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IMPROVING DATA TRANSMISSION RELIABILITY AND
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IMPROVING DATA TRANSMISSION RELIABILITY AND THROUGHPUT IN WIRELESS SENSOR NETWORKS

By

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ABSTRACT

IMPROVING DATA TRANSMISSION RELIABILITY AND THROUGHPUT IN WIRELESS SENSOR NETWORKS

By

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Improving data transmission reliability and throughput in wireless sensor networks is a challenging task. The lossy nature of wireless communication and rapidly changing environment has caused tremendous problems in transmitting data packets between sensor nodes. Our key objective here is to maximize the overall transmission throughput. Before investigating various approaches to accomplish our goal, we start with an extensive study of how radio signals behave in complex environments where obstructions and reflections occur. We then design and implement a MAC layer overlay that consists of channel access scheduling and lost packet retransmission. The channel access scheduling mechanism is designed based on a hierarchical tree structure where each intermediate node collects data from multiple sources and forwards them to its parent at a higher level. The lost packet recovery can retransmit lost packets without reliance on any acknowledgments. We evaluate our protocol on both Mica2 and Tmote sensor testbeds, which shows that the data transmission throughput can be significantly improved.

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1. Introduction

1.1 Motivation

Recent advancement in wireless communications and electronics has enabled the development of low-cost sensor networks. A wireless sensor network comprises small sensing devices that are powered by batteries, equipped with a small processor and a limited memory. Each sensor has the ability to sense, compute, and communicate. In order for sensors to communicate with each other, they use multihop forwarding via wireless channels. Sensor networks have been widely deployed in certain applications such as disaster monitoring, battle field surveillance, and handicap assistance. Some of these sensor network applications suffer from obtaining reliable data transmission and high packet transmission throughput between sensor nodes due to the lossy nature of wireless communication and rapidly changing environment.

In this thesis, we aim at improving data transmission reliability and maximizing the overall transmission throughput in sensor networks. Before investigating various approaches to accomplish our goal, we start with an extensive study of how radio signals behave in complex environments. We then design and implement a MAC layer overlay which consists of channel access scheduling and lost packet retransmission.

1.1.1 Radio Signal Behaviors

Some sensor network applications make use of radio signal strength (RSS) for range estimation. In sensor networks, radio signal strength is defined as signal power received by a reference antenna. Radio signal strength is suitable for range estimation because RSS information can be collected easily without any additional cost with each signal sent and received. 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 occur continuously. Therefore, radio signal strength does not always fall off linearly or theoretically with distance.

In the first part of this thesis, 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 environments. The purpose is to show how great the effects of reflections and obstructions are on RSSI characteristics. We demonstrate our methodology in a natural forest with highly dense tall trees and bushes using 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 these experiments 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].

The analysis of the overall RSSI data collections from different experiments tends to give us an idea about its behavior in different cases. Unfortunately, some of the experiment results are unexplainable because the environment changes rapidly and therefore, affects signal strength. This shows that signal strength is not only a bad indicator for distance measurement but also a weak means of packet transmission. For example, a packet will be either corrupted or dropped if the signal strength is too low for the transmission to be carried on. This leads to a relatively low transmission throughput in certain "unpredictable" environment. However, we extend our research using a different approach to improve the data transmission throughput.

1.1.2 Receiver-Centric Approach

The main task of a sensor network is to periodically send data to the sink, which is the main unit that collects and processes data. Sensors usually work on light load unless there are suddenly activated by unexpected events where they need to forward a huge amount of data back to the sink within a short period of time. In such a case, it requires high throughput of data transmission, which is the primary objective of our approach. However, the channel contention, together with the lossy nature of wireless communication, makes it hard to achieve the high throughput of data transmission in wireless sensor networks. Therefore, to achieve such high throughput via colliding channels, two possible approaches are i) reduce channel collision by scheduling channel access among neighboring sensors; ii) ensure reliable data transmission by retransmitting lost packets.

Certainly we know that communication throughput in a wireless sensor network can be severely degraded by channel collisions since wireless channels can interfere with each other during broadcasting. This is a serious problem in a wireless sensor network when a large number of sensors keep forwarding data packets to the base station. To solve this problem, several Time Division Multiplex Access (TDMA)-based Medium Access Control (MAC) protocols [16] [17] have been proposed to statically assign time slots for channel access for neighboring sensors. However, TDMA is hard to deploy in wireless sensor networks since it needs a global view of the entire network topology and static time slot assignment cannot adapt to dynamic network change. Moreover, TDMA reduces channel utilization if idling time slots exist. On the other hand, the Carrier Sense Multiple Access (CSMA)-based MAC protocol is more flexible to changing network topology and easy to deploy in wireless sensor networks. Several well-known MAC protocols such as S-MAC [18], T-MAC [19], and B-MAC [20] have used the CSMA mechanism. However, the problem with CSMA is that it may increase channel collision.

Some hybrid protocols combining both CSMA/TDMA [21] [22] have been proposed to compromise the disadvantages of both CSMA and TDMA.

For the second part of this thesis, we propose a receiver-centric protocol that implements a channel access scheduling on the CSMA MAC layer and integrates lost packet recovery. The proposed protocol that acts as an overlay between network layer and link layer is designed to improve CSMA. It uses a tree-based topology where each intermediate sensor receives packets from multiple sources and then forwards those packets to its parent at higher level. The basic unit consists of one parent (receiver) and multiple sources (senders). The receiver manages scheduling and retransmission.

1.2 Objectives

We have several objectives in this thesis. We first experimentally study how radio signals behave in certain environment settings. Some environmental factors have severe effects on radio signal strength and thus, affect data packet transmissions. Most of the factors are unavoidable because they happen so naturally in the environment, and therefore, environment is unlikely to be tailored for better data communication throughput. Since tailoring the environment to obtain better packet transmission throughput is not a viable solution, we therefore implement a combined approach using channel access scheduling and lost packet recovery to improve data transmission throughput, even if the transmission has to take place in a more complicated environment settings. This is our second objective in this research.

1.3 Organization

Chapter 2 discusses related work in two different scopes. In Chapter 3 we present an extensive study of radio signal strength and its behavior in different complex environments. We then describe the receiver-centric approach used to improve the throughput in data packet transmission in Chapter 4, where we define the problem definition and its basic idea and mechanisms to improve throughput in sensor networks. In this chapter, we also include the experimental configuration and evaluation results for both channel access scheduling and lost packet retransmission. In Chapter 5 we conclude our research work and present future work.

2. Related Work

2.1 Related Work in Radio Signal Behaviors in Complex Environments

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 conducted recently to determine its accuracy and consistency for ranging. Most of the studies are focused on 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 summarizes 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 indoor room 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 in the surrounding area. Lastly, a slightly different environment is selected, which 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.

Table A: Summary of Factors Affecting Radio Signal Strength

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

Most systems that use RSS for ranging report 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 be 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 way 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 presence of reflections and obstructions. The effect of obstructions on RSS is certainly easier to be tested as compared to reflections, because one 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 reflection effects since reflections can be caused by the floors, ceilings, walls, and other materials in the surroundings. In this paper, we have investigated 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.

2.2 Related Work in Channel Access Scheduling and Lost Packet Retransmission

Many approaches have been proposed to improve the performance of data transmission in wireless sensor networks. Some of these approaches have been described in the Introduction section. We continue the remaining related work in this section.

MAC is important in sensor network since multiple nodes transmit data via the shared channel. Therefore, it requires a good mechanism to control channel access among multiple nodes with the aim to reduce channel collisions. Several TDMA-based protocols use the idea of time slots assignment among nodes within the network topology [16] [17] [21] [23]. However, this protocol has several disadvantages: it requires global view knowledge of the network topology, it is inflexible, and it is non-scalable. Other TDMA-based solutions include SS-TDMA [31] and Infuse [32]. Conversely, the major MAC protocols that have been implemented in sensor networks are CSMA-based [18] [19] [20]. Hybrid solutions of CSMA and TDMA have been proposed to reduce channel collision while maintaining the flexibility of CSMA. For instance, Z-MAC has been used to switch between CSMA and TDMA depending on data transmission rate. Z-MAC uses TDMA for high data transmission rate and CSMA for lower rate of data transmission to maximize channel utilization. Another solution proposed, Funneling-MAC [22], uses TDMA in the area that is close to the sink and CSMA in the rest of the network. It is based on the idea that channel contention is much higher in the area closer to the sink. Therefore, TDMA is applied to that small area while CSMA is applied to the rest. Unlike these approaches, the receiver-centric approach neither replaces the CSMA nor complements the CSMA. Our approach aims to reduce channel collision while retaining the flexibility and scalability of CSMA by applying a media access scheduling on the CSMA. Our approach can also be integrated to the CSMA part of any hybrid solution.

It is necessary to control sending rate of data packet from sensors to the sink. Otherwise, channels may be overloaded when large numbers of sensors continuously send packets and compete for channel access. Therefore, several solutions to control packet sending rate based on the channel utilization have been proposed [24] [25] [26] [27] [28]. Unlike these approaches, our approach emphasizes channel access scheduling along with the control of packet sending rate in order to achieve high channel throughput.

3. Radio Signal Behaviors

3.1 An RSS Ranging System

In wireless sensor networks, one purpose of radio signal strength (RSS) is to estimate distances between sensor nodes. This is often used in sensor localization, sensor scheduling, and other types of applications. A 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 consists of a sender and a receiver. The 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 a certain distance from the sender. For each 100 message received, the receiver computes the mean RSSI and outputs 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 a signal can transmit 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 in the hallway on the third floor of the Michigan State University (MSU) Engineering Building. The result of the experiment is shown in Figure 1.

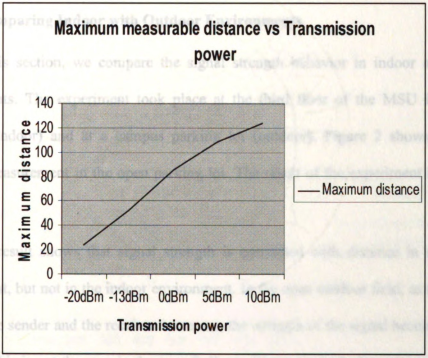


Figure 1: The maximum measurable distance between nodes for various transmission powers.

By increasing the transmission power, the sender can transmit 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 a longer distance.

3.2 Signal Strength Behaviors in Complex 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.

3.2.1 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 MSU Engineering Building (indoor) and at a campus parking lot (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 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 in many studies are often held constantly indoor.

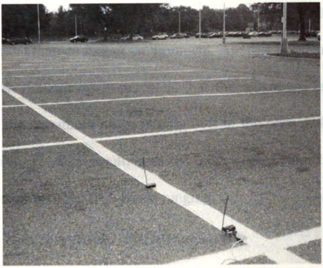


Figure 2: An open flat parking area without obstructions.

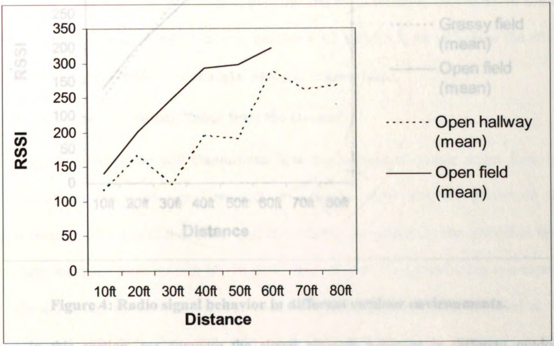


Figure 3: Radio signal behavior in indoor and outdoor environments.

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.

