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PACKET COMMUNICATIONS ON A MOBILE RADIO CHANNEL

Introduction

The cellular mobile phones first developed by AT&T Bell Laboratories operate in the 800- to 900-MHz band. A property of this mobile radio channel is that the FM signal undergoes multipath fading because of scattering and reflections from buildings and obstructions.^{1,2,3} As a result, the amplitude of the signal received at any point over distances of a few hundred wavelengths is not constant but varies randomly about a mean level with a Rayleigh distribution while its phase is uniformly distributed between 0 and 2π . When the instantaneous value falls substantially below that mean, a fade is said to occur and noise captures the receiver. If a voice signal is being transmitted, the received speech is interrupted with noise bursts that appear in the form of pops and clicks that may persist even under idle channel conditions. If digital data is being transmitted over the FM channel, these fades cause error bursts in the received data. (The use of the same RF channel in an adjacent cell causes co-channel interference. This interfering signal is also Rayleigh-distributed but is independent of the desired channel and leads to similar noise bursts.)

A number of data communication techniques has been suggested for this channel.³⁻⁶ In all cases, however, a message is encoded in an error-detecting code. Several copies of a message thus encoded are interleaved with similar copies of another message and then

transmitted to the remote end. This achieves a degree of robustness. However, because the transmitter always sends several copies of each message routinely, the throughput is reduced proportionately.

This report considers the possibility of transmitting data in packets over this channel. The packets are chosen to be sufficiently small so that most of them fall in the interfade time interval, thereby ensuring a high transmission efficiency. The link level protocol used is the high level data link control (HDLC) procedures defined by the International Standards Organization (ISO). This protocol is not specially designed for a fading channel, but was chosen because it is widely used in data communications. According to this protocol, a message is sent in frames or packets, each frame containing, among other things, a 16-bit frame check sequence for detecting transmission errors. The transmitter sends only one copy of a frame. If the receiver detects any burst errors, it discards the frame and requests a retransmission. As a result, the throughput is greatly increased. Moreover, currently there appears to be a trend toward packet-based switching systems in telecommunications networks where an end-to-end digital connectivity would be offered to customers by integrating both voice and data and transmitting them in packets over the networks.^{7,8} The technique described here opens up the possibility of transmitting packetized voice and data on a mobile radio channel.

Mobile Radio Channel Error Characteristics

In binary FM, the probability of error, P_e , in the received data depends on a number of parameters.⁹ First, it is a function of the received signal-to-noise ratio (SNR). The second parameter is the ratio, a , of the

