference between the highest and

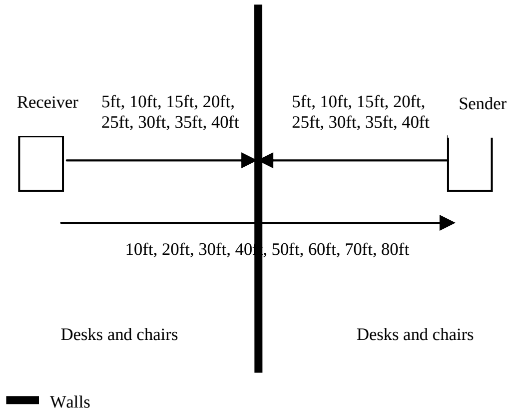

Figure 7: **Experiment configuration** to test the effect of elevation of sensor nodes on signal strength in two classrooms.

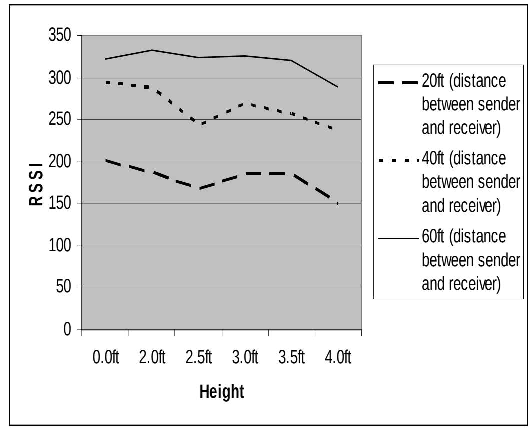

Figure 9: **Different elevations for the receiver**. The sender is placed on the ground at some fixed distances from the receiver.

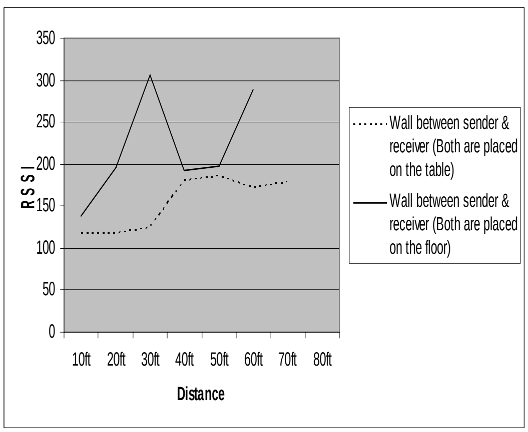

Figure 8: **The effect of lifting both sensors in an indoor environment**.

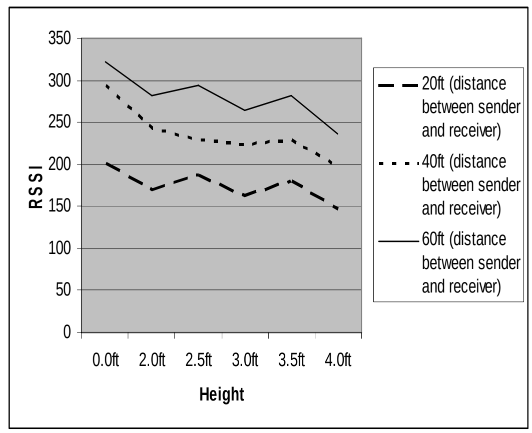

Figure 10: **Different elevations for the sender**. The receiver is placed on the ground at some fixed distances from the sender.

lowest height is just about 2ft. There are some RSSI measurement errors within this small scale. However, if we increase the scale for the height to about 1ft, then we will see more reasonable result, as predicted from the previous studies.

5.2 Effect of Obstructions

Obstructions are one of the major concerns in RSS ranging system. Radio signals lose strength when traveling through obstructions such as walls, floors, and vehicles. Large obstructions can even block a signal completely. In this section, we show how obstructions affect the signal strength behavior, and cause large error in range estimation. We will demonstrate the effects of obstructions in both indoor and outdoor environments.

