Mobile throughput of 802.11b from a moving vehicle to a roadside access point

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Abstract. This paper documents some tests of 802.11b wireless communication technology for vehicle to roadside communication. Data has been collected for a single vehicle communicating with a dedicated roadside antenna. The work is part of a larger effort to benchmark possible throughput of off-the-shelf wireless technologies. The results show that high-speed communication is possible over distances of up to 1 kilometer.

INTRODUCTION

Off the shelf wireless technology has advanced dramatically in the past few years. A wireless networking card is cheap, and provides plenty of bandwidth without incurring any fee for airtime. Taking a market driven view of hardware adoption, it is reasonable to suppose that drivers will have easy access to a device plus some type of commercial wireless card that operates on 802.11b or some similar technology. Several research projects at UC Irvine are considering using off the shelf technology such as WiFi cards for vehicle to vehicle and vehicle to roadside communication. Some example projects include providing information to campus visitors, announcing parking availability, and tracking arrival and departure times of vehicles. However, before diving into full scale implementation of these projects, it is first necessary to benchmark the real-world performance of 802.11b and related technologies (hereafter referred to as 802.11b for simplicity).

Several existing papers already document the performance of 802.11b, including *(5)*, *(10)*, *(1)*, *(2)*, and *(9)*. Most such benchmarking studies were aimed at computer science or wireless radio technology research, and as such were not interested in testing raw throughput values. Aziz's work *(1)* is more in line with the research needs of this project, although all of the mobile devices were assigned fixed IP addresses in advance. Outside of the academic literature, conventional wisdom on the topic ranges from claims that the Doppler shift will kill the 802.11b signal at any speed, to people who engage in "wardriving"—the practice of locating open WiFi access points by driving around with a tool such as Kismet *(4)*.

None of these studies satisfactorily addressed the simple vehicle to roadside throughput case. This paper documents some tests of 802.11b wireless communication technology for vehicle to roadside communication. Data has been collected for a single vehicle communicating with a dedicated roadside antenna. The work is part of a larger effort to benchmark possible throughput of off-the-shelf wireless technologies. The work is on-going, with further analyses of the data planned, and vehicle to vehicle tests still to be performed.

TEST EQUIPMENT

The test setup is as follows. Two Cisco AP 350 series wireless access points were mounted on buildings fronting Peltason Road. The access points were connected to building mounted 13.9dBd antennas. The antenna specifications are as follows:

- 3dB Beamwidth, Degrees E-Plane 30
- 3dB Beamwidth, Degrees H-Plane 34
- Enclosure Material UV Stable Polycarbonate
- Frequency, MHz 2400-2500
- Front to Back Ratio, dB 18
- Gain dBd 13.9
- Impedance (ohms) 50
- Mast Dia in(cm) 2-1/8(5.4)

FIGURE 1: A map of the study area. The **EG** building is in the upper half towards the right; the **MST** building is in the center of the map; the **X** in the lower left marks an intersection that is approximately 1 km from the MST building. (Orthographic image from USGS.)

- Mount Style Mast w/U-Bolts
- No. Elements 15
- RF Connector(f) N
- Ultralink Cable in.(cm) 12(30.5)
- Weight, lb(kg) 1 (.455)

The primary study area is shown in figure 1. One antenna was mounted on the Multipurpose Science and Technology (MST) building, shown in the center of figure 1, and the other was mounted on the Engineering Gateway (EG) building, just to the right of the MST building in figure 1. As one can see from the specifications, the antennas are directional antennas. Both are pointed in a westerly direction along Peltason Road, more or less towards the **X** marked in the lower left of figure 1.

Inside of the vehicle, wireless connectivity was achieved using a Lucent Orinoco Silver PCMCIA card, with a 5db gain omni directional external antenna plugged into the card and mounted on the vehicle roof using a magnetic mounting. The laptop powering the card was also connected to UCI-ITS's extensible data collection unit (EDCU) *(6)*, in order to obtain geographic information on the wireless signal. The system was also tested running on the EDCU directly, using the second generation EDCU's built-in 802.11b board, but the results have so far been unsatisfactory due to defects in the unit's design.

In order to test the wireless link capacity, the utility program Netperf was used *(3)*. Netperf is designed to test various aspects of a network connection. In this test, it was configured to repeatedly conduct throughput tests with a one-second duration. Other modes allow for variation in the sent signal socket size, the received signal socket size, the size of the sent signal blocks, and so on. Future tests will explore these variations in order to more fully characterize the wireless link.

The actual command line used for the Netperf program is as follows (all on one line):

```
netperf -l 1 -H jtorous.its.uci.edu -t TCP_STREAM -P 0 -- -m 1024
    -s 8092 -S 8092
```

In practice, since the polling rate of the GPS antenna is also 1 second, a Netperf reading was obtained for every other GPS reading, or once every two seconds.

