Performance Evaluation of a Protocol for Packet Radio Network in Mobile Computer Communications

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Abstract—**The need to provide computer network access to mobile terminals and computer communications in the mobile environment has stimulated and motivated the current developments in this area. Packet radio technology has developed over the past decade in response to the need for real-time, interactive communications among mobile users and shared computer resources. In computer communication systems we have a great need for sharing expensive resources among a collection of high peak-to-average (i.e., bursty) users. Packet radio networks provide an effective way to interconnect fixed and mobile resources. The results of an attempt to study the performance of the mobile packet radio network for computer communications over degraded channels are presented. We develop a model under fading conditions and derive a protocol for evaluating the performance of the mobile packet radio network (MPRNET) in terms of the packet error rate, packet delay, throughput and average number of retransmitted packets per cycle. The analytical results are presented and numerical examples are given to illustrate the behavior of these performance criteria as a function of packet transmission rate, packets transmitted per cycle, packet size, and vehicle speed with the help of appropriate plots.**

I. INTRODUCTION

THE NEED FOR fixed or mobile computer communications over long-haul or local area networks is widely understood now. Many mobile radio users are interested in data stored in computer files and it appears logical to transmit this data in a digital format [4]. Large computer installations, enormous data banks, and extensive national and international computer networks are now becoming available. They constitute large expensive resources which must be utilized in a cost effective fashion. The constantly growing number of computer applications and their diversity render the fundamental problem of accessing these large resources. Fortunately, radio communication has emerged as a method for providing remote terminal access to computers [14].

Recently, we have witnessed the development of packet radio technology to achieve information distribution and computer communications. This development is directly related to the rapidly increasing demand to provide effective communication services for data distribution. Multiple access and broadcast radio channels have been utilized to form networks which provide packet-switched communication. These packet radio networks are well-suited for computer communications in the ground mobile network environment, due to its rapid and convenient deployment capability, easy configuration possibility, and survivability. In addition, packet radio network technology offers a highly efficient way of using a multiple access radio channel with a potentially large number of mobile subscribers to support computer communications and to provide local distribution of information over a wide geographic area and its area coverage and connectivity may be increased easily [10]. A packet radio network can also coexist with other packet radio networks.

Packet radio technology is applicable to ground-based, airborne, seaborne, and space environments and is able to serve users whether on land, at sea, or in the air. Ground-based networks encounter perhaps the most difficult environment in terms of propagation and RF connectivity. Ground radio links, particularly when mobile terminals are involved, are subject to severe variations in received signal strength due to local variations in terrain, man-made structures and foliage. In addition, reflections give rise to multiple signal paths leading to distortion and fading as the differently delayed signals interfere at the receiver. As a result of these phenomena, RF connectivity is difficult to predict and may abruptly change in unexpected ways as mobile terminals move around. However, an important attribute of a packet radio system is its self-organizing, automated network management capability which dynamically discovers RF connectivity as a function of time for use in packet routing [17]. In mobile packet radio networks (MPRNET) the radio connectivity changes frequently because of the mobility of some of the packet radio units (PRU's). As the PRU's move, they lose and gain radio connectivity with each other at a rate that can be as high as several changes per minute in urban areas. Due to loss of connectivity in MRPNET a severe problem of route failure arises because of the creation of "route loops" or "a dead end." Restoration of the route is speeded up by making use of additional information in the neighborhood of the failure. This is especially important in a mobile environment due to the high frequency of altered connectivity [9].

The ground radio applications of packet communications include such things as communications among moving vehicles (e.g., taxicabs, ambulances, police cars, fire trucks, private fleets, etc.), communications among aircraft, and indeed communications among any mobile units or any widely distributed units in a sparse environment [5]. Packet radio networks should support mobile terminals and computers at normal vehicular ground speeds within the area of coverage with full connectivity. For ground mobile radio, network

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diameters on the order of 100 mi are appropriate, but the system architecture should allow the geographic area of coverage to be expanded at the expense of increased end-to-end (ETE) delay across the network [17]. One of the difficulties faced in a mobile network is that the number of users in a given RF connected area and the amount of traffic these users generate as a function of time is difficult to predict [8].

A mobile computer communication network can generally be defined by the following features: its host computers and terminals, communication processors, topological layout, communication equipment and transmission media, switching technique, mobile unit and protocol design [13]. These features are chosen to accomplish the function of the network subject to specified performance requirements. The performance measures most commonly quoted include message delay, message throughput, error rate, reliability, and cost. When mobile operations are involved, the measurements indicate temporary degradation in the performance, affecting both throughput and delay. By proper selection of the dominant network protocol parameters, the degradation can be substantially reduced [11]. Improved performance under mobile operations is needed for all traffic types, to reduce the load on the radio channel and improve overall network performance. Several methods for such improvements have been discussed in [11].

