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Outdoor Measurements on WaveLAN Radio

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OUTDOOR MEASUREMENTS ON WaveLAN RADIO
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Abstract

Outdoor propagation measurements were performed on the WaveLAN radio. These were done in a simulated platoon environment. Packet drop rates were measured at distance intervals. It was found that fading exists in such an environment, and may be caused by reflection from car bodies. The range of the WaveLAN is about 80 meters, less than the manufacture’s claim. Moving tests were performed at highway speeds and in traffic. The results are similar to those obtained in stationary tests.
Executive Summary

Here are some key results:

1. Range = 82 meters
2. Packet loss rate at this range < 3.5%
3. Fading may be caused by reflection from vehicle bodies, but frequency-selective fading also observed. These results are inconclusive.
4. Moving tests showed no significant difference from stationary tests.

These are important results and are very applicable to transportation problem solving. The radio’s range needs to be large enough for communication. Fading needs to be examined because it affects the reliability of the system.
1.0 Motivation for measurements

Radio communications between vehicles aids in the control of an Automated Vehicle Control System (AVCS). In a platoon configuration proposed by PATH, the vehicles in a platoon are linked in a wireless Local Area Network (LAN) using the token bus protocol. The goal of this project is to find a radio with the data rate, range, and packet error probability required by this system.

Outdoor measurements were performed with the WaveLAN radio. The WaveLAN is a wireless ethernet modem made by AT&T, and has a raw bit rate of 2Mbits per second. For more information, refer to [WaveLAN manuals]. These measurements were made to demonstrate the degradation in performance in an outdoor, mobile channel, and to provide motivation for more detailed channel measurements that require using signal analyzers and signal generators. The channel characteristics obtained can be used to build a channel simulator, which can be connected to the antenna ports of radios to simulate the outdoor, mobile channel in a laboratory. Since outdoor measurements are often time-consuming, and conditions are not repeatable, indoor tests are much more desirable.

Packet loss rate was recorded in outdoor environments with the WaveLAN radio. The results showed that fading exists in the channel between the end cars in an average size platoon. We verified that fading was caused by vehicles in the platoon, and that the loss characteristics were consistent with a 2-path model, described in the next section. A moving test conducted on the highway showed no significant degradation in performance from the stationary cases. In both moving and stationary tests, at under 100 meters, the losses were small, with most round-trip packet loss rates below 2% (1% one-way). At distances of up to 160 meters, transmission is still possible, but is strongly dependent on a line-of-sight path.

These results indicate that the channel between the vehicles at the front and rear ends of a platoon does indeed suffer from fading, and more detailed tests are needed to fully characterize it for the purpose of channel simulation.

2.0 Description of channel and channel model

The channel of interest here is between the two vehicles at the ends of a platoon. In a token bus architecture, the “token” is passed down from the lead car to the end car through successive cars in the platoon. It is then passed from the end car to the lead car directly.
This final link is long -- it is about 100 meters for a 10-car platoon, and suffers from fading and interference. The other links in the token bus are much more secure, because they are short (only between successive vehicles) and there is always a dominant line-of-sight path. The length of this link is constant, since all the vehicles in the platoon travel at the same speed, and keep a constant following distance in steady state. However, the environment is time-varying, because the entire platoon travel at highway speeds of approximately 60 miles per hour. Assuming all the vehicles in a platoon are of the same body type, i.e cars instead of trucks or vans, and assuming the antennae are mounted on the top of the cars, there is a line-of-sight path most of the time. It is likely that reflections from other vehicles on the highway contribute to the received signal and at times cause destructive interference. This effect is also time-varying, because vehicles are in relative motion with each other, although only slowly compared to the actual speed of the vehicles.

A very simple model of this channel is a 2-path model, shown in the following picture.

![2-path model of propagation](image)

We assume that the car bodies are perfect conductors, so their reflection coefficient has magnitude 1 and phase 180°. The above picture illustrates the scenario in which the reflection from one of the vehicles in the platoon reaches the receiving antenna. Since the difference in length between the 2 paths is much less than a wavelength (30cm), and the phase difference between them is 180°, the received amplitude is very small. If the positions of the vehicles are such that no reflected wave reaches the receiving antenna, then the line-of-sight path dominates, and the expected signal is good. There is never a ground-reflected path because of the tight spacing of the vehicles.