DATA COLLECTION

Several trips were made on multiple days on Peltason, along Bison, and in and around the nearby streets and parking lots in the vicinity of the two building mounted antennas. The wireless antennas were using a unique SSID, which was also entered into the mobile radio, in order to prevent association with other wireless networks in the test area. Tests using Kismet showed that there were at least 40 different access points in the study area at the time the tests were conducted. The test procedure was controlled by a script, as follows:

1. power up and begin driving
2. associate with an access point
3. establish a DHCPCD connection with an access point
4. test loop
   (a) poll the GPS antenna for time and position
   (b) run the Netperf test for the time and position

Once the DHCPCD connection was established for a particular test run, it was not necessary to reestablish the 802.11b antenna's assigned IP address, even if the vehicle moved from one access point (AP) to the other, or moved out of range entirely, since both APs are on the same subnet. When the vehicle moved out of range of the access points, the Netperf call would stall for an extended time period while it waited for a response. During that time, GPS readings would continue to be recorded, so that the points where no contact was possible are also recorded.

COLLECTED DATA

Data was collected over several days. To date, $3,263$ GPS observations have been recorded within the test area using the above procedure. Of those, there are 417 observations of non-zero 802.11b throughput values. The maximum throughput observed was 4.62 Mbps, which compares favorably with what would be expected using 802.11b in the more typical indoor environment. More interesting is the fact that this maximum throughput value was measured while the vehicle was traveling at 30.7 mph. The measurement was taken at an approximate distance of 159 meters from the MST building access point.

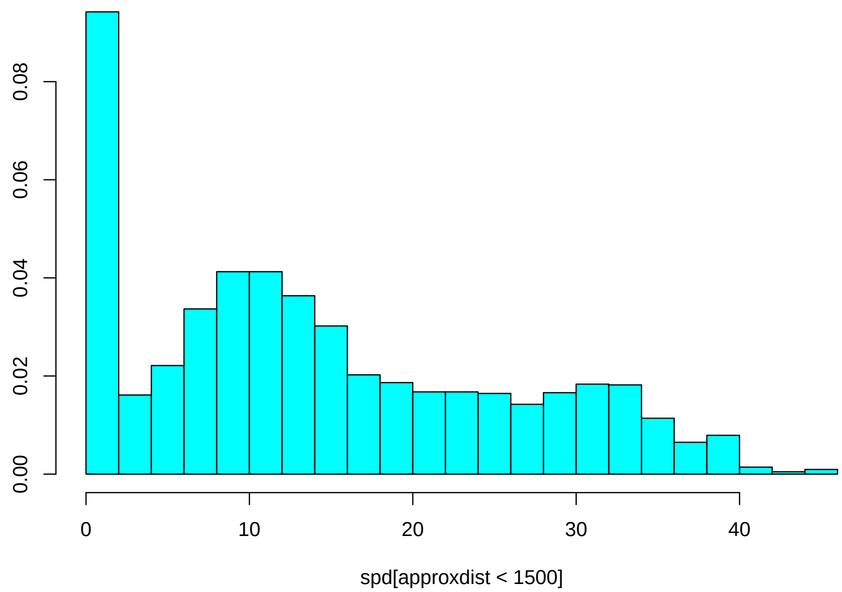

FIGURE 2: Histogram of speeds for observations points within 1500 meters of MST antenna

Speed effects

Within the collected data, there is no immediate relationship between increasing speed and decreasing throughput. This is because distance and line of sight are more important variables, and must be controlled for first. Comparing figure 2 against figure 3 shows no immediately obvious differences in the distribution speeds for all points and those with 1 Mbps or greater throughput. Comparing the histograms for figure 3 and figure 4 (greater than 4 Mbps throughput) shows a slight shift in the peak to the left, indicating that higher throughputs tend to occur at lower speeds. However, the high throughputs also occur at 35 to 40 miles per hour, which is the speed limit within most of the test area.

