An Empirical Analysis of Communication Links in Embedded Wireless Networks

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ABSTRACT
Embedded wireless networks have been widely used, from social networking to disaster response. Despite their increasing application, developers still face many challenges. One of the most significant is ensuring reliable communication between communicating devices. In this paper, we present an empirical examination of some of the key factors that affect the quality of wireless links in outdoor environments. Specifically, we study the effects of height differences between devices, device orientation, and data transmission rate on communication quality.

Categories and Subject Descriptors
C.2.0 [Computer-Communication Networks]: Data Communications

General Terms
Experimentation, Wireless Communication

Keywords
Embedded networks, sensor networks, radio link quality, network design

1. INTRODUCTION
Embedded wireless networks have been widely used in social networking, environmental monitoring, and disaster response, to mention only a few applications [2,3,6,7,9]. Still, these applications suffer from reliability problems. One of the most significant is an inability to guarantee message delivery between devices. For a message to be received successfully, the radio link quality between devices must be above a certain threshold.

There are several metrics used to measure the quality of communication, such as Received Signal Strength Indicator (RSSI), Signal to Noise Ratio (SNR), Link Quality Indicator (LQI), and Packet Reception Rate (PRR). RSSI, SNR, and LQI are hardware-based measurements, while PRR is a software-based measurement. We use PRR in this paper since it is the metric developers are most familiar with and can relate to. PRR corresponds to the ratio of the number of packets received to the number of packets sent [13]. Accordingly, higher PRR means fewer packets lost and better communication quality.

PRR is divided into three quality regions: high, mid, and low. High- and low-quality regions are stable, while the mid-quality region is not stable. PRR in the mid-quality region is more sensitive to factors affecting link quality [16].

There are many factors that affect link quality, including transmission distance, transmission power level, data transmission rate, physical obstructions, device orientation, interference, and height differences. Accordingly, when deploying a network, these factors must be taken into account. Developers must ultimately make decisions regarding the placement of nodes, their orientation, and the data transmission rate used, among others. Changes in these aspects of a deployment may significantly impact communication reliability, as well as the benefits an application offers.

In this paper, we study the effects of three factors affecting radio link quality: height differences between devices, differences in device orientation, and data transmission rate. We limit our studies to outdoor environments, which represent the majority of embedded network deployments. We also study noise floor, a measure of external interference, to understand its effect on the studies since it cannot be controlled. Further, we examine experiment repeatability to ensure the quality of our data.

Paper Organization. We present a series of independent studies. Each includes a description of the experimental setup, a discussion of the results, and a quantitative summary. Section 2 describes the noise floor study. Section 3 describes the height difference study. Section 4 describes the orientation difference study. Section 5 describes the transmission rate difference study. Section 6 describes the experiment repeatability study. Section 7 discusses elements of related work. Finally, Section 8 concludes and provides pointers to future work.

2. NOISE FLOOR
Motivation. Noise floor is a measurement of external interference. Interference can be either internal or external. Internal interference is interference generated from within a network (i.e., other devices sending messages). External interference is interference generated outside a deployed network (e.g., Wi-Fi connections, cell-phone communication). In general, lower noise floor results in better communication. Noise floor is a variable that we cannot control in our stud-
Experiment Setup. We developed an application for TinyOS 2.x [4,15] using the Control Flow Mediator pattern described in [17], which periodically measures noise floor by sampling the radio’s RSSI register. When execution starts, the application initializes the radio and samples the RSSI register on all available channels, from 11 – 26, which vary in frequency from 2405MHz – 2480MHz in 5MHz increments [13]. Sampling follows the approach highlighted in [14]. The value is sent to a serially-connected basestation and recorded by a Java application.

We ran our experiments on TelosB devices [8], which we refer to as “motes” hereafter. TelosB motes use a CC2420 radio chipset, which is compliant with IEEE 802.15.4 standards. We chose TelosB motes due to their wide adoption in the domain. The maximum transmission rate is 250kbps; however, the maximum achievable rate is decreased to 35kbps with TinyOS [13].