Because vehicles in a platoon are relatively still with respect to each other, one consequence of this model is that fades last forever. So if a platoon starts out in a configuration such that there is destructive interference between the lead car and the end car in the manner described above, the condition persists unless an algorithm actively changes the spacing so no such interference occurs. This fading is not frequency-selective, because all frequency components are phase-shifted by 180° when reflected by the metal roof.

A more accurate model would incorporate the effects of scattering of the atmosphere, reflections from vehicles in adjacent lanes, and reflections from structures near the road. The contribution of these paths to the received signal is much smaller than the line-of-sight element. But when the line-of-sight element is nearly canceled by the strong reflection, these paths become significant. This suggests that we can model the channel as one of 2 possible channels, one in which a strong line-of-sight path exists, and one in which the received signal is the sum of multiple paths of random phase and amplitude. If the
number of reflected paths is large enough, these are Rician and Rayleigh fading channels. Depending on the configuration of the vehicles in the platoon, one of them gives a more realistic description of the channel.

Results of our experiments are consistent with this model. Fading was observed at regular intervals in a simulated platoon, suggesting the cancellation of the line-of-sight path by the reflection from car roofs. The following is a description of the experiments and results.

3.0 The Experiments

The experiments involved stationary and moving tests, in which a pair of wireless radios were positioned far apart while sending and receiving packets. Since channel between adjacent cars in a platoon is very reliable because of the presence of a strong line-of-sight path, we are interested only in the channel between the lead car of a platoon and the end car. Also, we are interested only in the radio propagation characteristics in the outdoor environment, and are not considering the effects of in-band interference or media access control.

The questions we wanted to answer were: what is the range of the WaveLAN? How is transmission affected by vehicles in the platoon, and by vehicles in adjacent lanes? How is the moving channel different from the stationary channel? If fading is significant, then more detailed channel measurements are needed to determine the exact mechanisms that cause the fades. Our results in the following pages indicate that this is the case.

3.1 Equipment

The following equipments were used:

1. 2 WaveLAN wireless packet radios, connected to QW8963 antennas made by Antennex for 896-970MHz.
2. 22GHz spectrum analyzer, connected to a WaveLAN antenna.
3. 2 4-door sedans equipped with PCs. Each is installed with one WaveLAN radio.

Distances were measured by marking the road with chalk every 20 feet. For finer measurements, a tape rule was laid on the ground and numbers were read off of it, with reference to a part of the vehicle.

3.2 Test program

A ping-pong test program was written in C for the QNX environment. There are 2 versions of the program, one called “home-station” and one called “mobile-station.” “Home-station” is set to run without any inputs from the keyboard, and “mobile-station” is controlled by keyboard inputs. The following sequence of tasks are performed:

- Car “mobile-station” initiates numbered packets starting with packet number 1 and sends it to the “home-station,” which is at the other end of the platoon.
• “Home-station” waits for packets addressed to it, and retransmits it back to the sender. Hence, it is always set to receive and it transmits only when it receives a packet.

• After “mobile-station” transmits a numbered packet it switches to receive mode and waits for “home-station” to send the packet back. It doesn’t receive the packet it sent out in 100ms, it times out and records the number of the lost packet.

• Whenever “mobile-station” receives the retransmitted packet from “home-station” or times out, it transmits the next numbered packet.

• The WaveLAN has a register to keep track of the packets received with CRC errors. However, we never observed CRC errors in received packets, and hence only recorded the number of dropped packets. We record the number of dropped packets to compute the packet error rate.

