Packet Data Transmission Over Mobile Radio Channels

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Abstract—**In mobile radio, Rayleigh fading poses the main threat to accurate data transmission. When a data packet encounters a fade, it is highly likely that errors will occur and that the packet will have to be retransmitted. The duration of each packet has a strong influence on the quality of the mobile radio data link. Short packets are less likely to encounter fades than long packets. On the other hand, short packets are more burdened by overheads. A mathematical model of the dynamics of Rayleigh fading is used here to explore the optimum duration of data packets. The performance criterion is the rate of information transfer through the mobile radio channel. In addition to packet size, the information rate depends on: the speed of the mobile terminal, the channel bit rate, the size of the packet header, and the fade margin of the modulation and coding techniques. In particular, our attention is focused on line rates of 16 kb/s and 256 kb/s. These are representative of the rates proposed for digital mobile radio systems in North America and Europe, respectively. At 16 kb/s, the optimum packet size is approximately 17 bytes (8.5 ms duration). At 256 kb/s maximum throughput occurs when the packet contains about 48 bytes (1.5 ms duration). The precise optimum depends on vehicle speed, header size and fade margin. In any event, the optimum packets are considerably shorter than the 125-byte packets customarily employed in terrestrial and satellite systems.**

I. Mobile Radio Data Link

In a mobile radio system, the role of the data link is to ensure error-free transmission of information packets between mobile units and base stations. Rayleigh fading poses the main threat to accurate packet reception. When a packet encounters a fade, it is highly likely that transmission errors will occur and that the packet will have to be retransmitted. The data link provides error detection, acknowledgements of the quality of received packets, and retransmission of packets with errors.

The duration of each packet has a strong influence on the quality of the mobile radio data link. Short packets are less likely to encounter fades than long packets. On the other hand, short packets are more burdened by overheads. A major goal of our work is to explore the optimum duration of data packets transmitted over fading mobile radio channels. The performance criterion is the rate of information transfer through the mobile radio channel. In addition to packet size, the information rate depends on: the speed of the mobile terminal, the channel bit rate, the size of the packet header, and the fade margin of the modulation and channel coding techniques.

Karim has demonstrated that the dynamics of mobile radio channels call for short data packets [1]. Karim's conclusions are based on simulations of fading channels carrying 40 kb/s signals with a fade margin of 15 dB. In the work reported here, we use a mathematical model of the fading channel characteristics to derive formulas for data link throughput and delay. From these formulas it is possible to obtain numerical performance measures for any combination of system variables.

In particular, we focus our attention on line rates of 16 kb/s and 256 kb/s. These are representative of the rates proposed for digital mobile radio systems in North America [2] and Europe [3], respectively. At 16 kb/s, the optimum packet size is approximately 17 bytes (8.5 ms duration). At 256 kb/s maximum throughput occurs when the packet contains about 48 bytes (1.5 ms duration). The precise optimum depends on vehicle speed, header size and fade margin. In any event, the optimum packets are considerably shorter than the 125-byte to 1250-byte optimum packet sizes of terrestrial and satellite channels [4].

II. The Data Link Packet Structure

We investigate the high-level data link control (HDLC) protocol [4]. Applied to a wireless access system, it is referred to as LAPC, link access protocol on the control channel [5]. Fig. 1 shows the packet structure. The packet is divided into fields, each with a special purpose. In addition to the information field, used for network control or user communications, there are five fields that comprise the packet header. The first is the opening flag (one byte). Next is an address field that can be two or three bytes long. The control field contains one byte. The frame check sequence consists of two bytes of error-detecting information; and the closing flag is identical to the opening flag. Depending on the application, the closing flag of one packet may coincide with the opening flag of the next packet. It follows that the contents of the packet header (flags, addresses, control field, and frame check sequence) add up to six, seven or eight bytes. We have calculated transmission efficiency and delay for packet headers with six bytes and packet headers with eight bytes.