We carried out our experiments in an open grass field with the motes mounted on a 4-foot stake. This height guarantees the absence of physical obstructions from grass. The basestation was powered by a 133Wh external battery to provide an extended period of operation. We sampled the noise floor across all available channels for a period of 9 hours, 2 minutes, and 24 seconds.

Results. Figure 1 shows the results of the noise floor measured over time. The x- (horizontal), y-, and z-axes (vertical) represent the channel number, the sample number, and the noise floor measurements in dBm, respectively. On average, we recorded 7.7 samples per second on each channel, for a total of 3,675,414 sample points. Notice that channels 17 and 18 had more outlier points. This suggests that these channels exhibit noise spikes and hence are not appropriate to use in this particular environment.

Table 1 presents a summary of the average, standard deviation, minimum, and maximum noise floor values for each channel. The average noise floor across all channels is -98.425 dBm, which is close to the minimum value that can be stored in the RSSI register: \( \approx -100 \text{ dBm} \) [13]. Notice that the smallest and largest range of values were on channels 11 and 25, respectively. Although channel 13 has the highest noise floor average, it has the smallest standard deviation. The difference between the average noise on channel 13 and the channel with the lowest average noise (i.e., channel 12) is only 0.767 dBm.

Summary. When collecting data of the type we desire, the best channel to use is the one that offers the least variability in terms of noise floor [12]. Hence, channel 13 fits this requirement for the rest of our studies.

3. EFFECT OF HEIGHT DIFFERENCES

Motivation. When deploying a network, developers must make decisions regarding mote placement. This includes consideration of height differences between motes. Changes in height result in changes in the effective distance between motes. Small changes in distance should in principle have limited effect on PRR. In this section, we study the effect of such differences.

Experiment Setup. We developed an application that measures the PRR between two motes and varied the height difference between them. The setup involves three motes: a sender S, a receiver R, and a mote that measures noise floor N. When the application starts, S sends messages at a specific rate for a certain duration using a specified transmission power level. R counts the number of messages received. At the end of the experiment, R sends the collected information to a basestation to record the results. While the application is running, N also sends the measured noise floor to the basestation for logging. (Both R and N are connected serially to the basestation.)

R and N were placed on 4-foot stakes. N was placed 6 inches behind the receiver mote. S was placed at distances of 34 and 48 feet from the receiver. The height of the stake on which S was mounted varied from 2 to 6 feet, in increments of 1 foot. S sent messages at a rate of 30 messages per second for 30 seconds, for a total of 900 messages. Messages were
Table 2: Effect of Height Difference on PRR

<table>
<thead>
<tr>
<th>Height (feet)</th>
<th>Power Level</th>
<th>PRR at 34' (%)</th>
<th>PRR at 48' (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>94.33</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>96.33</td>
<td>5.22</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>98.83</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>96.67</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>84.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>99.33</td>
</tr>
</tbody>
</table>

Sent at transmission power levels of 2, 3, and 4. (Power levels vary from 1 to 31 in 1 unit increments. These values correspond to non-linear changes in dBm, ranging from less than -37 to 0 dBm, respectively [13]). Based on the results presented in Section 2, we ran the experiments using channel 13. All motes had the same orientation. Figure 2 depicts a sample deployment for distance 34.

**Results.** Table 2 summarizes the PRR values recorded across the experimental trials. The first column represents the stake height on which S was placed. The second column represents the power level used. The last two columns represent the PRR for distances 34 and 48 feet, respectively. From the table, we notice that at power level 2, no messages were received regardless of height or distance. This is because R is beyond the transmission range of S. Near perfect packet reception is observed for power level 4 in each case. This is because R is well within the transmission range of S. Accordingly, varying the height of the sender’s stake has no effect on PRR. The results are more interesting for power level 3. When the motes were placed 34 feet apart, we notice that as the height difference between S and R increases, PRR decreases. However, the change in PRR is not significant, except for height 6. Changing the stake’s height resulted in a decrease in PRR of 4.55, 2.53, 2.19, and 14.5% for heights of 2, 3, 5, and 6 feet, respectively. The results are more interesting for power level 3 when the motes are placed 48 feet apart and PRR falls in the mid-quality region. We notice that the previous observation does not hold. In fact, varying the height could result in an increase in packet reception rate, as seen when S was placed on 2- and 5-foot stakes. In these cases, we notice a significant increase in the packet reception rate. However, we notice a significant decrease in the packet reception rate for heights 3 and 6. In summary, changing the stake’s height when the motes were 48 feet apart resulted in a PRR change of 61.86, -91.56, 61.67, and -100% for heights 2, 3, 5, and 6 feet, respectively. (Negative values correspond to a decrease in PRR, while positive values correspond to an increase in PRR as compared to the PRR at height 4 feet).