3.2.2 Comparing Different Outdoor Environments

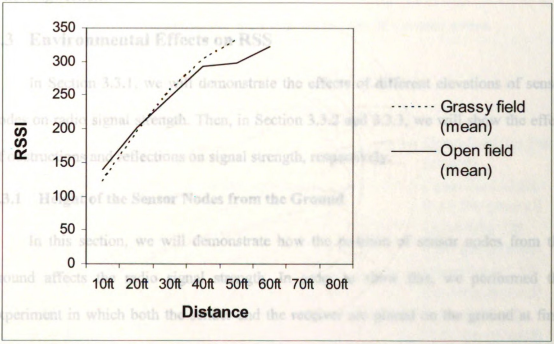


Figure 4: Radio signal behavior in different outdoor environments.

In this section, we compare the signal strength behavior in different outdoor environments. The experiment took place at a small soccer field and at the parking lot on Service Road as shown in 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.

3.3 Environmental Effects on RSS

In Section 3.3.1, we will demonstrate the effects of different elevations of sensor nodes on radio signal strength. Then, in Section 3.3.2 and 3.3.3, we will show the effect of obstructions and reflections on signal strength, respectively.

3.3.1 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 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 in two classrooms. Similarly, both the

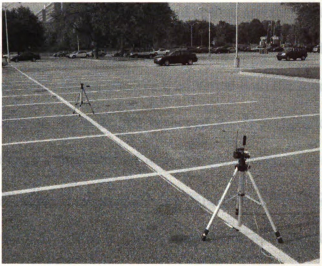


Figure 5: The assistance with tripods to raise the sensor nodes.

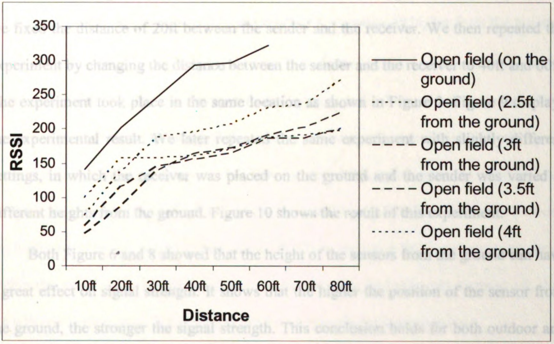


Figure 6: Elevation of sensor nodes affects signal strength in the outdoor environment.

sender and the receiver are placed on the ground at first, and then, we lifted both sensors from the ground to the height of 2.5ft 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 were positioned at the same height. However, we are interested in determining how 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 repeated the same experiment with slightly different settings, in which the receiver was placed on the ground and the sender was 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 overcome most of the obstructions (e.g. 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 3.3.2. However, there is a difference between indoor and outdoor environments. There is a linear correlation between signal strength and distance in the outdoor field, but not in the 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 either passes through the obstacle and has weaker signal strength after passing it, or it is 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 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 a more error-free result, as predicted from the previous studies.

3.3.2 Effects of Obstructions

Obstructions are one of the major concerns in RSS ranging systems. 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

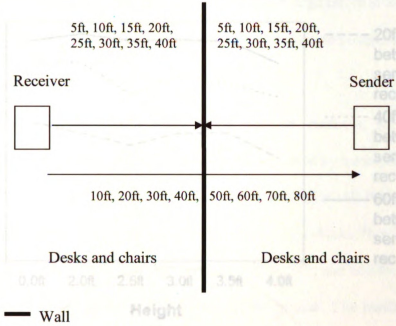


Figure 7: Placement of sensor nodes in two classrooms.

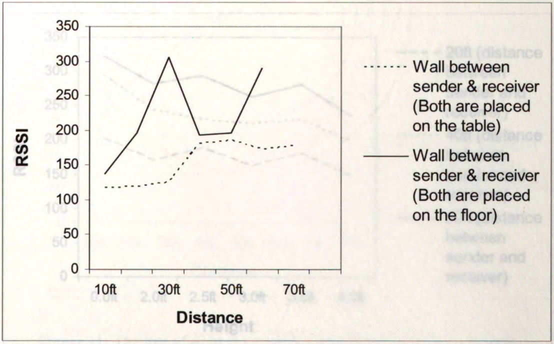


Figure 8: The effects of lifting both sensors in the indoor environment.

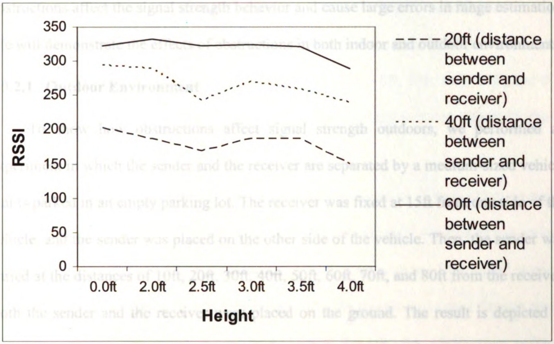


Figure 9: The effects of different elevations of receiver on signal strength.

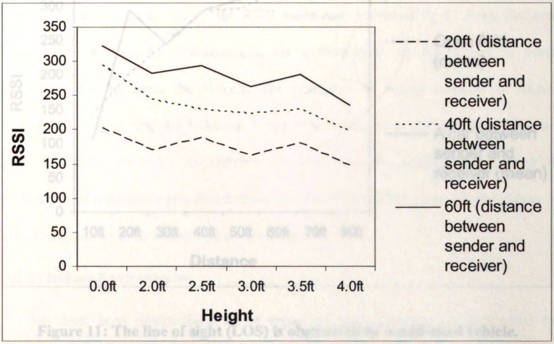


Figure 10: The effects of different elevations of sender on signal strength.

obstructions affect the signal strength behavior and cause large errors in range estimation. We will demonstrate the effects of obstructions in both indoor and outdoor environments.

3.3.2.1 Outdoor Environment

To show how obstructions affect signal strength outdoors, we performed an experiment in which the sender and the receiver are separated by a medium-sized vehicle that is parked in an empty parking lot. The receiver was fixed at 15ft from one side of the vehicle, and the sender was placed on the other side of the vehicle. Then, the sender was varied at the distances of 10ft, 20ft, 30ft, 40ft, 50ft, 60ft, 70ft, and 80ft from the receiver. Both the sender and the receiver were placed on the ground. The result is depicted in Figure 11.

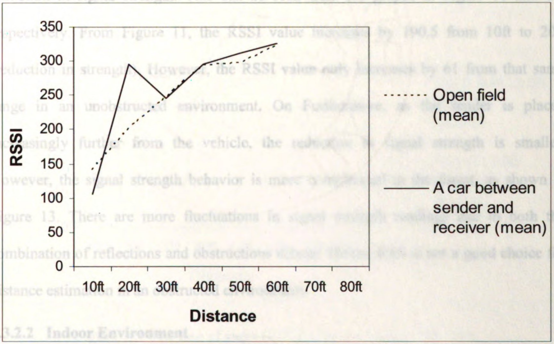


Figure 11: The line of sight (LOS) is obstructed by a mid-sized vehicle.

Additionally, we performed another experiment in a more complex outdoor environment. The experiment is located in a natural forest clustered with tall trees and bushes and it is not a flat open area. Therefore, we used 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, RSS is not a good choice for distance estimation in an obstructed environment.

3.3.2.2 Indoor Environment

To show how obstructions affect signal strength indoors, we performed two experiments in which the sender and the receiver were separated by a wall in both experiments. The first experiment took place in two classrooms. These classrooms were

Figure 12: A natural forest with a cluster of tall trees and bushes.

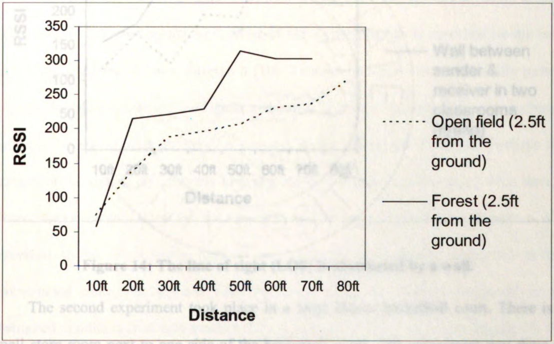


Figure 13: The line of sight (LOS) is obstructed by tall trees.

separated by a wall. In order to minimize the effect of other obstructions, we rearranged the tables and chairs in both classrooms. Figure 7 on page 14 shows the arrangement in the classrooms. The sender was placed in one classroom and the receiver was placed in the other classrooms. Both were placed on the floor. Before we measured the RSSI of the received signal, we varied both the sender and the receiver at the same distance from the wall each time. Figure 14 shows the result of the experiment.

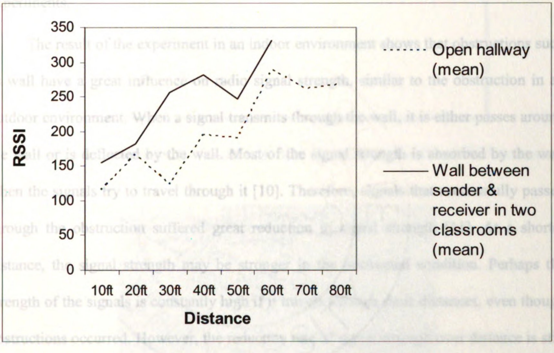


Figure 14: The line of sight (LOS) is obstructed by a wall.

The second experiment took place in a large indoor basketball court. There is a small store room next to one side of the basketball court. The experiment was done in three different ways in which both the sender and the receiver were placed on the ground each time. First, we found 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 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 a photo 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 varied 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 obstructions such as wall have 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 is 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 successfully passed through the obstruction suffered great reduction in signal strength [11]. At a shorter distance, the signal strength may be stronger in the obstructed condition. Perhaps the strength of the signals is constantly high if it travels 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 compared to the unobstructed ones. Furthermore, the maximum range that can be measured in an obstructed condition is clearly smaller than in an unobstructed one. From Figure 18, the maximum range is only 30-40ft in the presence of the wall, which is less than the one without the wall. Hence, RSS ranging can provide large errors in distance estimation since it is highly sensitive in an obstructed environment.

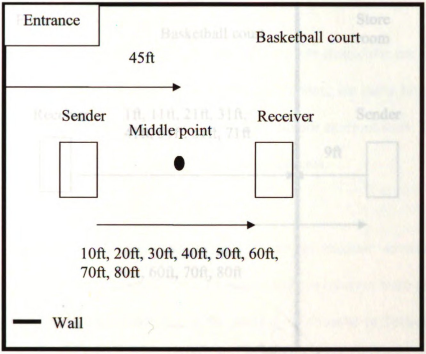


Figure 15: Environment for baseline metric measurement without obstructions.

Figure 16: The real environment shown in Figure 15.

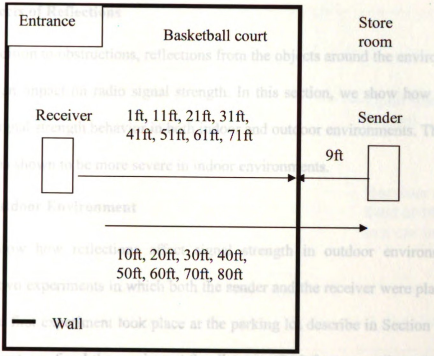


Figure 17: The setting in a basketball court for testing wall effects.

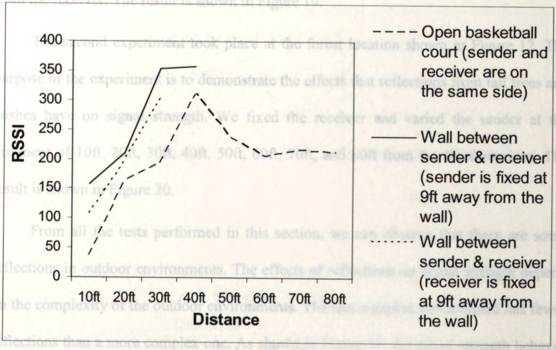


Figure 18: The line of sight (LOS) is obstructed by a wall in Figure 17.