III. Packet Retransmission

A. Error Detection

A cyclic redundancy check (CRC), based on the 16-bit frame check sequence, reveals the presence of binary errors

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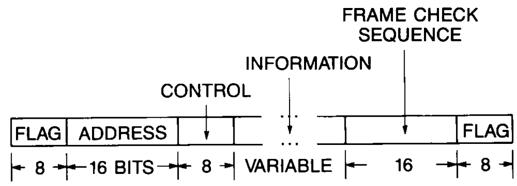

Fig. 1. Data link packet structure.

in the received packet [6]. All error patterns containing two errors, or any odd number of errors, are detectable, as are many other error patterns. When the redundancy check indicates an error-free packet, the receiver sends an acknowledgement packet to the transmitter. While this packet conforms to the HDLC structure, Fig. 1, it has no information field. It is thus much shorter than the information packet, and therefore, more likely to be received accurately. A CRC failure stimulates a negative acknowledgment, also conveyed by an HDLC frame with no information field.

Because propagation times are considerably shorter than packet durations in wireless access applications, there needs to be very little delay between the original transmission and subsequent retransmission of a packet with errors. In our analysis, we ignore this delay and assume that only packets with errors require retransmission. (This corresponds to a "selective repeat" protocol or a "stop-and-wait" protocol with waiting time negligible relative to packet duration [4].)

B. Packet Transmission Errors

The probability of a packet failure depends on the modulation and coding techniques of the physical layer of the mobile radio system and on the state of the channel when the packet is transmitted. Our analysis defines two channel states, "fade" and "interfade." At each instant, the state of the channel depends on whether the signal-to-noise ratio exceeds a certain threshold. This threshold is chosen to establish a high probability that a packet transmitted entirely in an interfade interval will be received without an error. In our calculations, we ignore the effects of errors in packets transmitted in interfade intervals and we make the conservative assumption that if any part of a packet is transmitted when the channel is in a fade state, the packet will require retransmission.

C. Success Probability

These simplifying assumptions enable us to apply analyses of level crossings of Rayleigh fading signals to derive the probability of successful transmission as a function of system variables. Fig. 2 shows the nature the squared envelope of a Rayleigh fading signal as a function of time. It also shows the threshold that defines the fade and interfade states of the channel. The statistics of the fade intervals and interfade intervals depend on the ratio of this threshold to the mean level of the fading signal. Expressed in decibels, we refer to the reciprocal of this ratio as M, the *fade margin* of the data link. M has an important influence on system performance. It depends on the mobile radio modulation and coding scheme, and on the frequency reuse pattern of the mobile radio system. The reuse

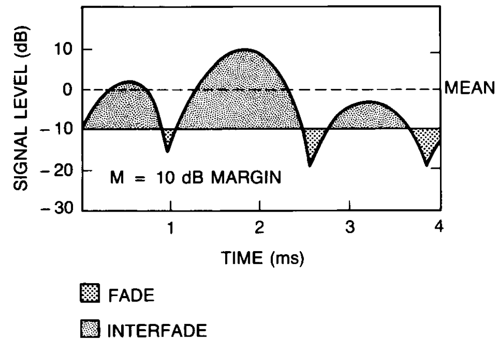

Fig. 2. Level crossings of a Rayleigh fading signal, 10 dB fade margin.

pattern determines the mean signal-to-impairment ratio, since a principal source of cellular radio impairment is interference from other transmissions in the same frequency band.

To analyze the probability of successful packet transmission, we consider a fading cycle comprising an interfade interval and the subsequent fade interval. If a packet of duration p s is to be received without errors, its transmission must begin at least p s before the end of the interfade interval. Conditioned on t_i, the duration of the interfade interval and on t_f, the duration of the fade interval, the probability of successful transmission is

$$s(t_i, t_f) = \frac{t_i - p}{t_i + t_f}, \qquad p < t_i. \\ = 0, \qquad \text{otherwise.} \tag{1}$$

The overall probability of successful transmission is

$$s = \int_p^\infty \int_0^\infty s(t_i, t_f) f(t_i, t_f)\, dt_i\, dt_f, \tag{2}$$

where $f(t_i, t_f)$ is the joint probability density function of the interfade interval and the fade interval. In the Appendix, we show that s depends on:

1) the packet duration, p s;
2) the carrier wavelength, λ m;
3) the speed of the mobile terminal, v m/s; and
4) M dB, the fade margin.