5.2.1 Outdoor Environment

To show how obstructions affect signal strength outdoor, we performed the experiment in which the sender and the receiver are separated by a medium-sized vehicle that is parked at the parking lot in front of the International Center. The experiment is done in the following way. The receiver is fixed at 15ft from one side of the vehicle, and the sender is placed on the other side of the vehicle. Then, the sender is varied at the distances of 10ft, 20ft, 30ft, 40ft, 50ft, 60ft, 70ft, and 80ft from the receiver. But, for the distance of 10ft, both the sender and the

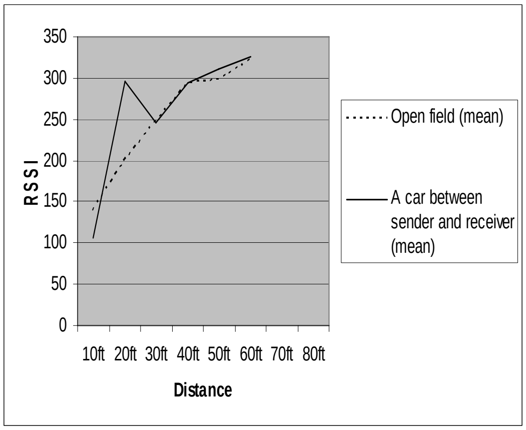

Figure 11: **Car Obstruction** The line of sight (LOS) is obstructed by a medium-sized vehicle that is placed between a sender and a receiver in an outdoor parking lot.

Figure 12: **Complex Outdoor Data** in a natural forest with cluster of tall trees and bushes.

receiver are placed on the same side. Both the sender and the receiver are placed on the ground. The result is depicted in Figure 11.

In addition to that, we performed another experiment in a more complex outdoor environment. The experiment is located in a natural forest in the Baker Woodlot and Rachana Rajendra Neotropical Migrant Bird Sanctuary on Bogue Street. The forest is clustered with tall trees and bushes. Besides, it is not a flat open area. Therefore, we use two tripods to lift both the sender and the receiver up to 2.5ft from the ground. In the experiment, we fixed the receiver and then varied the sender at the distances of 10ft, 20ft, 30ft, 40ft, 50ft, 60ft, 70ft, and 80ft from the receiver. Figure 12 depicts the experimental environment and Figure 13 shows the experimental result, respectively.

The result of the experiment shows that obstructions can have great effect on signal strength. When the transmitting signal reached the obstruction, it is either passes around the obstruction or deflected by the obstruction [2]. A great portion of the signal strength is absorbed by the obstacles (eg. car and trees) when the signals try to pass through them. Therefore, signals that have successfully passed through the obstruction suffered reduction in signal strength. This can be seen from the graphs in Figure 11 and 13, respectively. From Figure 11, the RSSI value increases by 190.5 from 10ft to 20ft (reduction in strength). However, the RSSI value only increases by 61 from that same range in an unobstructed environment. On Furthermore, as the sender is placed increasingly further from the vehicle, the reduction in signal strength is smaller. However, the signal strength behavior is more complicated in the forest, as shown in Figure 13. There are more fluctuations in signal strength readings due to both the combination of reflections and obstructions effects. Hence, in an obstructed environment, RSS is not a good choice for distance estimation.

5.2.2 Indoor Environment

To show how obstructions affect signal strength indoor, we performed two experiments in which the sender and the receiver are separated by a wall in both experiments. The first experiment took place in two classrooms on the first floor in the Engineering Building. These classrooms are separated by a partition. In order to minimize the effect of other obstructions, we rearranged the tables and chairs in both classrooms. Figure 7 on page 5 shows the arrangement in the classrooms. The sender is placed in one classroom and the receiver is in the other ones. Both are placed on the floor. Before we measure the RSSI of the received signal, we vary both the sender and the receiver at the same distance from the wall each time. Figure 14 show the result of the experiment.

