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A Discussion of the WaveLan Radio as Relevant to Automated Vehicle Control Systems

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A Discussion Of The WaveLAN Radio As Relevant To Automated Vehicle Control Systems

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Abstract

The WaveLAN radio, currently being used to implement the control loop communication in PATH, is investigated. We measured data rate and packet overhead using a ping-pong program and a demodulator circuit. We determined its MAC scheme with 3 experiments. We also simulated multipath fading effects using a tunable short-stub. The results show that the WaveLAN's spread spectrum does not combat multipath fading. We concluded that the WaveLAN is adequate for 1 platoon per cell, but no more than that because of limited bandwidth.
Executive Summary

The key results are:

1. data rate = 2Mbits/sec
2. packet overhead = 0.2ms
3. no hand-shake occurs in MAC
4. spread spectrum does not combat multipath fading.

These results are extremely applicable to transportation problem solving. Knowledge of data rate and packet overhead determines tells one whether there is enough capability to support the needs of PATH platooned vehicles. Knowledge of MAC protocol tells one whether hidden node problems can arise. (Yes) Results from fading experiments show that WaveLAN radios do suffer from multipath fading.
1. Introduction

A robust communication system is vital to the control of autonomous vehicles in an automated highway system. In the plan proposed by the PATH project, vehicles travel in platoons of up to 20 at highway speeds and with following distances of less than 2 meters. They must be in constant radio contact with the rest of the platoon to maintain stability and safety. This form of communication requires high data rate and low delays. Communication is also needed when a vehicle merges into a platoon or leaves one. A third form of communication has to provide the link between each vehicle and a central station. This link offers guidance and traffic control. [3] The last two forms of communication have less stringent requirements than the first. In this paper, we mainly evaluate the WaveLAN radio's ability to support the control loop of intra-platoon communication. [1]
2. WaveLAN Radio

2.1 Advantages of the WaveLAN

The WaveLAN radio is a wireless ethernet connection that operates at 916MHz, in the spread-spectrum band between 902 and 928MHz. It requires only a personal computer to operate and plugs into an expansion slot. This is a commercially available product made by NCR Corporation, a division of AT&T, for indoor wireless ethernets, such as in an office environment or in a warehouse. It is reliable and has good documentation. Also, there is existing commercial driver software written for this board. Although we still need to write our own driver for the specific needs of this project, the existing code serves as a good reference and makes our task easier. The WaveLAN radio uses an Intel 82686 LAN controller which performs the media access control tasks and transmits and receives without interaction from the CPU, therefore saving processor time. (But we will see later that the MAC layer is not very efficient.) For these reasons the WaveLAN is an attractive choice.

For detailed functions, please refer to “Interface Specification for the WaveLAN AT Network Interface Card,” and documentation on the Intel 82686 LAN Controller microprocessor. [2], [3].

2.2 Overview of Technology

The WaveLAN is a circuit board that plugs into the motherboard of a personal computer. It has an “F” type cable TV connector for the dual antenna. Programming the WaveLAN is done through I/O registers on the board.

The WaveLAN uses Direct Sequence Spread Spectrum in the 902-928MHz band.

![Figure 1.1 Block diagram of WaveLAN modulation](Image)

The data rate is 2Mbps. This bit stream is multiplied by an 11-bit spreading code, so the rate becomes 22Mbps. This bit stream redundancy and has increased noise immunity. This signal is then modulated using Differential Quadrature Phase Shift Keying. The output are symbols belonging to a constellation in the complex plane. The real and imaginary parts modulate spread spectrum pulses and are modulated with cosine and sine waves at the carrier frequency. The spread spectrum pulse is chosen to for maximum spreading in the frequency domain. The symbol rate is 11Mbps, because bits are mapped onto the complex plane in one of 4 symbols, so each symbol represents 2 bits. The bandwidth is then 11MHz.

More detailed technical information and specifications can be found in “An Engineer’s Story of WaveLAN.” [4]
3. Technical Details

This part of the paper describes the experiments performed with the WaveLAN radios. We are interested in these characteristics, discussed in three sections: packet time, media access control, and multipath fading. We wanted to verify the specifications given by the manufacturer and gain a deeper understanding of how this radio works from first-hand experience.

3.1 Data Rate and Packet Time

The control loop for a platoon requires high data rate and high reliability, because the stability of this link is crucial to safety. In a platoon of up to 20 cars, each car is required to update its velocity and acceleration every 20 milliseconds for a stable control system. The detailed form of communication between vehicles in a platoon is discussed in [5]. (In [5], the time required between each transmit is 50ms, 20ms is the more up-to-date number.) This means every vehicle has 1ms to transmit a packet. This is a very stringent requirement, and as we will see, difficult to achieve in a radio medium.