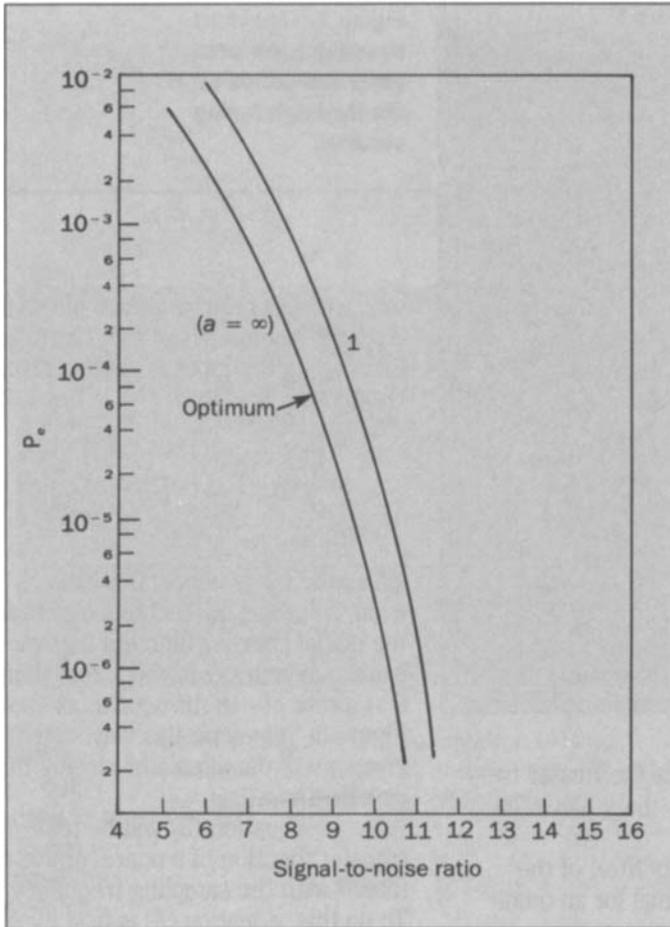


Figure 1. The probability of error as a function of signal-to-noise ratio for two values of a in binary FM, assuming that the channel dispersion is zero.

signal goes into a fade, the data bits in the faded portion of the signal are in error with probability 0.5. The severity of these fades depends, among other things, on the fade level and the vehicle speed. For example, at 850 MHz and 20 miles per hour (mi/h), the signal falls 15 dB below its mean about 10 times a second and remains below that level about 3 ms. Hence the signal is in a fade approximately 3 percent of the time. Thus, for a -15 dB fade, assuming the probability of a faded bit being in error to be 0.5, the burst errors during that fade will result in a bit error rate of 0.015. If the carrier frequency and speed remain the same, the signal goes into a -10 dB fade at a rate of approximately 18 times a second with an average fade duration of about 5.3 ms. In this case, the signal is in a -10 dB fade about 9.54 percent of the time. In both cases, the errors caused by the Rayleigh fades far exceed the purely random errors discussed earlier. Also, because the random errors can be taken care of by error-correcting codes, they are ignored, and only the fade-induced burst errors are considered.

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peak frequency deviation to the noise bandwidth. For a well-designed system, a is about unity. Finally, P_e is a function of the channel dispersion b . The latter is the distortion introduced by the channel and is proportional to the derivative of the received FM envelope. For fixed values of the first two parameters, P_e is minimum when $b = 0$. Figure 1 shows the probability of error in the received data as a function of the SNR for two values of a in the presence of additive white Gaussian noise with $b = 0$. The expression $a = \infty$ gives the minimum error rate that is theoretically attainable. It is observed that for $a = 1$ with a 10-dB SNR, the error rate is approximately 4×10^{-5} , while for a 15-dB SNR, it is orders of magnitude less.

For a mobile radio, a second source of impairment is the Rayleigh fades. When the

Simulation of the Mobile Radio Channel

A hardware simulator for the mobile radio channel is described in Reference 10. Results presented in this report were obtained by simulating the Rayleigh fading channel on a computer. Following is a brief description of that simulation technique.

The envelope of the electric field e and hence that of the signal received at a mobile antenna may be expressed as^{2,11}

$$e = x_1 \cos \omega_c t + x_2 \sin \omega_c t \quad (1)$$

where x_1 and x_2 are two independent Gaussian random variables with zero mean and equal

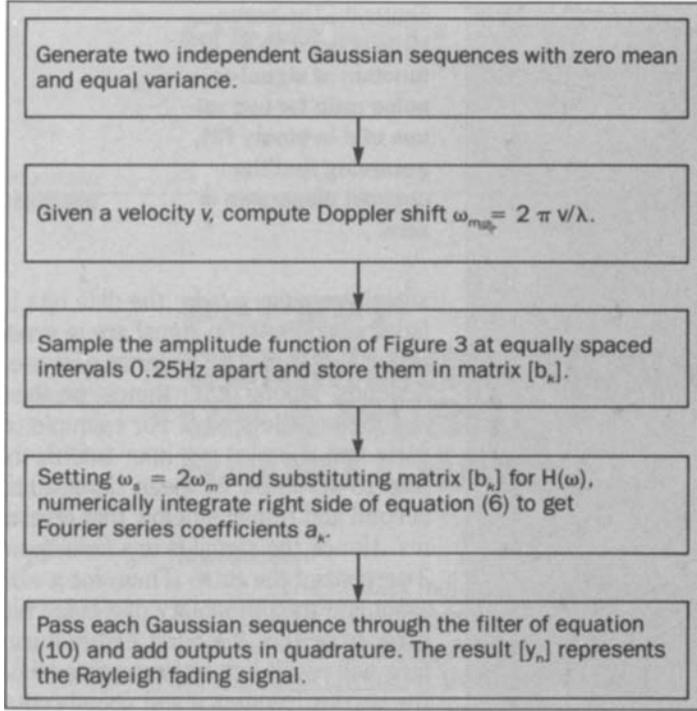


Figure 2. Flowchart describing the computer simulation of the Rayleigh fading channel.

