CycleNet: Empirical Analysis of 802.15.4 in Mobile Scenarios

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Abstract

We present empirical data of communication between 802.15.4 devices in static and mobile scenarios. We evaluate the body factor between two devices in a cycling environment and show it has a significant impact on communication. Our findings show that RSSI is severly hampered as an indicator of reception quality and that LQI serves as a much more reliable indicator in a mobile setting. Additionally, we show that different bicycling speeds do not adversely affect 802.15.4 communication.

1 Introduction

With the rising cost of oil, interest in alternative means of commuting has increased tremendously. One popular form of transportation is bicycling. Throughout the world, bicycles are the main source of transportation and are participated in as both sport and hobby. Nevertheless, many cities lack adequate bicycle paths and accommodations for cyclists. With foreseen greater interest in bicycling, cyclist themselves can take part in networking amongst fellow riders to share information with each other and city planners. Lightweight, low power, and autonomous embedded devices can allow for a greater experience for people throughout the bicyclist spectrum; from the casual rider to the cycling enthusiast.

We examine different aspects of inter-cycle communication to better understand factors which can affect application and protocol design for people-centric sparse mobile network. Our research looks to model mobile to mobile communication between bicycles using 802.15.4 devices with empirical measurements. The devices we use for our experiments are MICAz motes which are produced by Crossbow [2]. They have the CC2420 Chipcon radio [1] that uses the unlicensed 2.4 GHz ISM spectrum with a data rate of 250kbps. The MAC layer is CSMA and the physical layer does QPSK modulation [23]. It provides a received signal strength indicator(RSSI) and a link quality indicator (LQI) for each packet received. Packet reception rate (PRR) is extracted through the use of sequence numbers.

The case of bicycles communicating statically is first presented to attain a sound understanding of human interference. The body factor is shown to give large amounts of attenuation for a range of body types. Furthermore, we show that within close range (one bike length) the limited speeds of bicycles have little to no affect on bicycle communication in comparison to the static scenario. Yet, the body factor is a large source of attenuation in which the communication range is cut dramatically. This is in large part due to the orientation of cyclists in relation to each other. In general, there is a leader and a series of followers. Our experiments for both static and mobile cases are reflective to these formations. Moreover, our research caters to bicyclists who participate in groups rather than by themselves.

There is a dearth of research in mobile communication for people-centric sensing. Previous studies have had limited findings on either the body factor or mobile scenarios with low power radios. Much previous work has looked at static communication which reports phenomena such as asymmetric links, gray receptions areas, antenna orientation sensitivity, height sensitivity, and other complex radio behavior [18, 14, 21, 7, 22]. In [16] the authors present empirical experiments for the characterization of 802.15.4 devices worn by people in low mobility environments. But, there has yet to be any characterization of people-centric communication in highly mobile environments. Our research is the first study to deal directly with the issue of speed variability when characterizing 802.15.4 communication. Moreover, we extrapolate on the body factor for such environments.

From our experiences in dealing with cyclists and mobile embedded devices we discuss difficulties encountered and give suggestions for plausible sparse mobile bicycle systems. We discuss how networking bicycles can improve the overall bicycling experience. What this paper does not present is a full framework for a full bicycling system. Nor does this paper discuss privacy issues which can arise from openly sharing data.

In §2 we consider related work. In §3 we present our hardware and software used for our experiments. We present in §4 and §5 our static and mobile experiments, respectively. We discuss the ramifications for system designers in the mobile context in §6. Finally, we conclude with future work in §7.

2 Related Work

Previous work in characterizing 802.15.4 has mainly focused on static scenarios. In [14, 21] factors which add to the random nature of 802.14.5 radio waves are quantified. These factors include antenna orientation and variations across different radios.

Mobile networks include [13, 5, 8, 15]. These networks are delay tolerant networks where nodes are sparse and must be power efficient. Eisenman et al. presents many advantages in the networking of bicycles [3]. Their paper shows that through the use of wireless embedded devices much information can be attained about the cyclists' experience. This includes information about the short and long term performance of the cyclist, fitness levels, pollutants, noise, trails taken, and on-line feedback during rides. Our work looks at low power inter-bicycle communication for systems such as theirs and presents the factors which can cause unreliable connectively in mobile bicycle networks.

Moreover, our focus is on communication between cyclists in groups rather than lone cyclists whose only aim is to have their data reach a central station. Information can be attained more efficiently (e.g. power) by having cyclists cooperate. Discussion of an incentive system or how to handle malicious user behavior is outside of the scope of this paper.

In [19, 18, 22] the LQI, RSSI, and PRR were analyzed quantifying the effects of distance, time, and direction for indoor and outdoor environments.

802.15.4 is meant for low power devices and thus we do not enumerate the abundant research in high powered radios such as 802.11. Previous work also looked at the body factor for radio communication [16, 12, 6, 17, 10, 4] but of these only [16] did so for low power radios. Moreover, our experiments are in bicycling environments where there are rapid environmental changes, a factor none of the aforementioned research explores.