Two experiments were conducted to find out the actual data rate, not counting overhead. The first is a ping pong test, in which 2 WaveLAN radios bounces a packet back and forth following this sequence:

“B” is set to receive;
“A” sends a packet to “B,” and waits to receive;
“B” gets the packet, sends it back to “A,” and waits for the next packet;
“A” gets the packet, sends it back, and so forth, for 1000 times.

The average time for 1 packet to be sent and returned is calculated and plotted.

2. Ping pong test with 2 radios
This plot is linear, its slope depends on the bit rate. Using 2 points on this graph, at 612

3. **bund-trip time vs. packet size**

bytes and 768 bytes, we calculate the bit rate:

\[
\frac{768 - 512}{7.185 - 5.135} \times 1000 \text{ ms} \times \frac{8 \text{ bits}}{\text{byte}} \times 2 = 2 \times 10^6 \left(\frac{\text{bits}}{\text{sec}}\right)
\]

This number is consistent with the manufacturer’s claim.

The minimum packet return time is about 1 millisecond. This is the overhead that comes with each packet, including preamble, addressing, and framing information, and also CPU processing time.

4. **Timing diagram for round-trip test**
The next experiment determines the exact time the transmitter is on during a transmission. We took the signal from the WaveLAN board and demodulated it down from the 915MHz carrier frequency to baseband and observed this waveform on the oscilloscope. The WaveLAN was programmed to transmit every few milliseconds. When a packet is being transmitted, the output is a signal with bandwidth of about 13MHz. When the transmitter is idle, the waveform is just flat, as shown below. The approximate time it takes to transmit packets of 8 byte packets is 0.23ms and 0.40ms.

6. Oscilloscope waveform for packets of different length: 8 byte packets and 60 byte packets are 0.23ms and 0.40ms. At 2Mbps, the total number of bytes transmitted in these times are \( \frac{230 \times 2}{8} = 57.5 \text{ bytes} \) and \( \frac{400 \times 2}{8} = 100 \text{ bytes} \). We deduce that the overhead is 80 bytes, or 0.2ms. From the information given in the manual for the Intel 82686 LAN controller chip, we can count only 14 bytes of preamble and other framing information, which takes \( \frac{14 \times 8}{2} = 56 \mu\text{sec} \). The rest of this time (144 \mu\text{sec}) may be the time allotted for the radios to synchronize.

We recall from the first experiment that the round trip time for an 8 byte packet is 1.1ms. This includes the transmission time for 2 such packets, each containing 8 bytes of data and 60 bytes of header. Of the 1.1ms, total transmission time is

\[
\frac{(8 + 50) \text{ bytes} \times 8 \left( \frac{\text{bits}}{\text{byte}} \right) \times 2}{2 \times 10^9 \left( \frac{\text{bits}}{\text{sec}} \right)} = 464 \mu\text{sec}
\]

and the rest is CPU processing time, which is 1.1 - 0.464 = 0.636ms. There are several reasons for the long processing time. First, the computers that ran the WaveLAN radios in these tests were hooked up to a network and performing ethernet duties in the background. Second, polling was used instead of interrupts to perform these tests. Free-standing machines running interrupt-driven programs will have shorter processing times.

Assuming the platoons use 60 byte packets in the control loop, we need to ask how many
cars the WaveLAN radio can support, per length of highway. There is only 1 spreading code
in the current version of WaveLAN, so only 1 radio can transmit at a time in one cell. In a
20-car platoon, each vehicle gets 1 ms to transmit a 60-byte packet, which takes at least
0.4 ms, so 40% of the radio medium is taken up by one platoon. Since in a slotted ALOHA
scheme, the theoretical efficiency is 36%, we conclude that only one 20-car platoon can exist
in one cell. A cell is the area covered by the WaveLAN, which is a circle of radius 250 m. On a
highway, this means in a stretch of 500 m, only one 20-car platoon can exist. Clearly this is
not satisfactory for our purposes. In the future we need a communication system that uses
the available resources much more efficiently. For example, an infrared system can accom-
modate many more platoons because different platoons can transmit at the same time and
not interfere with each other. Or, a radio system with much wider bandwidth and shorter
range is needed to increase the capacity per length of highway.