The first analysis of packet radio performance assumed that packet collisions were the major cause for loss of a packet and subsequent retransmission. More recently [15], efforts to design packet radio systems to operate over degraded channels have been undertaken. The channel throughput and packet delay, the two primary performance criteria in computer communications, have been extensively studied for basic system concepts such as pure ALOHA, slotted ALOHA, and CSMA [14], [16]. However, we need to consider the effect of link errors due to noise and fading too. In the absence of fading the noiseless assumption is quite good, but on a fading channel the signal-to-noise ratio becomes a critical parameter. The approach here is to model the problem under fading conditions and develop a protocol for evaluating the performance of the mobile packet radio network in terms of packet error rate, packet delay, and average number of packets retransmitted per cycle, as a function of packet transmission rate, packet size, the number of packets transmitted per cycle, and vehicle speed.

II. MODEL DESCRIPTION

Experiments in urban areas have shown that noise impulses occur every few milliseconds in both the UHF and L bands, principally due to automobile ignition noise. A packet has a very high probability of encountering one or two impulses and therefore some form of error correction is required [18], if an essentially error-free performance for computer communication is desired. A target objective of no more than one undetected packet error per 10^6 packets assuming 1000 bit packets, a 100 k-bit/s data rate, and 100 percent occupancy.

In the ground-based mobile packet radio network performance degradation occurs due to transmission errors resulting from packet collisions, noise, fading, and probably shadowing too. The present model assumes that transmission errors are caused only by fading, i.e., errors due to other sources of noise and interference are not considered. Fading occurs due to multipath propagation of the signal in which nulling or reinforcement of the direct path signal results [7]. Fading phenomena are often characterized by a specific type of short-term multipath signal reception whose amplitude follows the Rayleigh distribution [2], [7].

Packet radio techniques are used for communications between mobile terminals and computer networks. In these techniques, a message is decomposed into a number of packets which are transmitted individually to one or more destinations where they are assembled to reconstruct the original message. An overhead message is attached to each packet. The overhead message contains information about the addresses of the originating source and the destination, routing information, and check-sum bits for error detection [7], [6].

Let

- L Message length (bits).
- B Packet length (bits).
- b Overhead message length (or, packet overhead) (bits).
- M Number of packets in the message.
- R Packet transmission rate (bit/s).

Hence,

$$\text{total packet length} = (B+b) \text{ bits}$$

$$\text{packet duration } T = \left\{\frac{(B+b)}{R}\right\} \text{ s.}$$

Also,

$$M = \frac{L}{B}.$$

The transmission of packets is conducted in cycles. Each cycle consists of the transmission of N consecutive packets plus a short time interval to allow for the reception of the acknowledgment message [6], [7].

III. PROTOCOL DESCRIPTION

In any communication system, and in particular, a computer communication system, it is essential to have a set of well-designed basic control procedures to insure efficient, correct, and smooth transfer of information in the system. Traffic management is a set of rules that ensures the smooth and orderly exchange of information among elements of a computer network. Its main functions are protocol, routing, flow control, and monitoring [12]. Protocol is a word borrowed from the terminology of political diplomacy to describe the rules governing orderly exchange of information between different computing equipment in a predetermined fashion [13].

We describe and analyze a protocol derived from the "stop-and-wait" control procedures [6]. According to this protocol, the transmitting unit sends one packet of data at a time and waits for an acknowledgment (ACK) from the receiving unit before proceeding. If the transmitting unit does not receive an ACK after a certain time-out period, the same packet is retransmitted. This operation is repeated for a predefined number of times until the ACK is received. However, when the channel is unreliable, the transmitting unit may be instructed to give up retransmitting the packet. We assume that the acknowledgment traffic is carried by a separate channel and is received reliably. In this protocol, the packet transmission is conducted in cycles. Each cycle represents the transmission of N packets plus an ACK time-out period. The ACK message informs the sending unit of the first packet that was found in error such that in the following cycle this packet and the following ones are to be retransmitted along with some new packets. Based on an estimation of the signal level at the receiving location or on the frequency of packet errors, the number of packets per cycle N can be adjusted.

The protocol is conducted as follows [1], [7], [13].

1) At the start of each cycle, the transmitting unit starts transmitting N packets before it stops for a short interval t_a.
2) The receiving unit sends an ACK signal immediately after the reception of the N packets indicating the address of the first packet that was found in error.
3) The addressed packet and the packets following it are then rescheduled for the transmission in the following cycle.

An important parameter of the algorithm described above is the number of packets per cycle, N. For a certain set of system parameters, N can be adjusted to provide the minimum delay per message. More important is the fact that N can be made adaptive to the status of the channel to achieve minimum delay in the ever changing environment of the mobile system. We notice that the case when $N = 1$ represents the well-known stop-and-wait strategy, and the algorithm described above is a generalization of this strategy.

IV. ANALYSIS

Assumptions

In the analysis, we make several simplifying assumptions to reduce the complexity of the problem. These assumptions may not model the real world, however, they lead to some useful and interesting results.