interested in relative values of the signal, the transfer function $H(\omega)$ that has to be realized for shaping the input is obtained from that equation:

$$H(\omega) = \left[1 - \left(\frac{\omega}{\omega_m} \right)^2 \right]^{-1/4} \quad (3)$$

This function is unbounded at $\omega = \omega_m$. However, following the technique of Reference 10, the actual transfer function that we shall realize has a maximum at $0.95\omega_m$, and then falls off to 0 at a rate of -18 dB/octave, as shown in Figure 3. It is done this way so that the output envelope of the simulator closely fits a Rayleigh distribution.

Equation (3) will be realized as the transfer function of a nonrecursive digital filter¹² with the sampling frequency $\omega_s = 2\omega_m$. To do this, equation (3) is first expanded in a Fourier series:

$$H(e^{j\omega T}) = \sum_{k=-\infty}^{\infty} a_k e^{-jk\omega T} \quad (4)$$

where $T = 2\pi/\omega_s$, and a_k is the Fourier coefficient given by

$$a_k = \frac{1}{\omega_s} \int_{-\omega_m}^{\omega_m} H(\omega) \cos\left(\frac{2\pi k\omega}{\omega_s}\right) d\omega \quad (5)$$

Because H is an even function, equation (5) reduces to

$$a_k = \frac{2}{\omega_s} \int_0^{\omega_m} H(\omega) \cos\left(\frac{2\pi k\omega}{\omega_s}\right) d\omega \quad (6)$$

variance, say, E_{rms}^2 , and ω_c is the carrier frequency. The amplitude of e , then, has a Rayleigh distribution.

The spectral density $S(\omega)$ of the envelope of the received signal for an omnidirectional antenna is given by

$$S(\omega) = \frac{E_{rms}^2}{\omega_m} \left[1 - \left(\frac{\omega - \omega_c}{\omega_m} \right)^2 \right]^{-0.5} \quad (2)$$

for $|\omega - \omega_c| \leq \omega_m$

where $\omega_m = 2\pi V/\lambda$ is the Doppler shift owing to the vehicle speed V and carrier wavelength λ .

The flowchart of Figure 2 describes the simulation. First, we generate two independent Gaussian random sequences, each with zero mean and variance E_{rms}^2 . Each of these random sequences is then passed through a digital filter that is constructed in the following manner.

Refer to equation (2). Taking ω relative to ω_c and noting that we are only

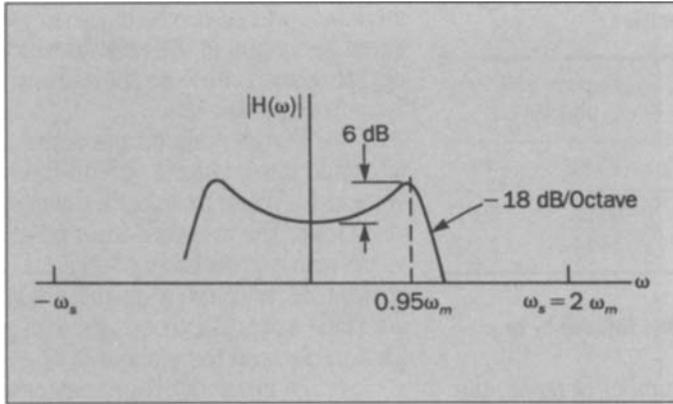


Figure 3. Transfer function $H(\omega)$, equation (3), realized by a digital filter to simulate $S(\omega)$ of equation (2) for the Rayleigh fading envelope of an FM wave. The sampling frequency is ω_s .