3 Implementation

Our experiments consisted of MICAz motes which have CC2420 radios, 8-bit Atmel processors, 512kB of flash storage, and are powered by two AA batteries [2]. The CC2420 radio is capable of transmitting at several power levels between -24dBm to 0dBm and can select among several channels within the band of 2400MHz and 2483.5MHz. Throughout our experiments we transmitted at the highest power level and set the frequency to 2480MHz. This gives a spacing of 18MHz from the center frequency of the last channel (11) of 802.11b [9]. The radio has a minimum reception sensitivity of -90dBm [1]. The antenna was always set in an upright position, although when in an uncontrolled setting we would see that the antenna would alter its position as the ride progressed. As reported in [21, 14] this can cause reception degradation.

Our sensor board is the MTS420CA. It provides GPS locations, acceleration, barometric pressure, light sensor, humidity sensor, and temperature. The GPS location accuracy is reported to be within 10 meters [2] and this has been our findings with our data.

The software was written in TinyOS [20]. It consisted of a receiver, sender, and GPS application. An endpoint application was written in C for the uploading of the data.

4 Static Experiments

In this section we discuss the methodology we follow for the static experiments and the results that we derive. The motivation for conducting a series of static experiments is found in previous studies about the influence that the body has in sensor network communication [16]. It is impossible to avoid the presence of the body in our mobile experiments for obvious reasons. Thus, we believe that a preliminary analysis of this factor, specifically applied on a biking scenario, is fundamental to have a better understanding of the results in a mobile scenario. All the static experiments are conducted on an open field. In order to avoid possible interference from 802.11 we use an orthogonal channel as previously mentioned. The motes are positioned on wooden sticks aligned at a distance of 5'9" (one bike length) from each other. The first stick hosts the sender, while the other sticks support the receivers. Each experiment consists of 2 packets sent every second for 15 minutes (1800 packets). There were a total of three trials for each scenario. Pack-

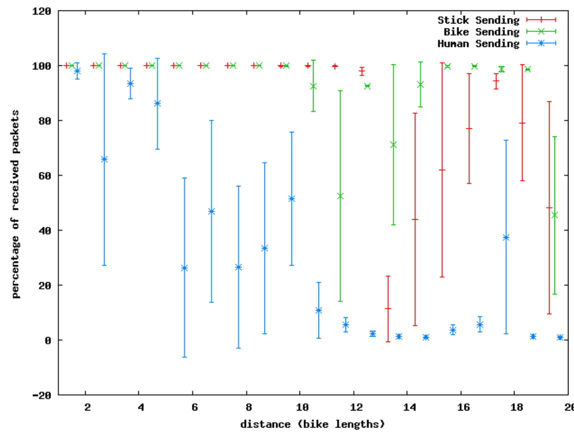

Figure 1: Average of received packets for three different scenarios: stick, bike and human body on a bike.

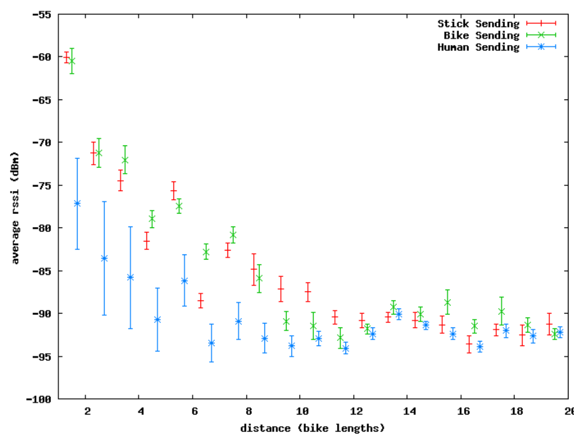

Figure 2: Average RSSI for three different scenarios: stick, bike and human body on a bike.

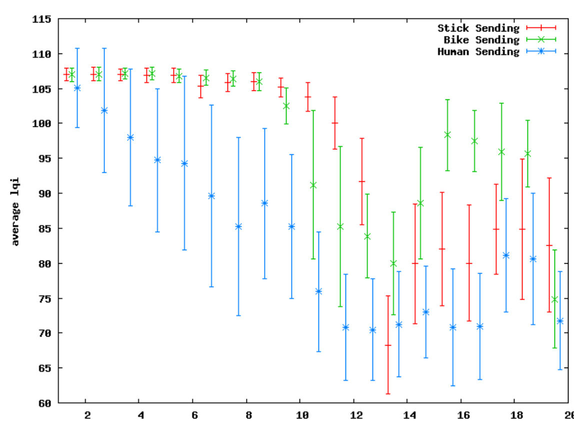

Figure 3: Average LQI for three different scenarios: stick, bike and human body on a bike.

Figure 4: Static scenario: stick. The sender is located on the first stick, the receivers are positioned on the following sticks.