1) The traffic introduced into the network consists of fixed-length packets generated according to a Poisson process, i.e., the packets are introduced into the network according to a Poisson process.
2) A packet radio node can be either in the receiving mode or in the transmitting mode. If a packet radio node is in the transmitting mode when a packet arrives, it is lost.
3) Individual user transmissions are independent of one another and that successive user packet transmissions are independent.
4) The transmission errors will occur only because of the signal fade below the receiver threshold level, which means that thermal noise, ignition noise and different sources of interference and signal distortion have negligible effects in the presence of fade.
5) The channel is in one of two possible states at any time:
   a) the ON state represents the case when the received signal is above the threshold level; and
   b) the OFF state represents the case when the signal is below the threshold level.

   This representation is illustrated in Fig. 1. This assumption is justified for most digital modulation techniques which usually exhibit a sharp threshold behavior [3].
6) The packet is received correctly if and only if the whole packet was contained in a nonfade interval, t_2 (Fig. 1). This means that the packet is assumed to have at least one detected error if it overlaps to any extent with a fade slot.
7) The nonfade interval t_2 is exponentially distributed.
8) The envelope of the fade interval t_1 is Rayleigh distributed.
9) Outbound channels considered and all terminals are within range and in line-of-sight of each other.

Let

t_a Acknowledgment delay.
t_1 Fade interval.
t_2 Nonfade interval.
t_3 Interfade interval.
τ Packet delay (or wasted time) per message due to channel error.
η Average number of retransmitted packets per cycle.

The density function of the variable "t_2" can be written as

$$f_{t_2}(t)=\frac{1}{T_2}\exp\left(-\frac{t}{T_2}\right), \qquad t>0 \tag{1}$$

where T_2 is the average value of the variable t_2.

The probability that all N packets are received correctly (i.e., zero retransmission) is given by the probability that the nonfade interval t_2 will last for a period longer than the N-packet's transmission time.

$$\begin{aligned} P(0)&=\frac{T_2}{T_3}P[t_2>NT]\\ &=\frac{T_2}{T_3}[1-P[t_2\le NT]]\\ &=\frac{T_2}{T_3}\left[\exp-\left(\frac{NT}{T_2}\right)\right]. \end{aligned} \tag{2}$$

This is also the probability of success P_S for N packets of duration T seconds each to be received correctly without any retransmission. Here, T_2 and T_3 are the average values of the random variables t_2 and t_3, respectively.

It follows that the packet error rate is given by

$$\begin{aligned} P_b&=1-P_S=1-P(0)\\ &=1-\frac{T_2}{T_3}\left[\exp-\left(\frac{NT}{T_2}\right)\right]. \end{aligned} \tag{3}$$

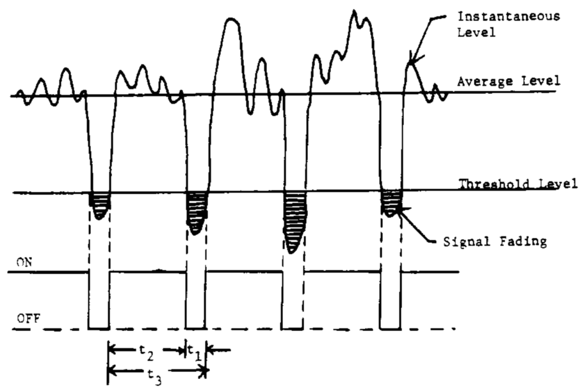

Fig. 1. ON-OFF characteristics of the land-mobile data channel.

In general, the probability that n out of N packets are retransmitted is

$$P(n)=\frac{T_2}{T_3}\,P[(N-n)T<t_2<(N-n-1)T]$$
$$=\frac{T_2}{T_3}\left[\exp-\left(\frac{(N-n)T}{T_2}\right)-\exp-\left(\frac{(N-n+1)T}{T_2}\right)\right]. \tag{4}$$

This equation is valid for $n = 1$ to $(N - 1)$.

The probability that N packets are to be retransmitted is

$$P(N)=\frac{T_1}{T_3}+\frac{T_2}{T_3}\,P[t_2<T]$$
$$=\frac{T_1}{T_3}+\frac{T_2}{T_3}\left[1-\exp-\left(\frac{T}{T_2}\right)\right] \tag{5}$$

where the first term represents the possibility of transmission cycle starting at a fading slot, while the second term represents the case where nonfade interval is less than the duration of a single packet.