Microwave radios, however, should be used in maneuvering, since such activities require
non-line-of-sight communication. The WaveLAN is well-suited for this purpose because here
a high data rate is not required, but due to the randomness of the physical orientation of the
link a line-of-sight system is out of the question. Of course, the vehicle-to-central station link
has to be accomplished with radio also.
3.2 Media Access Control

The WaveLAN uses CSMA/CA, which stands for Carrier Sense Multiple Access/Collision Avoidance. This is not an IEEE standard. A wireless ethernet protocol 802.11 is currently under way. Since the exact MAC used by the WaveLAN is not clear from its documents, and a hand-shake scheme is generally associated with the term “Collision Avoidance,” we needed to find out whether the WaveLAN implements this scheme. We found that it does not use any hand-shake in its MAC layer. (The possibility of a hand-shake protocol was first suggested by Dr. Manjari Asawa.)

In a hand-shake protocol, collisions are detected at the receiver. The transmitter and receiver establish a secure link before any data is transmitted, they use a RTS/CTS hand-shake, shown below.

![RTS/CTS hand-shake](image)

When “A” wants to send something to “B,” it sends a “Request To Send” (RTS) signal alerting “B.” If “B” hears no other radio transmitting, it sends a “Clear To Send” (CTS) signal to “A” telling it to go ahead. But if “C” is on, “B” cannot hear the RTS, so it doesn’t respond, and “A” times out and sends another RTS. This scheme makes sure that “A” transmits only when “B” can hear “A.” The following experiments show that this is not what happens in the WaveLAN.

3.2.1 Test #1: 1 Transmitter, No Receiver

In this experiment, one WaveLAN is set to transmit at regular intervals, with no receiver. The WaveLAN recorded no collisions, and data packets were sent. We know this because in the demodulated waveform of the transmitted signal on an oscilloscope, packets with different data lengths had corresponding transmission times. These results lead us to believe no hand-shake is required for transmission, otherwise only Request-To-Send signals would be sent, instead of actual packets.

![Transmission time for different size packets](image)

3.2.2 Test #2: Transmit with No Receiver and Interference

This test demonstrates the carrier sense function at the transmitter. “A” was set to transmit continuously, and “B” was set to transmit and record the number of retries. Again, no receiver is present.
We found that “B” recorded various number of retries up to 16, the maximum allowed by the WaveLAN. Since there was no receiver, we know the transmitter is responsible for detecting “collisions,” backing off, and retrying. The following illustration shows how this works:

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Signal from “A”

Retries 1 2 3 4 5 (transmit because free)

“B” listens at random times, and transmits if no one else is.

9. Carrier Sense Multiple Access/Collision Avoidance

This test shows that collisions are not detected at the receiver, but at the transmitter. One reason this may be preferred over a RTS/CTS protocol is that a hand-shake requires at least 3 packets to be sent for each data packet: RTS, CTS, and the actual data. This is a lot of overhead. On the other hand, the disadvantage of simply sensing the radio medium at the transmitter is that collisions can still occur, if the interferer is out of range of the transmitter, but in the range of the receiver. Consider the following situation, where “B” can hear both “A” and “C.”

```

A ———— B ———— C

Range of “A” ———— Range of “C”
```

10. “C” is “hidden” from “A,” i.e “A” can’t hear “C,” but “B” can hear both “C” and “A.”

Suppose “C” is transmitting, to some receiver “D,” and “A” tries to transmit to “B.” “A” cannot hear “C” so it thinks the medium is free and transmits, but “B” can hear both “A” and “C,” it gets a garbled message. At this point, a higher level protocol in “B” needs to request a retransmit from “A.”

3.2.3 Test #3: Two WaveLANs Transmitting Continuously

In the third test, two WaveLANs were programmed to transmit almost continuously, in such a way that if only one was transmitting, it would be transmitting about 90% of the time:

```
11111111 11111111 11111111 11111111
```

“A” transmitting almost continuously

We found that if one WaveLAN (“A”) has the channel, it has an advantage and gets to transmit continuously for a while, while the other one (“B”) keeps listening for an opening. Once “B” gets control, it has the advantage and transmits while “A” tries to find the opening. So the waveform from each antenna shows a continuous signal as shown above, interrupted by periods of silence.

3.2.4 Conclusion about MAC

We have determined the MAC used by the WaveLAN radio. There is no hand-shake between
the transmitter and receiver, and collisions are detected at the transmitter. The transmitter listens to the frequency band of the signal and transmits if it doesn’t detected anyone else transmitting.

This scheme has a few problems. First, the transmitter may not always detect a collision because of hidden nodes. Second, This scheme is “unfair” in that once a transmitter has control of the radio bandwidth it has an advantage over someone else trying to get in.