The second experiment took place in a basketball court on the first floor of IM Circle. There is a small store room next to one side of the basketball court. The experiment is done in three different ways in which both the sender and the receiver are placed on the ground each time. First, we find the middle point of the basketball court. We then varied both the sender and the receiver at the distances of 5ft, 10ft, 15ft, 20ft, 25ft, 30ft, 35ft, and

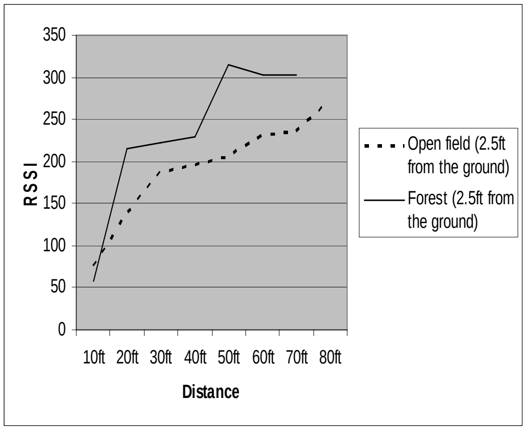

Figure 13: **Trees Obstructions** The line of sight (LOS) is obstructed by tall trees in the surroundings. The signal strength is relatively weaker in the obstructed forest.

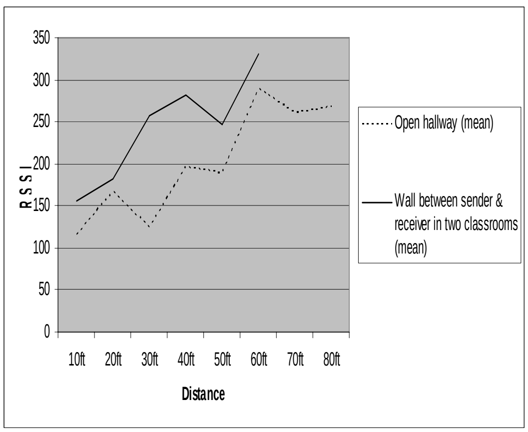

Figure 14: **Wall Obstruction in Classrooms** The line of sight (LOS) is obstructed by a wall that separates a sender and a receiver, each placed in two different classrooms.

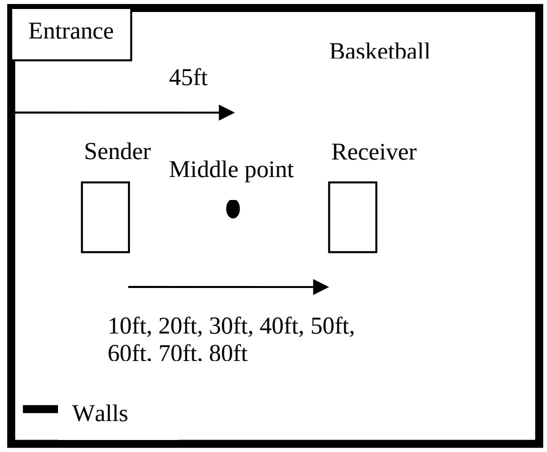

Figure 15: **Baseline Metric** Signal strength measurement in the basketball court with no obstructions.

Figure 16: **Indoor Data** The experiment setting shown in Figure 15.

40ft from that middle point. Both sensors are placed on the same side. This result is used as a baseline comparison and is depicted in Figure 15. Figure 16 shows the real picture of this setting. Second, we fixed the sender at a distance of 9ft away from one side of a wall (in the store room) and then we vary the receiver at the distance of 1ft, 11ft, 21ft, 31ft, 41ft, 51ft, 61ft, and 71ft from the other side of the same wall (in the basketball court). This setting is shown in Figure 17. Lastly, we repeated the second experiment by reversing the position of the sender and the receiver. Figure 18 shows the combinations of the results of the experiments.