Equations (2), (4), and (5) satisfy the obvious condition

$$\sum_{n=0}^{N}P(n)=P(0)+\sum_{n=1}^{N-1}P(n)+P(N)=1. \tag{6}$$

The expected value of the retransmitted packet per cycle is given by

$$\eta=\sum_{n=0}^{N}nP(n)=\sum_{n=1}^{N}nP(n) \tag{7}$$
$$=\sum_{n=1}^{N-1}nP(n)+NP(N)$$
$$=\frac{T_2}{T_3}\sum_{n=1}^{N-1}n\left[\exp-\left(\frac{(N-n)T}{T_2}\right)-\exp-\left(\frac{(N-n+1)T}{T_2}\right)\right]$$
$$+N\left[\frac{T_1}{T_3}+\frac{T_2}{T_3}\left[1-\exp-\left(\frac{T}{T_2}\right)\right]\right]$$
$$=\frac{T_1}{T_3}N+\frac{T_2}{T_3}N\left[1-\exp-\left(\frac{T}{T_2}\right)\right]+\frac{T_2}{T_3}\left[\exp-\left(\frac{NT}{T_2}\right)-\exp-\frac{(N+1)T}{T_2}\right]\cdot\sum_{n=1}^{N-1}n\exp\left(\frac{nT}{T_2}\right)$$
$$=\frac{T_1}{T_3}N+\frac{T_2}{T_3}\left[N\left[1-\exp-\left(\frac{T}{T_2}\right)\right]+\left[\exp-\left(\frac{NT}{T_2}\right)-\exp-\frac{(N+1)T}{T_2}\right]\cdot\sum_{n=1}^{N-1}n\exp\left(\frac{nT}{T_2}\right)\right]$$
$$=\frac{T_1}{T_3}N+\frac{T_2}{T_3}\left[\left\{\exp-\left(\frac{NT}{T_2}\right)-\exp-\left(\frac{(N+1)T}{T_2}\right)\right\}\cdot\left\{\frac{N\left[1-\exp-\left(\frac{T}{T_2}\right)\right]}{\left[\exp-\left(\frac{NT}{T_2}\right)-\exp-\left(\frac{(N+1)T}{T_2}\right)\right]}+\sum_{n=1}^{N-1}n\exp\left(\frac{nT}{T_2}\right)\right\}\right]$$
$$=\frac{T_1}{T_3}N+\frac{T_2}{T_3}\left[\left\{\exp-\left(\frac{NT}{T_2}\right)-\exp-\left(\frac{(N+1)T}{T_2}\right)\right\}\cdot\left\{N\exp\left(\frac{NT}{T_2}\right)+\sum_{n=1}^{N-1}n\exp\left(\frac{nT}{T_2}\right)\right\}\right]$$
$$=\frac{T_1}{T_3}N+\frac{T_2}{T_3}\left[\left\{\exp-\left(\frac{NT}{T_2}\right)-\exp-\left(\frac{(N+1)T}{T_2}\right)\right\}\cdot\left\{\sum_{n=1}^{N}n\exp\left(\frac{nT}{T_2}\right)\right\}\right]$$
$$\eta=\frac{T_1}{T_3}N+\frac{T_2}{T_3}\left[\{\alpha^{-N}-\alpha^{-(N+1)}\}\left\{\sum_{n=1}^{N}n\alpha^{n}\right\}\right] \tag{8}$$

where

$$\alpha \triangleq \exp(T|T_2).$$

We know that

$$\sum_{n=1}^{N-1}\alpha^n=\sum_{n=0}^{N-1}\alpha^n-1=\frac{1-\alpha^N}{1-\alpha}-1$$

$$\sum_{n=1}^{N-1}n\alpha^n=\frac{\alpha}{(1-\alpha)^2}\,[N\alpha^N-N\alpha^{N-1}+1-\alpha^N]$$

$$\sum_{n=1}^{N} n\alpha^n = \frac{\alpha}{(1-\alpha)^2}\left[N\alpha^N - N\alpha^{N-1} + 1 - \alpha^N\right] + N\alpha^N. \tag{9}$$

Substituting (9) into (8), a closed form expression for the expected value of the retransmitted packet per cycle results,

$$\eta = \frac{T_1}{T_3}N + \frac{T_2}{T_3}\left[\{\alpha^{-N}(1-\alpha^{-1})\}\right.$$

$$\left.\cdot\left\{\frac{\alpha}{(1-\alpha)^2}\left[N\alpha^N - N\alpha^{N-1} + 1 - \alpha^N\right] + N\alpha^N\right\}\right]$$

$$= \frac{T_1}{T_3}N + \frac{T_2}{T_3}\left[\frac{\alpha^{-N}}{\alpha(1-\alpha^{-1})}\left[N(\alpha^N - \alpha^{N-1})\right.\right.$$

$$\left.\left. + (1-\alpha^N)\right] + N(1-\alpha^{-1})\right]$$

$$= \frac{T_1}{T_3}N + \frac{T_2}{T_3}\left[\frac{1}{\alpha(1-\alpha^{-1})}\left[N(1-\alpha^{-1})\right.\right.$$

$$\left.\left. + (\alpha^{-N}-1)\right] + N(1-\alpha^{-1})\right]$$

$$= \frac{T_1}{T_3}N + \frac{T_2}{T_3}\left[\frac{N}{\alpha} + \frac{(\alpha^{-N}-1)}{\alpha(1-\alpha^{-1})} + N - N\alpha^{-1}\right]$$

$$\eta = \frac{T_1}{T_3}N + \frac{T_2}{T_3}\left[N - \frac{(\alpha^N - 1)}{\alpha^N(\alpha-1)}\right]. \tag{10}$$

In the protocol under consideration, the transmission of M packets is conducted in cycles. Each cycle represents the transmission of N packets each of size $(B + b)$ bits plus a time-out interval t_a. The time required per cycle is

$$T_c = t_a + N\left(\frac{B+b}{R}\right) \tag{11}$$

and we assume that acknowledgment delay is $t_a = b/R$.