Figure 5: Static scenario: bike. The sender is located on the bike's handlebar, the receivers are positioned on wooden sticks.

ets were of the default TinyOS size of 29 payload bytes [20].

The first series of experiments investigated the communication between motes with the sender mounted on a stick, on a bike, and on a bike with a person, respectively. Deduced from Figure 1 for the first two scenarios the reception is near 100 percent until the 11th bike length at which point there is a drop off. A person blocking the line of sight of the receiver, introduces a new element of disturbance, the body factor, which causes dramatic decreases in packet reception. The disturbance is reflective in RSSI and LQI. From Figure 2, for the stick and bike, after 11 bike distances the RSSI enters a gray zone where it does not directly correlate to PRR. But with the addition of a body, the gray zone is reached in half the distance. A peculiar fact lies in the greater variance for the body factor when under 12 bike lengths, and the small variance (with the ex-

Figure 6: Static scenario: human with bike. The sender is located on the bike's handlebar, the receivers are positioned on wooden sticks.

ception of length 17) of 12 or greater where reception is outstandingly low (less than 10%). The greater variance shows that even when within close proximity the PRR can vary wildly. The tail end where reception variance is much less shows that those few packets which were received had a very attenuated signal. Figure 3 has plots of LQI against bike distance, form this graph we can infer that LQI represents a reliable source for packet reception even with the body interference. Our experiments confirmed the fact, shown by another study [19], that RSSI is a good indicator of packet reception when its value is above the threshold of -87 dBm. Yet, the RSSI value quickly becomes inutile when greater than 5 bike lengths, being outside the decible range.

These results and previous work [16] induce us to further explore the body factor in order to determine if different body types can affect the communication. The radio frequencies in the 2.4 GHz band are attenuated by water and water is the main constituent of the human body. Thus, the radio performance degrades in presence of a human body between the sender and the receivers. The second set of experiments aims to quantify the impact on the communication of bodies of different size. As for the previous experiments the metrics that we consider are PRR, RSSI and LQI. We run the experiments with four different bodies that weight 125 lbs, 155 lbs, 168 lbs and 207 lbs.

The results of the percentage of received packets are shown in Figure 7, for the first three bike lengths the reception is excellent (near 100%), for larger distances the reception experiences a significant drop caused by the body attenuation. The different body weights do not seem to affect the quality of the communication as was found by [16]. Figure 8 and Figure 9 are the plots for RSSI and LQI, respectively. RSSI is a reliable indicator of packet reception when above -87 dBm, while below this threshold the packet reception can vary radically, reverberating our findings from our previous experiments which shows the limitations posed by body interference. LQI once again mirror the packet reception as found by [18]. It is important to point out that for all three metrics that we considered, the values for different body weights follow the same patterns; such that there is consistency in the results of different bodies for the same distance, while the randomness prevails if we analyze the values for different distances. The only exception to this case is with the flucuant reception by the 155lbs person at bike length 13. We are unsure as to the reason of this occurance.

From the results and insights we have gained from static settings we transition to mobile scenarios where the body factor is always present.

5 Mobile Experiments

In this section we discuss the methodology we followed for the mobile experiments and the results that we derive. While in the static scenario we tried to isolate the body factor, in the mobile scenarios we tried to isolate the speed and distance factors. For all our mobile experiments we fastened the motes with a Velcro strap on the bike's handle bar.

We investigate the communication of the motes for different speeds. Data was collected during a ride on a bike path in the Santa Barbara area as shown in Figure 10. Each experiment consisted of 5 packets sent every second for 5 minutes (1800 packets). There were a total of three trials for each scenarios (i.e. 5, 10 and 15 mph). From the graph in Figure 11 we observe that the packet reception does not appear to be affected by different speeds, as the PPR stays close to 99%. This result is confirmed by the plots with the average RSSI in Figure 12 and LQI in Figure 13.

In Figure 14 we can see the different trials plotted over time. The PRR experiences some fluctuations, but the values are in the range of 96%-100%. Both the RSSI (Figure 15) and the LQI (Figure 16) values for this trip represent a good indicator of packet receptioon due to the close proximity of the sender to the receiver (one bike length). Speeds in the range of 5 to 15 mph seems not affect the communication.

Figure 17 shows the CDF of the RSSI. With good reception over 95% of the packets are over the -87dBm threshold. Figure 18 is the CDF for the LQI, which also shows the distribution of packets having a very low chip error rate with over 95% of the packets with a strong LQI of 103.