From the number of dropped packets and the total packets sent, we can find the probability of packet loss. Since this is a round-trip test, the probability of packet error during the round trip is

\[
P(\text{error in forward trip}) + P(\text{correct forward trip}) \times P(\text{error in return trip}) = p + (1-p)p
\]  

EQ 1

where \( p \) is the probability of error for a one-way transmission. We can estimate the probability of round trip error by dividing the number of bad packets by the total number of packets sent, therefore we can find \( p \). In his paper, the loss percent is listed as percent of packet loss for round-trip transmissions. The probability of one-way loss is approximately 1/2 of this number if it is sufficiently small, <5% or so.

3.3 Experiment 1: Simulating a platoon

In this experiment, the two vehicles equipped with WaveLANs were spaced 82 meters apart, with 4 other stationary vehicles parked halfway in between to simulate the platoon configuration. More vehicles were not available to simulate a full platoon. This arrangement also somewhat simulates the propagation environment between lead cars in adjacent platoons in the same lane.

The car running “mobile-station” was moved forward and back and packet loss rate was observed at different locations. We found several fades spaced many feet apart. Starting at about 82 meters from “home-station,” the “mobile-station” was moved toward the “home-station.” The first fade gave a loss rate of 60 out of 2000, or 3%. The second fade was 2.7 meters away from the first, and the loss rate was 63 out of 1000, or 6.3%. The
third fade was 6.2 meters away from the second fade, and the observed loss rate was 79 out of 1000, or 7.9%. This is shown in the following illustration.

![Diagram](image)

**FIGURE 5.** Distance between successive fades for tail car in simulated platoon.

The region between fades exhibited very small loss rates, on the order of 1 out of 2000. We found that fades were several feet long in distance. At 0.6m from the first fade and 0.9m from the second, the packet loss rate went down to 0.15% and 0.05%.

512 byte test packets were used. The reason for the large packet size is because larger packets have a higher loss rate than smaller sizes, and fades were easier to detect using these large packets. Earlier experiments had shown a correlation among loss rates and packet size. This fact, combined with that there were no CRC errors in the received frames, leads us to believe that packets are dropped when errors occur in the middle of a packet, as well as during synchronization. Longer packets have more chances of being "hit" by bit errors, and therefore are dropped more often.

The observed packet loss vs. distance is consistent with the 2-path model outlined in section 2.0. In the above figure, each fade may be due to reflection from different vehicles in the platoon. The non-fading parts in between may correspond to positions when no reflection reaches the receiving antenna.

### 3.4 Experiment 2: Investigate the effect of middle car on transmission

This experiment further characterizes the effect of a vehicle between the transmitter and receiver, and provides more clues to the mechanism that causes fades. Again we spaced out the 2 vehicles with WaveLAN radios about 82 meters apart and placed another car between them. This middle car was moved forward and back, and packet loss rate was recorded for different positions of the middle car.

![Diagram](image)

**FIGURE 6.** Moving middle car
The results are plotted below.

**FIGURE 7. Fading versus middle car position**

Since the 40m mark was the midpoint between the transmitter and receiver, we expected to find a fade there, because the metal roof of the middle car would create a strong phase-reversed second path to cancel the LOS path. **This** was not the case. We also expected to find a symmetrical plot, but it’s difficult to say whether the above is symmetrical or not. These measurements were very crude -- they consisted of looking out the car at marks on the road every 6 meters, and gauging by eye the position of the front wheel of the car. (We used the front wheel as a reference)

As a result, the only thing we can say about this experiment is that the propagation characteristics are affected by the position of the middle car, and that we observed 5 fades at 6 - 15 meters apart.

When the measurements were made with no car in between, 37 out of 2000 packets were lost for 50-byte packets, and 299 out of 2000 packets were lost for 512-byte packets. These loss rates are higher than those recorded with the middle car in place. **This** is because there is not a clear path to ground, which causes destructive interference.

We believe that the fades are caused by the cancellation of a reflected path and the line of sight path. **This** can happen for the following positions of the middle car:
1. Reflected from hood of the middle car, through front and rear windshields, to the receiver. Since the hood is sloped down in the front, this occurs not when the hood is at the midpoint between the transmitter and receiver, but closer to the antenna to the back of the middle car.

![Figure 8](image1.png)

FIGURE 8. Reflection from hood.