Substituting $z = e^{j\omega T}$ in equation (4) and retaining only 21 terms in the series, we obtain the desired digital filter transfer function

$$H_D(z) = \sum_{k=-10}^{10} a_k z^{-k} \quad (7)$$

This, however, is not a causal filter. To obtain one, it is necessary to introduce a delay of ten samples. The result is the transfer function of a 21-term nonrecursive digital filter

$$H_D(z) = z^{-10} \sum_{k=-10}^{10} a_k z^{-k} = \sum_{i=0}^{20} a_{i-10} z^{-i} \quad (8)$$

Its unit pulse response, $\{h_n\}$, is given by $h_n = a_{n-10}$. Notice that the unit pulse response has been truncated by a rectangular window. To reduce the resulting Gibb's oscillations, we truncate the unit pulse response, instead, by the Hanning window:

$$W_i = 0.5 \left(1 - \cos \frac{2\pi i}{21} \right)$$

Thus, the transfer function is

$$H(z) = \sum_{i=0}^{20} W_i a_{i-10} z^{-i} \quad (9)$$

Hence for any input signal x_n , the output y_n of the filter for $n \geq 20$ is given by

$$y_n = \sum_{i=0}^{20} W_i a_{i-10} x_{n-i} \quad (10a)$$

If $n < 20$,

$$y_n = \sum_{i=0}^n W_i a_{i-10} x_{n-i} \quad (10b)$$

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Two independent Gaussian random sequences are passed through the above filter, and the outputs added in quadrature. The result $\{y_n\}$ represents the envelope of the Rayleigh fading signal received at a mobile antenna.

To obtain the short-term statistics on this signal, $\{y_n\}$ is normalized with respect to its root mean square value, y_{rms} :

$$y_{rms} = \left[\frac{1}{N} \sum_{n=0}^N y_n^2 \right]^{1/2}$$

Expressing the result in dB, the normalized sequence is then $\{y'_n\}$ where

$$y'_n = 20 \log_{10} \left(\frac{y_n}{y_{rms}} \right)$$

Table I. Fade Statistics for a Few Fade Levels and Velocities

Vehicle Speed (mi/h)	Fades per second		Average fade duration (ms)		Average interfade interval (ms)	
	-10 dB	-15 dB	-10 dB	-15 dB	-10 dB	-15 dB
20	18	10.8	5.31	2.88	50.25	89.71
70	64	38.4	1.49	0.81	14.14	25.23

Factors Affecting Transmission Efficiency In a Packet Communication

Table I gives the number of fades, the average fade duration, and the average interfade interval for a few fade levels and velocities.

From the table it is apparent that the total number of error-free packets depends on the expected value of the interfade interval. It also, of course, depends on the size of a packet. If a packet is too large compared with the interfade interval, then most of the time it would be corrupted with a fade and hence would require a retransmission. If, on the other hand, the packet is too small compared with the average fade duration, it would be completely embedded in a fade and hence require a number of retransmissions. (Similarly, a partly faded packet is discarded and must be retransmitted.) If, in addition, the receipt of a packet is to be acknowledged, as is customary in any packet protocol, the reverse channel, being also subjected to similar but statistically independent fades, would cause the acknowledgment to be occasionally corrupted with error bursts. Thus the number of successful packets would be further reduced. Hence one can expect the performance to be determined by the size of the packet and the fade statistics. Also, because the number of fades per second

increases with the vehicle speed with a consequent reduction in the interfade interval, the performance cannot be the same at all speeds for a fixed packet size.

Figure 4 shows the distribution of the interfade interval for a -15 dB fade for two velocities. While its expected value is 89.8 ms at 20 mi/h, the interfade interval exceeds that value with a probability of about 0.25. Similarly, at 70 mi/h, the probability that the interfade interval exceeds its expected value of 25.2 ms is seen to be about 0.27.