The result of the experiment in an indoor environment shows that obstruction such as wall has a great influence on radio signal strength, similar to the obstruction in an outdoor environment. When a signal transmits through the wall, it is either passes around the wall or deflected by the wall. Most of the signal strength is absorbed by the wall when the signals try to travel through it [10]. Therefore, signals that have successfully passed through the obstruction suffered great reduction in signal strength [11]. At shorter distance, the signal strength may be stronger in the obstructed condition. Perhaps the strength of the signals is constantly high if travel through short distances, even though obstructions occurred. However, the reduction rate of signal strength over distance is still perceived to be distinctively high in an obstructed environment than the unobstructed ones. Furthermore, the maximum range that can be measured in an obstructed condition is clearly smaller than in an

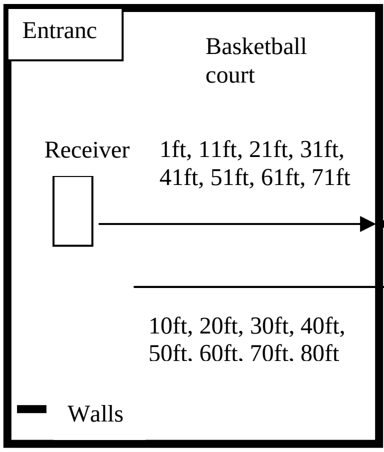

Figure 17: **Experiment setting** to test the effects of wall on signal strength in a basketball court.

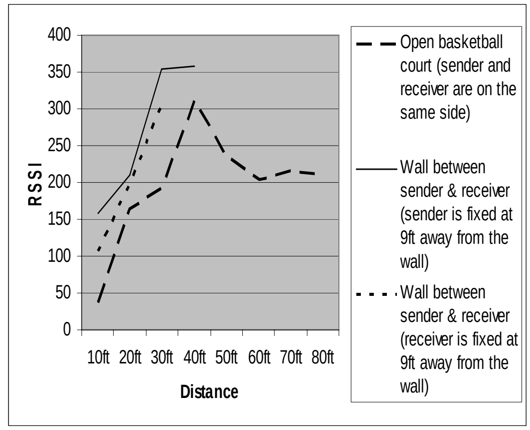

Figure 18: **Wall Obstruction in Basketball Court** The line of sight (LOS) is obstructed by a wall that separates the sender and the receiver. Radio signals lose strength when traveling through the wall.

unobstructed ones. From Figure 18, the maximum range is only 30-40ft in the present of the wall, which is less than the one without the wall. Hence, RSS ranging can provides large error in distance estimation since it is highly sensitive in an obstructed environment.

5.3 Effect of Reflections

In addition to obstructions, reflections from the objects around the environment can also cause an impact on radio signal strength. In this section, we show how reflections affect the signal strength behavior in both indoor and outdoor environments. The effect of reflections is shown to be more severe in indoor environments.

5.3.1 Indoor Environment

To show how reflections affect signal strength indoor, we performed three experiments in which both the sender and the receiver are placed on the ground. In the first experiment, we fixed the receiver at the distance of 1ft from a wall and varied the sender at various distances from the receiver. The experiment took place in the hallway on the third floor of the Engineering Building. The experiment is then repeated by fixing the receiver at 8ft from the same wall. Figure 19 shows the experiment setting. The result is shown in Figure 20.

In the second experiment, we fixed the sender at the distance of 50ft from the same wall that is used in the previous experiment. The experiment is done in the hallway on the third floor of the Engineering Building, which is the same location as in the previous experiment. We then varied the receiver at various distances from the same wall. Figure 21 shows the experiment setting and the result is depicted in Figure 22.

Lastly, we performed the experiment in a basketball court on the first floor of IM Circle. We fixed the receiver at the distance of 13ft from a wall, in which there are some benches in front of the wall. We then varied the sender at various distances from the receiver. Received RSSI value is collected for each distance. The experiment is then repeated by fixing the receiver further away from the same wall that is 26ft from the wall. Figure 23 shows the experiment setting. The result is shown in Figure 24.