In the expression for s, the first three of these variables appear in the dimensionless quantity,

$$x = \frac{pv}{\lambda}, \tag{3}$$

which is the number of carrier cycles the terminal traverses while it transmits one packet. Figure 3 displays the relationship of s to x for $M = 10$, 15, and 20 dB.

IV. Theory of Data Link Performance

Fig. 3 indicates that for a given fade margin M, as the terminal speed or the packet duration increases, the probability of successful transmission decreases. With a low s, there is a high probability of retransmission, a high delay, and a low

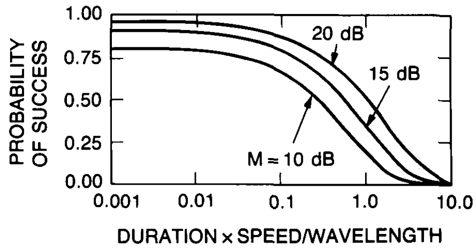

Fig. 3. Probability of successful packet transmission related to packet duration, vehicle speed, and signal wavelength.

capacity in terms of packets per second. On the other hand, short packets have a high proportion of overhead material, which limits the amount of useful information transmitted.

We assume that the terminal generates packets at random with a fixed probability r of a new packet in each p-second timeslot and that the terminal has a buffer to hold packets awaiting retransmission. Then, we can analyze the packet transmission process as a queue [7]. In each timeslot, packets enter the queue with probability r and leave the queue with probability s. Therefore the maximum arrival rate is s packets per timeslot. With $r \geq s$, packets enter the buffer faster than they can leave and the queue grows without limit. The expected delay is

$$\frac{1-s}{s-r} \text{ timeslots}$$

or

$$D = p\frac{1-s}{s-r} \text{ s.} \tag{4}$$

The packet throughput is r/p packets per second. If the channel rate is R_c b/s, there are pR_c bits per packet of which H bits comprise the packet header. Thus the number of information bits per packet is $pR_c - H$ and the information rate of the data link is

$$R_d = \frac{r}{p}(pR_c - H) \quad \text{b/s.} \tag{5}$$

A normalized throughput measure is $\eta = R_d/R_c < 1$, the number of information bits per channel bit:

$$\eta = r\left(1 - \frac{H}{pR_c}\right). \tag{6}$$

Our figure of merit for the data link is the value of η corresponding to a specified upper bound $D_{\max}$ on packet delay. In (4), with $D \leq D_{\max}$, the maximum packet rate is

$$r_{\max} = s - \frac{p}{D_{\max}}(1-s) \text{ packets per timeslot.} \tag{7}$$

We are usually interested in p on the order of 1 – 10 ms, while $D_{\max}$ for most applications is on the order of hundreds of milliseconds. In these ranges, $r_{\max}$ is nearly equal to s. Therefore, for convenience, we will take our measure of transmission efficiency to be η^*, the value of η in (6) with $r = s$ (corresponding to $D_{\max} \to \infty$). Thus, to explore the relationship of η^* to p, and other system variables, we first calculate s by numerical integration of (22). Then we obtain η^* from (6) with $r = s$.

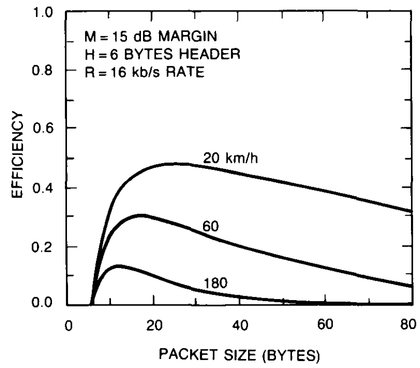

Fig. 4. Peak efficiency as a function packet duration for three vehicle speeds in a 16 kb/s system.