Defining the transmission efficiency η as a ratio of the successful transmissions to the total number of transmissions attempted in conformity to the protocol (see below), it is possible to derive an upper bound on η . Let p be the packet size and D_{av} the expected value of the interfade interval for a given fade level. Then, assuming that the information is sent out in contiguous packets, the number of packets per second, n_s , in either direction that are not in a fade is given by

$$n_s \leq N_R \frac{D_{av}}{p}$$

where N_R is the number of fades per second. Hence, considering that a transmission is successful only if the packet and its acknowledgment by the receiver are both received correctly,

$$\eta = (n_s p)^2 \leq (N_R D_{av})^2$$

Assuming the average fade duration to be d_{av} , and noting that $N_R = (d_{av} + D_{av})^{-1}$, η can also be written as

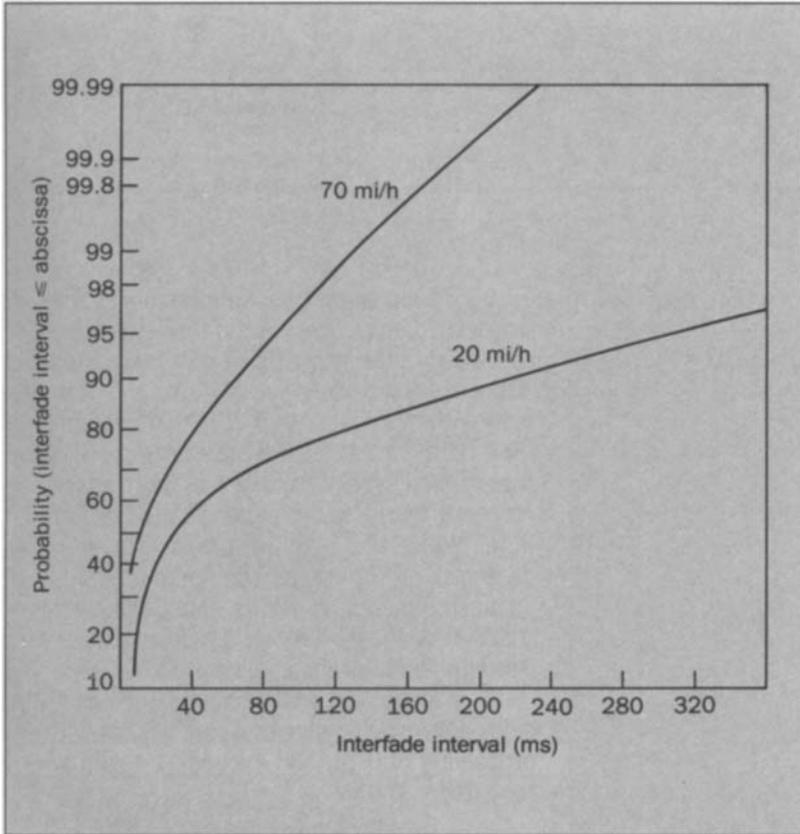


Figure 4. Interfade interval distribution for a -15 dB fade for vehicle speeds of 20 and 70 mi/h.

The link access procedure for the signaling channel D (LAPD) of the Integrated Services Digital Network (ISDN) standard defined in the International Telegraph and Telephone Consultative Committee (CCITT) recommendations is a subset of the HDLC procedures. See, for instance, Reference 14. Thus, our results will also hold for the ISDN LAPD and other similar protocols.

Results

Two important parameters in packetized data transmission are associated delay and throughput or transmission efficiency. They are obtained from computer simulations and shown in Figures 5, 6, 7, and 8.

Delay. Figure 5 shows the average delay as a function of the packet size p for two speeds. (These delays do not include the packetizing delay at the transmitting end, the propagation delay, or the delay caused by processing at the receiving end.) For small values of p , the average delay is also small. This is because a large percentage of packets succeed the first time without a need for a subsequent retransmission. For larger values of p , the delay increases rather rapidly. For example, at 20 mi/h, with $p = 4$ ms, the average delay is 1.5 ms, whereas for $p = 16$ ms, the delay is 30 ms. At 70 mi/h, the corresponding delays are, respectively, 4.5 ms and 100 ms. When p approaches the expected value of the interfade interval (discussed earlier), the delay becomes excessively large. For instance, it is more than 1.0 s at 20 mi/h and about 0.3 s at 70 mi/h. This is anticipated because in this case most of the time a frame would be corrupted with an error burst. For a fixed value of p , the delay increases with higher speed.

$$\eta \leq \left(1 + \frac{d_{av}}{D_{av}}\right)^{-2}$$

Using Table I for 20 mi/h and a -15 dB fade, $\eta \leq 0.94$. Later, our results will be compared with this bound.