Distance effects

The effect of distance was surprising. The distance histograms are shown in the following figures. Comparing the histogram for all points in figure 5 with that for all positive throughput points in figure 6 shows that positive throughput is more likely to occur at points closer to the antenna, as expected. However, examining figure 7 shows that high throughput values are even more likely to occur at distances between 800 and 1000 meters than between 200 and 400 meters. If one drives the road and observed the topology, the reason for this is clear. The antenna on the MST building is pointing directly at the intersection of Bison and California. Then, in addition to the directionality of the antenna, there is a line-of-sight blockage that occurs due to the hill located between the MST building and the intersection of Bison and Peltason. Thus as a vehicle drives towards the MST building from the 73 freeway (not shown off the lower left of figure 1), it will enter a region

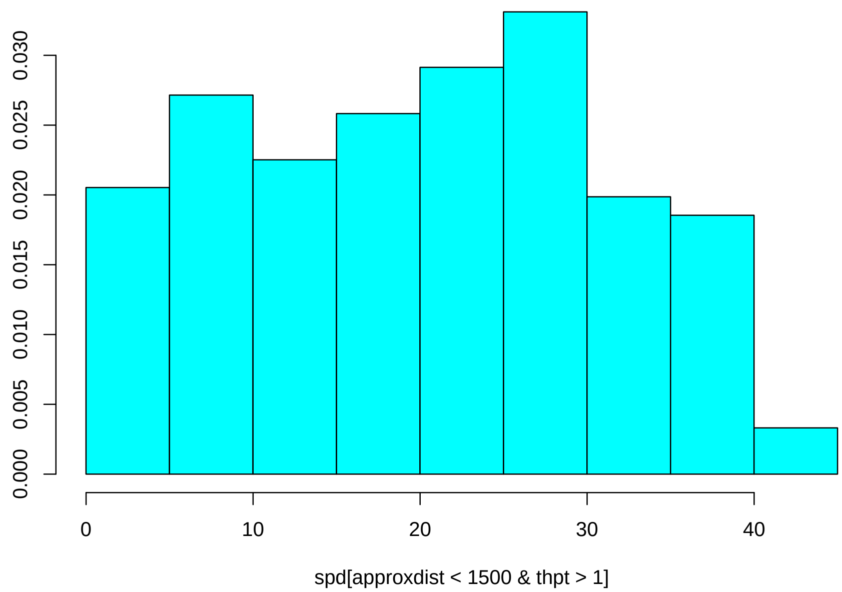

FIGURE 3: Histogram of speeds for observations points within 1500 meters of MST antenna, with 802.11b throughput greater than 1 Mbps.

of high capacity at Bison and California, lose the connection entirely as it turns onto Peltason, and then suddenly pick up a strong, high-throughput signal again as it crests the hill and rounds the curve towards the MST building.

An additional, more thorough test of network throughput, performed outside of a vehicle within the area of the intersection of Bison and California (approximately 1000 meters away from the MST building antenna) showed that the connection could sustain throughput of 3.56 Mbps $\pm 2.5\%$ at 99% confidence level, based on a series of 10 second duration Netperf tests. This site is marked by the **X** in the lower left of figure 1, and is conveniently located immediately outside of a Starbucks coffee outlet which made wireless testing convenient (although at the added expense of possibly more ambient noise on the 802.11b channel).

Figure 8 depicts a map showing the test area and the points of non-zero throughput. In a color version of this document, the red circles indicate points where greater than 4 Mbps throughput was measured. This includes the intersection of California and Bison, as well as the area of road immediately adjacent to the two antenna sites. The MST building antenna is located at the corner of Circle View and Peltason (the left triangle) and the EG building antenna is located just to the right of the intersection of Los Trancos and Peltason (the right triangle).

Line of sight

As can be seen from the map of figure 8, the connectivity is highly directional. This is for two reasons. First, the antennas are directional, and are pointing in a westerly direction along Peltason.

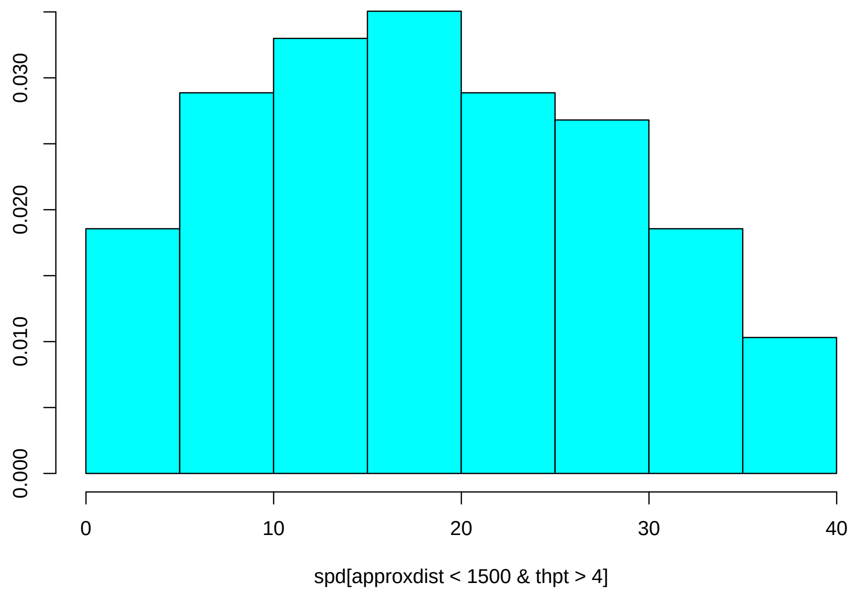

FIGURE 4: Histogram of speeds for observations points within 1500 meters of MST antenna, with 802.11b throughput greater than 4 Mbps.

