Vehicle-to-Vehicle Communications For AVCS Platooning

Vehicle-to-vehicle radio links suffer from multipath fading and interference from other vehicles. This text discusses the impact of these effects on communication networks supporting, in particular, AVCS. The statistical models for this channel are used to evaluate the performance of a network involving many links. The performance of Time Division Multiple Access (TDMA), Direct Sequence Code Division Multiple Access (DS-CDMA), and Frequency Hopping with TDMA in this environment are compared. Reliability of the radio link is investigated by specifying the radio spectrum occupation for a given required reliability of the radio link.

4.1 Introduction

In order to combat the effects of multipath fading and associated doppler shift as well as interference from other links multiple access schemes such as Time Division Multiple Access (TDMA), Direct Sequence Code Division Multiple Access (DS-CDMA), and Frequency Hopping with TDMA are investigated. Shladover [4] and Hitchcock [8] have shown that message delays within a platoon environment can have dire consequences. Thus the performance of these various multiple access schemes is quantified by Packet Erasure Rates (PER) as well as Reliability (probability of a successful message reception in a fixed time interval) for a given spectral allocation. Network protocol and frequency reuse in a platoon scenario will also be discussed.

Section 4.2 discusses the platoon model in which the communication links are located and the various elements that will affect the channel and communication link are highlighted. In Section 4.3 the channel model is described. Sections 4.4 and 4.5 deal with the modulation and multiple access schemes that are implemented in this channel. Section 4.6 discusses network protocol and frequency sharing procedures. In Section 4.7 the numerical results of the issues discussed in the preceding sections are formulated. Section 4.8 summarizes these results and draws conclusions and recommendations of this study.

4.2 Platoon Model

Shladover, et al., [4] have proposed a method of efficient vehicle control by grouping vehicles in platoons. “It requires electronically linked cars to travel in instrumented lanes with facilities to allow the vehicles to join and exit platoons smoothly at highway speeds. Estimates suggest that a [single automated lane] could carry as much traffic as three or four ordinary lanes. Platoons of up to four cars at speeds of 55 m.p.h. and up have already been tested and plans to test platoons of up to 20 cars are being implemented. It is possible to obtain very accurate lane holding (within 15 cm when under a variety of anomalous conditions) while maintaining excellent ride quality. Highway lanes could be much narrower once automated. High-precision vehicle-follower control appears possible when dynamic data obtained by ranging sensors are combined with communication between cars.” [3]

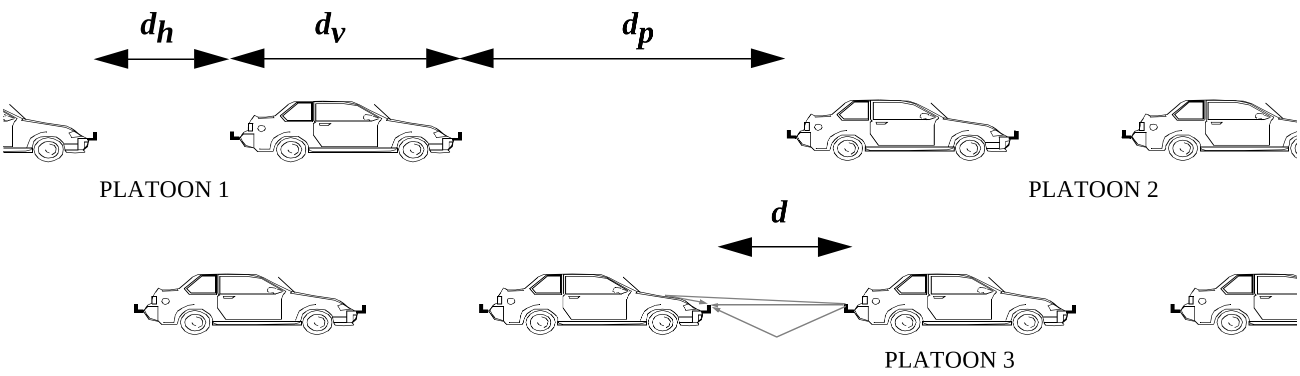

Figure 4.1 Platoon Model

We consider AVCS in a platoon environment, where a platoon consists of *N* vehicles. As depicted in Fig. 4.1, the distance between vehicles is denoted as d_h, and is on the order of 1 or 2 meters [4]. The vehicle length, platoon following distance, and lane width are denoted as d_v, d_p, and d_l respectively, while the communication link under study is denoted as *d*.

In slotted access cellular mobile transmission schemes different cells transmit over different frequencies in order to reduce interference. Frequency bands can be reused in cells spaced far enough apart such that the interfering energy between these cells is negligible. Each platoon, including the distance between the platoons, d_p, is considered a cell. Unlike most cellular radio schemes, the cells here are in relative motion with each other, since platoons in either lane may have a net difference in velocities. Thus we define two frequency reuse distances, d_r and d_s. The distance d_r is the reuse distance within a lane, whereas d_s is the reuse distance between lanes.

Thus for TDMA, if a cluster of *C* different frequencies is used, the frequency reuse distance within a lane is

$$d_r = C_r(d_p + (N-1)(d_v + d_h)) \qquad (1)$$

whereas the reuse distance between lanes for both TDMA and CDMA is

$$d_s = C_s d_l . \tag{2}$$

Thus for TDMA $C = C_r C_s$ radio channels are required, each with bandwidth BT. Messages are of relatively short duration, typically a few hundreds of bits. The required transmission bandwidth is determined by the cycle duration T_c during which all vehicles in a platoon transmit their speed and acceleration data. Since CDMA transmission suppresses interference, successive platoons and platoons in other lanes may use the same channel.