Figure 3 illustrates the conjectured behavior that caused the variation in PRR — multi-path interference. Assume S is sending messages to R. The circles represent radio signals. In general, messages propagate in a spherical direction. Consider the dashed lines representing two possible directions in which a message may propagate. These dashed lines hit the ground and are reflected back in the air. The reflected messages may be strong enough to cause interference. In Figure 3a, both S and R are placed at the same height. The reflected message is received by R in one case when the dashed line crosses R. We attribute this to the original and reflected signals being roughly in phase (or the reflected message is very weak). In Figure 3b, S is placed higher than R without changing the distance. The reflected message is received by R in one case when the dashed line crosses R. We attribute this to the original and reflected signals being roughly in phase (or the reflected message is very weak). In Figure 3c, R did not receive the reflected message. Similarly, in Figure 3c, R did not receive the reflected message when S was placed at the same distance but at a lower height. Figures 3b and 3c represent the cases for distance 48 and heights 2 and 5 feet, R was able to receive the reflected message. For these heights, even though d and d” are greater than d, PRR was higher. This
<table>
<thead>
<tr>
<th>Orientation (degrees)</th>
<th>Power Level</th>
<th>PRR at 34 (%)</th>
<th>PRR at 48 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>98.83</td>
<td>61.78</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>90</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>96.63</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>180</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>37.67</td>
<td>78.56</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>270</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>98.83</td>
<td>45.55</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3: Effect of Orientation Change on PRR

Suggests that the increase in PRR in this case was a result of message reflection and not ground distance. In other words, the other cases experienced multi-path effects.

Finally, Figure 4 illustrates the noise floor measured by \( N \) when \( S \) was at height 2 feet and distance 34 feet. The figure shows the noise floor measured as follows: 35 seconds with no transmission, 30 seconds with \( S \) sending at power level 4, 5 seconds with no transmission, 30 seconds with \( S \) sending at power level 3, 5 seconds with no transmission, 30 seconds with \( S \) sending at power level 2, and 35 seconds with no transmission. From the figure, we notice that the noise floor is consistent throughout the experiment when there is no transmission. The noise floor varied between -92 and -95 dBm, which is well within the noise floor measurements summarized in Section 2. This suggests that noise floor had little (if any) effect on our results.

**Summary.** Varying the height difference between \( S \) and \( R \) has a negligible effect when PRR is almost perfect or nil and the height of \( S \) and \( R \) are the same. Otherwise, the effect is significant as PRR is in the mid-quality region. The change in PRR can be positive or negative depending on whether \( R \) receives reflected messages.

### 4. EFFECT OF ORIENTATION

**Motivation.** When deploying a network, developers must make decisions regarding mote orientation. Radio propagation roughly follows a solid disk model. Accordingly, small changes in orientation should not have a significant impact on packet reception. In this section, we empirically study how varying a mote's orientation affects packet reception.

**Experiment Setup.** We used the same software described in Section 3. We placed all motes on 4-foot stakes. \( N \) was again placed 6 inches behind \( R \), and \( S \) was placed at distances 34 and 48 feet from \( R \).

The orientation of the sender node varied as follows: (i) \( S \) is parallel to \( R \) (0 degrees), (ii) \( S \) is rotated 90 degrees, (iii) \( S \) is rotated 180 degrees, and (iv) \( S \) is rotated 270 degrees.