Due to transmission errors under considerations, on the average "η" packets are to be retransmitted per cycle. The total time required to transmit M packets is

$$T_t = \frac{M}{N-\eta}T_c. \tag{12}$$

But the minimum time required to transmit L bit message at transmission rate R bit/s is L/R, therefore, the packet delay per message due to channel error is

$$\tau = T_t - \frac{L}{R}$$

$$= \frac{M}{N-\eta}T_c - \frac{L}{R}$$

$$= \frac{M}{N-\eta}\left[\frac{b}{R} + N\left(\frac{B+b}{R}\right)\right] - \frac{L}{R}$$

$$= \frac{L}{R}\left[\frac{(N+1)b + NB}{B(N-\eta)} - 1\right]. \tag{13}$$

This expression contains the parameters, N, B, b, R, L which are constants and therefore the only unknown is the average number of retransmitted packets per cycle "η," which has been stated before in (10).

Let

f_D Doppler frequency shift.

λ Carrier frequency wavelength.

ρ $= \dfrac{P_T}{P_R} = \dfrac{\text{threshold power level}}{\text{rms power level}}$.

V Mobile vehicle speed.

Then,

$$f_D = \frac{V}{\lambda}.$$

The channel parameters T_1, T_2, and T_3 are related to the Doppler frequency shift f_D and the relative power level ρ by [2], [3]

$$T_1 = \frac{\exp(\rho) - 1}{f_D\sqrt{2\pi\rho}} \tag{14}$$

$$T_2 = \frac{1}{f_D\sqrt{2\pi\rho}} \tag{15}$$

$$T_3 = \frac{\exp(\rho)}{f_D\sqrt{2\pi\rho}}. \tag{16}$$

The average delay per message (τ) or the average delay per packet can be calculated using (13), (10), (14), (15), and (16).

From (3), the probability of success (P_S) for a packet of length T second is

$$P_S = \frac{T_2}{T_3}\left[\exp - \left(\frac{T}{T_2}\right)\right].$$

Substituting for T_2 and T_3 we get

$$P_S = \exp\left[-(\rho + f_D\sqrt{2\pi\rho}\,T)\right]. \tag{17}$$

Therefore, the packet error rate is given by

$$P_B = 1 - \exp\left[-(\rho + f_D\sqrt{2\pi\rho}\,T)\right]. \tag{18}$$

This expression gives the probability that a packet transmitted over the channel will have at least one detected error.

The channel throughput (S) defined as the average number of packets generated per transmission time, i.e., the input rate normalized with respect to T, is given by

$$S = \frac{(N-\eta)}{T_c}T. \tag{19}$$

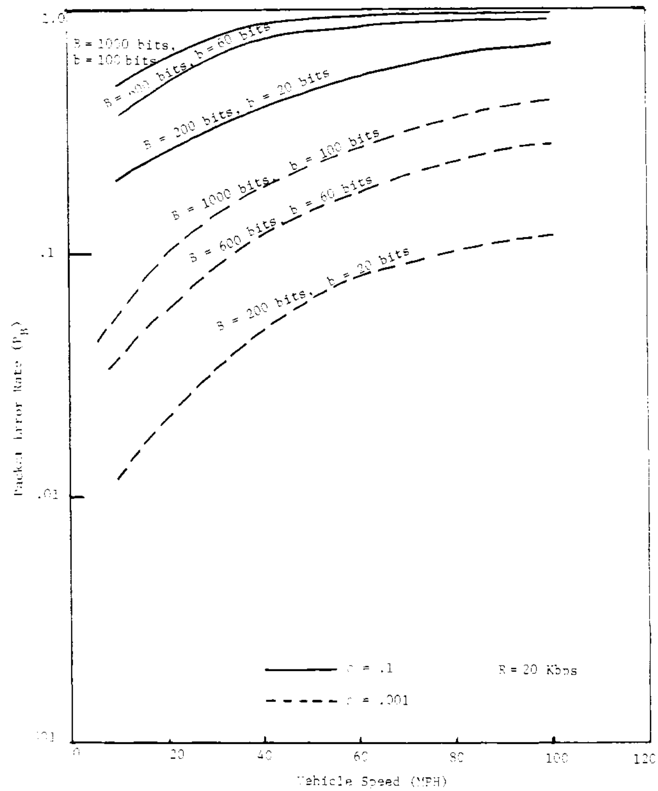

Fig. 2. Effect of vehicle speed on packet error rate. (Packet size and overheads.)