4.3 Radio Channel Model

For large separation distances the local mean power approximately falls off according to an inverse fourth power law. From the analysis and empirical values for path loss, the free-space loss dominates propagation between antennas of vehicles belonging to same platoon, where there may be a line-of-sight component ($d_i < N(d_v + d_h) << d_t$) and plane earth loss for interference signals propagating from one platoon to another, where the propagation distances are large. Therefore the n^{th} vehicle in a platoon receives an normalized interference signal with power p_m from the $m+n+1^{th}$ (for $m=1,2,3...$) vehicle given by

$$\bar{p}_m \approx m\left(d_v + d_h\right)^{-\beta_1} \tag{3}$$

and interference from two co-channel platoons with normalized power $\bar{p}_r$ given by

$$\bar{p}_r \approx d_r^{-\left(\beta_1 + \beta_2\right)} d_t^{-\beta_2} \quad . \tag{4}$$

In a dispersive Rician fading channel, energy arrives at the transmitter from reflections as well as a dominant wave, which we define as the phasor sum of a direct line-of-sight wave and a strong ground reflected wave. Thus the received signal of the i^{th} vehicle is in the form

$$v_i(t) = c_0 \cos\left(\omega_c t + \Phi_0 + \psi_i(t)\right) + \sum_{k=1}^{K} c_k \cos\left(\omega_c t + \Phi_k + \psi(t - T_k)\right) \quad , \tag{5}$$

where the constant c_0 represents the amplitude of the dominant component, as found in (7), and Φ_0 the phase delay in the dominant component. The variables c_k, Φ_k and T_k represent the amplitudes, phases and delay times of the k^{th} reflected wave (k = 1, 2,....,K). Digital phase modulation is incorporated in $\psi_i(t)$. The reflections {k: $T_k < T_b$} are assumed to add coherently to the dominant component and along with the dominant component make up the first resolvable Rician path. The remaining reflections cause intersymbol interference.

We define the Rician parameter K_1 as the ratio of the power p_0 in the dominant component to the local-mean scattered power p_1 in the first resolvable path. The Rician parameter K_2 is defined as the ratio of the power p_0 in the direct line-of-sight component to the excessively delayed local-mean scattered power p_2. The local-mean power $\bar{p}$ is the sum of the power in the dominant component and the average powers in the scattered components ($\bar{p} = \bar{p}_0 + \bar{p}_1 + \bar{p}_2$). The Rician K factor, defined as the ratio of the power in the dominant component to the total scattered power is

$$K = \left(\frac{1}{K_1} + \frac{1}{K_2}\right)^{-1} . \tag{6}$$

Since the local mean power of the dominant component varies with distance, as shown in the previous section, the above Rician parameters, although not stated explicitly, are also functions of distance.

This channel behaves as a narrowband Rician-fading channel with Rayleigh distributed intersymbol interference. For m = 0,1, or 2 and K_0 = 1,

$$c_0^2 = 2\bar{p}_0 = \frac{2pK}{1+K} \tag{7}$$

$$\overline{p_m} = \frac{\bar{p}K}{K_m(1+K)} . \tag{8}$$

In the following, K is assumed to be determined by the propagation environment and path length. The relative values of K_1 and K_2 are determined by the delay profile and the symbol rate. The probability distribution function of the signal amplitude, expressed in terms of the local-mean power $\bar{p}$ and the Rician K-factor becomes

$$f_\rho\langle\rho|\bar{p}, K\rangle = \frac{\rho(1+K)}{\bar{p}KK_1} e^{-K_1} exp\left(-\frac{\rho^2(1+K)}{2\bar{p}KK_1}\right) I_0\left(\rho K_1 \sqrt{\frac{2(1+K)}{\bar{p}K}}\right) \tag{9}$$

and thus for the instantaneous power we have

$$f_p\langle p|\bar{p}, K\rangle = \frac{(1+K)}{2\bar{p}KK_1}e^{-K_1}exp\left(-\frac{p(1+K)}{\bar{p}KK_1}\right)I_0\left(2K_1\sqrt{\frac{p(1+K)}{\bar{p}K}}\right) . \qquad (10)$$

For interfering signals, the propagation distance is significantly larger, and because of the relatively low antenna height, a line-of-sight component may not be present. In such cases, Rayleigh fading (Complex Gaussian) appears a reasonable model.