Transmission rate, duration, power levels, and radio channel were the same as described in Section 3.

**Results.** Table 3 summarizes the recorded PRR values across the experimental trials. The results for power levels 2 and 4 for both distances are consistent with our findings from Section 3. In such trials, changing the orientation of \( S \) had no effect on PRR. However, the results are more interesting for power level 3. At distance 34, rotating \( S \) by 180 degrees had a significant impact. Changing orientation resulted in a decrease in PRR of 2.02, 61.88, and 0% for orientations 90, 180, and 270 degrees, respectively. We conjecture that at distance 48, PRR is in the mid-quality region. The effect of orientation is different from that at distance 34 feet. Specifically, for orientations 90 and 270 degrees, PRR decreased significantly by 99.29 and 26.27%, respectively. Contrary to our expectations, PRR increased by 27.16% when \( S \) was rotated 180 degrees. (i.e., \( S \) was opposite to \( R \).)

Finally, Figure 5 illustrates the noise floor measured by \( N \) for distance 34 when \( S \) was rotated 180 degrees. The noise floor was measured in the same way discussed in Section 3. Notice that the dBm values for power level 3 are not high, as PRR was 37.67%. The noise floor is similar to that discussed in Section 3, suggesting that the noise floor had little (if any) effect on our data.

**Summary.** In our experimental trials, when \( S \) and \( R \) are parallel and PRR is nil or near perfect, orientation change generally has a limited effect, except when \( S \) and \( R \) are in opposite directions. Otherwise, when PRR is in the mid-quality region, orientation has a significant effect.

### 5. EFFECT OF TRANSMISSION RATE

**Motivation.** When deploying a network, developers must make decisions regarding the data transmission rate. On the one hand, when the transmission rate is too low, network capacity is wasted. On the other hand, when the transmission rate is too high, network throughput may decrease due to packet collisions and message corruption. In this section, we study the effect of transmission rate variation on PRR.

**Experiment Setup.** We used the same software and physical parameters described in Section 3. The distance between \( S \) and \( R \) was 70 feet. \( S \) sent messages using power level 14 at rates of 30 and 75 messages per second for 20 seconds, for a total of 600 and 1500 messages, respectively. The payload size was 20 bytes. We ran the experiments on each radio channel. Each setup was repeated 10 times.

**Results.** After running the trials for 30 messages per second, the PRR was at 100%, except at the third trial where it was 99.8%. When \( S \) sent 75 messages per second, the results were similar: the PRR was at 100%, except for the seventh trial where it was 99.9%. We conclude that varying the transmission rate has a negligible effect across all experiments, as sending 75 messages per second is well within the maximum data rate threshold [13].

**Summary.** Our experiments show that transmission rate variations have a negligible impact on PRR when the rate is well within the throughput limit. In the future, we will study transmission rate impacts as the rate approaches the throughput limit.
6. EXPERIMENT REPEATABILITY

Motivation. To ensure that the conclusions of the preceding sections are valid, the data must be reliable. Experiments conducted in the same environment, with the same parameters should result in consistent data. In this section, we study experiment repeatability to ensure the validity of the data collected in the previous sections.

Experiment Setup. We used the same software and physical parameters described in Section 3. We varied the distance between $S$ and $R$ from 1 to 100 feet in 10-foot increments. $S$ sent messages at a rate of 75 messages per second for 20 seconds, for a total of 1500 messages. We used all radio transmission power levels. These settings resulted in 341 different experiments, which comprised one set. We repeated this set 5 times on different days.

Results. Figure 6 summarizes the variations in PRR for the 5 sets across all distances covered. Figures 6a, 6b, and 6c represent the variations for distances 1 – 30, 40 – 70, and 80 – 100 feet, respectively. (The data is split over 3 figures to improve readability.) Each point represents the difference between the maximum and minimum PRR values recorded across the 5 trials. From the figures, we notice that the range of power levels in which data is inconsistent generally increases with distance. We believe the reason for this is that PRR becomes sensitive to orientation and height differences with distance. Even slight orientation/height changes can result in wide variability in packet reception. This sensitivity could be attributed to the PRR being mostly in the mid-quality region.