2. Reflected from roof of middle car. This is a flat surface so this reflection happens when the middle car is exactly in between the transmitter and receiver.

![Figure 9](image2.png)

FIGURE 9. Reflection from roof.

3. Reflected from trunk lid of middle car, through front and rear windshields. This surface is almost flat, so we expect this reflection to take place when the trunk is at the midpoint.

![Figure 10](image3.png)

FIGURE 10. Reflection from trunk.

4. Reflection path goes through front and rear windshield of the middle car and is reflected by ground. This happens for 2 different positions.

![Figure 11](image4.png)

FIGURE 11. Through windshields and reflecting off of ground.

5. Over the top of the middle car and reflected from ground. Again this happens for 2 different positions.

![Figure 12](image5.png)

FIGURE 12. Over top of parked car, reflection off of ground.

Overall, we should find these 7 fades at the appropriate positions. Our plot shows 5 such spots. This may be because we did not record for the full range of positions of the middle car and missed 2 of the expected fades. Or, two or more of the fades may overlap.

The fades measured in this experiment showed packet loss rate of under 2% for 50-byte packets, and under 4% for 512-byte packets. But since measurements were taken only at 10-foot intervals, we may not have captured the worst fades. The next set of measurements should be taken closer together to ensure a more accurate picture of the fade patterns.
ments show that there are places where the fading is much worse, although these fades only cover a small region.

3.5 Experiment 3: Fading profile with obstructed ground-reflection path

In this experiment we measured and plotted a high-resolution fading profile for a path length of about 82 meters, with one parked vehicle between the transmitter and receiver. One of the vehicles with the WaveLAN radio was moved and packet loss rate was observed about every 15 centimeters, about half of the wavelength. Since we did not have access to more cars, a full platoon was impossible to simulate. We used one parked car in the middle to make sure the ground reflection path is blocked, and that the fading is caused by reflections from the car body.

A spectrum analyzer was also used to observe the signal spectrum. The spectrum analyzer used the antenna that came with the WaveLAN antenna, and the WaveLANs used the QW8963 antennas. The spectrum analyzer was placed in the AMC sedan and its antenna and the antenna from the WaveLAN radio were placed on the roof next to each other, about 8 centimeters apart.

A severe fade was recorded that spanned 0.5 meters. This fade had loss rates of almost 100% at places. The next fade was recorded at 6.5 meters away, it was less severe and its loss rate was 139 out of 2000, or 7%.

The following is a plot of the spectrum analyzer reading at several frequencies, plotted against position of the transmitter/receiver.

![Fading test 11/7/95](image)

**FIGURE 13. Signal strength at 3 frequencies vs. position of antenna**
Using the scale in the above plot, severe fading was observed at 158cm, 191cm, and 209cm. For these positions the received spectrum at 915MHz are between -57dBm, and -62dBm, and the receiver is in or close to a fade.

We can make several conclusions from these results. First, the fades are further apart than those observed for the case when there are 4 vehicles parked between the transmitter and receiver. We guess this is because the number of paths is smaller with only one car in the middle. Second, the fades are stronger than before. This may be because again there are fewer paths. For example, if only 2 paths exist and they have almost the same attenuation but are 180 degrees out of phase, then the combined signal is very weak. But if there are more paths then total cancellation is unlikely. For this experiment, there is a line-of-sight path, and only one reflected path from the car body. The middle car is positioned so the ground reflection path is blocked.

The spectrum of the received signal exhibited frequency-selective fading. As the receiving antenna was moved, the notch in the spectrum shifted in frequency.

FIGURE 14. Frequency-selective fading

This is not consistent with the assumption that the second path is the reflection from the roof of the middle car, which implies the two paths are nearly equal in length. Therefore, more work has to be done to understand the causes of fading.