The factor that we consider on the second set of mobile experiments is the distance between the

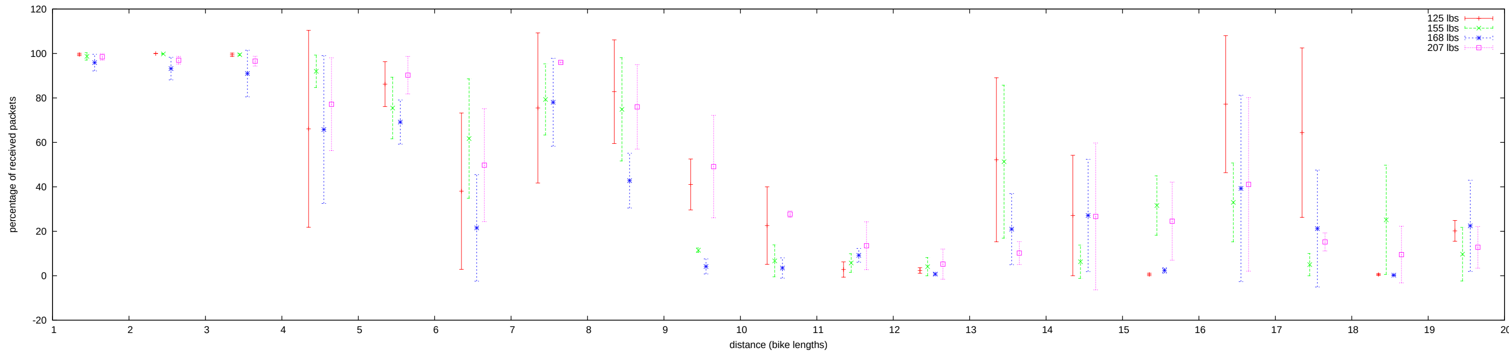

Figure 7: Average of received packets for different body weights.

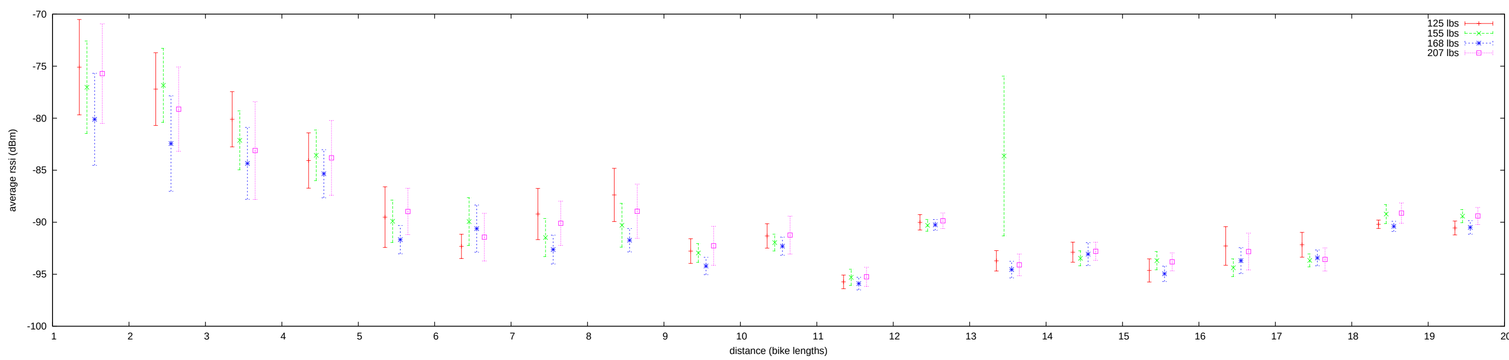

Figure 8: Average RSSI for different body weights.

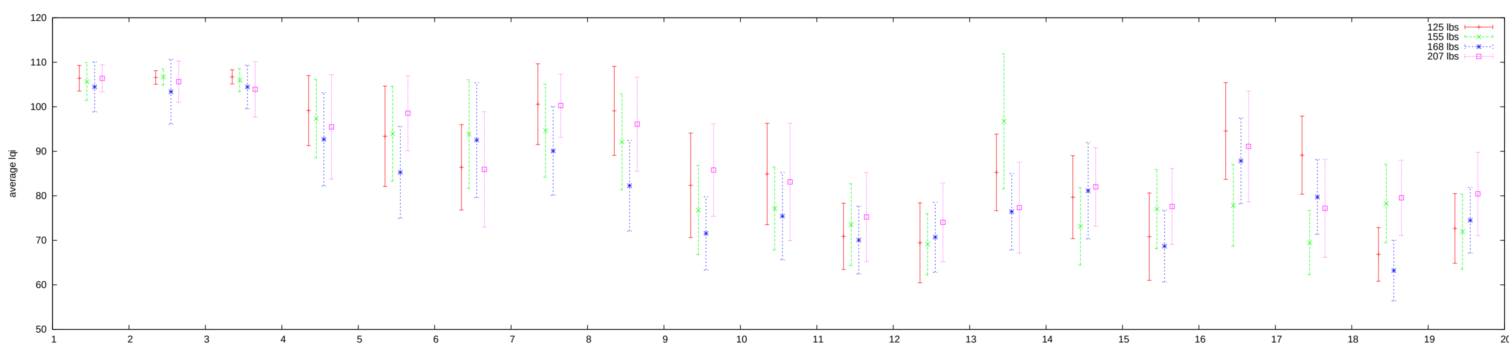

Figure 9: Average LQI for different body weights.