From all the tests performed in this section, we can observe that reflections can have a great influence on radio signal strength in indoor environments. From the Figure 20, 22, and 24, the radio signal strength appeared to be stronger indoor than signal strength measured outdoor (open field). The difference in signal strength is caused by the reflections from objects in the experiment environment such as walls, floors, ceiling, and other buildings. Since both the sender and the receiver are placed on the ground, the transmitting signals can get reflections from the ground. The reflections caused by the floors can be reduced by lifting both the sensors higher from the floor. Some studies have shown that the effects related to ground reflections will disappear if the distance from ground of sensors nodes is greater than 0.97m [4]. Radio signals are transmitted through waves and the radio

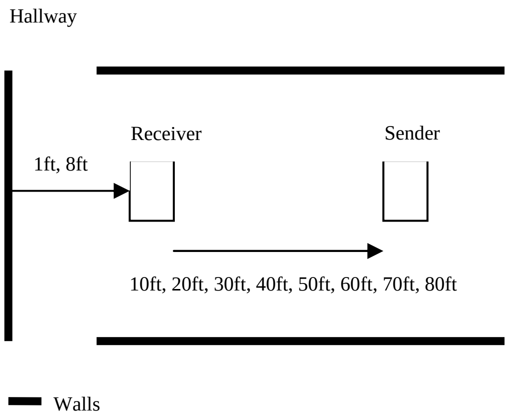

Figure 19: **Hallway Setting** Experiment to test the effect of reflections from the walls in a hallway indoor. The position of the receiver is fixed at 1ft and 8ft from a wall in the hallway. The sender is varied at various distances from the fixed receiver.

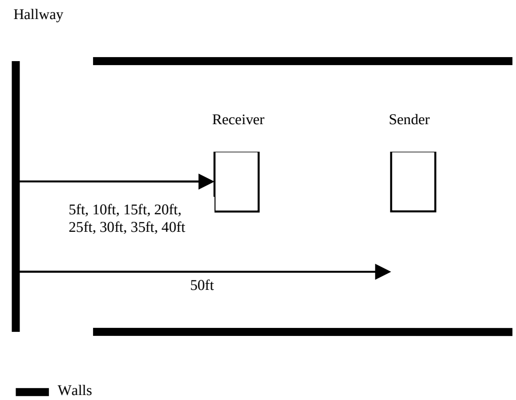

Figure 21: **Hallway Setting** Experiment to test the effect of reflections from the walls in a hallway indoor. The position of the sender is fixed at 50ft from a wall in the hallway. The receiver is varied at various distances from the fixed sender. By fixing the sender's position, we ensured that all signals that are transmitted from the sender are traveling in the same distance to the wall.

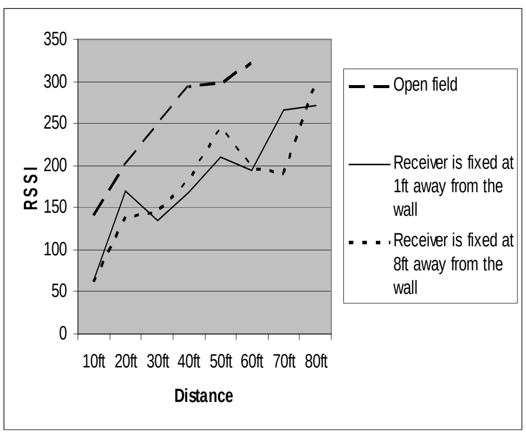

Figure 20: **Hallway Reflections** The effect of reflections from the wall on signal strength in a hallway in an indoor environment. The receiver is fixed at 1ft and 8ft from a wall in the hallway. The receiver measures the RSSI value for each distance from the sender. Both the receiver and the sender are placed on the ground. The open field result is used as bases for comparison.

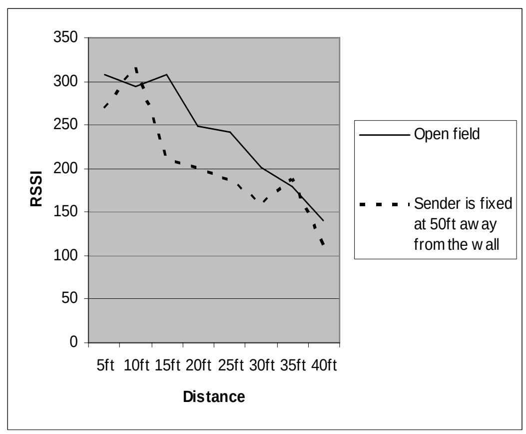

Figure 22: **Hallway Reflections** The effect of reflections from the wall in a hallway in an indoor environment. The sender is fixed at 50ft from a wall in the hallway. The receiver measures the RSSI value for each distance from the sender. Both the receiver and the sender are placed on the ground. The open field and open hallway results are used as bases for comparison.