3.6 Experiment 4: Moving test

Before a moving test was done, range measurements and measurements with one vehicle in the adjacent lane were performed stationarily. The range with no vehicle in between the transmitter and receiver was measured to be about 200 meters maximum. Beyond this distance there was no reception. Within 200 meters there were fades. With no vehicles between the transmitter and receiver but a vehicle in the adjacent lane, we observed no effect on the packet loss rate. The vehicle in the adjacent lane was a mini-van with glass windows all around. In the past, we have observed packet loss corresponding to vehicles moving by, most of which had high profiles, such as full-size vans, pick-up trucks and sport-utility vehicles. From this we tentatively conclude that vehicles with low metal profiles do not effect transmission, while those with metal surfaces at the level of the antennae do.

The moving test was performed on Interstate-80, on the stretch from the Richmond Field Station to the Sacramento River. The two vehicles with the WaveLAN radios were taken. Several packet loss measurements were performed with 50-byte packets and 100 - 400 packets...
packets per run. The number of packets per run is smaller than for the stationary tests because conditions change more quickly in a moving environment, and the distance between the test vehicles is changing. Distance between the vehicles were measured by recording the time each vehicle passed some structure along the highway, such as overpasses and signs. Here are some measurements.

<table>
<thead>
<tr>
<th>separation</th>
<th>lost/sent</th>
<th>% lost</th>
<th>environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>89 m</td>
<td>1/100</td>
<td>1</td>
<td>no car in between; concrete guards next to lane crowded</td>
</tr>
<tr>
<td>189 m</td>
<td>114/200</td>
<td>57</td>
<td>heavy traffic; no line-of-sight</td>
</tr>
<tr>
<td>159 m</td>
<td>0/200</td>
<td>0</td>
<td>open, mid to heavy traffic</td>
</tr>
<tr>
<td>240 m</td>
<td>21/400</td>
<td>5</td>
<td>cars and a tanker in between</td>
</tr>
</tbody>
</table>

The distances shown are measured crudely, they have tolerances of ±15 meters.

It was observed that at distances of under 100 meters, the transmission was good, with packet losses not exceeding 2%. The presence of car-type vehicles in between did not affect packet loss rate. At distances above 150 meters, packet loss rate can be very high, and the transmission depends strongly on the presence of a line-of-sight path. Note that the LOS path is still strong when only vehicles with low profiles are between the test vehicles, such as sedans. A few times the LOS path was blocked because of a tanker in between, or because the test vehicles were on opposite sides of a hill, and no packets were received.

Overall, the performance of the WaveLAN at highway speeds is not significantly worse than the stationary case.

4.0 Conclusion

Outdoor stationary and moving packet loss rate measurements were made on the WaveLAN Radio. The results of the stationary tests showed that in the channel between vehicles at the ends of a platoon, fading exists at regular intervals of 2·6 meters. This is consistent with a 2-path model, in which a reflected element from the roof of a vehicle in the middle of the platoon adds destructively to the line-of-sight element. This happens for some configurations of the vehicles. For other configurations when the reflected element does not reach the receiving antenna, the reception was good. In another stationary test, changing the position of a vehicle between the transmitter and receiver had an effect on the packet loss rate. This confirms that fading is due at least partly to vehicles in the platoon.

The stationary tests were conducted at a distance of approximately 82 meters between the transmitter and receiver, the length of a 9-car platoon. Even in the fades, most of the round-trip packet loss rates were below 2%, which translates into a packet-loss rate of 1% for one-way transmission. But the highest round-trip loss rate was observed to be 7.9%. 

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A moving test was conducted on 1-80 at 50-60mph. At under 100 meters, the packet loss rates were on the order of 1%. For up to 200 meters, transmission was still possible, although loss rate can be high when the line-of-sight path is obstructed by trucks and curvature of the road. Since communications needs to established in the forming stages of a platoon, we need a range of larger than 100 meters and closer to 200 meters. Therefore if the WaveLAN is to be used, then high gain antennae are required.

Measurements performed with the WaveLAN provide only packet loss information. More direct measurements, made with a signal generator and signal analyzer, will show more clearly what factors cause the observed fading. They can also show how the channel varies with time. Results from the WaveLAN packet loss rate tests suggest the need to characterize this time-varying fading channel, so we can gauge the performance of other radios in this environment.

Reference


[2]. “Intel 82586 LAN Controller,” Intel Corporation