V. PERFORMANCE EVALUATION

The land-mobile data channels are characterized by a high error rate (10^{-1} – 10^{-3}) mainly due to the frequent signal fading and the rapid variation of the received signal level. The average signal-to-noise ratio varies considerably (10–30 dB) over the relatively small service area resulting in different error rates and error distributions at different geographical locations within the service area [2], [3], [7]. The message delay due to channel error could be minimized by optimizing the packet length for a certain set of system parameters. However, since the system parameters vary from one location to the other, a variable packet length is required to keep the delay at its minimum value. Because of the complexity associated with variable packet length model analysis, a better alternative will be to transmit more than one packet at a time before the transmitting unit stops and waits for the ACK signal. The number of packets transmitted at a time can then be made adaptive to the status of the channel, to keep the message delay close to its minimum value in all locations [6].

Experimental evidence indicates [18] that a maximum packet size of 1000 bits seems to be a satisfactory choice for the vast majority of computer communications requirements. For portable digital terminals (as with real-time computer speech input) packet sizes of a few hundred bits are more than sufficient. To conduct tests with automobiles in the MPRNET ground computer communications a target speed of 100 mi/h is considered sufficient in the early stage.

To illustrate the behavior of the performance parameters like packet error rate, packet delay and optimum number of packets transmitted per cycle that will minimize delay, we choose carrier frequency of 850 MHz. Fig. 2 shows vehicle speed versus packet error rate (P_B) for a fixed transmission rate and for two different values of the signal-to-noise ratio (SNR). It is observed that higher SNR gives better error rate performance, also the performance degrades rapidly with the increasing vehicle speed and after about 80 mi/h, the degradation is slow. Higher packet size and overheads lead to increased error rates. Fig. 3 shows vehicle speed versus packet error rate (P_B) for a fixed packet size and overhead and again for two values of the signal-to-noise ratio. It is observed that higher SNR is desirable for better error rate performance. Here, again the performance degrades rapidly with the increasing vehicle speed and after about 80 mi/h, the degradation is slow or almost constant. Higher rates of packet transmission leads to better performance, particularly if the transmission rate is increased from 100 k-bit/s to 1000 k-bit/s, the packet error rate drops down by about 27 percent for 10 dB SNR and by about 10 percent for 30 dB SNR. In Fig. 4, we plot vehicle speed versus message delay due to channel error caused by retransmissions. Here, we have chosen a set of typical values for L, R, B, b to study the performance of the model. Here again, higher SNR leads to better performance. We observe that for a certain packet length the message delay is minimized for an optimum value of N, the number of packets transmitted per cycle. For an SNR of 10 dB, $N=1$ minimizes the delay while for SNR of 30 dB, $N = 2$ is the optimal value. For nonoptimal values of N, the delay performance is very poor for low SNR and poor for higher SNR. The degradation of delay performance as a function of vehicle speed is more severe for lower SNR than for higher SNR. For 30 dB SNR, the message delay almost stabilizes after 100 mi/h. Channel throughput (S) is shown in Fig. 5 for

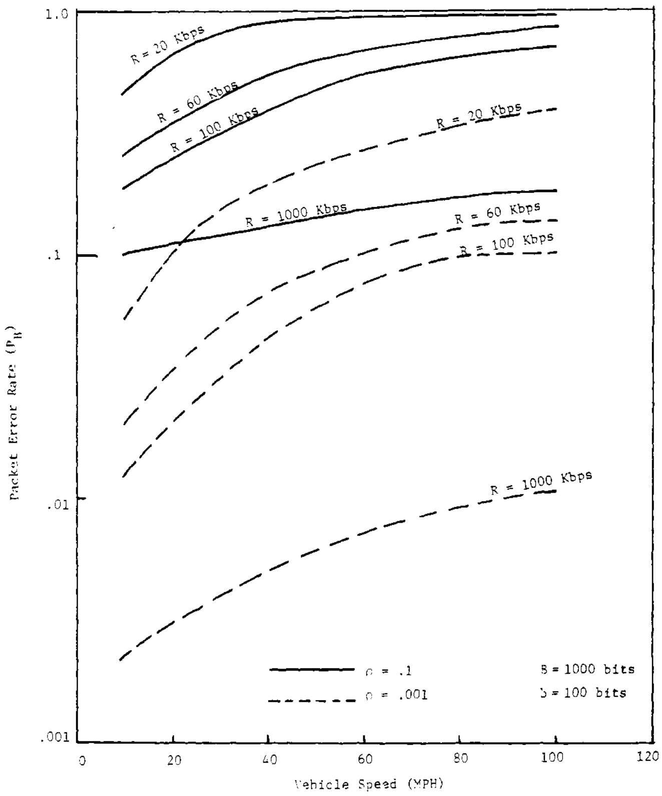

Fig. 3. Effect of vehicle speed on packet error rate. (Packet transmission rate.)