Variations in our data are more significant at distances where PRR falls in the mid-quality region. This is consistent with the findings reported by Wahba et al. [16]. Accordingly, we conclude that the data collected in our experiments is indeed repeatable especially when PRR is in high- and low-quality regions.

Summary. Because the data obtained from our experiments is largely repeatable, we conclude that the data in our studies is reliable.

7. RELATED WORK

Here we survey prior work focused on empirical analysis of radio link quality in embedded networks.

Ahmed and Fisal [1] study the packet reception rate in underground deployments. The authors use an underground testbed where they place TelosB motes at different depths. The motes report signal strength to a connected laptop. The authors note that the signal strength varies with the logarithm of distance. Further, the PRR drops significantly with increased depth due to the absorption of radio waves by soil, rock, and water. The authors based their results on experiments at depths of 0, 10, and 20 cm underground.

Ren et al. [10] study radio link quality in wearable health monitoring systems. The authors study the effects of radio transmission power, body posture, and environment on link quality. Data was collected from experiments in which a user placed a mote on his/her body and changed body posture from sitting to standing to walking. The authors considered three environments: a lab room, a grass field, and a corridor. Due to the difference in deployment environments, as well as body motion, the authors reach findings that are different from ours. Specifically, PRR is lower at shorter distances when compared to the results we obtained.

Hauer et al. [5] study the effect of 802.11b wireless networks on radio link quality in wearable networks. The authors generate controlled traffic using two laptops that communicate wirelessly. The authors found that wireless communication between the laptops has a negative effect on radio link quality. Generating more 802.11b wireless traffic leads to an increased noise floor, which in turn leads to increased packet loss. It is worth mentioning that the authors limited their experiments to urban environments.

Son et al. [11] study the effect of radio transmission power on radio link quality. From their experiments, the authors found that increasing radio transmission power increases the aggregate radio link quality in the network only to a certain
threshold, since increasing transmission power results in consuming more network capacity. Another observation is that longer distances between nodes may exhibit better link quality than shorter distances. This is mainly due to multi-path effects resulting from the indoor environment where the experiments were run. The authors also studied the effect of physical obstructions on radio link quality by placing nodes in different locations in offices in a building. Varying node location led to variations in link quality because of the presence of physical obstructions (i.e., desks and chairs). Finally, the authors conducted experiments at different times of the day and found that radio link quality varied according to the building occupancy where the experiments were conducted. Despite the insightful results the authors present, the same assumptions cannot be applied to outdoor deployments.

Finally, Wahba et al. [16] provide an empirical model to predict radio link quality as a function of radio transmission power and inter-node distance. The model focuses on outdoor deployment environments that are free of obstructions and any significant interference. However, the model is based on experiments run using TinyOS 1.x. Due to changes in the radio MAC protocol in TinyOS 2.x, the model would not be accurate in our case.

8. CONCLUSION

We started with the observation that radio link quality must be understood if applications of embedded networks are to increase at the current rate. In this paper, we studied the variation of noise floor over time. We then studied three factors that affect radio link quality: height differences, device orientation, and transmission rate. We reached the conclusion that the effect of height differences and device orientation increases as inter-node distance increases, which can be the result of PRR being in the mid-quality region. Further, transmission rate has no significant effect as long as the rate is within the throughput limit. Finally, we studied data repeatability and found that in general the data is consistent over time, except for a few outliers when PRR lies in the mid-quality region.

Looking to the future, we plan to study how PRR changes as transmission rate approaches or exceeds the throughput limit. Further, we plan to study the effects of other factors affecting radio link quality. Specifically, we will investigate the effect of radio transmission power, inter-node distance, and physical obstructions on radio link quality. We will limit our study to outdoor environments, which represent the majority of embedded network deployments.

Acknowledgments

This work is supported by the National Science Foundation through awards CNS-0745846 and DUE-1022941.

9. REFERENCES