4.4 Modulation Scheme

Ideally the bit error rate for BPSK modulation in a time-invariant AWGN channel is [14]:

$$P_b(e) = \frac{1}{2}erfc\sqrt{\frac{E_b}{N_0}} , \qquad (11)$$

where N_0 is the (one-sided) spectral power density of the AWGN, E_b is the constant received energy per bit ($E_b = p_0T_b$) and erfc(.) denotes the complementary error function [15]. The in-phase component of Rayleigh fading co-channel interference may be approximated as Gaussian noise, giving a mean error probability of [10]

$$P_b\left(e|\rho, \overline{p_r}, \overline{p_2}\right) = \frac{1}{2}erfc\left(\sqrt{\frac{\frac{1}{2}\rho^2T_b}{\bar{p}_rT_b + \bar{p}_2T_b + N_0}}\right) , \qquad (12)$$

An approximation often used for the probability of bit error in Code Division Multiple Access (CDMA) is

$$P_b\langle e|\rho, \overline{p_t}, \overline{p_2}\rangle = \frac{1}{2}erfc\left(\sqrt{\frac{\frac{1}{2}\rho^2T_b}{\frac{\left(C_s\bar{p}_tT_b + \bar{p}_2T_b\right)}{N} + N_0}}\right) \qquad (13)$$

where N is the spreading gain of the CDMA scheme and C_S is the frequency reuse factor between lanes. The average BER can then be found by integrating over the Rician pdf of the signal amplitude given in (9)

$$\overline{p_b} = \int_0^{\infty} \frac{\rho(1+K)}{\bar{p}KK_1} e^{-K_1} exp\left(-\frac{\rho^2(1+K)}{2\bar{p}KK_1}\right) I_0\left(\rho K_1 \sqrt{\frac{2(1+K)}{\bar{p}K}}\right) \times P_b\langle e|\rho, p_r, p_2\rangle d\rho\ . \tag{14}$$

4.5 Multiple Access Schemes

In this section we compare TDMA, TDMA with slow frequency hopping interferers, and Direct Sequence CDMA (DS-CDMA) with regards to Packet Erasure Rates (PER). We use spreading mainly to suppress interference. In other applications the frequency diversity of CDMA is also exploited. However the delay spread is too small. Dynamic power control cannot be easily used as mulitple receivers.

4.5.1 Packet Erasure Rate s

A packet erasure occurs when bit errors are in excess of the correcting capabilities of the error correction coding being implemented. Slow and fast Rician fading of the wanted signal are considered with a block error detection code that can correct up to M errors in a block of L bits.

With fast fading, the duration of the packets is substantially longer than the time constants of the multipath fading. This is the case with continuous wave CDMA transmission with a bit rate of 5 kbps and a carrier frequency of 1 GHz and vehicle speed of 30 m/s (~70 miles/hour). The received signal experiences several fades during packet transmission. We assume that during one bit time, the channel characteristics do not change, but that the received amplitude are statistically independent from bit to bit, even though the receiver remains perfectly locked to the wanted signal. So the probability of undetected packet errors for BPSK is obtained from

$$P\langle e|\bar{p}_o, \bar{p}_r\rangle = 1 - \sum_{m=0}^{M} \binom{L}{m} \left(1 - \overline{p_b}\right)^{L-m} \left(\overline{p_b}\right)^m \tag{15}$$

where the average bit error probability $\overline{p_b}$ is defined in (14).

Slow fading occurs when packets are of sufficiently short duration, that the received amplitude and carrier phase may be assumed to be constant throughout the duration of the packet. This condition is satisfied if the motion of the mobile terminal during the transmission time of a block of bits is negligible compare to the wavelength. This is the case with TDMA transmission at a rate above 100 kbps to accomodate user bit rates of 5 kbps with an average frame of 20 cars per platoon. The probability of packet erasure in a block of L bits with M bit correction is found by averaging the probability of packet error over the Rician fading of the wanted signal. In our case,

$$P\langle e|\bar{p}_o, \bar{p}_t\rangle = \int_0^{\infty} \frac{(1+K)}{2\bar{p}KK_1} e^{-K_1} exp\left(-\frac{p(1+K)}{\bar{p}KK_1}\right) I_0\left(2K_1\sqrt{\frac{p(1+K)}{\bar{p}K}}\right)$$

$$\times \left\{1 - \sum_{m=0}^{M} \binom{L}{m} \left(1 - \frac{1}{2} erfc\left(\sqrt{\frac{pT_b}{\bar{p}_r T_b + \bar{p}_2 T_b + N_0}}\right)\right)^{L-m} \left(\frac{1}{2} erfc\left(\sqrt{\frac{pT_b}{\bar{p}_r T_b + \bar{p}_2 T_b + N_0}}\right)\right)^{m}\right\} dp \quad .(16)$$

4.6 Network Protocol

Our TDMA radio protocol is as follows: the lead vehicle transmits a message containing speed and acceleration to the second vehicle, upon reception of a report by the n^{th} vehicle, the n^{th} vehicle sends its report. The performance of the radio link can be quantified by the probability that a message can be successfully transmitted across a platoon from one vehicle to another. We define the completion of a message through a platoon in this manner as a cycle. If a vehicle does not recognize a message or erroneously detects a message, the cycle is interrupted. To ensure safe operation of the AVCS vehicle control system, we require a very small probability of undetected errors. On the other hand we wish a large probability that a cycle is completed successfully. The n^{th} vehicle transmits its report after it has successively received messages with bit pattern which differed in less than M_2 places from a valid codeword of the $n\text{-}1^{th}$ vehicle. A message is assumed to be received successfully and reliably if the detected bit sequences does not differ in more than M_1 places from a valid code word. It is not necessary to take $M_1 = M_2$. In fact if $M_1 < M_2$, the terminal may transmit its own status assuming that it's turn to transmit has arrived, yet not entirely relying upon the data in the received packet because of a large number of bit errors. The performance of the network is quantified by finding the probability that the $(n\text{-}1)^{th}$ vehicle successfully transmits its report to the n^{th} vehicle, with $M_1 < M_2$. In an AVCS environment the lead vehicle generates data that all vehicles in the platoon require[4], thus we are also interested in the probability that the lead vehicle successfully transmits its report to the n^{th} vehicle, this occurs if each hop has less than M_1 bit errors.