V. Numerical Performance Evaluation

Our purpose is to explore the dependence of our efficiency measure η^* on packet size and on: the header size, the vehicle speed, the fade margin, and the transmission rate. First, we examine the relationship of η^* to packet length,

$$p_B = pR_c \text{ bytes} \tag{8}$$

for several combinations of the other parameters. This information is relevant to system design. We then consider performance of established systems by holding the packet size constant and assessing throughput and delay as functions of vehicle speed, fade margin, and packet arrival rate.

A. 16 kb/s Channel Rate, 850 MHz Carrier

Fig. 4 shows η^* as a function of p_B for packets with $H =$ 6 bytes of header information and a system fade margin of $M = 15$ dB. For each vehicle speed, there is an optimum packet size that decreases with increasing speed. High vehicle speeds imply short interfade intervals that favor short packets. At 20 km/h, the optimum p_B is 25 bytes, which leads to a peak efficiency of $\eta^* = 0.478$ information bits per channel bit. At 60 km/h, the maximum efficiency is only 0.302, achieved with a packet size of 17 bytes. At 180 km/h, the highest value of η^* is 0.133, corresponding to 12 bytes per packet.

Performance is very sensitive to fade margin as indicated in Fig. 5, which applies to vehicles traveling at 60 km/h. Here we display η^* as a function of p_B for fade margins of 10, 15, and 20 dB. A high fade margin implies long interfade intervals, and therefore, high efficiency and a large optimum packet size. With a 20 dB fade margin for example, the maximum efficiency is 0.405 information bits per channel bit, double the maximum efficiency (0.199) of a system with a 10 dB fade margin.

If the header has eight bytes, rather than six, the optimum packet size is longer and the peak efficiency is lower. Thus, in Fig. 6, we show η^* as a function of p_B for the two header

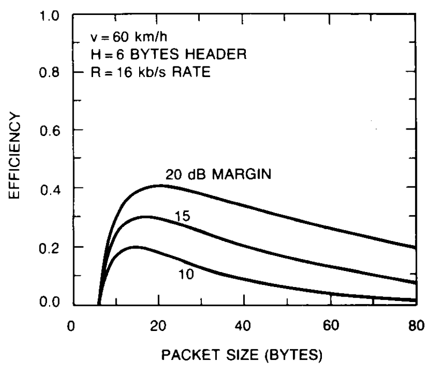

Fig. 5. Peak efficiency as a function packet duration for three fade margins in a 16 kb/s system.

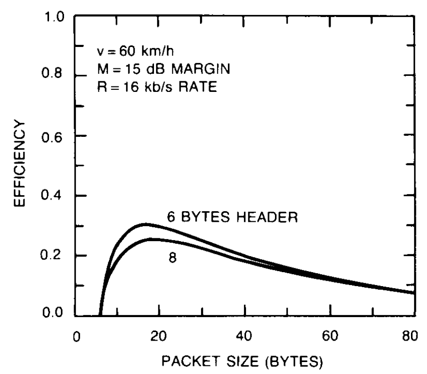

Fig. 6. Peak efficiency as a function packet duration for two header sizes in a 16 kb/s system.

sizes in a system with a 15 dB fade margin and a vehicle speed of 60 km/h. Increasing the header from six bytes to eight extends the optimum packet length to 21 bytes from 17. It reduces the peak efficiency form 0.302 to 0.254.

Table I is a summary of our examination of 16 kb/s transmission at 850 MHz. It shows the optimum packet duration, both in bytes (p_B) and in milliseconds (p), and the corresponding efficiency for all combinations of $M = 10$, 15, 20 dB; $v = 20$, 60, 180 km/h; and $H = 6$, 8 bytes.

B. 256 kb/s Line Rate, 900 MHz Carrier

Relative to 16 kb/s transmission, a 256 kb/s system is considerably more hospitable to the HDLC protocol. For a given packet size, the probability of successful transmission over a 256 kb/s channel is much higher than over a 16 kb/s channel. This is because the packet transmission time is shorter by a factor of 16 (the ratio of bit rates) which means that it is far more likely that a packet will be confined to an interfade interval. It follows that the optimum packet size and the corresponding peak efficiency are both higher in a 256 kb/s system than in a 16 kb/s system.