A hand shaking routine involving RTS-CTS packets can be implemented in software. This scheme is not implemented in the commercial driver available to us. It is an inefficient use of bandwidth because of the overhead associated with transmitting each packet.
3.3 Multipath Fading

Multipath fading occurs when there is a line-of-sight path and a strong ground reflection between the transmitter and receiver, and the 2 signals interfere destructively. The earth can be modeled as a perfect conductor. It reflects electromagnetic waves well, and phase-shifts the wave by 180°. If the path difference between the ground reflection and the line-of-sight element is multiples of a wavelength, the 2 signals have 180° phase difference and cancel out, this can result in a loss of signal and data. Also, the received signal level fluctuates wildly in a fade region. This too can cause a loss of data because the automatic gain control of the receiver can't adjust quickly enough, and the output may saturate, causing an error.

The position of the fade depends on antenna height from ground. In our application, the antennas should be placed on top of the car to guarantee the best visibility in all directions, this is about 1.4m. At this height, the first fade occurs at 11.8m, from simple geometry.

\[
\frac{(d + \lambda)^2 - d^2}{(2 \times 1.4)^2} = \frac{3 \times 10^8}{915 \times 10^6} = 0.3279 \, \text{m} \; ; \quad d = 11.8\text{m}
\]

The first fade is the most severe one, because the path difference is smallest. Larger path difference means the reflected wave is attenuated significantly more than the line of sight element, which would dominate.

Fortunately, multipath fading due to ground reflection is not likely to occur in a platoon configuration, simply because of the position of the vehicles. Professor J. P. Linnarts showed that high error rates can occur at the following distances of platooned vehicles due to fading. However, in this analysis the antenna was placed on the bumpers, whereas in a real system it would more likely be placed on the top of the car. When the vehicles follow each other closely, there is no clear path to ground. Nevertheless, this has to be measured.

Multipath fading can occur during a maneuver, but in this case it is merely an annoyance,
since this communication requires neither low loss nor high reliability. If we lose a packet we simply retransmit. Having said that, we would still like to minimize the effect of multipath to achieve best performance.

In the worst theoretical scenario, we can assume the ground to be a perfect conductor that reflects 100% of incident power, phase-shifted $180^\circ$. Radiated electromagnetic power varies inversely proportional to distance squared, and the electric field strength varies inversely proportional to distance, since $P(r) = \frac{1}{2} |E(r)|^2/2\pi$, where $E(r)$ is the electric field magnitude at distance $r$, and $Z$ is the wave impedance. For the first fade, the antenna separation is 11.8m, from above, and the second path has length $11.8 + \lambda$, or 12.13m. The electrical fields due to the two components add destructively:

$$\frac{E_R}{E_{LOS}} = \frac{11.8}{12.13} = 0.97$$

$$\frac{E_{LOS} - E_R}{E_{LOS}} = 0.027$$

The resulting electric field strength is 2.7% of the LOS signal without interference, this is a 31.3dB reduction in power. So in theory, there can be a great reduction in power due to multipath. Indeed, many papers investigate the effect of multipath and show from both calculations and analysis that deep fades can occur. But our situation may not be as bad as it seems. First, most of the papers on multipath fading assume a low user antenna and high central station antenna. The fading for this geometry is more severe than that in a link between two antennas low to the ground. This is because in the former, the path difference in a fade between the two competing paths is very small compared to either path, whereas there is a bigger difference between the two paths in the latter case, compared to the average path length. Therefore for the second case, the LOS path is more dominant than in the first case, and the cancellation between the 2 paths is not as great. Also, we can choose to use vertically polarized transmit waves, which minimizes multipath fading from ground reflections.

We simulated the multipath phenomenon with coaxial cables and attenuators. The setup is shown below. We can tune the short-circuit stub to knock out certain frequencies, similar to

13. Simulating multipath with short stub

the cancelation of 2 signals in multipath. Although the 2 phenomena are different, both cause frequency-specific attenuation. With this setup we obtained attenuation of 0-30dB. But because the antennas were placed close together in this experiment, even with 30dB of attenuation, the packet loss rate is still very low. We did record errors when attenuators were added. To find out what will really happen in a outdoor environment, we need to measure the power received outdoors at distances of about 11.8 meters.
We were able to assess the effect of frequency-selective attenuation on a signal. At a position where the path difference is $\lambda$ at 915 MHz, we can calculate the attenuation at 902 MHz and 928 MHz. The wavelengths for these frequencies are listed below:

<table>
<thead>
<tr>
<th>Table 1: $h$ vs. frequency</th>
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<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>915 MHz</td>
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<tr>
<td>902 MHz</td>
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<td>928 MHz</td>
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In the position of a fade for a 915 MHz wave, at the outer edge of the band, the path difference is 6.06°. We can calculate the attenuation due to a LOS wave added to a ground-reflected wave (180° ± 5.05°) out of phase.