4.7 Numerical Results

The length of each vehicle, d_v, was assumed to be 5 meters; the lane width, d_l, 3 meters; the distance between automated cars, d_h, 1 meter; and the average velocity of an automated vehicle was assumed to be 70 m.p.h. The distance of the radio link under study, d, was varied from 0.1meters to 10meters. Typically, $K = 7dB$ $(K_1 \approx 5)$ is reasonable for most vehicle-to-vehicle channels, $K_1 = 10$ is assumed as an upper bound. All vehicles transmit data with the same power. The signal to noise (AWGN Gaussian) ratio was set to 10 dB at a distance of d = 10 meters.

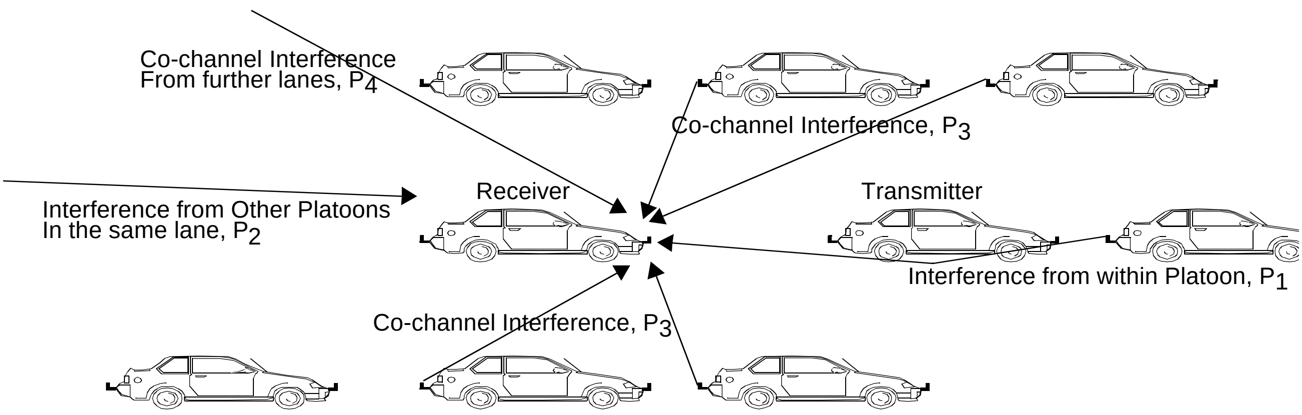

Figure 4.2 Assumptions about Interference in radio link

The radio link suffers from interference from within its platoon (P_1), from platoons in the same lane (P_2), and co-channel interference from platoons in other lanes (P_3 and P_4). In all simulations we assume that the target vehicle is joining an infinitely long platoon. It should be noted that in TDMA transmission each vehicle within a platoon is given a time slot in which to transmit, thus P_1 will be zero; while for CDMA type transmission all vehicles transmit at the same time, thus P_1 must be taken into account. We assume P_2 is negligible since transmissions from other platoons must be reflected off vehicles, road surface, and surroundings before reaching the receiver. These reflections will greatly attenuate the signal. We thus set $d_r = C_r = 0$ in (2) . To obtain an upper bound on the P_3 and P_4 we assume that an infinitely long platoon would transmit as close as possible to the receiving vehicle. Lacking accurate measurements, it was assumed that these signals would attenuate by10 dB for each lane traversed, thus P_4 would be 10 dB less than P_3.

4.7.1 Bit error rate s

We will first show bit error rates (BER) as a function of distance as described in (12)- (14) and compare them to a channel model in which a strongly reflected ground wave is not present.

Fig. 4.3 examines the effect of varying the reuse pattern C_r for CDMA transmission employing horizontal polarization or vertical polarization. For N = 32, the bit error rates show a great change only when C_r = 1. For other curves (not plotted here) it appeared that for a reuse pattern is greater than one or two and N > 32 the bit error rates remain relatively the same, independent of spreading factor and reuse pattern. We will concentrate on CDMA with a reuse factor C_r = 2 and a spreading factor $N = 32$, since this will give nearly the same performance as other schemes, but with minimal bandwidth.