The quantitative consequences of these effects can be observed in Fig. 7 which, except for the different transmission rate and carrier frequency, applies to the same conditions as Fig. 4: 15 dB margin and six bytes in the header. Here, we have an optimum packet size at 60 km/h of 48 bytes and a peak efficiency is 0.679. (At 16 kb/s the corresponding numbers are 17 bytes and 0.302.) Furthermore, the optimum in Fig. 7 is much broader than in Fig. 4. Table II presents data on optimum packet size (both in bytes and milliseconds), and on peak efficiency for 256 kb/s transmission at 900 MHz.

TABLE I
PERFORMANCE DATA FOR 16 kb/s TRANSMISSION AT 850 MHz
OPTIMUM PACKET SIZE AND DURATION, PEAK EFFICIENCY

	Fade Margin	20 dB	15 dB	10 dB
			6 bytes header	
20 km/h	packet size (bytes)	31	25	21
	packet duration (ms)	15.5	12.5	10.5
	efficiency	0.576	0.478	0.363
60 km/h	packet size (bytes)	21	17	14
	packet duration (ms)	10.5	8.5	7.0
	efficiency	0.405	0.302	0.199
180 km/h	packet size (bytes)	14	12	10
	packet duration (ms)	7.0	6.0	5.0
	efficiency	0.220	0.133	0.065
			8 bytes header	
20 km/h	packet size (bytes)	37	30	25
	packet duration (ms)	18.5	15.0	12.5
	efficiency	0.535	0.434	0.320
60 km/h	packet size (bytes)	25	21	17
	packet duration (ms)	12.5	10.5	8.5
	efficiency	0.357	0.254	0.158
180 km/h	packet size (bytes)	17	15	13
	packet duration (ms)	8.5	7.5	6.5
	efficiency	0.176	0.098	0.042

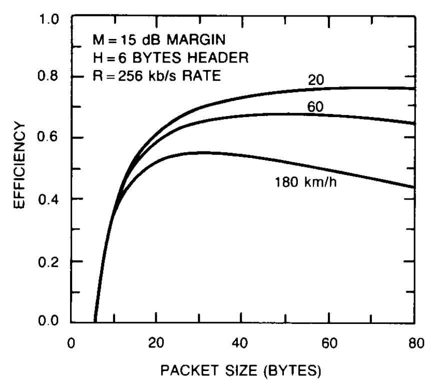

Fig. 7. Peak efficiency as a function packet duration for three vehicle speeds in a 256 kb/s system.

C. Operational Performance Data

The curves presented in the previous sections display the effects of packet size on efficiency for fixed vehicle speeds and fade margins. This information is valuable to the system designer. In a specific system, on the other hand, the packet size will be constant and the vehicle speed and fade margin

TABLE II
PERFORMANCE DATA FOR 256 kb/s TRANSMISSION AT 900 MHz
OPTIMUM PACKET SIZE AND DURATION, PEAK EFFICIENCY

	Fade Margin	20 dB	15 dB	10 dB
			6 bytes header	
20 km/h	packet size (bytes)	95	78	65
	packet duration (ms)	3.0	2.4	2.0
	efficiency	0.835	0.766	0.657
60 km/h	packet size (bytes)	59	48	40
	packet duration (ms)	1.8	1.5	1.3
	efficiency	0.758	0.679	0.566
180 km/h	packet size (bytes)	38	31	25
	packet duration (ms)	1.2	1.0	0.8
	efficiency	0.644	0.552	0.436
			8 bytes header	
20 km/h	packet size (bytes)	112	91	76
	packet duration (ms)	3.5	2.8	2.4
	efficiency	0.818	0.747	0.636
60 km/h	packet size (bytes)	72	55	47
	packet duration (ms)	2.3	1.7	1.5
	efficiency	0.732	0.649	0.535
180 km/h	packet size (bytes)	45	37	30
	packet duration (ms)	1.4	1.2	0.9
	efficiency	0.608	0.512	0.396