From law of cosine,

$$c^2 = a^2 + b^2 - 2ab\cos(5.05°)$$

Assuming in the above figure, $b$ is nearly equal to $a$, $c = 0.0881a$, or 21 dB down in power. Even though this is still a big reduction, it is better than the 31 dB attenuation suffered by the 915 MHz wave in the same position.

In the WaveLAN, the transmit pulse spectrum is maximum in the center, shown below.

14. Spectrum of WaveLAN spread spectrum transmit pulse

Traditionally, spread spectrum is used to combat multipath fading, because when one frequency in the spread spectrum band experiences a fade, the other frequencies may not, and some of the energy is still received. [131] But the spectrum of the pulse used by WaveLAN is still quite narrow, so that when the center frequency is at a minimum due to 2-path fading,
the sides are attenuated enough that most of the energy is still in the middle.

Multipath attenuation was simulated with a short-circuit stub tuned to knock out the energy at 915 MHz. It shows what we can expect the spectrum of the received pulse to look like in a multipath fading environment. The attenuation on the edges of the bands is about 10 dB less severe than in the middle of the band. But, the pulse still contains most of its energy in the middle of the spectrum, despite that it's greatly attenuated.

Frequency hopping, on the other hand, may take better advantage of this difference in attenuation in the band. Frequency hopping uses a range of carrier frequencies, all of which have equal energy. We can program the radio to transmit in the band with the least severe attenuation, shown below:

As this picture shows, if the fade is stronger at 915 MHz than at 928 MHz, we can concentrate all the energy at 928 MHz and avoid 915 MHz altogether, getting a 10 dB increase in signal power. We should note, however, that direct sequence is the dominant technique used in commercial products. This is because direct sequence boasts higher data rate, better noise immunity, and simpler implementation than its counterpart. Also, analysis shows that the error rate increases dramatically for FH systems as the ratio of bits per hop increases beyond 1. Since we would like to send hundreds of bits per hop, more work needs to be done on FH vs DS for our purposes.

Another effect of fading is wild fluctuations in power near a fade. So if the received power changes too quickly, the automatic gain control can't keep up and the output can saturate. We did one simple experiment with the short-circuit stub by changing its length quickly and recording the number of packet lost, see Figure 3.12. Changing this length near the fade caused errors, while changing the length but keeping clear of the fade did not cause any packet loss. This leads us to believe that rapidly changing power level such as that caused by a fade will cause some packet loss. But there is also the possibility that because we were moving the stub so violently that some by-product of the vibration caused the packet loss, rather than the actual variation in power.
4. Conclusion

From these tests done indoors, we have a better understanding of WaveLAN radio. Our main goal is to assess whether it is a good candidate for communication between vehicles on the automated highway. We investigated packet time, media access control, and multipath fading.

We found that platoons control functions require high reliability and data rate. The WaveLAN would be able to support only one 20-car platoon in one cell of 500m long. This is clearly not enough for a working system, but may be okay for testing up to one full-length platoon. It's difficult for the WaveLAN to achieve multi-platoon control loops because only one channel is available to all the radios on the road. From this we conclude a line-of-sight system is better to implement the control loop, or a radio system with much wider bandwidth.

The WaveLAN has a simple MAC scheme. It listens for a free carrier before it transmits and backs off a random time if the frequency band is occupied. This is called Collision Avoidance by the manufacturer, AT&T, as there is not yet an IEEE standard for wireless ethernet media access control. There is no hand-shake between the transmitter and receiver. Collisions result in garbled messages and can be detected at a higher level. In the wireless medium, a hand-shake scheme would be bandwidth inefficient because of the high overhead associated with each packet sent. An RTS/CTS protocol requires 3 packets per data packet transfer. Since the packet overhead is at least as long as the actual content, this at least doubles the amount of time the channel is busy.

We investigated and simulated multipath fading in the lab. Theoretically there can be a 30dB attenuation in a fade at 11.8m. But the road is not a perfect conductor so this figure would be less in reality. More importantly, the geometry of platoons would not permit a clear path to ground, so there is little chance of ground reflection cancellation in a platoon. We should note that the reflections from cars need to be considered also.

In the case of a maneuver and multipath fading, more data is needed from outdoor tests to assess the severity of the situation. It is not clear whether at 11.8 meters away, a 30dB decrease in signal power will cause a loss of signal. But even if the received power is enough for reception, fluctuations near a fade can saturate the automatic gain control and cause an error.

In the future, the WaveLAN needs to be replaced by a more efficient system to implement the control loop. But as a development tool for other components of the system, it is adequate for one 20-car platoon. It is reliable, easy to use, and well characterized.
References