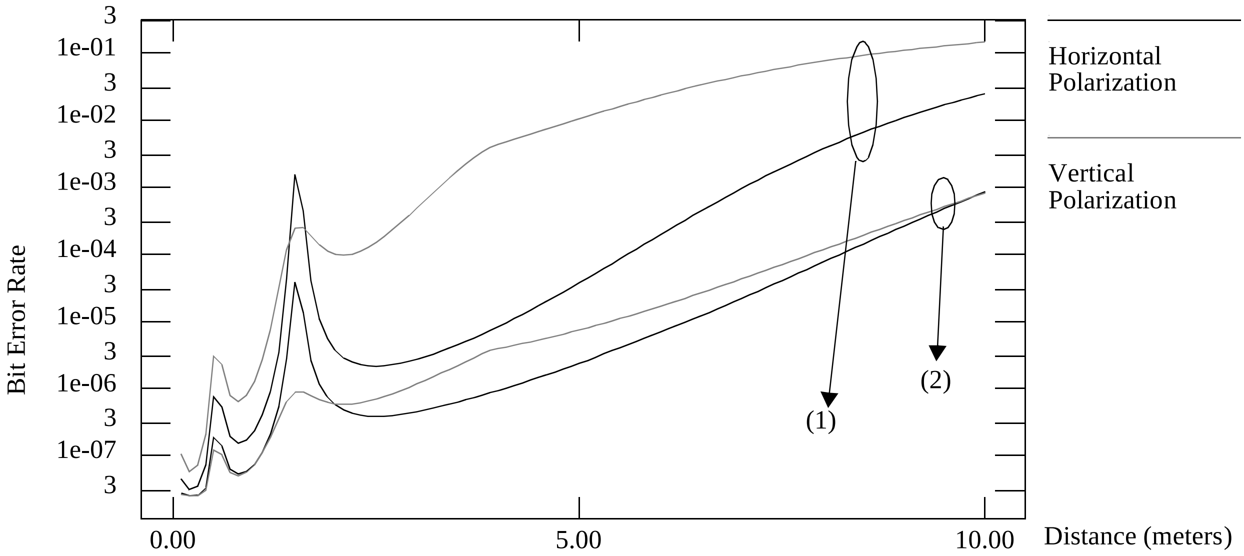

Figure 4.3 Bit error rates for CDMA: $N = 32$ with vertical and horizontal polarization. (1) $C_r = 1$ (2) $C_r = 2$.

The effects of varying frequency reuse patterns for TDMA is presented in Fig. 4.4. Here we see that unlike the CDMA case varying the reuse pattern has a significant impact on the bit error rates, thus TDMA is more sensitive to interference than CDMA. However as C_r increases the gain in performance decreases. So by using more bandwidth (increasing C_r) we get smaller and smaller gain in performance (lower BER). We will concentrate on TDMA with a reuse pattern of $C_r = 3$.

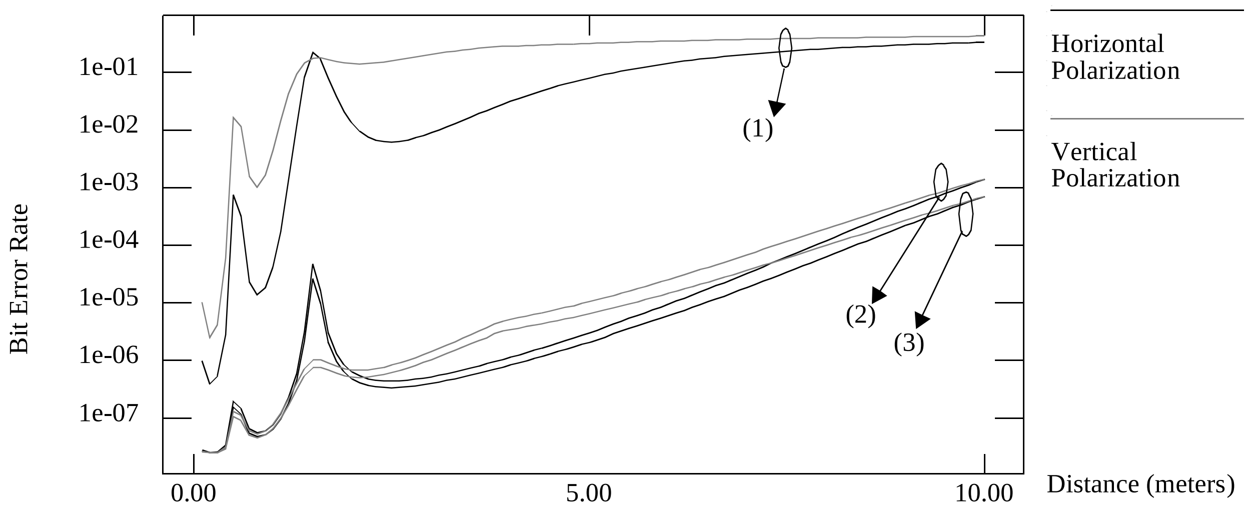

Figure 4.4 Bit error rates for TDMA with vertical and horizontal polarization. (1) $C_r = 1$ (2) $C_r = 2$. (3) $C_r = 6$.

4.7.2 Packet Erasure Rate s

As explained in Section 4.5 the assumptions were a fast fading channel for CDMA and a slow fading channel for TDMA. We also assume a packet length of L = 76 bits with one bit correction (M_1 = 1) [34]. Fig. 4.5 compares TDMA and CDMA packet erasure rates with horizontal polarization. It should be noted that these system require different bandwidths. Although the bit error rates for TDMA with $C_r = 3$ and CDMA with $C_r = 2$, $N = 32$ were nearly identical, the packet error rates for the same situation differs significantly. In order to increase the performance of TDMA one can use Slow Frequency Hopping within each platoon a TDMA type polling scheme is implemented. However a different carrier frequency for each platoon is chosen, according to a pseudo-random hopping sequence, at the end of every packet reception. Thus from Fig. 4.3, the co-channel interference power P_3 and P_4 are reduced since there is a large probability that adjacent lanes use different carrier frequencies. For a reuse pattern $C_r = 2$, two independent sets of hopping frequencies (H) are used. A reuse factor of $C_r = 3$ and a set of $H = 10$ hopping frequencies outperforms the CDMA and TDMA.