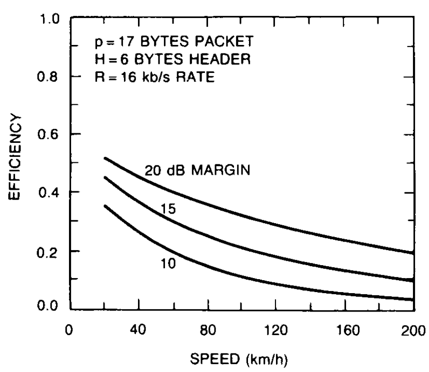

Fig. 8. Performance characteristics of a 16 kb/s system—peak efficiency as a function of vehicle speed for three fade margins. Packet duration is 17 bytes (8.5 ms).

will vary. Thus to assess system performance, we will consider packets optimized for $v = 60$ km/h and $M = 15$ dB and investigate performance as a function of vehicle speed and fade margin. Fig. 8 pertains to 16 kb/s transmission and packets with six bytes in the header. In Table I, we select the total packet size to be 17 bytes, optimum for a 15 dB fade margin and 60 km/h speed. Note that with a 15 dB fade margin the peak efficiency ranges from 0.451 at 20 km/h to 0.100 at 200 km/h. Peak efficiency is higher when the fade margin is 20 dB and lower when $M = 10$ dB.

Until now we have considered the peak efficiency corresponding to a packet arrival rate r, equal to the transmission success probability s. As the actual transmission rate approaches this peak value, (4) predicts that the transmission delay increases without bound. This is shown in Fig. 9 which shows delay as a function of packet arrival rate for the 17-byte

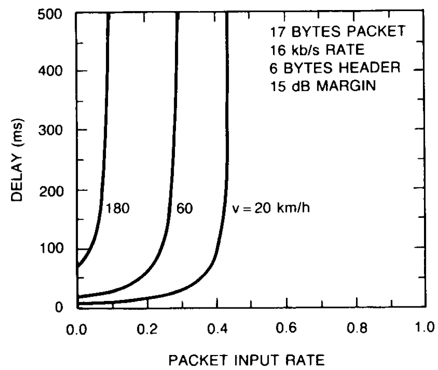

Fig. 9. Performance characteristics of a 16 kb/s system—packet delay as a function of packet input rate for three vehicle speeds. Packet duration is 17 bytes (8.5 ms).

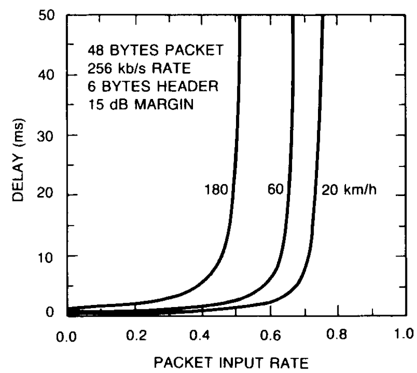

Fig. 10. Performance characteristics of a 256 kb/s system—packet delay as a function of packet input rate for three vehicle speeds. Packet duration is 48 bytes (1.5 ms).

packets that are optimum for $v = 60$ km/h and $M = 15$ dB. Here the packet input rate is expressed as a fraction of the maximum rate of a 16 kb/s channel. Thus, with 17 bytes (136 bits) per packet, a 16 kb/s channel can carry no more than $16000/136 = 118$ packets per second, which corresponds to $r = 1$ in Fig. 9. Here we see that at high vehicle speeds, a 16 kb/s channel can support only very limited HDLC packet communication (on the order of ten packets per second, or 110 information bits per second at $v = 180$ km/h).

Fig. 10 shows that the situation is much less critical at 256 kb/s. Here each packet contains 48 bytes and the maximum packet rate of the channel is 667 packets per second. With the packet duration 1.5 ms, the average delay is substantially shorter than in a 16 kb/s system with 8.5 ms (17 byte) packets.