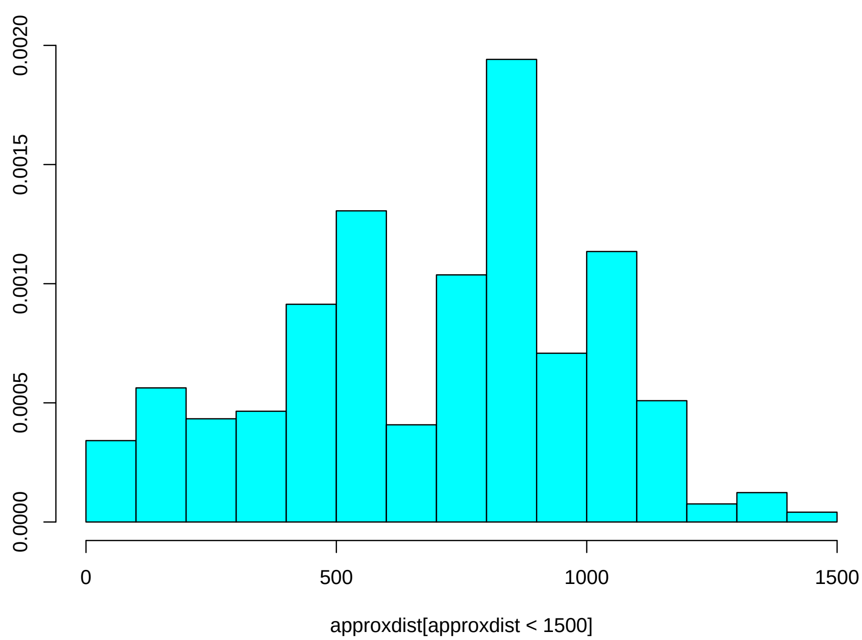

FIGURE 5: Histogram of distance for observation points within 1500 meters of MST antenna

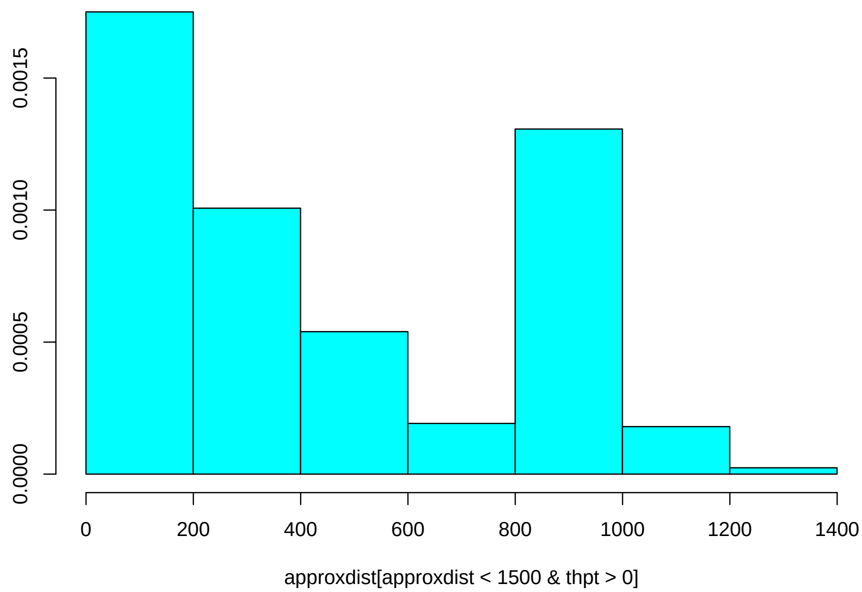

FIGURE 6: Histogram of distance for observation points within 1500 meters of MST antenna, with 802.11b throughput greater than 0 Mbps.

Second, 802.11b requires a clear line of sight. As one approaches the Engineering Gateway building from the east, the EG antenna is blocked by the eastern half of that building, which stairsteps out towards the road. As one approaches the MST building from the west, the line of sight is blocked by the curve and by a hill, so that as a vehicle crests the hill and rounds the curve, it suddenly jumps from no connection, to being in an optimal position to establish a wireless connection with the MST building antenna.