3.3.3 Effects 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.

3.3.3.1 Outdoor Environment

To show how reflections affect signal strength in outdoor environments, we performed two experiments in which both the sender and the receiver were placed on the ground. The first experiment took place at the parking lot describe in Section 3.3.2.1. 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 19.

The second experiment took place at the forest location shown in Figure 12. The purpose of the experiment is to demonstrate the effects that reflections from tall trees and bushes have 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. The result is shown in Figure 20.

From all the tests performed in this section, we can observe that 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 19, the signal strength behaves as if it were in an open space environment. However, signal strength exhibits a slightly more complicated behavior in the forest as shown in Figure 20. There are more trees and

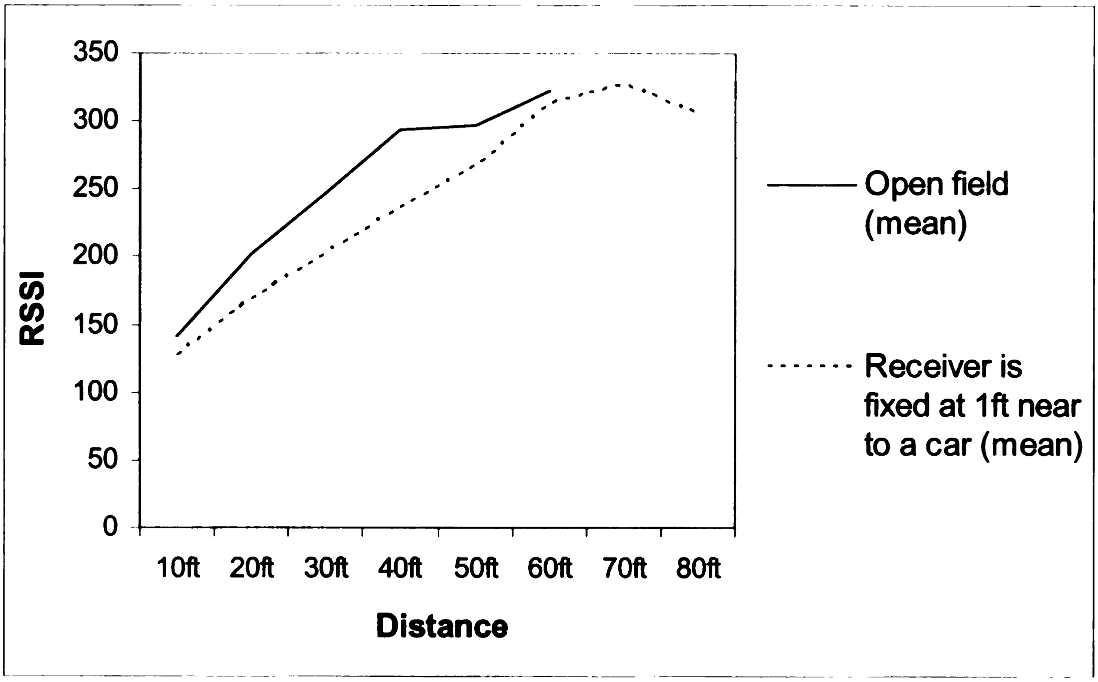


Figure 19: The effects of reflections from a mid-sized vehicle.

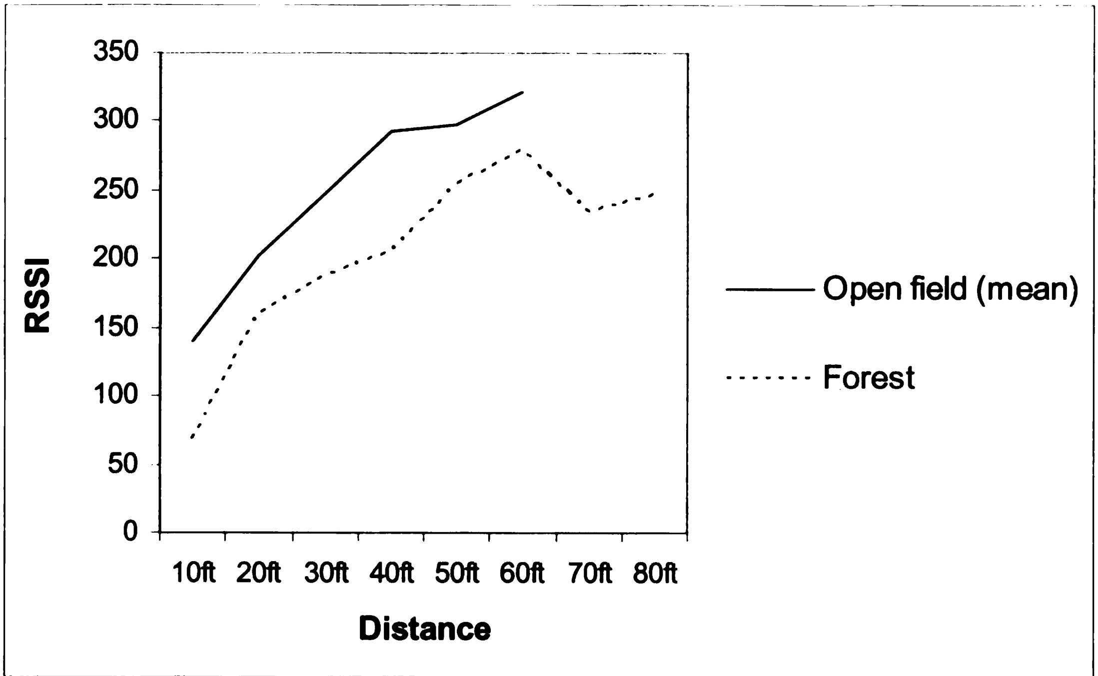


Figure 20: The trees reflections on signal strength.

bushes in the experiment surroundings, and that can possibly cause some reflections. Despite 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.

3.3.3.2 Indoor Environment

To show how reflections affect signal strength indoors, we performed three experiments in which both the sender and the receiver were 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 same hallway location described in Section 3.2.1. The experiment was then repeated by fixing the receiver at 8ft from the same wall. Figure 21 shows the experiment setting. The result is shown in Figure 22.

In the second experiment, we fixed the sender at the distance of 50ft from the same wall that was used in the previous experiment. The experiment was done in the same hallway as in the previous experiment. We then varied the receiver at various distances from the same wall. Figure 23 shows the experiment setting and the result is depicted in Figure 24.

Lastly, we performed the experiment in a large indoor basketball court as described in Section 3.3.2.2. 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. The received RSSI value was collected for each distance. The experiment was then repeated by fixing the receiver 26ft away from the same wall. Figure 25 shows the experiment setting. The result is shown in Figure 26.

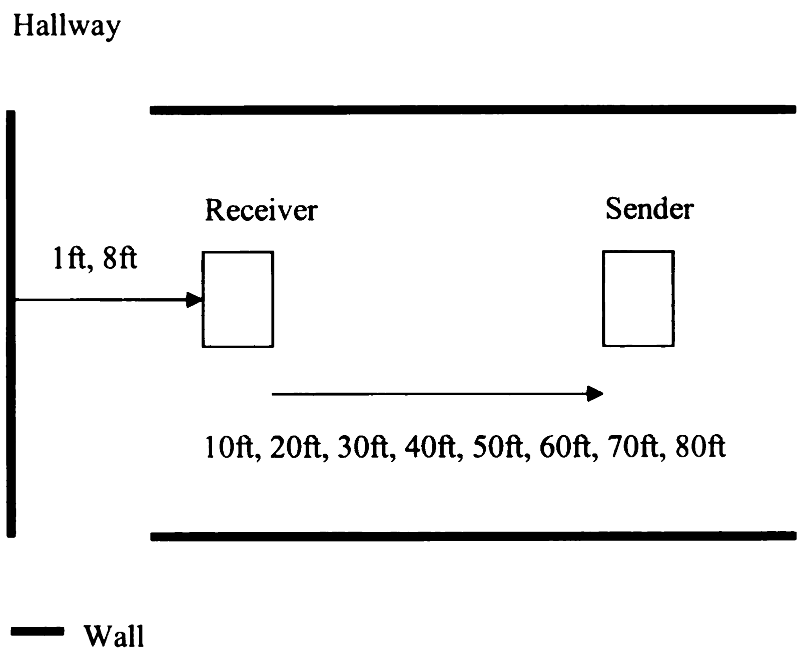


Figure 21: Hallway setting for testing wall reflections while fixing the receiver.

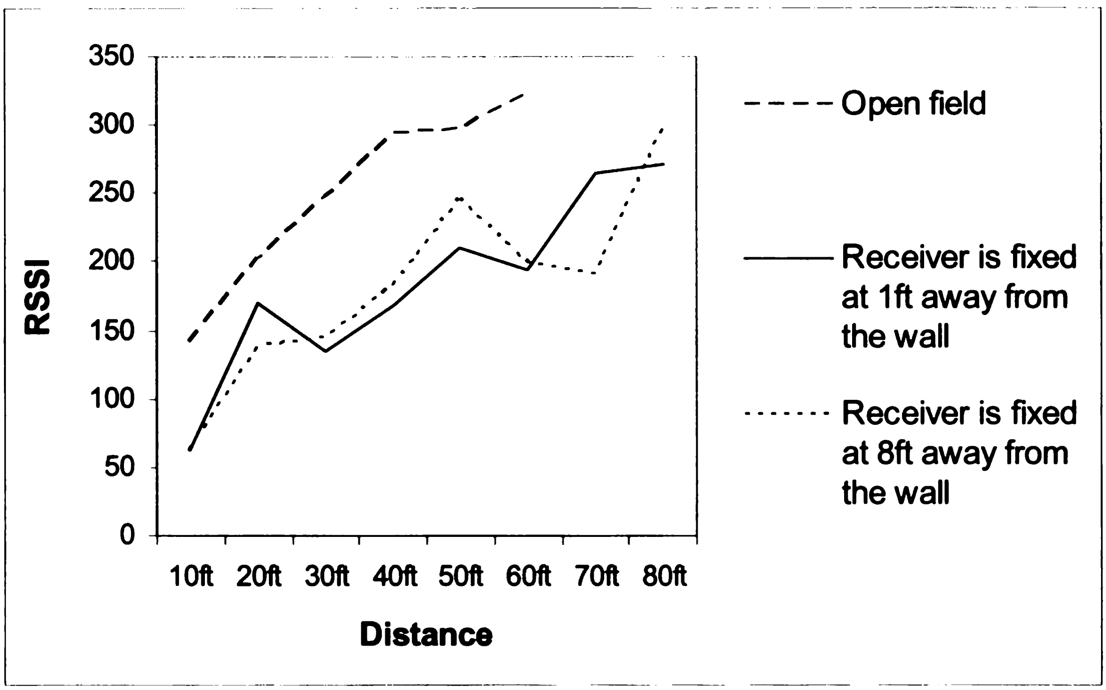


Figure 22: The effects of wall reflections on signal strength for Figure 21.