VI. DISCUSSION

This paper shows how Rayleigh fading limits the performance of the high-level data link control protocol. For accurate reception, an HDLC packet must be transmitted entirely in an interfade interval. As a consequence, HDLC in a fading environment functions best with shorter packets than an

HDLC system operating over a nonfading channel. HDLC optimum packet size and peak efficiency increase with increasing fade margin and decrease with increasing vehicle speed.

The bit rate of the radio channel has a critical effect on the optimum packet size and the peak efficiency of an HDLC data link. A low bit rate implies a long packet duration for a given packet size in bytes. Thus for a particular vehicle speed (60 km/h) and fade margin (15 dB), the optimum packet size for a 16 kb/s channel is only 17 bytes (8.5 ms). With 256 kb/s transmission, the optimum is 48 bytes (1.5 ms). With 6 bytes in the packet header, the peak information rate at 16 kb/s comes to 3127 b/s. At 256 kb/s, the corresponding figure is 152,096 b/s. Taking into account the 16:1 ratio of transmission rates the capacity of the 256 kb/s system (at $v = 60$ km/h and $M = 15$ dB) exceeds that of the 16 kb/s system by a factor of 2.6.

After transmission rate, the variable that has the strongest effect on protocol performance is fade margin. With 16 kb/s systems highly susceptible to fades, it is important that the coding/modulation techniques of these systems, and the frequency reuse patterns, provide the highest possible fade margins.

Our performance estimates are based on a mathematical model of the dynamics of a Rayleigh fading channel and on a simplifying assumption about errors in HDLC packets. The combined model of signal fading and packet errors facilitates rapid computation of performance measures that previously required elaborate simulations. On the other hand, details of the model require further attention. For example, the probability distribution of interfade intervals, (14), should be compared with empirical data in order to either verify its validity, or to modify its form to better conform to experimental evidence.

Appendix
Success Probability Derivation

We refer to theoretical work by Rice [8] to derive a computationally tractable formula for s, the probability of successful packet reception, in (2). First we establish the following notation:

- ρ the ratio of the fading threshold to the root mean square envelope. The fade margin is $M = -20 \log_{10} \rho$:
- t_f the duration of a fade, i.e., the length of time the envelope remains below the fading threshold;
- t_i the interfade duration, i.e., the length of time the envelope remains above threshold (t_f and t_i are random variables);
- $\langle x \rangle$ the expected value of the random variable x.
- f_m $= v/\lambda$ Hz where v m/s is the speed of the mobile terminal and λ_m is the wavelength of the carrier (f_m is the maximum Doppler frequency of the fading.)
- u $= t_f/\langle t_f \rangle$, the normalized fade duration;
- $F(u)$ the cumulative probability distribution of the (normalized) fade duration.

Rice derives an asymptotic formula for $F(u)$, valid as $\rho \to 0$:

$$F(u) = \left(\frac{2}{u}\right) I_1 \left(\frac{2}{\pi u^2}\right) \exp\left(-\frac{2}{\pi u^2}\right). \quad (9)$$

Here $I_1(\cdot)$ is the modified Bessel function of order one. It has been observed in the laboratory [9] that this formula is valid for $M \geq 10$ dB, $\rho: \leq 0.01$. This means that the shape of the fade distribution is independent of the fade level for ρ sufficiently low. To derive s, the success probability, we require $f(u)$, the probability density function, which is the derivative of $F(u)$:

$$f(u) = \frac{8}{\pi u^4} I_0 \left(\frac{2}{\pi u^2}\right) \exp\left(-\frac{2}{\pi u^2}\right) - \frac{2\pi u^2 + 8}{\pi u^4} I_1 \left(\frac{2}{\pi u^2}\right) \exp\left(-\frac{2}{\pi u^2}\right). \quad (10)$$

The probability density of the unnormalized fade duration $t_f = u\langle t_f \rangle$ is

$$f_t(t_f) = \frac{1}{\langle t_f \rangle} f\left(\frac{t_f}{\langle t_f \rangle}\right). \quad (11)$$