Line of sight can be approximated by computing the angle between the vehicle and the antenna. This is shown in figure 9. The angle between the MST building antenna and the intersection of Bison and California is 192 degrees. Figure 10 focuses on just the 34 degree band centered on 192 degrees.

In order to assess the combined impact of line of sight (angle), speed, and distance, a simple linear model was fitted to the data, using the glm function of the R language *(8)*. First, only the westerly data, defined as 192 degrees plus or minus 17 degrees, was included. This approximates the view from the MST building antenna, and reduces the impact of line of sight occlusions. The model fit produced the following results.

```
Call:
glm(formula = thpt[posthpt & west] ~ approxdist[posthpt & west] + spd[posthpt & west] +
    angle.off.192[posthpt & west])
Deviance Residuals:
     Min        1Q    Median        3Q       Max
-3.35155  -1.04839  -0.02285   1.14324   2.92448
Coefficients:
                                Estimate Std. Error t value Pr(>|t|)
(Intercept)                    4.9144968  0.3644517  13.485  < 2e-16
```

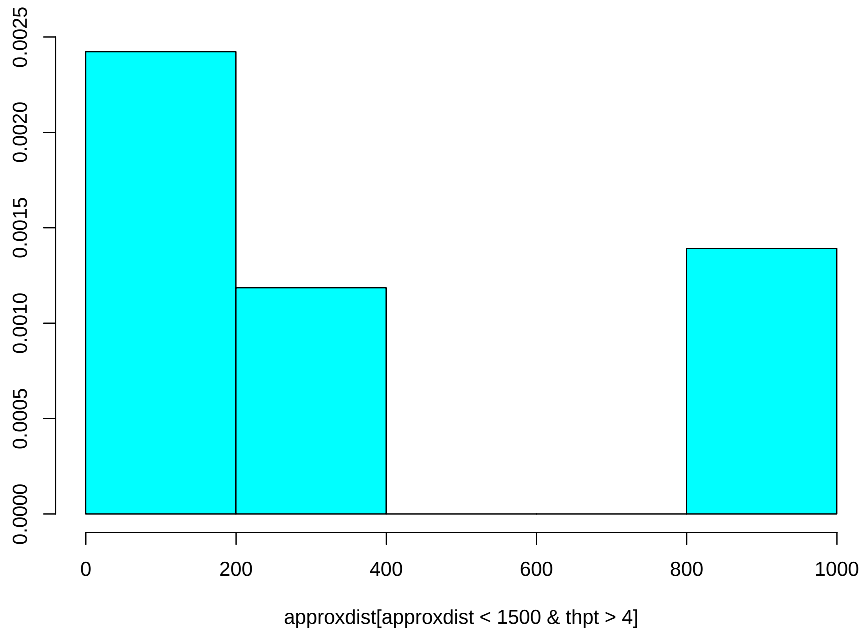

FIGURE 7: Histogram of distance for observation points within 1500 meters of MST antenna, with 802.11b throughput greater than 4 Mbps.

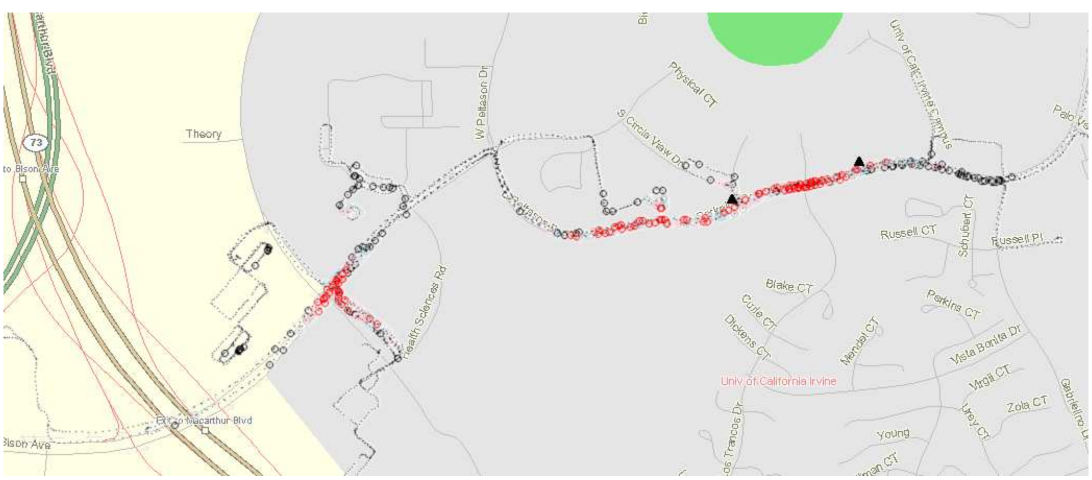

FIGURE 8: Map of 802.11b throughput test area. The circles indicate areas of positive throughput measurement. In a color map, the red circles indicate points where greater than 4 Mbps throughput was measured.