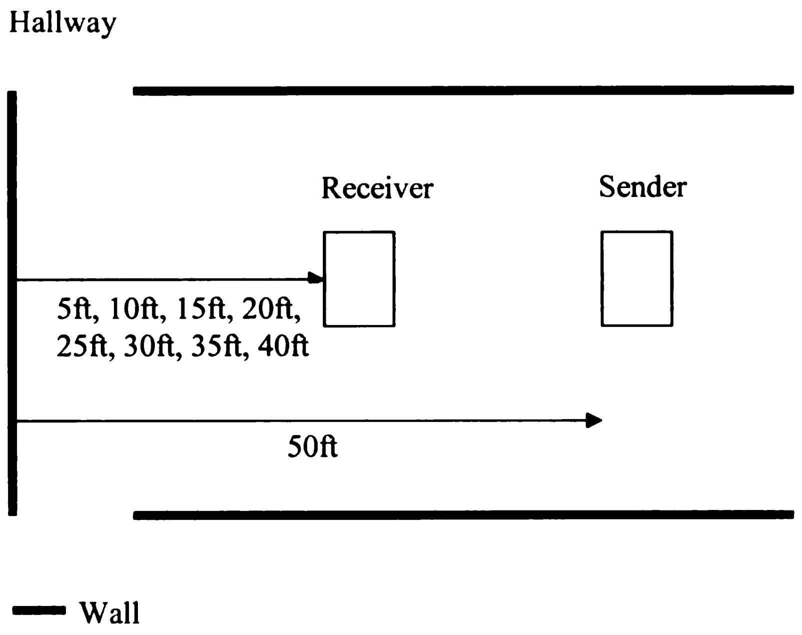


Figure 23: Hallway setting for testing wall reflections while fixing the sender.

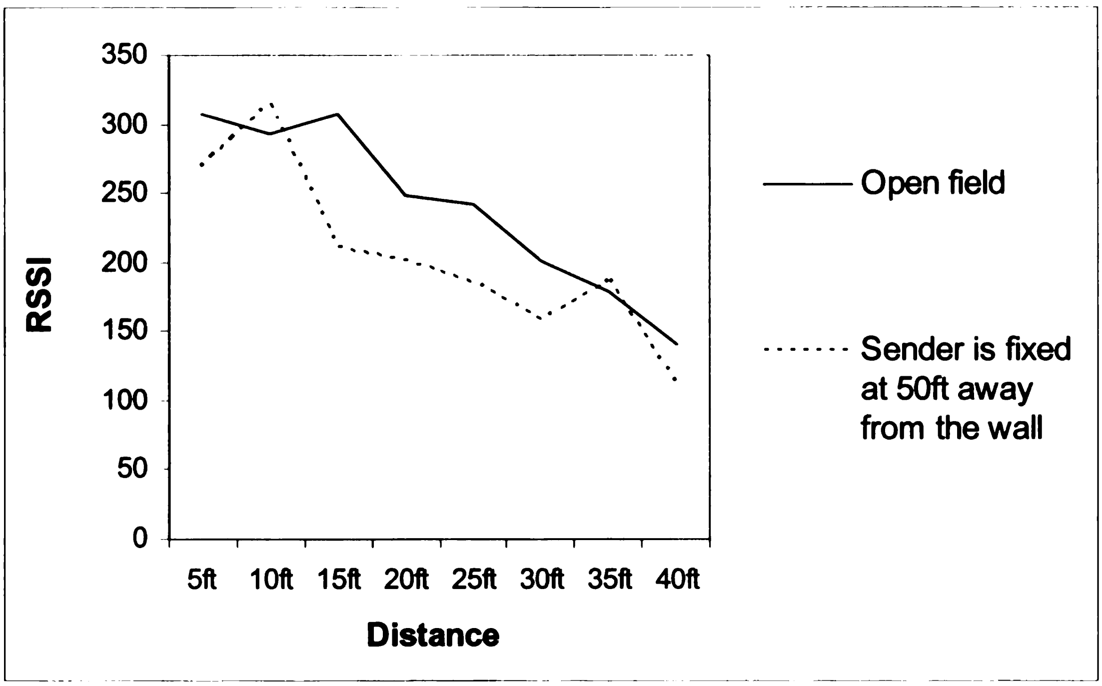


Figure 24: The effects of wall reflections on signal strength for Figure 23.

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 Figures 22, 25, and 27, the radio signal strength appeared to be stronger indoors than signal strength measured outdoors (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 the ground to the sensors nodes is greater than 0.97m [4]. Radio signals are transmitted through waves and the radio waves from the sender can take different paths while they travel and their strength can change when they 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 26. 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.

3.4 Summary

We have demonstrated 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

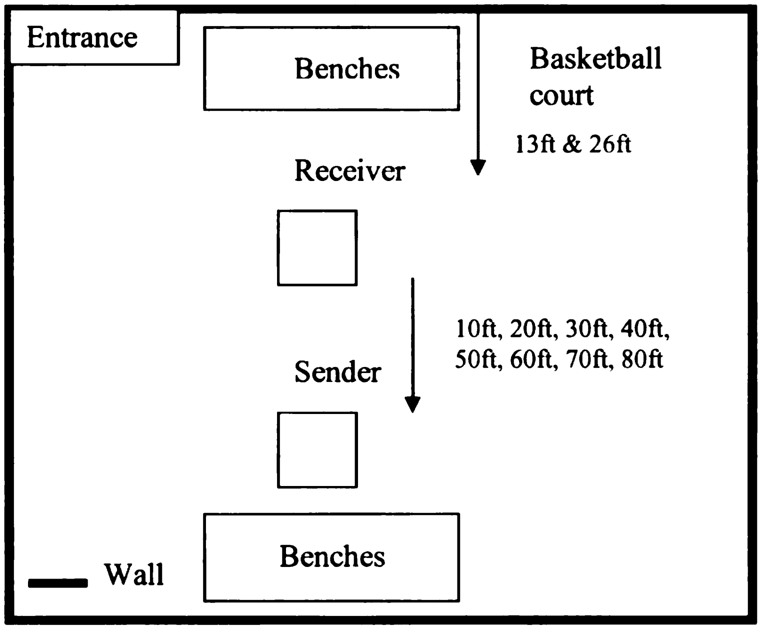


Figure 25: Basketball court setting for testing wall reflections while fixing the receiver.

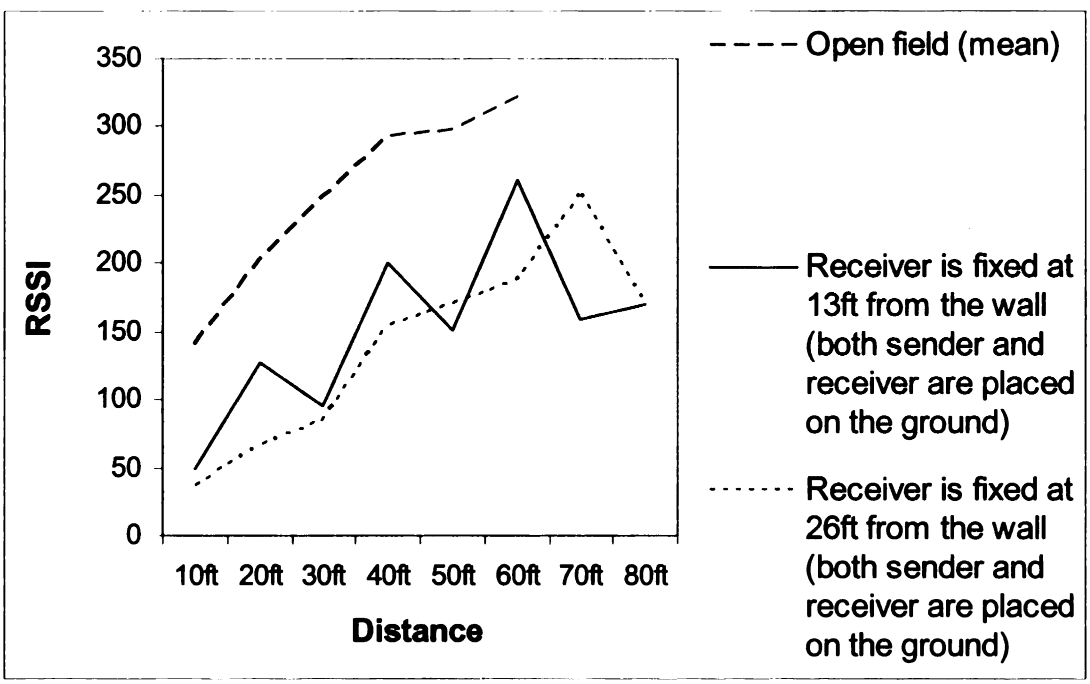


Figure 26: The effects of wall reflections on signal strength for Figure 25.

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 indoors. 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 penetrates over, it loses its strength [3]. This happens 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 the obstacle. This usually happens in indoor environments, in which there are a number of nearby objects 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. 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 appears 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. This shows that environment changes have great effects on signal strength. Weak signal strength tends to corrupt or drop packets during transmission, and therefore, results in a relatively low data transmission throughput in "unpredictable" environment. In the next section of this thesis, we extend our research to improve the data transmission throughput without considering any environmental factors.

4. Receiver-Centric Protocol

Our previous experiments with RSS demonstrate that tailoring the environment for better data transmission throughput is a very difficult task since signal strength that is used as a means for packet transmission becomes very weak when obstructions and reflections exist. Based on this result, we look for another alternative to achieve better transmission throughput without rely on the environment. Therefore, we introduce a protocol called receiver-centric, which is a MAC layer overlay that aims to improve communication throughput of sensor networks. The receiver-centric protocol consists of two parts: the channel access scheduling and the lost packet retransmission.

4.1 Channel Access Scheduling

We present the issues of media access control in sensor networks and discuss how these issues can be addressed by our approach.

4.1.1 Problem Definition

Data collection in wireless sensor networks acquires numerous sensors to simultaneously send packets through radio channels of the same frequency. Therefore, media access control (MAC) needs to control the access to these shared channels among neighboring sensors. Major MAC protocols [18] [19] [20] implementing Carrier Sense Multiple Access (CSMA) have been widely deployed for this application due to its high flexibility and adaptability. CSMA uses a carrying sensing multiple access mechanism to schedule neighboring sensors to access a shared channel. Each sensor has to listen to the shared channel and forward packets only if the channel is idle. Therefore, it is possible that two sensors will forward packets at the same time when they both acknowledge that the channel is idle. This causes collision and corrupts packets. To solve this problem, the back-off mechanism is proposed. A sender may back-off for a random time before sending out packets. A sender may keep resending a packet multiple times when a group of senders try to send packets at a high transmission rate. This event intensifies the collisions among packets and thus, reduces its transmission throughput. To reduce channel collisions, the receiver-centric approach imposes a channel access scheduling, which aims to improve CSMA. The design and implementation of channel access scheduling are described in the following subsection.