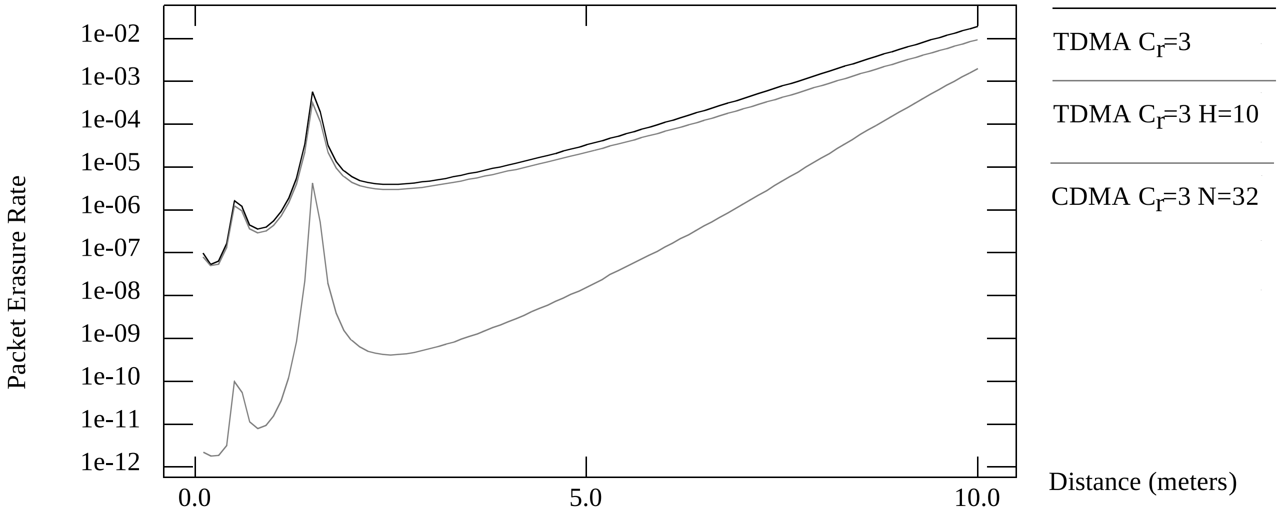

Figure 4.5 Comparison of CDMA, TDMA, and slow frequency hopping.

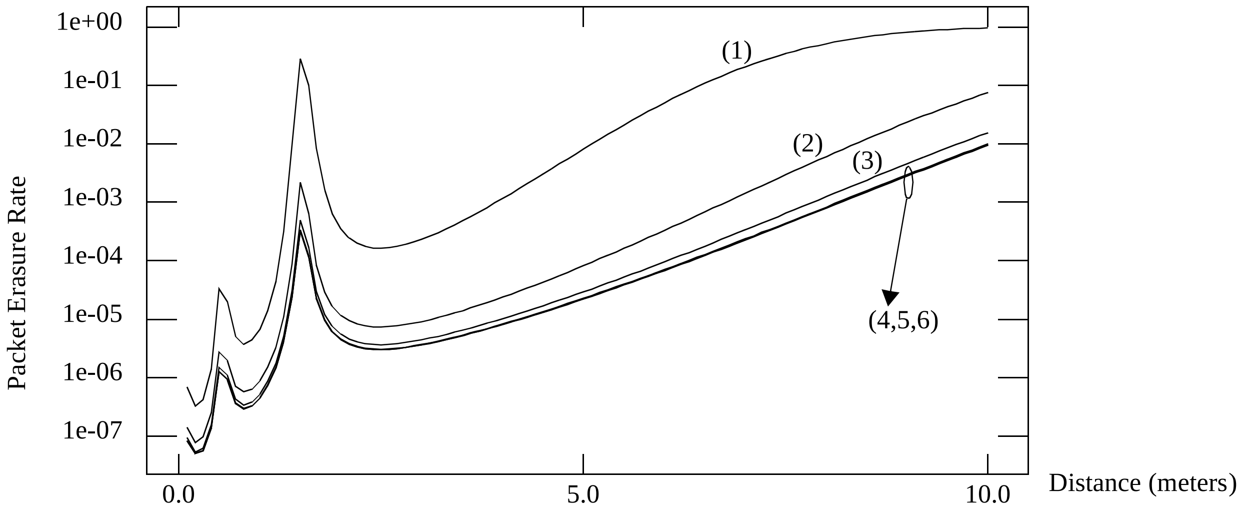

Figure 4.6 TDMA with slow frequency hopping for various reuse factors (C_r) and Hopping Frequencies (H). (1) C_r=1 H=10 (2) C_r=1 H=100 (3) C_r=2 H=10 (4) C_r=2 H=100 (5) C_r=3 H=10 (6) C_r=3 H=100.

Fig. 4.7 shows that vertical polarization yields better results for distances less than three meters and slightly higher packet erasure rates for distances greater than three meters.