Link Level Protocol

The link level protocol used in our simulation is the HDLC standard.¹³ To compute the total delay in a worst-case situation, it has been necessary, however, to slightly modify the error recovery procedure of the HDLC protocol. When the receiver detects burst errors in a frame, it discards that frame and sends a repeat request, whereupon the transmitting end retransmits that frame. This sequence is repeated until the frame is received correctly at the destination.

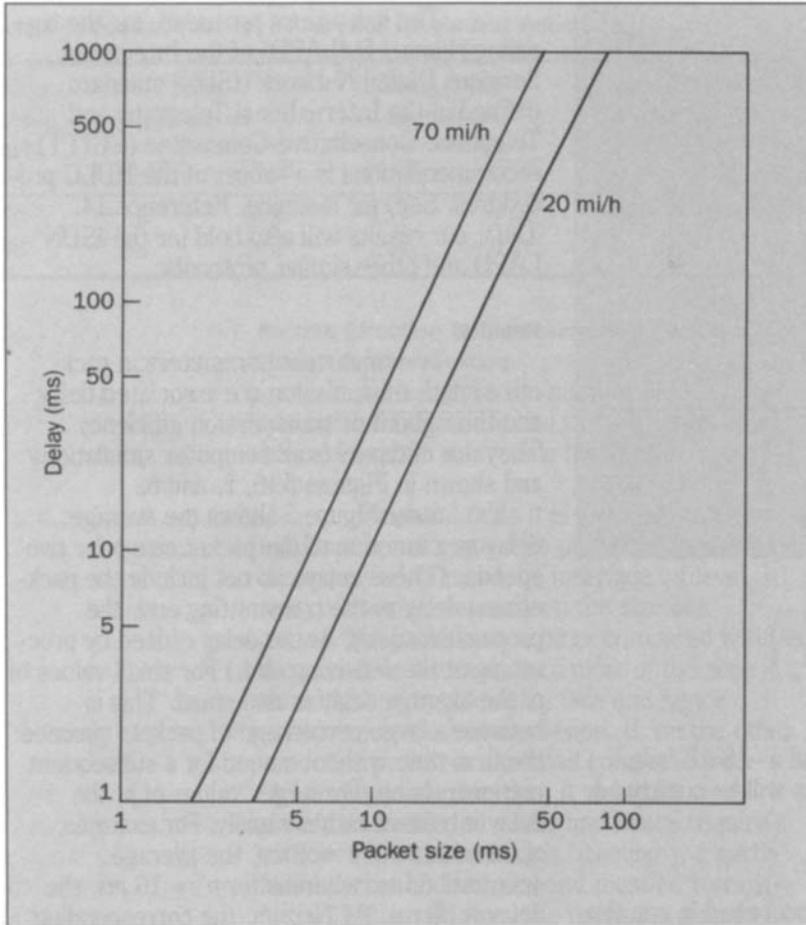


Figure 5. Average delay as a function of the packet size for two vehicle speeds.

Delay Distribution. Figures 6 and 7 show the delay distribution function for two vehicle speeds with the packet size as a parameter. At 20 mi/h, for a packet size of 4 ms, the delay is zero with a probability of 0.91. This indicates that, on the average, 0.91 of the packets, when transmitted synchronously, will be received correctly by the receiving end the very first time. Notice also how this probability decreases as the packet size increases. For instance, when $p = 10$ ms, this probability is 0.82. Also, for $p = 4$ ms, the delay exceeds $4p$ only with a probability of 0.02.