4.1.2 Basic Idea

The receiver-centric protocol works with CSMA in channel access scheduling. Sensors are still using CSMA to access shared wireless channels. In the tree-based topology, the intermediate node acts as a parent and receives packets from multiple children; therefore, it becomes a perfect candidate to schedule packet transmission. The channel access scheduling is shown in Figure 27. The receiver-centric protocol takes advantage of the broadcast nature of wireless channels for scheduling purposes. The protocol uses two alternative approaches. First, we can reuse the acknowledgment packets (ACKs) to schedule children's packet transmission if a time-out mechanism is used by MAC. Due to its broadcast nature, the ACK sent to one of the children can be overheard by all children. Therefore, we schedule children's packet transmission by piggybacking a scheduling message to ACKs, where the message contains the ID of the children that are scheduled to send the packet in the next iteration. All children will overhear the message and each child will determine if it is its turn to send packets by matching the schedule ID to its own ID. If they match, the node will start sending packets; otherwise, it holds its transmission for the next schedule ID. It is easy to see that only scheduled child transmits packets, and thus, reduces channel

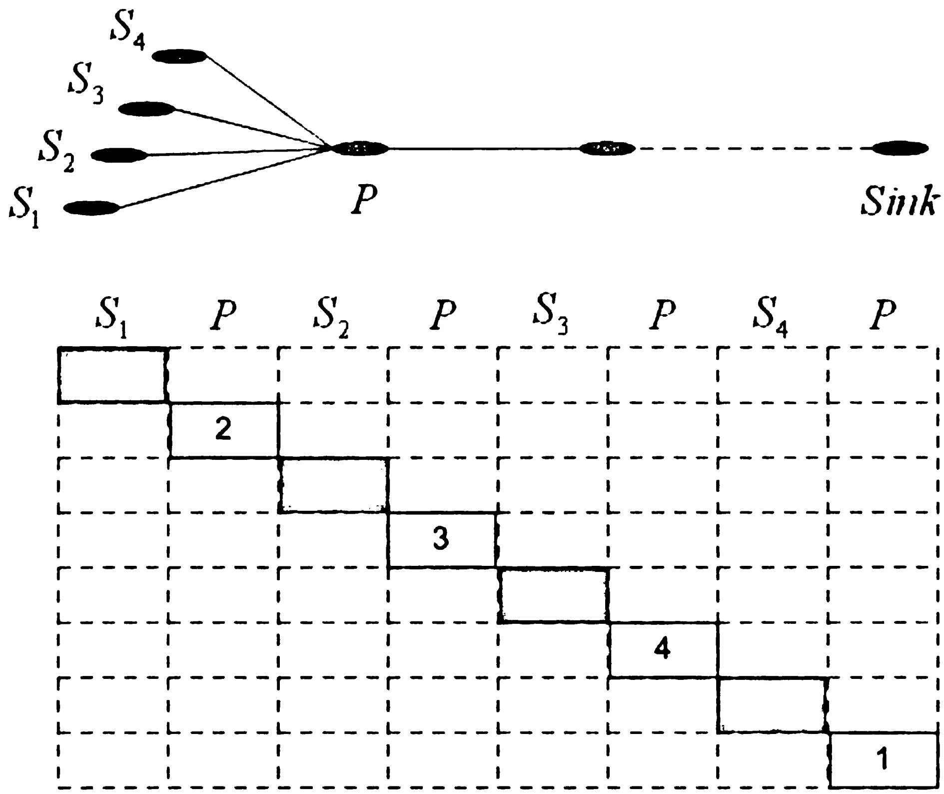


Figure 27: Receiver-centric protocol schedules time slots in a round-robin fashion via overhearing.

collisions. Note that the scheduling is only done within the basic unit, which is between its immediate parent and children. Second, we can use multihop forwarding without reliance on ACKs. When a parent receives packets from its children, it continues to forward the packets to the next hop by attaching a schedule ID to those packets so that the schedule ID can be overheard by its children.

4.1.3 Scheduling Mechanism via Overhearing

Each intermediate node contains a buffer, implemented using a queue, which stores all packets received from its children. These packets are buffered at the tail of the queue (enqueue operation). A background queue service task keeps fetching packets from the head of the queue and transmits the packet when it overhears the matching schedule ID (dequeue operation). To reduce channel collision, we insert a delay timer to dequeue operation so that the queue service task will hold for a certain time period before sending out the next packet. During this time, the children wait for the scheduling message from the parent via overhearing. The parent attaches a one-byte field that contains the next schedule ID to the packet. A child will start transmitting a packet if its ID matches the schedule ID; otherwise, the child will reset its delay timer and continue to wait for the next schedule ID. The channel access scheduling utilizes the round-robin fashion to ensure fairness among children, i.e. when the parent forwards a packet from child i, it will attach node ID $i+1$ to the scheduling field, and continuing in this fashion. Figure 27 illustrates the round-robin scheduling. When parent P forwards a packet from node 1, the node ID 2 is attached to that packet, which can be overheard by all its children. Only node 2 will start sending its packet in the next round while other nodes hold on to their transmission. All children will have their chance to transmit packet in the round-robin process without intensifying channel collisions.

4.2 Lost Packet Retransmission

Lost packets retransmission is widely used to ensure reliable data transmission in wireless sensor networks. However, our experiments show that the channel collision can also be intensified by lost packet retransmission. We define this problem and discuss how the receiver-centric protocol addresses this problem in the following discussions.

4.2.1 Problem Definition

It is necessary to retransmit lost packets in an unreliable wireless medium in an attempt to maximize the data transmission throughput. We illustrate this point by using a simple numerical analysis. Assuming that the packet loss rate of a wireless channel is r, the packet transmission success rate after n-hop forwarding will be $(1\text{-}r)^n$. Therefore, it can be measured that more than 40% of the packets will be lost after 6-hop forwarding when channel lost rate r = 0.1. This can severely degrade data transmission throughput since many packets are lost during the forwarding phase. One of the most basic approaches to retransmit lost packets is the time-out mechanism. In this approach, the sender will wait for an acknowledgment from the receiver after it transmits a packet, and will retransmit the packet if the acknowledgment is not received within a specific time period. This mechanism is simple and easy to implement. However, it may intensify channel collision and therefore reduce throughput in the following ways. First, the acknowledgment packets will compete with data packets for the communication channels and these acknowledgment packets are usually up to 15 bytes long. Therefore, the extra overhead of these acknowledgment packets cannot be ignored. Second, the acknowledgment packets may be lost due to unreliable wireless channels, which cause unnecessary retransmission. These duplicate packets, again, compete with other data packets for communication channels. Third, data packets may be dropped by the overflowed buffer on the receiver's side and the sender will not be aware of this situation and will retransmit packets unnecessarily. This will further cause severe channel collisions if all senders keep retransmitting lost packets.

To retransmit lost packets without intensifying channel collisions, we defer the retransmission decision to the receiver. The receiver will request the sender to retransmit packets only when necessary.

4.2.2 Basic Idea

The receiver-centric protocol uses a sequence-based counting mechanism to detect and retransmit lost packets. To detect lost packets between a sender and a receiver, the sequence-based mechanism labels all packets that are sent from the sender with continuous sequences, and lost packets can be detected by the receiver if it receives discontinued-sequence packets. Therefore, the receiver can request the sender to retransmit the lost packets using the discontinued sequence. Unlike the time-out approach, channel collision can be reduced significantly because i) acknowledgments are not used; ii) duplicate packets incurred by lost acknowledgment will not happen; iii) the receiver will not request for retransmission packets if its buffer is overflowed.

The sequence-based mechanism relies on strictly in-order sequence to detect lost packets, which may interrupt packet forwarding. If packet forwarding can be interrupted by lost packet retransmission, the situation will become worse if some packets cannot be recovered due to buffer overflow. These lost packets will always be detected by the following intermediate forwarding nodes, and these nodes will request the retransmission for the unrecoverable packets. The interruption occurs because the sequence-based

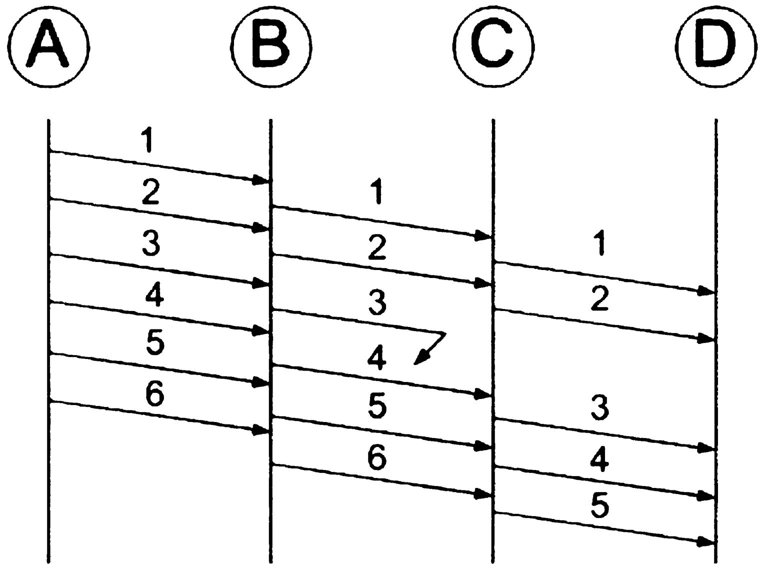


Figure 28: In Receiver-centric protocol, node C continues to forward packet 4, 5, and 6 even when packet 3 is lost.

mechanism uses strict continuous sequences that are maintained globally between the source and the sink. To solve this problem, we use a localized numbering mechanism to re-label each packet that needs to be forwarded. In this mechanism, when a node receives a packet, it will re-label the packet with a continuously increased sequence maintained in a local variable. As illustrated in Figure 28, each node maintains a local sequence numbering that is increased with received packets. When node C detects lost packet 3 based on discontinued sequence, node C can still continue to forward packets 4, 5, and 6 to node D since all packets are re-labeled by node C with new sequences. Therefore, packet interruption in one hop will not affect the continuous packet forwarding.

4.2.3 Request Lost Packets with Overhearing

To ensure continuous packet forwarding, the receiver-centric protocol does not use a dedicated message to request lost packets. Instead, the lost sequence is piggybacked to the data packets and the sender can be notified through overhearing. This mechanism uses the broadcast nature of wireless channels where packets forwarded by an intermediate node can always be overheard by its predecessor. By using this overhearing, all the bandwidth can be allocated to data packets when dedicated messages are avoided.

In the receiver-centric protocol, each forwarding node maintains a buffer that operates as a regular queue, i.e. a received packet is stored at the tail of the queue whereas a packet is transmitted at the head of the queue. Moreover, the queue is divided into three regions: sending region, receiving region, and recovery region. As shown in Figure 29, where the sending region contains all packets that wait to be sent, the recovery region contains all packets that have been sent, and the receiving region contains empty buffers that are destined for the new packets. Here, the sending region sends out packets at the *head* and receives packets at the *tail*. However, when a packet is transmitted, it will be moved temporarily from the sending region to the recovery region, which can be used to recover lost packets. The recovery of a lost packet is detailed in the following. We use an extra pointer, *vHead*, which pointed to the buffer containing the lost packets. When the lost packet is retransmitted, the *head* will continue to be used for packet forwarding. Here, *vHead* is used to look up the lost packet in the recovery region without having to screen through the entire region. This is achieved by renumbering a packet based on the index of the buffer containing the lost packet. Since the local sequence variable will increase simultaneously with the queue movement, the sequence number will be increased by 1 when a new packet is buffered into the queue, and the sequence number s assigned to the new packet is corresponded to the index i of the buffer containing that

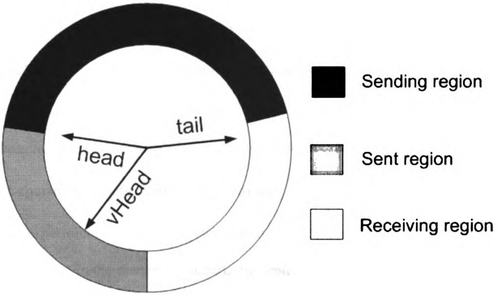


Figure 29: Receiver-centric protocol divides packet buffers into three regions: sending region, recovery region, receiving region.

packet. Therefore, we have $i = s$ mode N, where N is the buffer size. As a result, the index of a lost packet can be computed easily from its sequence number in O(1) time.

4.3 Performance Evaluation

We implement the receiver-centric protocol in TinyOS and evaluate the performance in both Mica2 and Tmote sensors. The key features of both Mica2 and Tmote are listed in Table B. We evaluate the performance of the receiver-centric protocol by comparing with the time-out retransmission enabled with acknowledgments (ACK) and the best-effort mechanism without acknowledgments (NACK). The following metrics are used in our evaluation.

Event throughput: the total number of unique packets received at the sink per second.

Packet injection interval: the time period between two consecutive packet transmissions (the sending speed of a sender).

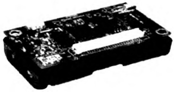
Buffer size: the length of transmission queue, which is the maximum number of packets that a forwarding node can store.

Data length: the number of bytes in a packet that is used to store collected data.