Figure 10: Colors of this figure match the figure of the average PRR for different speeds. The third trial is not shown for clarity because it double laps the second.

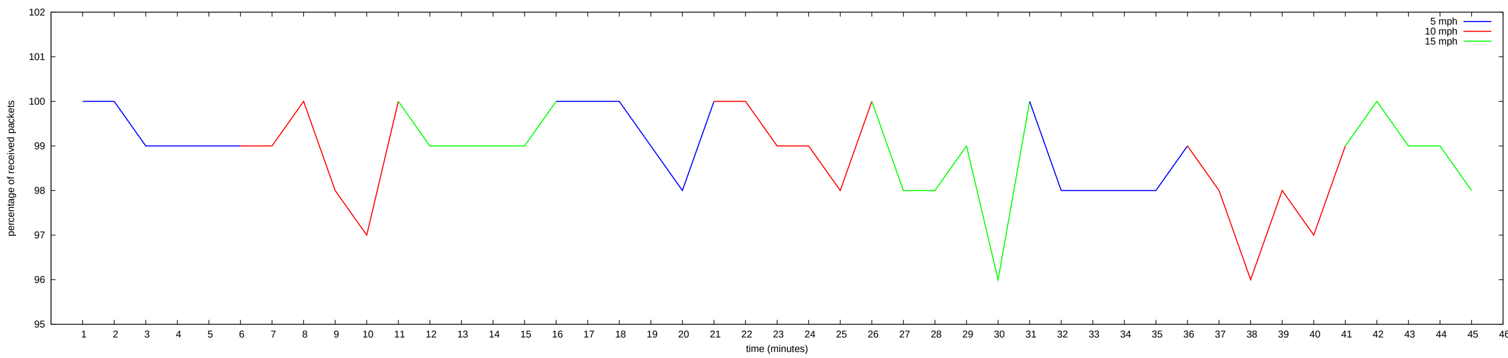

Figure 14: Average of received packets for different speeds at the constant distance of one bike length during a trip in the Santa Barbara area. Different colors signify different speeds.

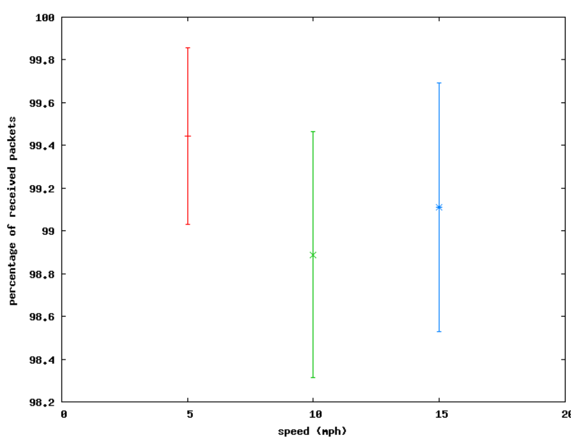

Figure 11: Percentage of received packets for three different speeds at the constant distance of one bike length: 5, 10 and 15 mph.

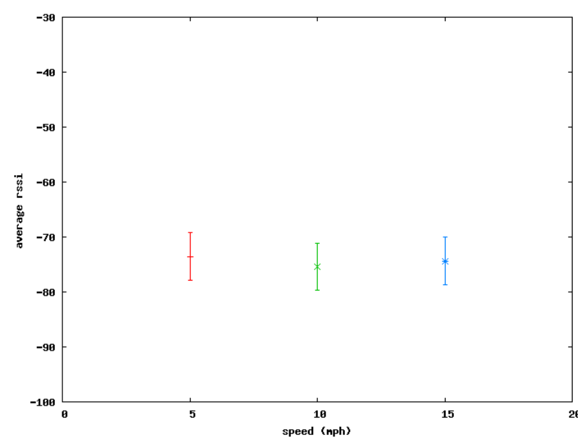

Figure 12: RSSI values averaged for three different speeds at the constant distance of one bike length: 5, 10 and 15 mph.

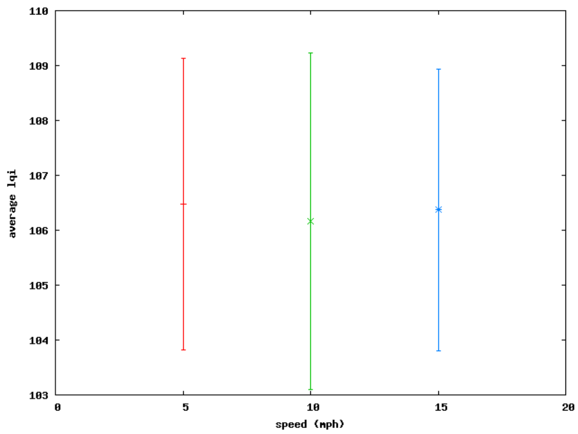

Figure 13: LQI values averaged for three different speeds at the constant distance of one bike length: 5, 10 and 15 mph.