When the vehicle speed is 70 mi/h, the delay, for a packet size of 4 ms, is zero with a probability of 0.74, and exceeds $4p$ with a probability of 0.07.

Transmission Efficiency. Figure 8 gives the transmission efficiency as a function of the packet size p . For $p = 1$ ms, the efficiency approaches 0.89 at 20 mi/h and 0.85 at 70 mi/h, compared with the upper bound of 0.94. For larger p , it decreases monotonically, and becomes virtually zero with $p = 150$ ms at 20 mi/h and $p = 44$ ms at 70 mi/h. In the 4- to 10-ms range, it varies from 0.83 to 0.65 at 20 mi/h, and from 0.64 to 0.42 at 70 mi/h. Thus, in this range, particularly for slower vehicle speeds, the efficiency remains fairly high. Also, when the packet size approaches the expected value of the interfade interval, the efficiency drops to about 0.15 for either speed.

Since the delay decreases and the efficiency increases with smaller values of p , it would appear that a very small packet size would be desirable. There are, however, some practical considerations in the choice of p . For every link layer protocol, there is some overhead in the data format. For example, in the

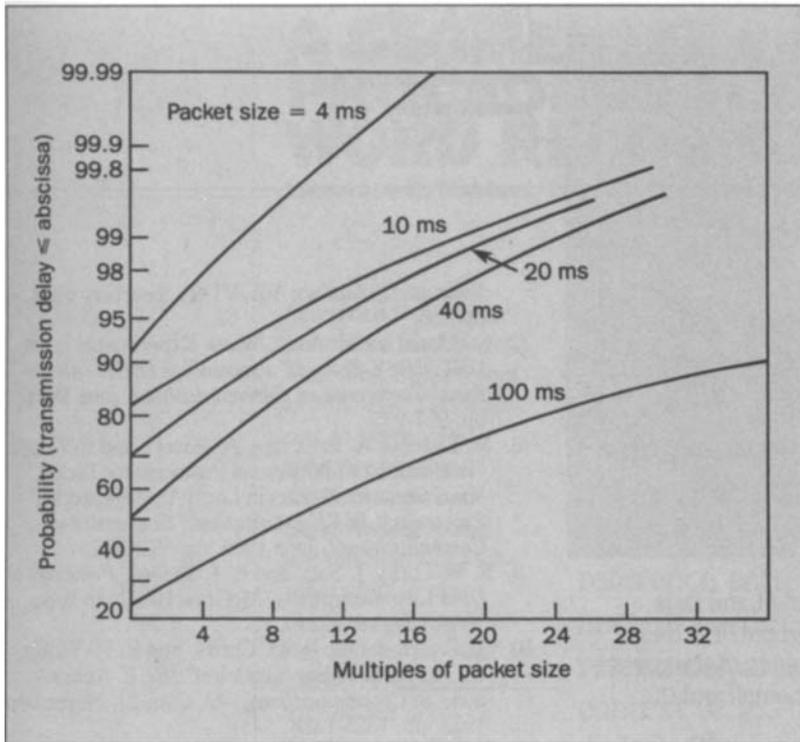
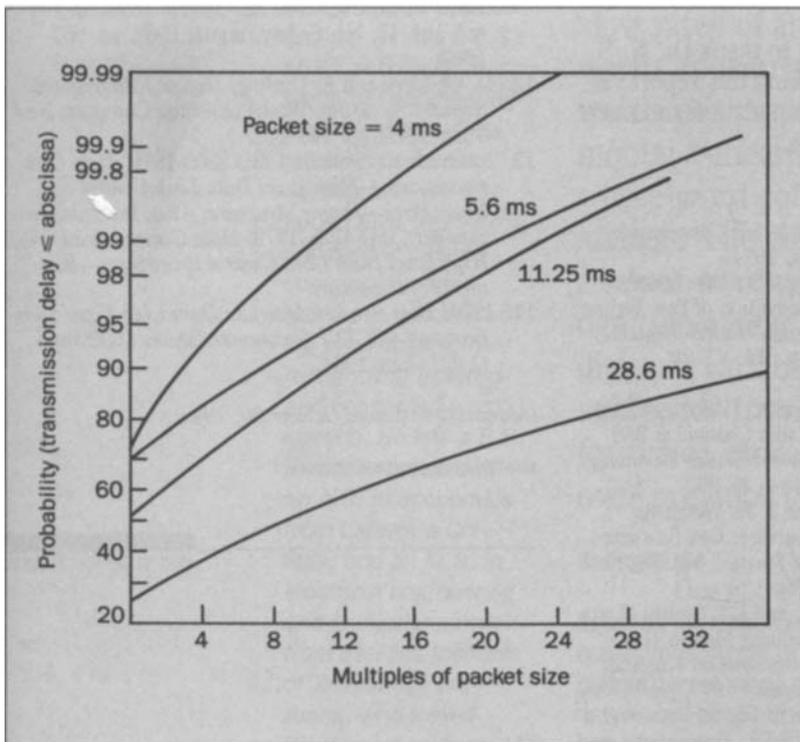


