VEHICLE-TO-VEHICLE COMMUNICATION FOR AVCS PLATOONING

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ABSTRACT

Vehicle-to-vehicle radio links suffer from power variations, multipath fading and associated Doppler spreading in frequency, as well as interference form other vehicles. These effects are investigated in the context of an Automated Vehicle Control Systems (AVCS) employing vehicle platoons. A statistical model for the channel is considered and the performance of the network involving many links is evaluated. We compare the performance of Time Division Multiple Access (TDMA), Direct Sequence Code Division Multiple Access (DS-CDMA), and Multi-Carrier Code Division Multiple Access (MC-CDMA). Reliability of the radio link is investigated by specifying the radio spectrum occupation for a given required reliability of the radio link.

INTRODUCTION

Vehicle-to-vehicle communication is of critical importance to automatic vehicle control. Although communication occurs only over relatively short range, from less than one meter to tens of meters, the communication links have to be extremely reliable, despite the presence of multipath reflections and interference from other links using the same frequency channel.

A slotted multiple access scheme is compared with code division multiple access schemes. Because of the short communication range and the corresponding small delay spread, DS-CDMA to avoid narrowband fading of the signal may require prohibitively large spreading factors. Therefore we use spreading mainly to suppress interference. Also the problem of dynamic power control for multiple receiver positions may affect the efficiency of spread spectrum for AVCS environment. Since the channel is likely to be constant only for periods during which the vehicle moves less than $\lambda/6$ meters, efficient and reliable link design requires messages from each vehicle to be shorter than a few milliseconds. This would be easier to achieve in high speed unspread burst (TDMA) transmission, since for a system with fixed bandwidth any spreading by a factor N implies an increase in transmission time by a factor N. On the other hand with CDMA continuous wave (CW) transmission is possible, which allows simpler synchronization and avoids large overheads for power on/off synchronization times. We thus compare DS-CDMA, MC-CDMA, and TDMA for a given reliability.

Vehicle-to-vehicle data communication mainly consists of the continuous (routine) exchange of telemetric data such as vehicle status, speed, and acceleration. In this paper we do not address occasional special maneuvering sessions or emergency messages which require exchange of more data. TDMA polling type of random access has been proposed[1]. We address a specific solution for frequency sharing techniques for transmissions between vehicles in one platoon. Synchronization of the slotted transmissions may be obtained from base stations located along the automated highway, or in a decentralized system, from other transmission by other vehicles. Such roadside base stations are required to support other AVCS and ATMIS services, such as route information, gathering of road traffic data, electronic toll collection, or for a micro-cellular highway telephone service. The issue of frequency sharing between platoons is addressed and we also estimate the required radio spectrum for a given required performance of the radio communication system.

PLATOON MODEL AND LANE CAPACITY

We consider AVCS in a platoon environment, where a platoon consists of N vehicles. The distance between vehicles is denoted as d_h, and is on the order of 1 or 2 meters[2]. The vehicle length and platoon following distance are denoted as d_v and d_p respectively. In TDMA transmission, successive platoons use different frequency bands to avoid mutual interference. If a cluster of C different frequencies is used, the frequency re-use distance is $d_r = C\,(d_p + (N-1)(d_v + d_h))$. For a highway with L lanes, LC 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 bandwidths. The transmission bandwidth here is dependant on the spreading factor employed.

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RADIO CHANNEL NETWORK MODEL

Available propagation experiments[3], show that the vehicle-to-vehicle radio link can be modelled statistically as a Rician-fading channel. The direct line-of-sight component is likely to be relatively strong compared to the reflected signal (large Rician K-factor), and the delay spread is likely to be relatively small because reflections occur in the immediate vicinity of the transmitter and receiver antenna.

Vehicles with bumper mounted directional antennas are considered. We model the propagation channel as a (dominant) direct component, with an amplitude determined by the path loss, a set of early reflected waves, adding coherently with the dominant wave, and intersymbol interference caused by excessively delayed waves, adding incoherently with the dominant component. The probability density function of the received instantaneous power is given by

$$f_p\langle p|\bar{p}, K_1, K_2\rangle = \left(1 + K_1 + \frac{K_2}{K_1}\right)\frac{e^{-K_1}}{\bar{p}}$$

$$\times exp\left(-\left(1 + K_1 + \frac{K_2}{K_1}\right)\frac{p}{\bar{p}}\right)I_0\left(2K_1\sqrt{\left(1 + K_1 + \frac{K_2}{K_1}\right)\frac{p}{\bar{p}}}\right)$$

where $I_0(\ )$ is the modified bessel function of the first kind and zero order, the Rician parameter K_1 is defined as the ratio of the local-mean scattered power of the early reflected waves to the power in the direct line-of-sight component, the Rician parameter K_2 is defined as the ratio of the excessively delayed local-mean scattered power to the power in the direct line-of-sight component, and $\bar{p}$ is the local mean power.