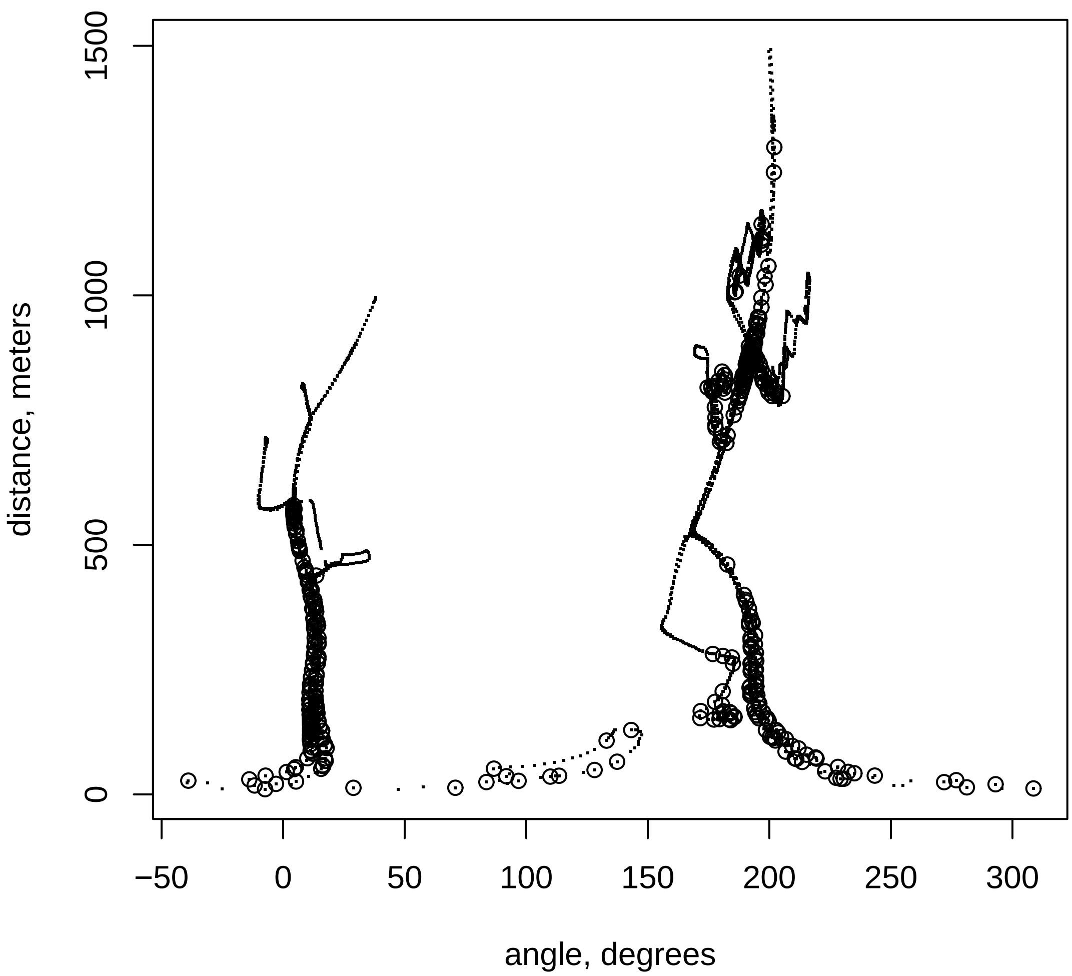

FIGURE 9: Angle versus distance for recorded points. Circles are points with positive throughput. Angle has been rotated such that zero is approximately east, and 180 is approximately west (inverted when compared to the map in figure 8).