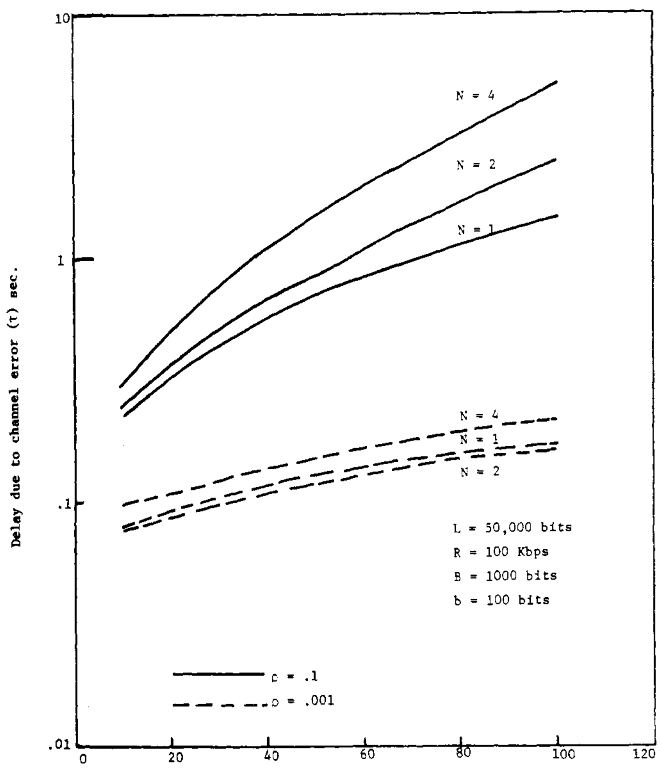

Fig. 4. Vehicle speed versus delay due to channel error.

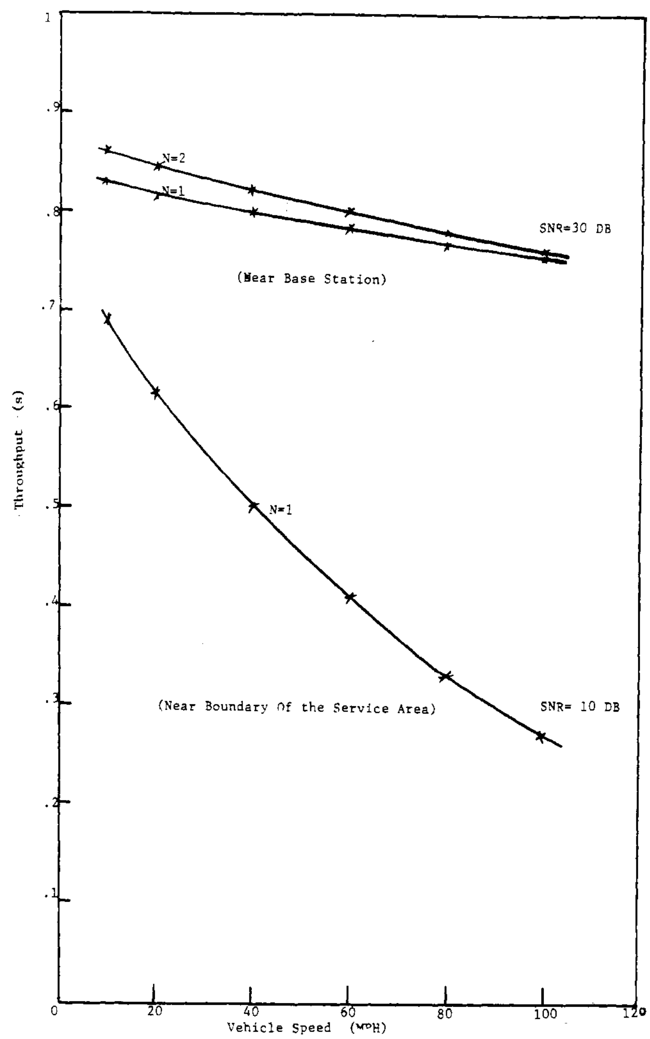

Fig. 5. Vehicle speed versus throughput.