The mean fade duration is related to the fade threshold and the maximum Doppler frequency [8] by

$$\langle t_f \rangle = \frac{\exp(\rho^2) - 1}{\rho f_m \sqrt{2\pi}}. \quad (12)$$

We can also derive the mean duration of interfade intervals:

$$\langle t_i \rangle = \frac{1}{\rho f_m \sqrt{2\pi}}. \quad (13)$$

However, there is no precise theory of the joint distribution of an interfade duration and the subsequent fade duration. To proceed with our work, therefore, we use the available information presented thus far and we assume that the interfade duration and the fade duration are statistically independent. We further assume that the interfade intervals conform to an exponential distribution with probability density

$$g(t_i) = \frac{1}{\langle t_i \rangle} \exp\left(-\frac{t_i}{\langle t_i \rangle}\right). \quad (14)$$

Under these assumptions, the joint probability density function $f(t_f, t_i)$, in (2), is the product of (11) and (14). The success probability is

$$s = \int_0^\infty \int_p^\infty \frac{t_i - p}{t_i + t_f} g(t_i) \frac{1}{\langle t_f \rangle} f\left(\frac{t_f}{\langle t_f \rangle}\right) dt_i \, dt_f. \quad (15)$$

In order to express this double integral in a form convenient for numerical integration, we first make the following substitutions:

$$\frac{t_i - p}{t_i + t_f} = 1 - \frac{t_f + p}{t_i + t_f} \quad (16)$$

and

$$u = \frac{t_f}{\langle t_f \rangle}. \quad (17)$$

This leads to

$$s = \int_0^\infty \int_p^\infty \left(1 - \frac{u\langle t_f \rangle + p}{t_i + u\langle t_f \rangle}\right) g(t_i) f(u)\, dt_i\, du$$
$$= \int_p^\infty g(t_i)\, dt_i \int_0^\infty f(u)\, du$$
$$- \int_0^\infty \int_p^\infty \frac{u\langle t_f \rangle + p}{t_i + u\langle t_f \rangle} g(t_i)\, dt_i f(u)\, du. \quad (18)$$

Using the formula for $g(t_i)$ in (14), we can obtain from (18)

$$s = \exp\left(-\frac{p}{\langle t_i \rangle}\right) - \int_0^\infty \exp\left(u\frac{\langle t_f \rangle}{\langle t_i \rangle}\right) \frac{u\langle t_f \rangle + p}{\langle t_i \rangle} \cdot \int_{\frac{u\langle t_f \rangle + p}{\langle t_i \rangle}}^\infty \frac{\exp(-t)}{t}\, dt f(u)\, du. \quad (19)$$

Note, in (19), that the packet duration p appears only in the ratio

$$\frac{p}{\langle t_i \rangle} = p f_m \sqrt{2\pi}\rho = x\sqrt{2\pi}\rho, \quad (20)$$

where x is the number of carrier cycles that the terminal traverses over the duration of a packet. Note also that the inner integral in (19) is a special function [10], $E_1(\cdot)$, defined as

$$E_1(y) = \int_y^\infty \frac{\exp(-t)}{t}\, dt. \quad (21)$$

Thus, we have for the success probability

$$s = \exp(-x\sqrt{2\pi}\rho)$$
$$- \int_0^\infty \exp\left(u\frac{\langle t_f \rangle}{\langle t_i \rangle}\right)\left(x\sqrt{2\pi}\rho + u\frac{\langle t_f \rangle}{\langle t_i \rangle}\right)$$
$$\cdot E_1\left(x\sqrt{2\pi}\rho + u\frac{\langle t_f \rangle}{\langle t_i \rangle}\right) f(u)\, du. \quad (22)$$

Computer programs for the Bessel functions in (10) and for $E_1(\ )$ in (22) are available commercially [11]. Incorporating these programs, we have written our own program [12], based on Simpson's rule, to obtain s numerically from (22).

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