4.3.1 Experimental Setup and Configuration

Our experimental system consists of two parts, the management part and the data transmission part. In the management part, the control message is broadcast from the sink to the entire network, which initializes the network with desired configuration parameters including the radio transmission power, the buffer size, and the packet data size. The sink also uses the control messages to trigger sources to start sending packets. The format of the control message is shown in Figure 30, which contains several fields including inject rate, transmission power, ACK field, and packet size. By setting those fields with proper values, sources can be initiated with different parameters for each testing. It is possible that control messages may be lost during the broadcast, which results that i) some sources may not be triggered; ii) intermediate nodes may not be initiated with proper transmission power and buffer size. We use two strategies to solve this problem. First, all packets received by the sink are forwarded to the laptop through the serial cable. The packets contain the source ID that generates the packets. By checking all received source IDs, the inactive sources that do not send packets can be identified and re-triggered. Since all the configuration parameters, such as the transmission power and buffer size, are included in the control messages, sources can be initialized with correct parameters as long as they can be triggered by the control messages. Second, sources can pass the configuration

Table B: Key Features of Mica2 and Tmote

Key Features	Mica2	Tmote
		
Interface	COM (Serial)	USB
Multi-Channel Radio Frequency	916 MHz	2.4 GHz
Maximum Power	5 dBm	40 dBm
Encryption	No	Yes
Outdoor Range	500ft	420ft
Cost	$200 per mote	$130 per mote

parameters to intermediate nodes through data packets. When sources generating data packets, they will initialize packets with the transmission power and buffer size. Therefore, intermediate nodes can reset the configuration parameters with the same values as long as they receive packets from sources.

```
typedef struct SF_CMD {
    uint8_t src;
    uint8_t CMD;
    bool bACK;
    uint8_t power;
    uint16_t injectRate;
    uint8_t num_children;
} SF_CMD;
```

Figure 30: Control message format.

We use three network topologies in our evaluation: the linear topology, the star topology, and the tree topology. Since we only evaluate the communication performance of a sensor network at the link layer, the routing function at the network layer is not included in our program. Instead, we use a fixed routing path in our test. This can be achieved by statically assigning a routing table when sensors are initially reprogrammed. For the three topologies used in our evaluation, we only need to define the child/parent relationship in the routing table, such that an intermediate node can receive packets from its children and forward packets to its parent.

Assisted by the management part, we can control the testbed and evaluate different approaches in the data transmission part. After we reprogrammed sensors with one approach, we conducted multiple tests with different settings of packet inject rate, buffer size and packets size. This is achieved by the control message broadcast from the sink. We detail our performance evaluation under various settings in the discussion below.

4.3.2 Channel Access Scheduling under Different Packet Injection Intervals

We first evaluate the event throughput of channel access scheduling under different intervals. In our test, two sources simultaneously send packets to a parent, which continue to forward the received packets to the sink. All packets received by the sink are further forwarded to the attached laptop, which can filter duplicated packets based on their unique packet IDs and compute event throughput of data transmission. Three approaches, including the receiver-centric with channel access scheduling, the ACK with CSMA, and the NACK with CSMA, are evaluated with both Mica2 and Tmote sensors. We evaluate how the packet inject rate affects the event throughput by varying the packet inject intervals. Figure 31 shows the event throughput of the three approaches in Mica2 sensors, and Figure 32 shows the event throughput of the three approaches in Tmote sensors. The tests on both platforms show that the receiver-centric protocol helps to improve the event throughput of CSMA when the packet inject interval is small. We also observe that the event throughput of NACK outperforms the ACK when the packet inject interval is small.

When the packet inject interval is increased to a large value (greater than 100 milliseconds), our test on Mica2 sensors shows that all the three approaches have close event throughput performance. Based on this test, we conclude that the ACK can intensify channel collision and degrade event throughput at high packet sending rate. We also conclude that the channel collision of both ACK and NACK approaches can be reduced by the channel access scheduling of the receiver-centric approach, and therefore high event throughput can be achieved under high packet sending rates.

4.3.3 Channel Access Scheduling under Different Number of Sources

We further evaluate the scheduling mechanism under different number of sources. Figure 33 (in Mica2) and Figure 34 (in Tmote) show that the event throughput is reduced with the increased number of sources. This is because i) the bandwidth is divided and less

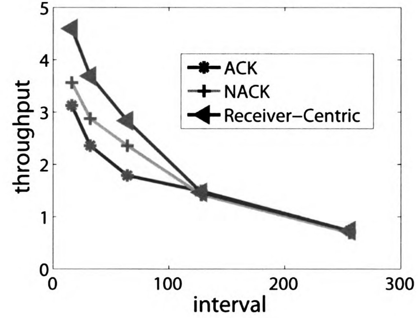


Figure 31: Scheduling in Mica2 under different packet injection intervals.

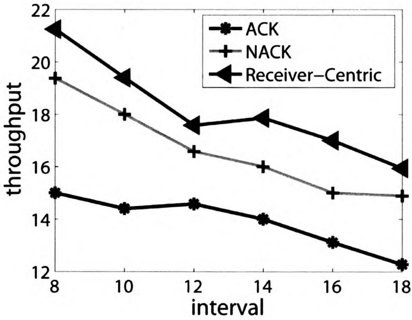


Figure 32: Scheduling in Tmote under different packet injection intervals.

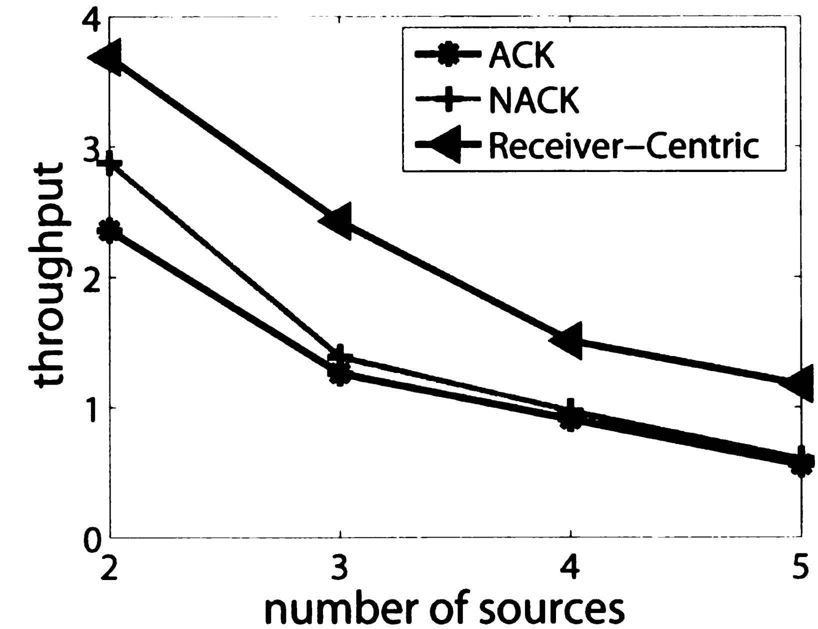


Figure 33: Scheduling in Mica2 under different number of sources.

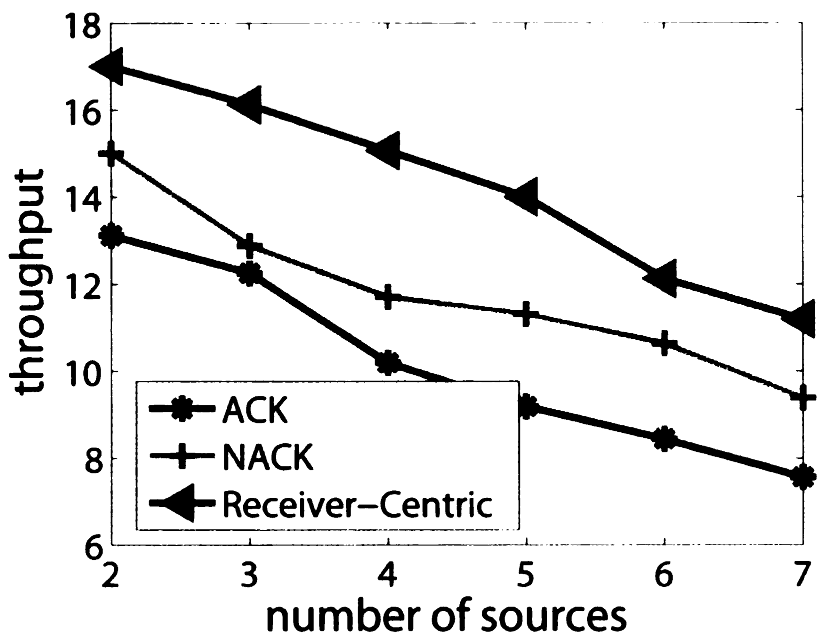


Figure 34: Scheduling in Tmote under different number of sources.

bandwidth can be reserved by an individual source and ii) increasing the number of sources intensifies the channel collisions, which results in more packets being lost during the transmission. Both figures also show that the receiver-centric approach outperforms the other two approaches at different number sources, because the scheduling mechanism reduces the channel collisions.

4.3.4 Channel Access Scheduling under Different Buffer Sizes

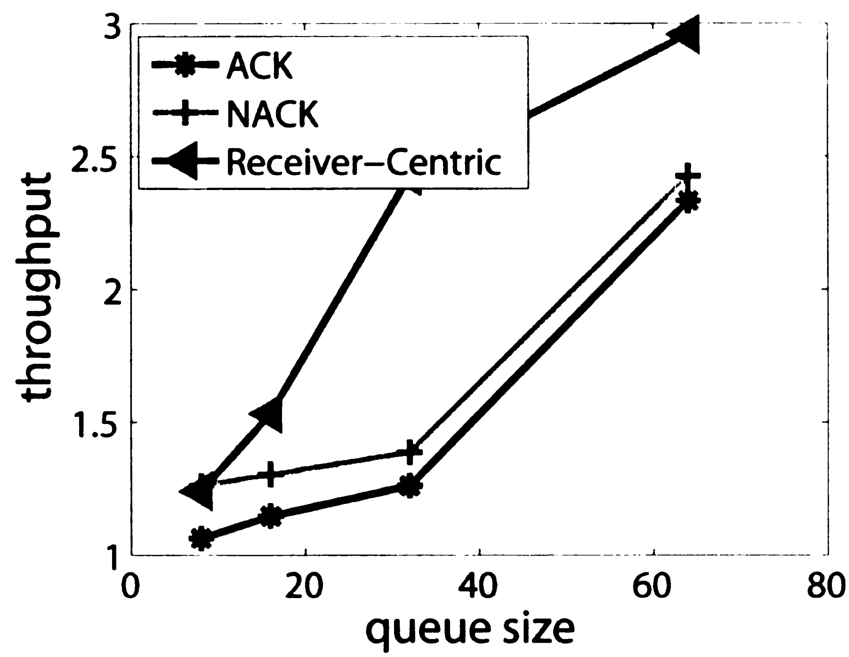


Figure 35: Scheduling in Mica2 under different buffer sizes.

We evaluate how the buffer size affects channel access scheduling on Mica2 sensors by varying the buffer size from 16 to 64. Figure 35 shows that the event throughput of all three approaches is increased when the buffer size is increased. The three approaches have close event throughput when the buffer size is small. However, the receiver-centric approach outperforms the other two approaches when the buffer becomes larger. All the three approaches have close and worst performance with small buffer size, because a large number packets are dropped due to buffer overflow. When sensors have sufficient buffer size, they can achieve higher event throughput. Particularly, this event throughput can be further improved by channel access scheduling of the receiver-centric approach.