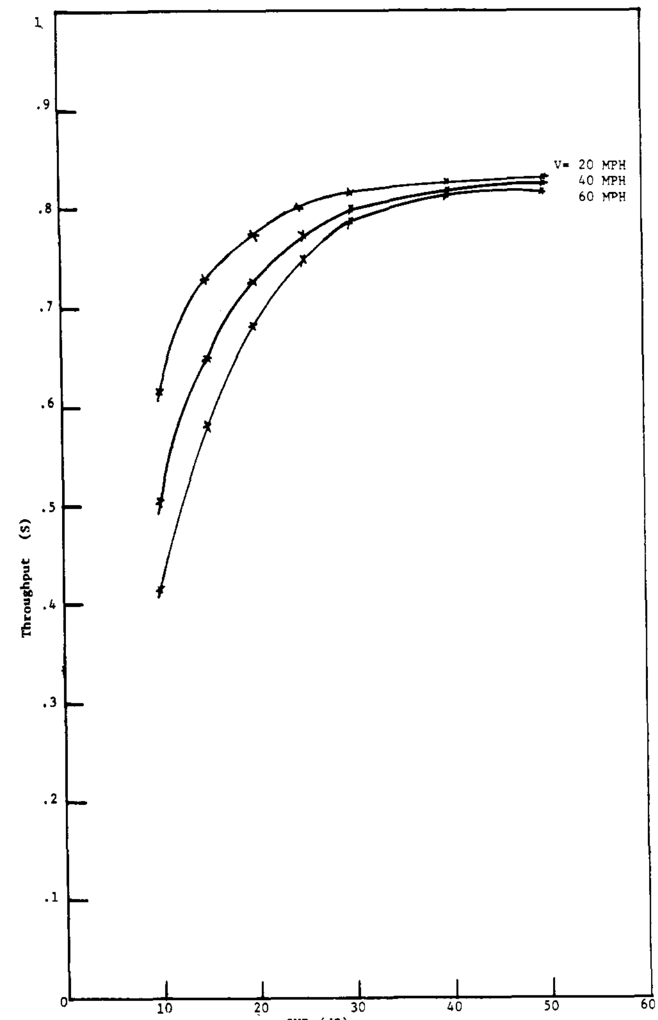

Fig. 6. Signal-to-noise ratio versus throughput.

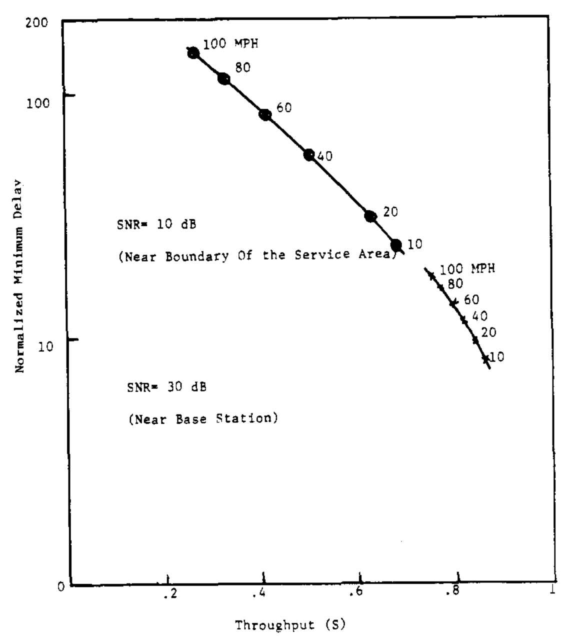

Fig. 7. Throughput versus normalized delay.

SNR of 30 dB and 10 dB, typical values near the base station and near the boundary of the service area, respectively. It is observed that the degradation in throughput performance is more severe for lower SNR, i.e., near the boundary of the service area whereas for higher SNR, i.e., near the base station the throughput almost stabilizes after about 80 mi/h. Fig. 6 shows the variations of throughput (S) with the SNR for different vehicle speeds. Lower vehicle speed gives better throughput performance. In Fig. 7 we have plotted normalized minimum delay versus throughput for the two extreme cases. The throughput-delay performance is far better near the base station than near the boundary of the service area. Once again, lower vehicle speed leads to better throughput-delay performance whether the user is near the boundary of the service area or close to the base station.

VI. CONCLUSION

We have developed a model and derived a protocol to analyze mobile packet radio network performance under degraded channel conditions. We came up with the analytical results for evaluating the performance of the protocol in terms of parameters like packet error rate, message delay, channel throughput and number of packets retransmitted per cycle. The behavior of these performance parameters was studied in relation to packet size, packet overhead, transmission rate, signal-to-noise ratio, packets transmitted per cycle and vehicle speed. We observed that the packet error rate performance, message delay and channel throughput performance degrades rapidly with vehicle speed up to about 80 mi/h, but above this speed the degradation is slow for reasonably good SNR, an interesting result indeed. The analysis presented is good for outbound channels. For inbound channels we need to take into account errors caused by the random access policy and particularly errors caused by packet overlaps.

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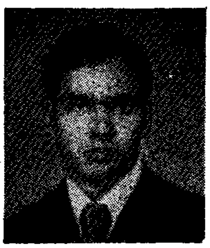

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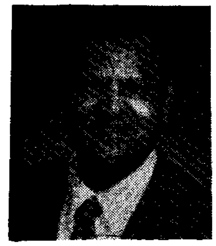

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