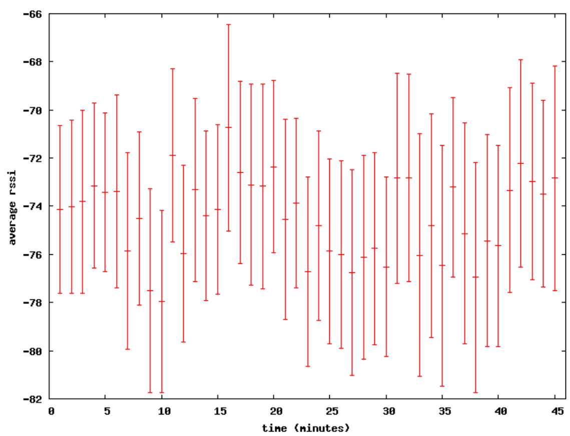

Figure 15: Average of RSSI values with standard deviation during a trip in the Santa Barbara area. The distance between the bikes is constant (1 bike length), while the speed is variable.

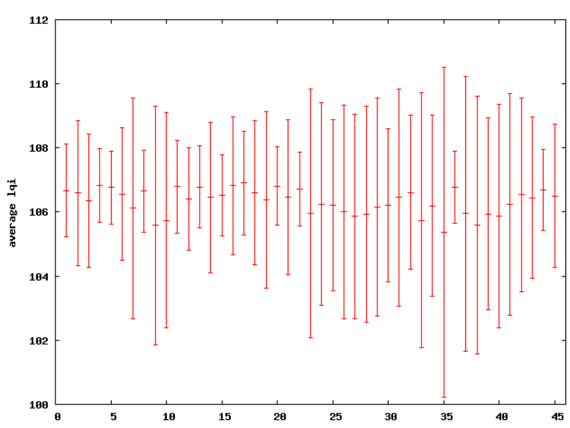

Figure 16: Average of LQI values with standard deviation during a trip in the Santa Barbara area. The distance between the bikes is constant (1 bike length), while the speed is variable.

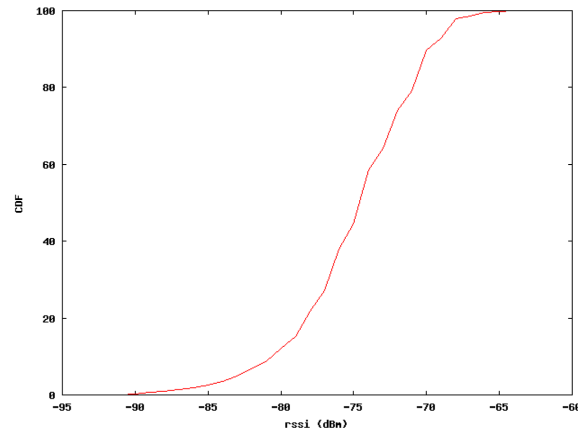

Figure 17: CDF of RSSI values for a trip in the Santa Barbara area. The distance between the bikes is constant (1 bike length), while the speed is variable.

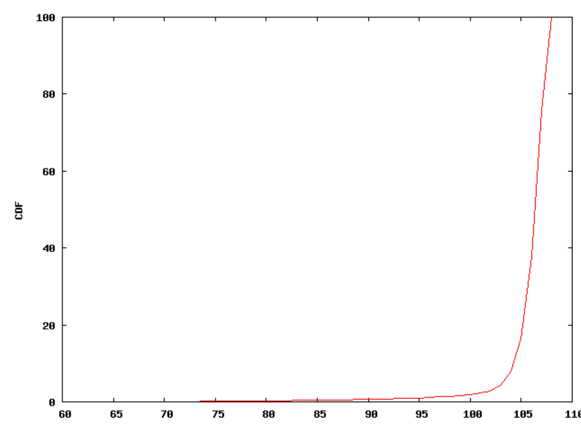

Figure 18: CDF of LQI values for a trip in the Santa Barbara area. The distance between the bikes is constant (1 bike length), while the speed is variable.

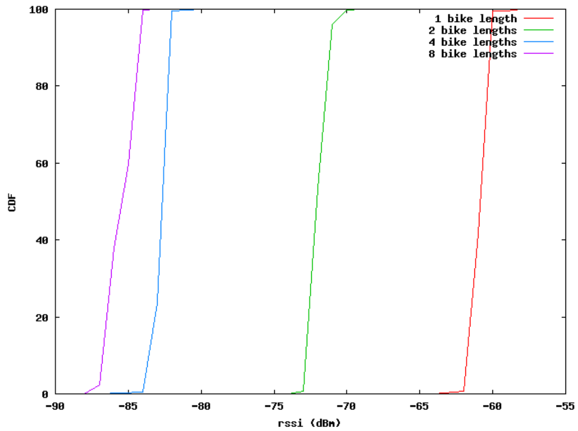

Figure 19: CDF of RSSI values for the static case for different lengths using a stick sender.