4.3.5 Lost Packet Retransmission under Different Packet Injection Intervals

To evaluate the lost packet retransmission of the receiver-centric protocol, we use only one source in both two-hop and three-hop topologies where a sender continuously sends 200 packets to the intermediate nodes and later forwards to the receiver. In addition, we compare our lost packet retransmission of our protocol against the lazy loss detection of efficiency-centric communication (ECC) protocol [29]. The lazy loss detection is somewhat similar to our recovery mechanism. It also uses the overhearing technique and sequence-based counting to detect lost packets. It then chooses either of two possible alternatives to notify the sender about the loss of packets: overhearing or retransmission request packet (RRP). For easier implementation, we use the second method, RRP. These implicit acknowledgments are necessary because they are used to remove sent packets from the buffer in order to free up space for newly received packets. For example, in Figure 36, which is taken from [29], node B detects the loss of packet 3 when it receives packet 4. Node B then recovers lost packet 3 by sending a RRP to node A. Note that multiple RRPs may be necessary to inform node A because link imperfection usually occurs. In addition, lazy loss detection needs to temporarily buffer any subsequent packets after detection of a lost packet to maintain the correct sequence of

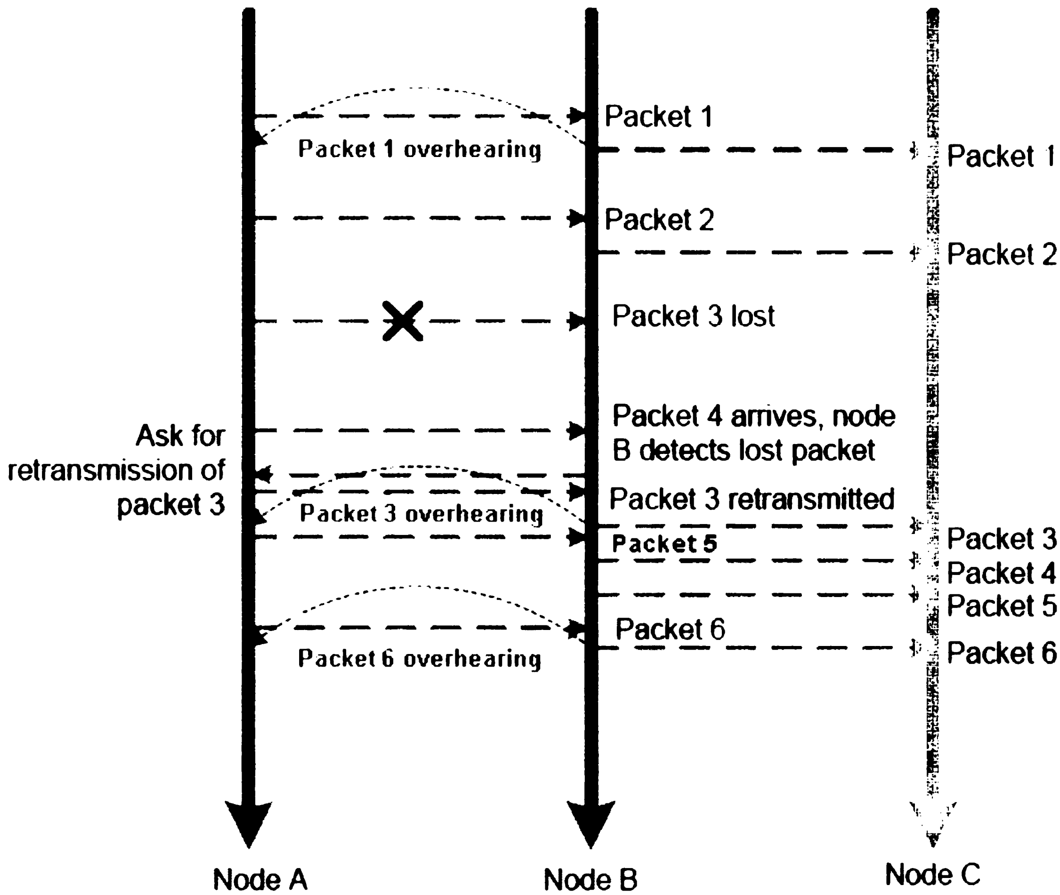


Figure 36: The basic principle of lazy loss detection.

Table C: Summary of key differences between RC and ECC

Key Differences	Lost Packet Recovery (RC)	Lazy Loss Detection (ECC)
Sequence Numbering	Local	Global
Lost Packet Detection	Re-number subsequent packets and forward to the next hop	Buffer subsequent packets until lost packet recovered

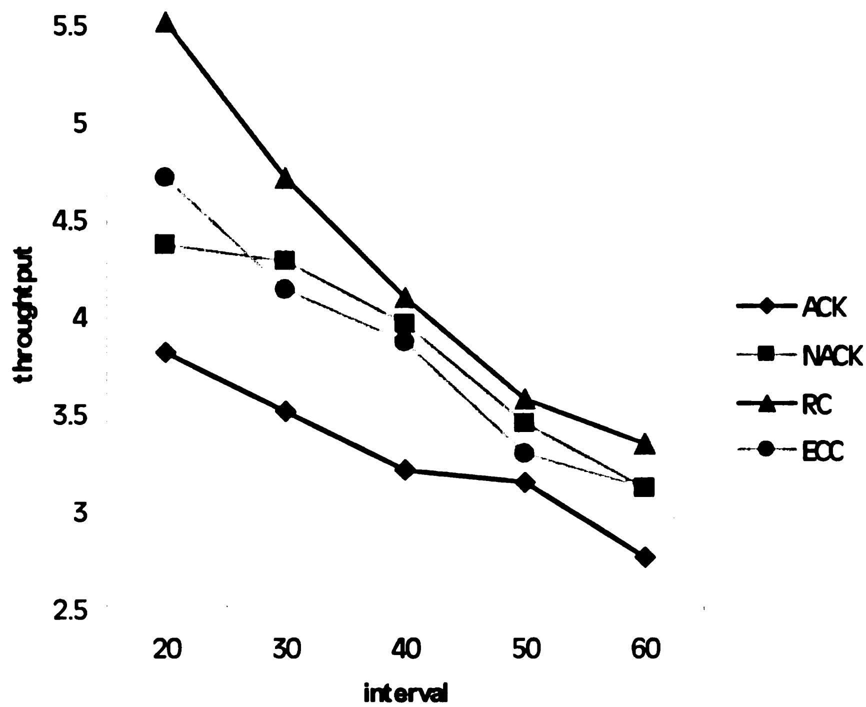


Figure 37: Lost packet retransmission in Mica2 under different packet injection intervals in three-hop topology.

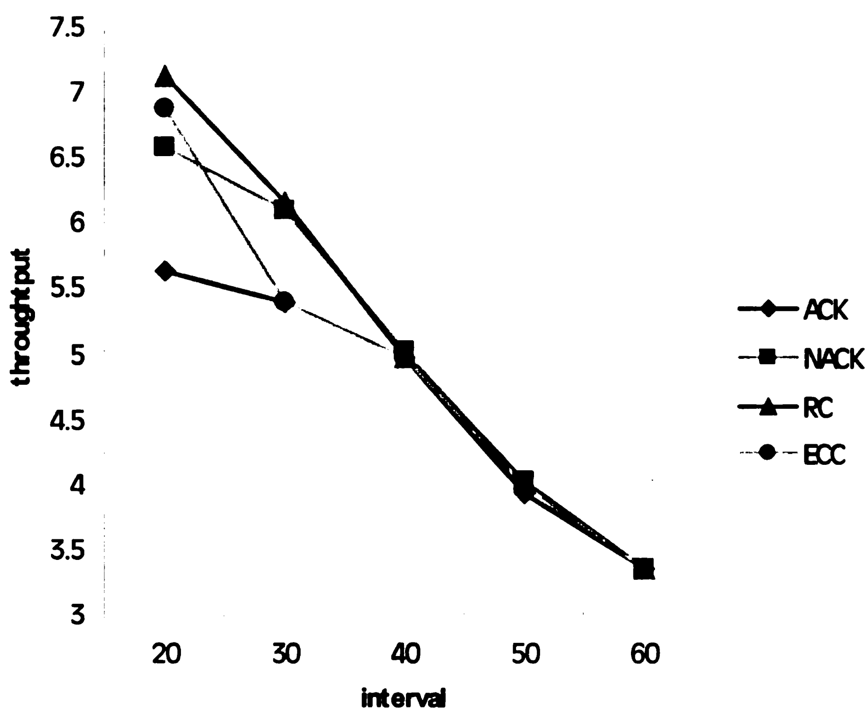


Figure 38: Lost packet retransmission in Mica2 under different packet injection intervals in two-hop topology.

packets. Table C summarizes the differences between our lost packet retransmission and lazy loss detection of ECC.

In this experiment, the event throughput is only determined by the lost packet retransmission since no channel access scheduling is necessary for only one source. Figure 37 shows that the ACK approach performs more poorly than any other approaches regardless of packet injection interval. This happens because the ACK approach intensifies channel contention, especially when packets are sent at higher rate, which lowers the event throughput. On the other hand, the NACK approach has a higher overall throughput than the ECC approach. Though both mechanisms will send a request retransmission packet back to the sender when a packet is lost, there is a higher probability that lost packets cannot be recovered with the ECC approach because buffer overflows occurs more frequently since it buffers all subsequent packets. A notable one is our receiver-centric approach which outperforms all other approaches because our approach can recover lost packets with very small overhead. However, Figure 38 shows that ECC closely approaches our protocol and performs better than NACK because network topology becomes much simpler when we repeat the same experiment using a two-hop topology.

4.3.6 Lost Packet Retransmission under Different Buffer Sizes

We evaluate how buffer sizes affect event throughput of the lost packet retransmission by varying the buffer size of all forwarding nodes from 4 to 64. The result in Figure 39 shows that receiver-centric performs worse when the buffer size is small, and outperforms other three approaches when the buffer size is larger than 4. The better performance with larger buffer size happened because more buffer space can be allocated

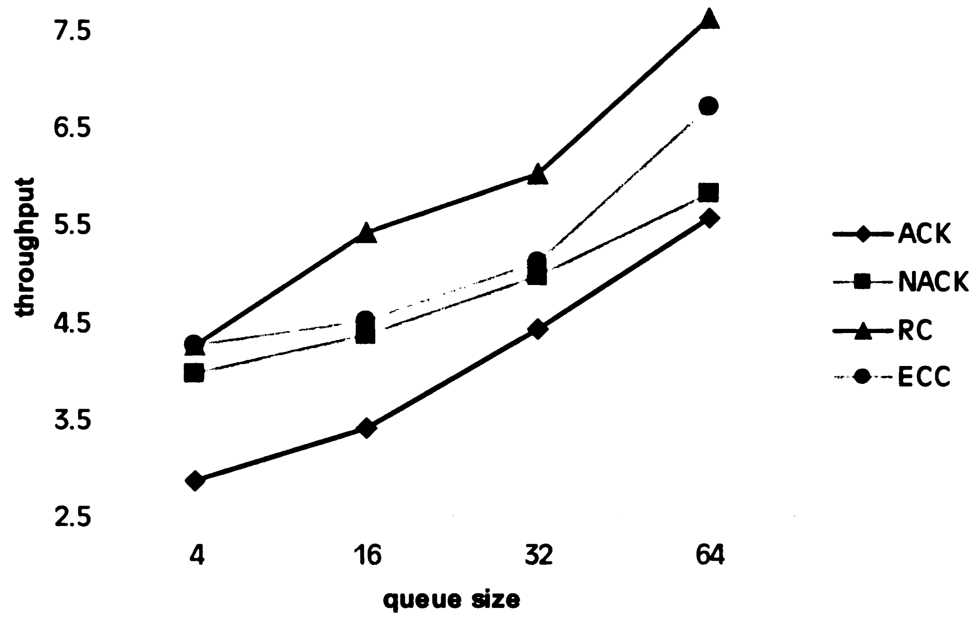


Figure 39: Lost packet retransmission in Mica2 under different buffer sizes in three-hop topology.