Figure 6. Delay distribution function at 20 mi/h with the packet size as a parameter.

Figure 7. Delay distribution function at 70 mi/h with the packet size as a parameter.



HDLC protocol, every packet contains an overhead of 5 bytes: 1 byte each for the flag, address, and control fields and 2 for the frame-check sequence. Thus, with a small packet, the information field also becomes small. Besides the delay and transmission efficiency, another design parameter is the ratio of the length of the information field to the packet size. At 40 kb/s, for example, with $p = 4$ ms, a packet will consist of 20 bytes of which 5 bytes are the overhead and the remaining 15 bytes are the information. Although the optimum choice of p would be application-specific, a reasonable range is 4 to 10 ms, over which the average delay is small and the efficiency high.

Summary

This report has explored the possibility of transmitting packetized data over a Rayleigh fading channel. The random errors due to the FM channel impairments have been ignored, and only burst errors that characterize the fading channel are considered. The protocol simulated is the widely used HDLC protocol which requires a frame to be retransmitted only when the remote end has detected errors in the received frame. Packets are sufficiently short so that most of them fall in the interfade time intervals. This leads to a high transmission efficiency. It is shown that the delay and throughput depend on the fade statistics. Also, for a given vehicle speed, they both improve monotonically as the packet size decreases. However, a smaller packet size increases the

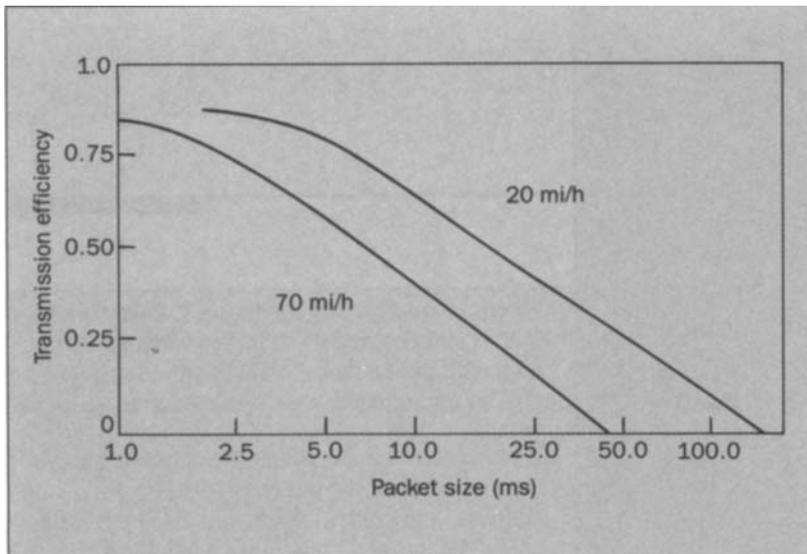


Figure 8. Transmission efficiency as a function of the packet size.

overhead fraction of the packet and thus reduces the effective throughput. Furthermore, there is a range of values of the packet size over which the delay is small and the efficiency high.

Acknowledgment

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