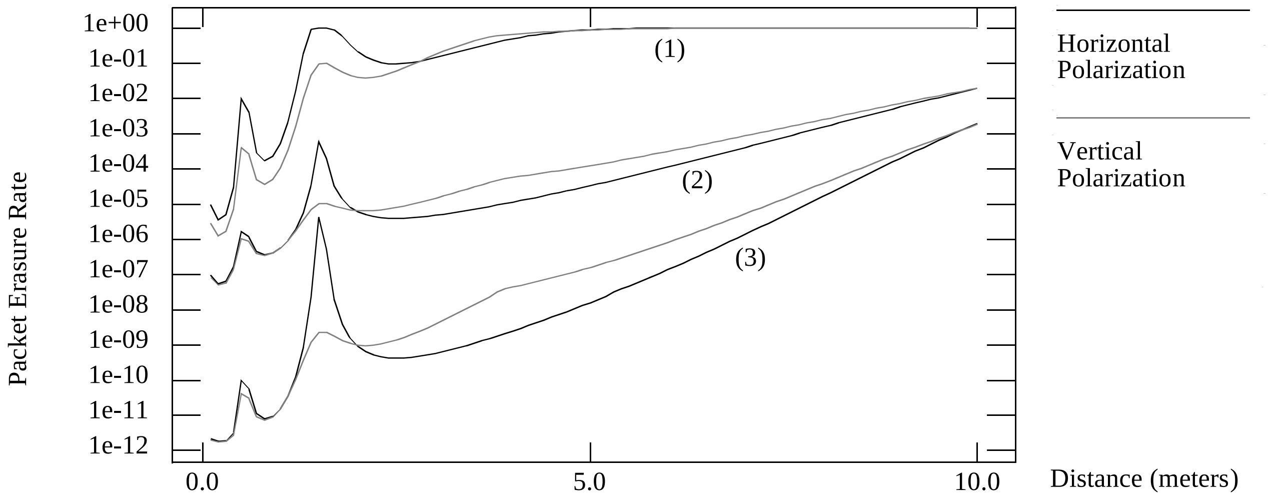

Figure 4.7 Comparison of TDMA and CDMA packet erasre rates for horizontal and vertical polarization. (1) TDMA C_r=1 (2) TDMA C_r=3 (3) CDMA C_r=2 N=32.

4.7.3 Reliability and Spectrum Allocatio n

This section quantifies the different bandwidth requirements of the previous schemes by presenting numerical analysis results of Reliability vs. Spectrum Allocation. Reliability *R(T,d)* is defined as the probability no message passes through our communication link in time *T* when the vehicles are at a distance *d*. For AVCS, it is relevant that updates arrive at least once every 50 msec, or so. We chose *T* = 50 msec and call T (as other sources also refer to this) as the deadline failure probability. In our results we have assumed a maximum *T=50 msec* at a link distance *d=10m* [4].

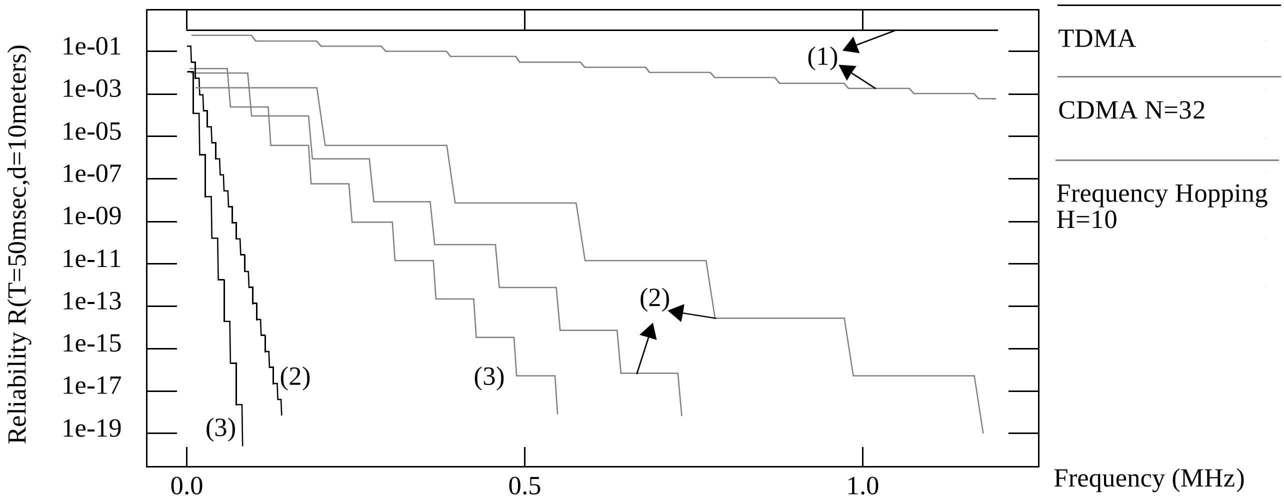

Figure 4.8 Reliability vs. Spectrum allocation for CDMA, TDMA, frequency hopping. (1) C_r=1 (2) C_r=2 (3) C_r=3.

Although CDMA C_r = 2, N = 32 gives better PER results than TDMA, it requires much more bandwidth. Thus we can implement TDMA by requiring very frequent transmissions and although many of these transmissions would be lost, we are guaranteed a successful transmission using less bandwidth than CDMA. The gain in PER by frequency hopping also came as a result of greater bandwidth requirements, although not as much as CDMA. Interestingly TDMA $C_r=3$ requires less bandwidth for a given reliability than TDMA $C_r=2$, since even though TDMA $C_r=3$ requires more frequency bands per lane, the gain in PER is large enough that fewer transmissions are required. We see that for frequency hopping this in not true.