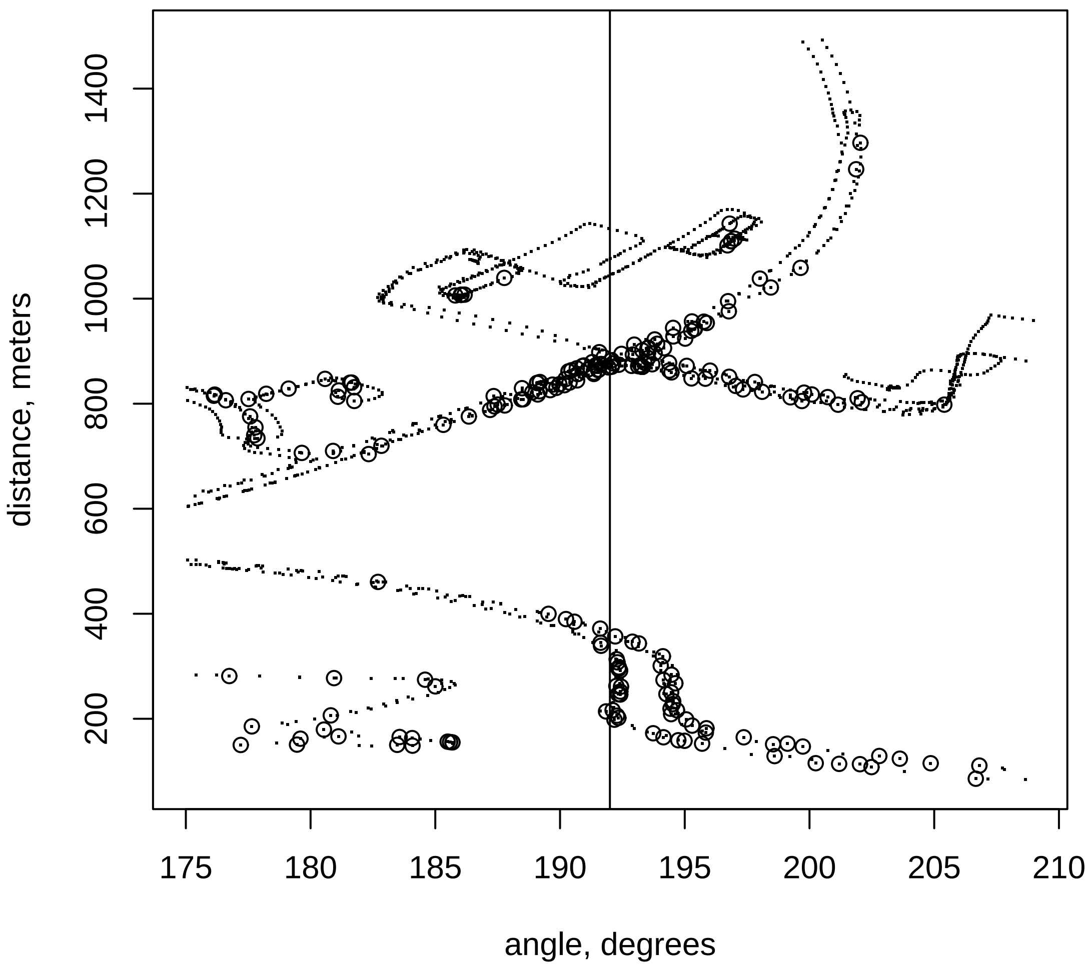

FIGURE 10: Angle versus distance for recorded points, for a 34 degree band around 192 degrees. Circles are points with positive throughput.

```
approxdist[posthpt & west]    -0.0019711  0.0003172  -6.214 2.65e-09
spd[posthpt & west]           -0.0248675  0.0088371  -2.814  0.00535
angle.off.192[posthpt & west] -0.1790187  0.0216300  -8.276 1.33e-14
```

All values are in the expected direction (negative), with distance and angle away from 192 degrees being more significant than speed. If angle is removed from the model, the speed coefficient is even less significant. Similar results are obtained if the acceptable angle is tightened further, to 192 degrees plus or minus 5 degrees, as follows.

```
Call:
glm(formula = thpt[posthpt & west.5d] ~ approxdist[posthpt & west.5d] + spd[posthpt & west
    .5d] + angle.off.192[posthpt & west.5d])
Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.2825  -1.2331   0.2676   1.1392   2.3799
Coefficients:
                                   Estimate Std. Error t value Pr(>|t|)
(Intercept)                       5.3367090  0.5936785   8.989 1.96e-15
approxdist[posthpt & west.5d]    -0.0020871  0.0005797  -3.600 0.000445
spd[posthpt & west.5d]           -0.0392422  0.0142851  -2.747 0.006834
angle.off.192[posthpt & west.5d] -0.2129229  0.0918814  -2.317 0.021988
```

As expected, the impact of angle of deflection away from 192 degrees is insignificant, as there isn't much deviation. Again, both distance and speed are significant, with their impact slightly higher (more negative) on throughput than for the wider, 34 degree data window.

The results are somewhat unsatisfactory in that the throughput values were not significantly reduced by either distance or speed. Instead, the largest effect was losing the line of sight. At distances greater than 1000 meters (moving away from California on Bison, towards the 73 freeway), the road drops down a slight hill, thus blocking the signal from the MST building antenna, limiting the value of distance measurements. Further, the intersection of Bison and California (located next to the large **X** in figure 1) is controlled by a stop sign. Without breaking the law, it is impossible to test the effect of higher vehicle speeds upon throughput at large distances.