waves from the sender can take different paths while they travel and their strength can change when they reflect on reflect on some obstacles [3]. The above results show that the reflected signals have stronger strength than original signals. On the other hand, we expected that the signal strength to be more correlated with distance in a larger room (eg. basketball court). However, this is not the case as we seen from Figure 24. This is because the radio signals have more opportunities to travel with different paths, and thus, create more signal interference [3]. As a result, signal strength will not be a good indicator for estimating distances between sensor nodes in indoor places due to the effect of reflections.

5.3.2 Outdoor Environment

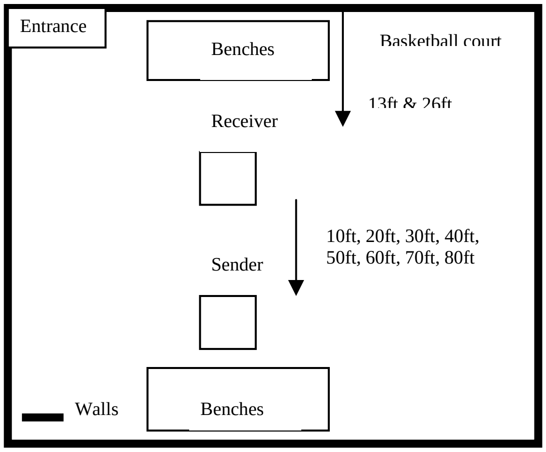

Figure 23: **Experiment Setting** to test the effect of reflections on signal strength in a basketball court (indoor). Both the sender and the receiver are placed on the ground. The receiver is fixed at different distances from the wall to compare the results. There are some benches in front of the wall.

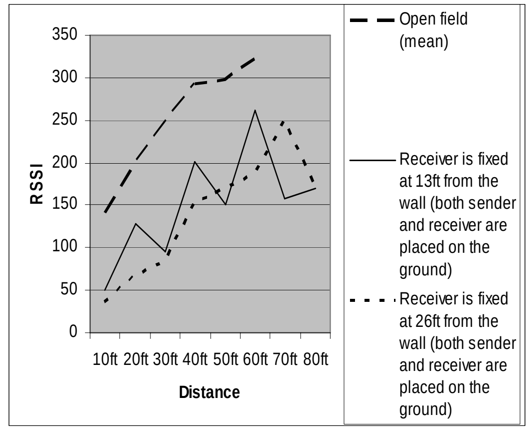

Figure 24: **Wall Reflections in Basketball Court** The effect of reflections from the wall on signal strength in a basketball court. The longer the distance the receiver is away from the walls in the indoor court, the lesser the effect of reflections on signal strength.

To show how reflections affect signal strength in outdoor environments, we performed two experiments in which both the sender and the receiver are placed on the ground. The first experiment took place at the parking lot in front of the International Center. In the experiment, we fixed the receiver at the distance of 1ft from a medium-sized vehicle and varied the sender at the distances of 10ft, 20ft, 30ft, 40ft, 50ft, 60ft, 70ft, and 80ft from the receiver. The result is shown in Figure 25.

The second experiment took place inside the Baker Woodlot and Rachana Rajendra Neotropical Migrant Bird Sanctuary on Bogue Street. The purpose of the experiment is to demonstrate the effects of reflections from tall trees and bushes on signal strength. We fixed the receiver and varied the sender at the distances of 10ft, 20ft, 30ft, 40ft, 50ft, 60ft, 70ft, and 80ft from the fixed receiver. Figure 26 shows the experiment setting in the research forest. The result is shown in Figure 27.