From proposed micro-cellular communications models and empirical data we conclude that free-space loss dominates propagation between antennas of vehicles belonging to same platoon, whereas plane earth loss dominates in interference signals propagating from one platoon to another. We thus model the pathloss for the wanted signal as,

$$\bar{p} \approx m\,(d_v + d_h)^{-\beta_1},$$

and the pathloss for the interference signals as

$$\bar{p} \approx d_r^{-(\beta_1\beta_2)}\,d_g^{-\beta_2},$$

where d_g is the turnover distance and values for β_1 and β_2 are based on empirical data.

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 appears to be a reasonable model.

PROBABILITY OF PACKET ERASURE

A packet erasure can occur when errors occur in excess of the correcting capabilities of error correction coding. In this section we describe some of the analytical models that may be used to evaluate the probability of packet erasure. '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 is considered.

CDMA

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 transmission of 5 kbits/sec, assuming a carrier frequency of 1 GHz and vehicle speed of 30m/s (~70 miles/hour), for CDMA transmission. Thus the received signal experiences several fades during packet transmission. For both DS-CDMA and MC-CDMA packet erasure rates are found assuming fast fading. DS-CDMA differs from MC-CDMA in the way spreading is accomplished. For DS-CDMA, every message bit is spread in frequency by multiplying by a faster chip sequence $c(t)$. Whereas in MC-CDMA every message bit is spread in frequency by sending this bit at various carrier frequencies determined by a chip sequence c_i. The transmitted signal $s(t)$ for DS-CDMA and MC-CDMA are as follows:

DS-CDMA: $$s(t) = a(t)\,c(t)\cos\omega_c t$$

MC-CDMA: $$s(t) = a(t)\sum_{i=1}^{n} c_i \cos\omega_c t$$

TDMA

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 burst transmission TDMA at 5kbits/sec with an average frame of 20 cars/platoon. Slow frequency hopping can be employed to improve the performance of TDMA transmission. With this scheme at the end of every packet reception a different frequency is chosen in order to transmit the next package. The the effects of co-channel interference is diminished. This increase in performance is achieved at the cost of increase in bandwidth.

RADIO NETWORK PERFORMANCE, RELIABILITY, AND SPECTRUM OCCUPATION

The performance or 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 a 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-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-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 in its platoon require[2], thus we also find the probability that the lead vehicle successfully transmits its report to the n^{th} vehicle, with $M_1 = M_2$.

Finite transmission speed and message delays cause packet losses on the radio channel, Hitchcock[4] has shown that these delays can have dire consequences in the performance of the system. In order to study the reliability of the system, a "reliability" measure R is defined as the probability that at least one successful update occurs during a period T. This does not imply that the entire AVCS system has a certain reliability R, and will result in a vehicle collision on an average of $T/(1-R)$ seconds. Given a reliability measure (R,T) we assume that the safety and control measures of the system perform within given parameters[4]. For a given reliability, the spectrum occupation is dependant on the multiple access scheme and frequency re-use pattern implemented.

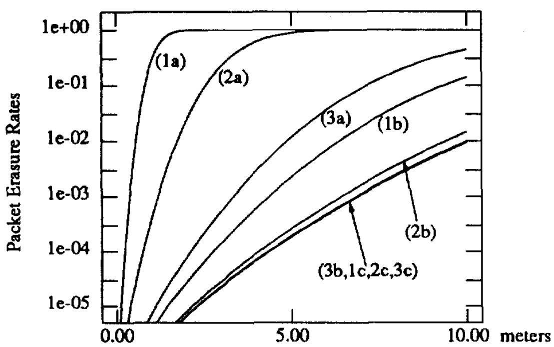

Fig. 1 TDMA Packet Erasure Rate vs. Link Distance (d_h)
SNR=10 dB at 10 m and packet length (L) of 76 with 1 bit correction (M).
(1) HF (number of Hopping Frequencies) = 1, (2) HF = 10, (3) HF =100, (a) C=1, (b) C=3, (c) C=6.

RESULTS

Packet erasure rates as a function of d_h, the distance between vehicles, for TDMA with slow frequency hopping are shown in Fig. 1. As can be seen, the performance of the channel is significantly enhanced by slow frequency hopping when a great deal of co-channel interference is present (C=1). However as the co-channel interference is reduced (by increasing the cluster size to C=6) frequency hopping has insignificant effects on the packet erasure rates. Also as the distance between vehicles approaches 10 meters performance degrades due mainly to co-channel interference. Fig. 2 compares packet erasures for MC-CDMA, DS-CDMA, and TDMA. Again performance in all three systems degrades as co-channel interference increases. By increasing the spreading factor (N) for CDMA or the number of hopping frequencies (HF) for TDMA better performance can be achieved, at the price of greater bandwidth. Fig. 3 illustrates this by plotting a given reliability vs. spectrum occupation. Here both TDMA and DS-CDMA with a cluster size of one (C=1) require excessive bandwidth for any reliability measure since from Fig. 2 we see that there is