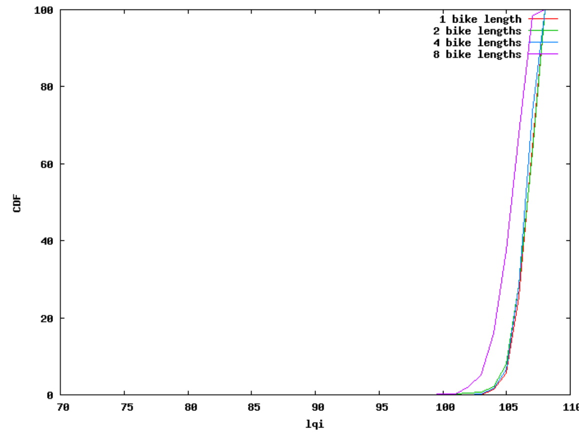

Figure 20: CDF of LQI values for the static case for different lengths using a stick sender.

sender and receiver. A series of experiments were run on different bike lengths: 1, 2, 4 and 8. Consider the average of received packets for these four different distances (Figure 21); the reception experiences a tremendous degradation when the distance increases, in fact for 8 bike lengths the reception is below 65% which is far less than in our reported static case without body interference. In Figure 22 we observe the degradation of the signal which enters the gray area where the threshold is not a good indicator of packet reception. On the other hand, the LQI is a better predictor of the packet reception, as we can see from Figure 23, where the values for 8 bike lengths are below 90.

Figure 24 shows the CDF of the RSSI for different lengths, and a clear pattern prevails where more of the distribution pushes toward weaker signals compared to the static CDF of no body interference in Figure 19. The distribution is far less distributed in the static case. This means less randomness and more predictability. The comparison for Figure 25 to Figure 20 is similar. With the addition of mobility and body factor, it is clear to see that there are great performance degradations for mobile bicycle systems.

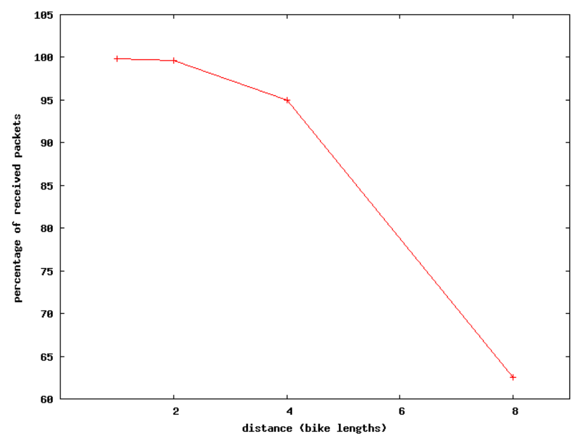

Figure 21: Percentage of received packets for four different bike lengths: 1, 2, 4 and 8.

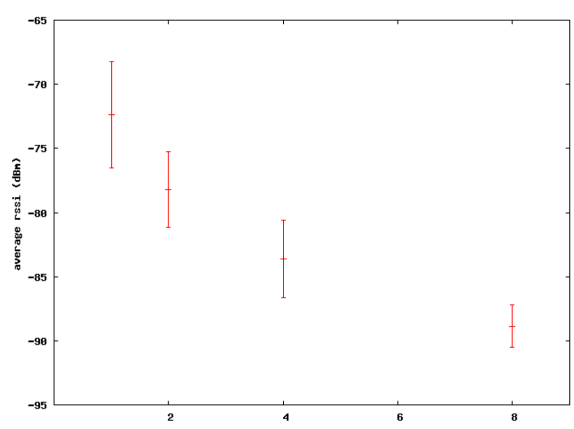

Figure 22: Average of RSSI values with standard deviation for four different bike lengths: 1, 2, 4 and 8.

6 CycleNet

In this section we discuss the motivation for bicycle networks and speak of other aspects which should be considered when building such networks.

In mapping the cyclist experience, Eisenman et al. in [3] shows many practical enhancements by the addition of wireless sensor networks. The end result is presented in a web portal for users to peruse. As previously mentioned, much information can be had from these sensors such as trail and speed measurements as shown by our own collected data in Figure 26. From this figure we see where we can im-

Figure 26: A trail mapping throughout the Santa Barbara, CA region. Different colors signify different speeds.