From all the tests performed in this section, we can observe that the there are some reflections in outdoor environments. The effects of reflections on signal strength depend on the complexity of the outdoor environments. The less complex environment has fewer reflections than a more complex one. As shown in Figure 25, the signal strength behaves as if it were in an open space environment. However, signal strength behaves a little more complicated in the forest as shown in Figure 27. There are more trees and bushes in the experiment surroundings, and that can possibly cause some reflections. Despite of the reflections, the signal strength is still correlated to distance for the range up to about 60ft. This shows that an outdoor environment could be an ideal place for RSS-based ranging even though reflections occurred.

5 Conclusions

We have demonstrated that how signal strength behaves in both indoor and outdoor environments. Signal strength does not correlate to the distance in an indoor environment, and it fluctuates over distance. Only a very small range of RSSI values can be used for estimating the distance between a pair of sensor nodes in an indoor environment. There are several factors that caused the signal strength to perform differently indoor. The effects of obstructions and reflections on signal strength are the major problems in RSS. Therefore, signal strength information is shown to be an unreliable indicator of distance in complex indoor environments due to obstacles and reflections [5]. When a signal travels through an obstruction, even if it successfully gone over, it losses its strength [3]. This happened because the obstruction can absorb the signal and weaken its signal strength [2]. More often, the signal not only goes through the obstacle, but it also gets reflected when it hits on the obstacle. This usually happened in indoor environments, in which there are a number of objects near to the surroundings such as walls, floors, and furniture.

Both the original signal and the reflected signal reach the receiver almost at the same time because they are traveling at the same speed of light. As a result of this, the receiver is not able to distinguish the two signals and it measures the received signal strength for both of them [6]. The transmitted and reflected signals are weaker than the original signal. The strength of both the transmitted and reflected signals depends on the angle at which it hits the obstacle [7]. However, obstructions and reflections do not have too much impact in an outdoor environment since there are apparently fewer objects in an outdoor field. As a result, an outdoor field appeared to be an ideal place for RSS ranging system [15].

Yet, there are still other factors that influence radio signal strength in RSS-based ranging. We have demonstrated that the higher the sensor nodes from the ground, the stronger the received signal strength. By lifting up the sensor nodes, we can possibly avoid most of the obstructions that can undermine the signal strength. Furthermore, we also showed that transmission power is correlated to distance. For instance, higher transmission power can be used for longer range estimation. By setting the transmission power to its highest, the signal is initiated with the strongest strength, and therefore, it can transmit for a longer distance.

Hence, RSS is shown to be inappropriate for range estimation especially in indoor environments. It does not produce reliable distance estimation based on RSSI. It is only good for very short range estimation. However, RSS provides more accurate results for estimating distance between sensor node pairs in an outdoor environment since the received signal strength is more correlated to distance.

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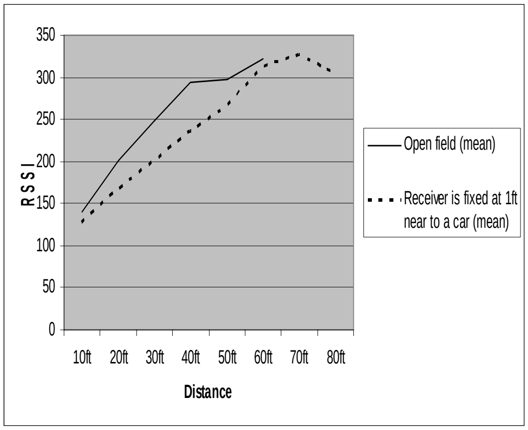

Figure 25: **Car Reflections** The effect of reflections from a medium-sized vehicle in an open parking lot. The open field result is used as a base for comparison. The receiver is fixed at 1ft from the vehicle, and the sender is varied at various distances from the receiver. The signal strength caused by reflections from the vehicle appeared to be slightly stronger (indicated by lower RSSI value) than signal strength in a non-reflected environment.

Figure 26: **Outdoor Data** in the Baker Woodlot and Rachana Rajendra Neotropical Migrant Bird Sanctuary.

Figure 27: **Trees Reflections** The receiver is fixed and the sender is varied at various distances from the receiver. The open field result is used as a base for comparison. The signal strength caused by reflections from the trees appeared to be slightly stronger (indicated by lower RSSI value) than signal strength in a non-reflected environment.

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