RELATED RESEARCH

As was mentioned in the introduction, several existing papers already document the performance of 802.11b, including *(5)*, *(10)*, *(1)*, *(2)*, and *(9)*. Most such benchmarking studies were aimed at computer science or wireless radio technology research, rather than simply testing and benchmarking raw throughput values. It was already noted that Aziz's work *(1)* is in line with the research needs of this project, although all of the mobile devices were assigned fixed IP addresses in advance rather than obtaining them dynamically.

Kosch and Schwingenschlögl *(5)* measure the throughput of 802.11b in a vehicle to vehicle and vehicle to roadside scenario in order to assess its suitability for communication in a vehicular environment. They conclude that such a use is possible, but their analysis is difficult to generalize and quantify. Further, their end goal is to establish stable point to point links so that network-wide, multi-hop routing would be possible.

Singh et al. *(9)* measure vehicle to vehicle communications under a variety of scenarios. The primary difference with the work reported here is the use of a 13.9 dBd narrow beam fixed antennas to improve the range of the roadside access points, and their use of 256 byte messages in Netperf rather than 1024 byte messages. Among their results are a report that vehicle to vehicle throughput was measured at 400 Kbps at 500 meters using external, omnidirectional antennas (gain unspecified). The maximum vehicle to vehicle throughput measured was about 2500 Kbps at close range, but the throughput was effectively zero for distances approaching 1 km. Clearly the fixed antenna has tremendously improved the throughput and range reported in this paper.

The FleetNet project has put out several papers relating to ad hoc vehicle to vehicle communications. Torrent-Moreno et al. *(10)* explore using 802.11 protocols to improve communications for broadcasting safety-related messages when a large number of vehicles are communicating over a vehicle to vehicle network. This paper and a more recent paper (Torrent-Moreno et al. *(11)*) examine performance of wireless networking *protocols* using simulation. Their purpose is to improve the protocols, and so do not answer questions about capacity today using off the shelf hardware.

There are also several research projects that examine high-level applications layered on top of a vehicle to vehicle and vehicle to roadside communications network. Typically, tests of off-the-shelf hardware are included as part of the project work in order to determine where improvements are needed. For example, another group of FleetNet researchers, Ebner et al. *(2)*, analyze several wireless technologies and protocols both analytically and empirically for the FleetNet project, and conclude that only UTRA TDD Ad-Hoc will support their need for a minimum of 5-hop vehicle to vehicle networking. Later, with a paper by Moske et al. *(7)*, the FleetNet project researchers report on the performance of their prototype vehicles which use 802.11b with external, 4 dBi antennas. Their single-hop tests are similar in nature to the test reported in this paper, but study received power fluctuation and packet loss over time at a variety of fixed distances, using a predefined, 1500 byte packet. Their single-hop tests also use static as opposed to moving vehicles. Their mobile tests explore the performance of a 3-hop system using the FleetNet protocols. Again, their focus is on multi-hop networking—a much more difficult problem than the single hop vehicle to vehicle and vehicle to roadside communications that is the subject of this paper.

Other published studies appear to presume that the technology will exist or be at least as good in practice as their simulated performance. Ziliaskopoulos and Zhang *(13)* simulate a vehicle to vehicle information system relying on an estimate of communications capabilities. Wu et al. *(12)* describe CORSIM simulation results, including the use of QualNet to simulate the wireless communication properties, for a routing protocol for carrying messages from one point to another over a vehicular network.

CONCLUSIONS AND FURTHER WORK

This report documents some preliminary results that were obtained for data throughput values from a moving vehicle communicating with a fixed, roadside access point over 802.11b. It has been shown that a signal is possible at distances of over 1000 meters, with a throughput of greater than 4 Mbps possible at those distances. By way of comparison, at this throughput one could download the PDF map file of UC Irvine available on the campus website within one second.

There are several tests which still need to be performed. First, the various parameters relating to the network performance test, such as the test message block size and the send and receive socket sizes, need to be varied to ascertain their impact upon the throughput. Second, it is desirable to measure instances where the throughput decreases to zero based on distance alone, and speed alone, in order to properly characterize the effects of these parameters. To date vehicle to access point communications has been limited only by line of sight considerations (buildings and hills). Third, the time to acquire an initial network connection was not measured. The tests documented only began once the mobile device had associated with the roadside access point. At driving speeds, the time to associate with an antenna may be longer that the time available to communicate. Finally, another important class of tests are vehicle to vehicle communications. These tests will follow more complete characterization of vehicle to roadside communications.

ACKNOWLEDGMENTS

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