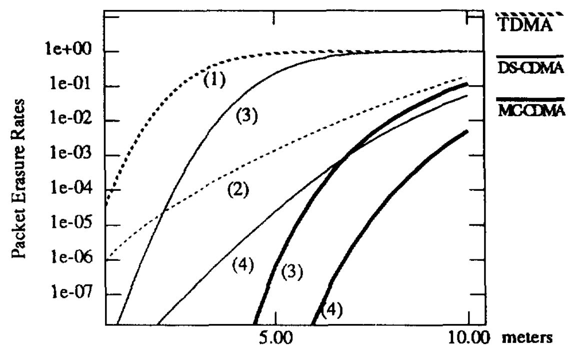

Fig. 2 Packet Erasure Rate vs. Link Distance (d_h)
SNR=10 dB at 10 m and packet length (L) of 76 with 1 bit correction (M).
(1) C=1 HF=10 (2) C=3 HF=10 (3) C=1 N=32 (4) C=2 N=32

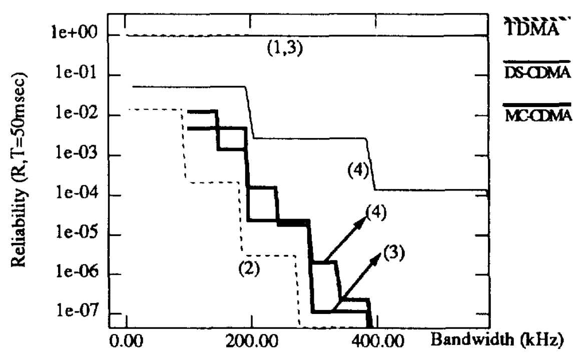

Fig. 3 Reliability (R,T=50msec) vs. Bandwidth, d_h=10m, L=76, M=1.
(1) C=1 HF=10 (2) C=3 HF=10 (3) C=1 N=32 (4) C=2 N=32

almost always a packet error. However TDMA (C=3 HF=10) requires less bandwidth for a given reliability than both CDMA schemes, even though it has a greater packet erasure rate. Thus for a given bandwidth, in the TDMA scheme one can keep retransmitting the packet and a successful transmission will be completed before an allotted time.

Fig. 4 and Fig. 5 illustrate how varying M_1 and M_2 will affect the network. The probability of successful transmission between two links in Fig. 4, requires all links to have less than M_1 errors. While in Fig. 5 only the link between n-1^{th} and n^{th} vehicle need to have less 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 is maintained. While for CDMA all vehicles transmit simultaneously, thus preservation of the cycle is not as important.

CONCLUSIONS

We have presented a comparison of TDMA, DS-CDMA, and MC-CDMA schemes in an AVCS platoon environment with Rician fading and Rayleigh interference. We have shown that CDMA undergoes fast fading while TDMA undergoes slow fading. Packet erasure rates were found in order to measure the performance of these multiple access schemes. However we also introduce a reliability measure and show that bandwidth considerations must be taken into account in the performance of each scheme.

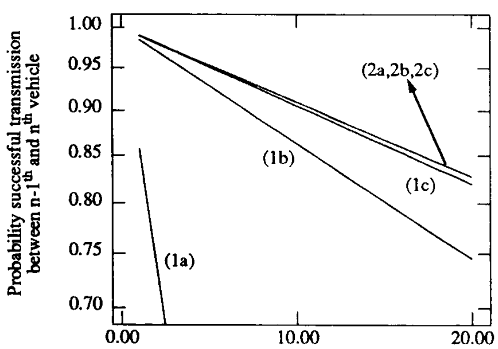

Fig. 5 Probability lead vehicle transmits to n^{th} vehicle vs. n, $M_1=M_2=1$, L=76, d_h=10m. (1) C=3 (2) C=6 (a) HF=1 (b) HF=10 (c) HF=100

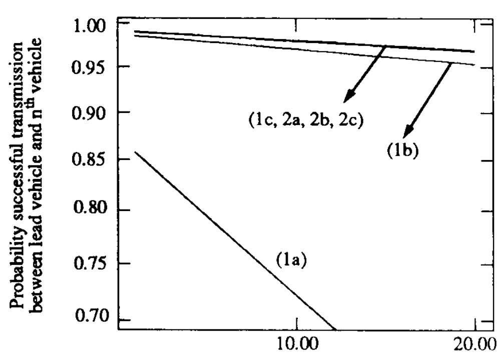

Fig. 4 Probability n-1^{th} vehicle transmits to n^{th} vehicle vs. n, $M_1=1$, $M_2=5$, L=76, d_h=10m. (1) C=3 (2) C=6 (a) HF=1 (b) HF=10 (c) HF=100

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