4.7.4 Network Protoco l

The preceding section described a network protocol for TDMA transmissions. The concept of a complete cycle through a platoon was developed and the idea propounded that the cycle sequence could be maintained without retransmission even though the received codeword differed from a valid code word by more than the distance accepted for error correction. Again employing the assumptions of the previous sections, it is shown how variations in M_1 (correcting distance used) and M_2 (error distance accepted for sync) affect the probability of cycle completion for both TDMA and frequency hopping.

Fig. 4.9 illustrates this. The probability of successful transmission between two links, requires all links to have less than M_1 errors. While the solid lines apply for only the link between $n\text{-}1^{th}$ and n^{th} vehicle which needs to have less than M_1 errors, while the *n-2* prior links need only to have less than M_2 errors. Thus for TDMA it is critical that a cycle be maintained. While for CDMA all vehicles transmit simultaneously, thus preservation of the cycle is not as important.

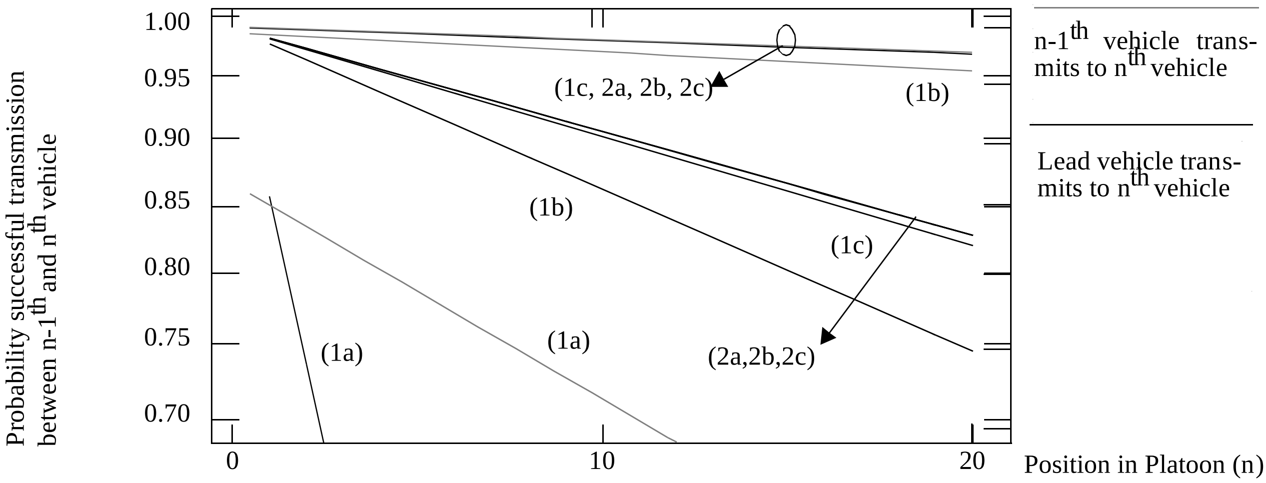

Figure 4.9 Probability of one vehicle in platoon transmitting to another vs. position in platoon. $M_1=M_2=1$, L=76, d_h=10m. (1) C=3 (2) C=6 (a) H=1 (b) H=10 (c) H=100

4.8 Conclusions

A statistical model for vehicle-to-vehicle radio channel applicable to AVCS communication was developed, taking into account multipath reflections and a dominant wave composed of a direct line-of-sight wave with a strongly ground reflected wave. The performance of this radio link was gauged by bit error rates, packet erasure rates, and deadline failure probability for a given bandwidth. These parameters were evaluated for three multiple access techniques: Time Division Multiple Access, (Direct Sequence) Code Division Multiplexing Access, and Time Division Multiple Access within a platoon with Frequency Hopping outside the platoon.

Our analysis showed that deep fades and large probability of packet loss can occur for distances less than three meters, due to the cancellation of the ground reflected wave and the direct line-of-sight wave. The effects of these fades could be reduced by employing vertical polarization as opposed to horizontal polarization. However for distance greater than three meters, horizontal polarization PER and BER performance showed an improvement over vertical polarization. The performance difference between polarization techniques for distances greater than three meters could be mitigated by decreasing co-channel interference (increasing the frequency reuse pattern thus increasing bandwidth). Thus if frequency reuse between lanes is employed, vertical polarization can be implemented in order to mitigate the effects of deep fades caused by the destructive interference between the ground reflected wave and the direct line-of-sight wave. Antenna diversity can also be used to increase performance [12].

The system under study was also found to be sensitive to co-channel interference. Our analysis showed that even for CDMA transmission, performance could be largely improved if adjacent lanes use different frequencies. However, increasing the reuse factor greater than two, for CDMA, and three, for TDMA, did not afford better performance. According to our computations and within the validity of our assumptions, CDMA provides lower packet erasure probabilities than TDMA or slow frequency hopping. However for a fixed bandwidth system, the reliability for a given bandwidth or delay line failure probability appears to be better with TDMA. Here we see a trade off between error probabilities and bandwidth. With CDMA increasing bandwidth results in lower error rates. However with TDMA even though the error rates may be greater than CDMA, many transmissions are possible since the bandwidth requirements of TDMA are minimal compared to CDMA. TDMA also affords the system designer to implement a protocol scheme in which correct packet reception is not necessary in order to transmit an update to the next vehicle. As our analysis showed by varying the allowable number of bit errors in a received packet the delay in a TDMA system can further be reduced.

4.9 References

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