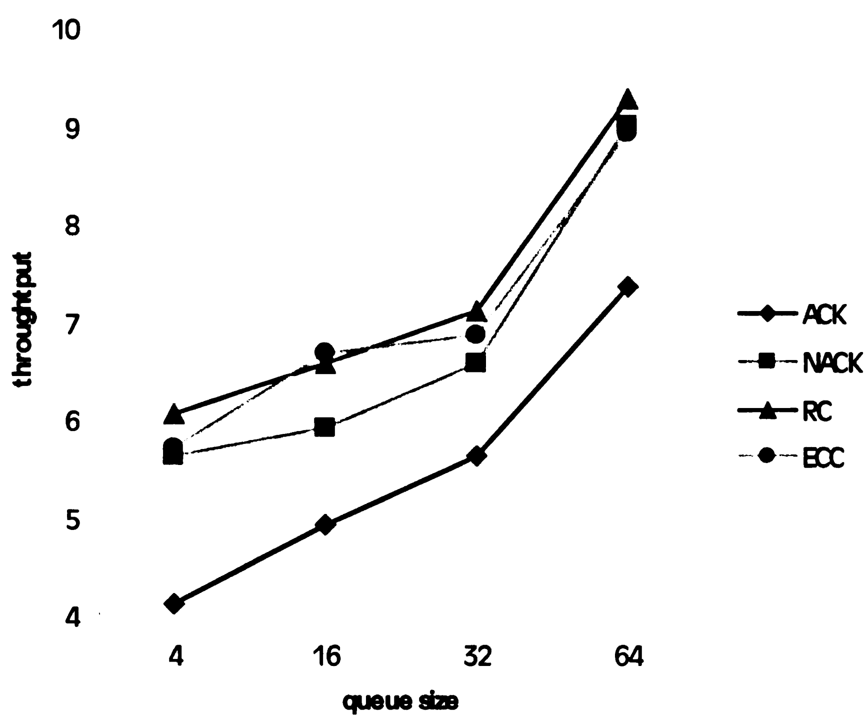


Figure 40: Lost packet retransmission in Mica2 under different buffer sizes in two-hop topology.

to the recovery region, which increases the possibility of recovering the lost packets. However, Figure 40 shows that receiver-centric has very little improvement in performance when we repeat the same experiment using a two-hop topology where only once intermediate node exists.

4.3.7 Lost Packet Retransmission under Different Packet Sizes

The event throughput can be affected by the packet size because larger packet sizes consume more bandwidth and are more easily lost during the transmission. We evaluate how packet size affects the event throughput by varying the length of the data field from 10 to 40 bytes. The default maximum data length is 29 bytes in TinyOS 1.13, we modify the system configuration to increase the maximum data length to 40 bytes. The comparison results of Figure 41 show that the event throughput of all the four approaches is reduced when the packet size becomes larger. However, the ACK approach has the lowest event throughput regardless of the size of data length. This happened because channel contentions are intensified by the ACK approach. The NACK approach performs much better than ECC at larger packet size. This is because when packet size becomes larger, more packets will be lost and cannot be recovered in the ECC approach. However, some of the lost packets can be recovered by the NACK approach, and therefore achieve higher event throughput. Among all the four approaches, the receiver-centric has the highest event throughput at different data lengths because packets are recovered with small overhead. We then repeat the experiment using a two-hop topology. Figure 42 shows that ECC has higher throughput than NACK as opposed to Figure 41. This is because channel contention is reduced in a much simpler topology, and therefore, more packets can be recovered.

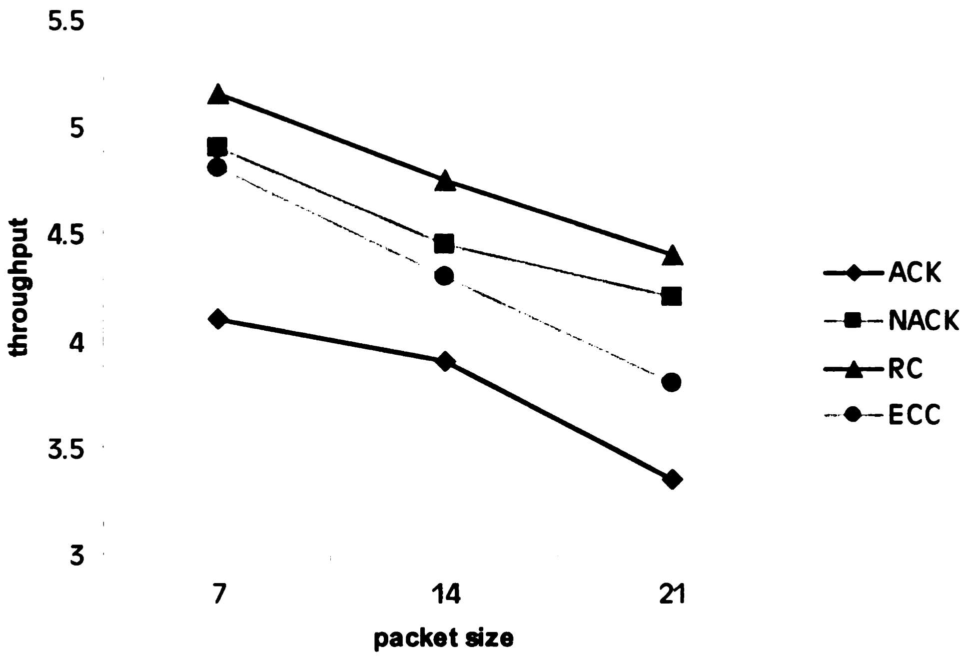


Figure 41: Lost packet retransmission in Mica2 under different packet sizes in three-hop topology.

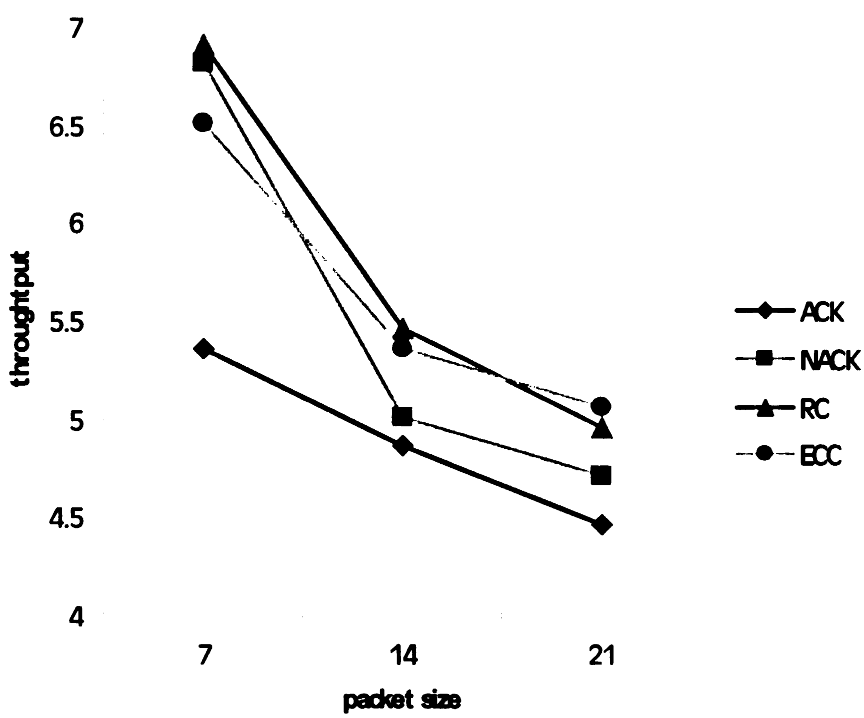


Figure 42: Lost packet retransmission in Mica2 under different packet sizes in two-hop topology.

4.4 Summary

We aim to improve data transmission throughput in sensor networks through two approaches. First, we enforce channel access scheduling to the CSMA, which improves channel throughput by reducing channel collisions. Our solution is flexible and scalable, and can be easily deployed in sensor networks. Second, we realize the sequence-based retransmission in the hop-by-hop recovery of sensor networks, which improves throughput by reserving all bandwidth resources for data transmission. We have implemented the channel access scheduling and sequence-based mechanism in TinyOS 1.13 and evaluated their performance on both Mica2 sensors and Tmote sensors. Our evaluation shows that the receiver-centric protocol can significantly improve transmission throughput of wireless sensor networks.

5. Conclusion and Future Work

In this section, we present the conclusion of our research and discuss possible future work to further improve our receiver-centric protocol.

5.1 Conclusion

To improve data transmission throughput, we first provide an overview of radio signal and their signal strength behavior in complex environments. Our study demonstrates that the lossy nature of wireless communication and rapidly changing environment have severe effects on radio signal strength, which is widely used for data packet transmissions. Secondly, we propose a new MAC overlay protocol that is designed to improve CSMA that further maximizes data transmission throughput.

The main contributions of this research are:

- To study how radio signals react in different environment settings where obstructions and reflections occurred randomly.
- To improve data transmission throughput, we build an efficient MAC overlay protocol in which we implement a channel access scheduling based on round-robin fashion to schedule nodes for packet transmissions

at specific time slots and a lost packet recovery mechanism based on number sequencing to retransmit lost packets.

- To analyze the feasibility of our approach by varying the input parameters to the control message that is used to configure and initialize the sensor nodes.

5.2 Future Work

In future, there are several possibilities that we can consider to further improve our performance in maximizing data transmission throughput. For channel access scheduling, we can consider not only round robin, but other types of scheduling methods such as FCFS (First Come First Serve) and priority scheduling. FCFS can be used as a baseline comparison metric for evaluation against the other two scheduling mechanisms. To implement priority scheduling, we can design in such a way that intermediate nodes that have more data packets to be forwarded to their parent node will be assigned a higher priority. The main idea behind this technique is that more buffer overflow cases can potentially be avoided for highly active nodes since more slots will be available for newly arriving packets. To utilize priority for scheduling, we need to introduce a new variable for each node that indicates its priority level within the parent-child structure. Priority scheduling can eventually cause more overhead because a check needs to be done at each scheduling point to determine which node will get to send a packet next. This is in contrast to our round robin that the next node with ID $i+1$, will get scheduled next. Note that the experiment configurations that we have been using to evaluate our protocol need to be changed. To evaluate the performance of priority scheduling, we have to initialize each source to send out a different number of packets for initial priority assignments.

Besides exploring different scheduling methods, we can also extend our receiver-centric protocol to work in a more randomized network topology. For example, each parent node can have a different number of children. Currently, our protocol is implemented based on the assumption that all parent have the same number of children at each level of the tree, which is certainly not the ideal case in real deployment. However, this extension requires a much more complicated node ID assignment during the initialization phase and may cause more overhead.

One of the limitations in our lost packet retransmission mechanism is that it only works in a linear topology where some intermediates nodes are placed between a source and a destination. The idea of using sequence-based counting and overhearing for detecting and retransmitting lost packets is fairly simple in a linear topology. However, things get complicated when we consider applying this mechanism in a random topology. This is partly due to the need for a parent to identify which child node requires resending the lost packets. When a lost packet is detected, we need to only notify the sender of this lost packet, and request for a recovery. This may incur some extra overhead during identification process.

To further assure our evaluation results, we can repeat the experiments by applying the same application to another type of sensing device (eg. mica2dot). Several TinyOS configurations and code modifications are required in order to accomplish the data collections.

If all the above improvements can be implemented, our receiver-centric protocol will become a practical solution for real deployment while maintaining high data transmission throughput.

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