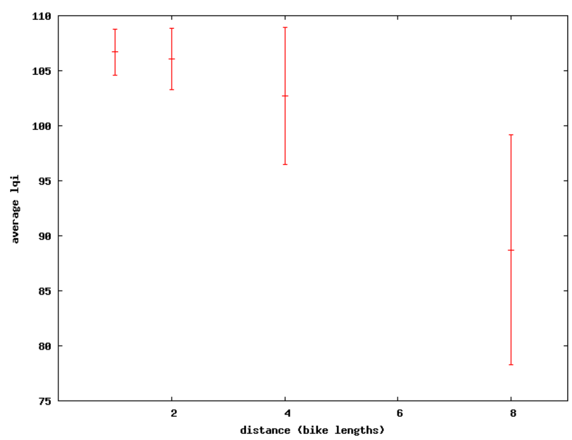

Figure 23: Average of LQI values with standard deviation for four different bike lengths: 1, 2, 4 and 8.

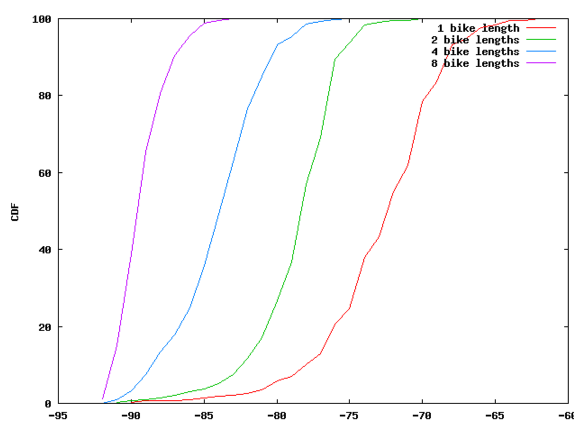

Figure 24: CDF of RSSI values for four different bike lengths: 1, 2, 4 and 8.

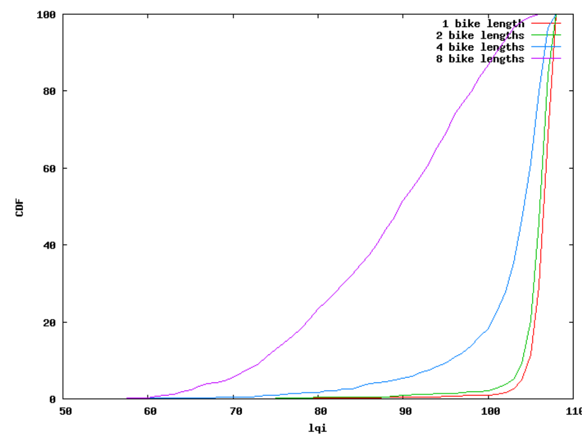

Figure 25: CDF of LQI values for four different bike lengths: 1, 2, 4 and 8.

prove our performance if training, or areas to avoid (slower regions) if we are looking for an efficient path for commuting to work.

When mounting the devices developers should consider two major issues. Firstly they must be placed where they do not interfere with the rider, such as the handle bars where they may rest their hands. The means of mounting must also be considered as to make sure it is placed firmly onto the bike. In our experiments we used Velcro, but the mote itself was exposed to harsh conditions of the weather. Thus a protective casing should be used to protect the device from both the weather and possible sweat from the user. Secondly, the mote should be placed with the correct antenna orientation, as placing it flippantly can adversely affect performance.

Another consideration is what kind of display should be used. One should be cognizant of the fact that the device is outdoors and should be visible during both night and day. We found it difficult without shadowing the mote with our hand to read the LEDS when dealing with the MICAz mote.

New applications for mobile bicycle networks have yet to be explored. When dealing with cooperative cyclists that travel in a group, there are opportunities for sharing resources which can lead to more efficient means of attaining data. An example of such an application would be cyclists taking turns in attaining power draining GPS fixes, which can cost more than 60mA to attain [11]. With larger groups more power can be saved amongst the cyclists, or a higher sampling rate can be achieved. Another example application is in the field of training where the heart beat monitor can be reported to other riders, letting them know when they need to slow down or speed up. Our last example has to do with trying to attain maximum distance for minimum effort. By attaching wind sensors the draft effect can be measured. Cyclists can get both real time data as well as a full picture offline as to where they had difficulty drafting with respect to others in the group.

7 Conclusions and Future Work

For future work we intend to attain more data to increase the accuracy of our findings. We postulate that with additional bodies in the line formation there will be greater attenuation, and thus needing multiple hops at the routing layer to overcome this additional body interference. Other formations will also be analyzed, such as the reception quality between parallel bicycles at different distances. With the use of GPS data we can also analyze reception quality over casual rides where there is no controlled speeds or set inter-bicycle distances.

Greater insight into mobile networks and radio reception allows system developers to create more intelligent protocols and applications. Our research has shown, in setting of high mobile networks, factors such as the body interference can play a great role in the performance of an application. By understanding that these factors exist developers are able to adjust and adapt to new situations and expand their domain. We have shown that RSSI becomes a very limited indicator in mobile situations except for the case of very close range. Furthermore, we have presented experiments showing that speeds of 15mph or less do not adversely affect communication when within close range.

8 Acknowledgements

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