

Mobile Packet Radio Networks: State-of-the-Art

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Performance evaluation of some channel access protocols for a Mobile Packet Radio Network

MUCH WORK HAS been done in the areas of packet switching, packet radio, and random communication channels. However, efforts combining these areas are not as plentiful. There are several reasons for this. One reason is, the packet communications area is relatively young. Much of the research into packet communications has been accomplished by computer scientists rather than communications engineers, with a resulting emphasis on architecture, protocols, software, and so on. Even the development of packet radio has not fostered extensive examination of link effects on system performances. The UHF line-of-sight links and SHF satellite links have been assumed to be perfect with packet collisions as the dominant error source, which is a good assumption under normal circumstances. However, abnormal circumstances including ionospheric scintillations and multipath fading are another source of error on degraded packet radio links, which characterize Mobile Packet Radio Networks (MPRNET). In this paper we define and discuss Mobile Packet Radio Networks and present their channel characteristics. The performance evaluation of some channel access protocols for a Mobile Packet Radio Network link, which is a typical example of a degraded packet radio channel, is described.

Introduction

Recently, we have witnessed the development of packet radio technology to achieve information distribution and computer communications, giving rise to the various information networks [1]. 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 communications. 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 [2]. It also provides local distribution of information over a wide geographic area, and its area coverage and connectivity may be increased easily. A packet radio network can also coexist with other packet radio networks. The main advantages of packet radio networks [3] over conventional networks is that they are not dependent on fixed topologies, are easy to establish, and can operate unattended. These characteristics allow terminals to be mobile and to be attached to a diversity of computing and sensor devices. The advent of cellular technology [4] is another milestone in the area of mobile communications and will play an important role in predicting the flavor of future mobile packet radio networks.

Mobile Packet Radio Network

A packet radio network is a store-and-forward packet switching system employing radio links. Functionally, it includes three types of devices: terminal, repeater, and station. A repeater provides area coverage for mobile terminals and also acts as a relay node. The station provides global control functions, gateway functions for interfacing with other networks, and initialization functions. In centralized hierarchical routing algorithms, all packet transmissions between nodes in the network are routed via the station. Furthermore, the station initializes and periodically updates repeater parameters for routing.

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Mostly, investigations have been limited to the study of stationary packet radio networks. The mobile packet radio system generalizes the stationary system by allowing every element of the hardware to be independently in motion. The advantages and applicability of this system arise from its capability of providing communications between mobile terminals (autos, ships, handheld devices, and so on) via mobile repeaters on vans, ships, or airplanes to a (potentially mobile) computer center or monitoring station. A repeater differs from a terminal, in that it is not a source or sink for information flow, and its objective is to extend the effective communication range of terminals to achieve wide coverage. Consequently, a mobile radio system would typically consist of a large collection of mobile terminals and a small number of repeaters; the mobility of the repeaters may be dictated by the application. Mobile radio systems have been available for many years; however, the principal mode of communication has mostly been through dedicated or reserved resources without resource sharing; hence, spectrum was not efficiently utilized. The packet radio system, on the other hand, is a multiple access random transmission scheme.

There exists a basic difference between the two systems, not only in the definition and analysis, but also the problems one must address. For instance, in a Packet Radio Network (PRNET), we try to determine the location of repeaters to achieve optimal coverage of a certain area and a repeater may be permanently placed in a precalculated location. In the Mobile Packet Radio Network (MPRNET), repeaters are assumed in motion [17]. In PRNET, a particular and predetermined zone is covered. In MPRNET, the covered zone varies with time; however, the requirements for the coverage of a particular area may be imposed. The routing algorithms and initialization algorithms developed for the PRNET are not compatible with the MPRNET, due to variations in the basic assumptions [5]. The available algorithms may no longer be optimal in a dynamic environment and, hence, new or modified algorithms are sought. In PRNET, once the system is initialized it will remain so unless there is a high failure rate of repeaters. In MPRNET, the system may become inoperative due to motion of the devices. Consequently, a frequent monitoring operation is required.

The technology of packet radio is applicable to ground-based, airborne, seaborne, and space environments, and is able to serve users on land, sea, or 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. In 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 MPRNET, a severe problem of route failure arises because of the creation of "route loops" or a "dead end" [6]. Restoration of the loop 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. 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.

The ground radio applications of packet communication include communications among moving vehicles (for example, taxicabs, ambulances, police cars, fire trucks, and private fleets), communications among aircraft, and communications among any mobile units or any widely distributed units in a sparse environment [7]. Packet radio networks support mobile terminals and computers at normal vehicular ground speeds, within the area of coverage with full connectivity. For ground mobile radio, network diameters of the order of 100 miles 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.

Mobile Packet Radio Channel Characteristics

A potential application of packet radio involves mobile users in an urban environment. Because of signal reflections from buildings and other structures, the signal arriving at the receiver consists of the sum of randomly delayed versions of the transmitted signal due to multipath. The signal amplitude has been found to be Rayleigh distributed [8].

A benign communication channel is defined as one in which additive white Gaussian noise (AWGN) is the only factor corrupting the demodulation process. We are concerned with channels on which, in addition to AWGN, the signal amplitude is a random process. The motivation for such a mathematical model is the physical phenomenon known as "fading," in which the signal amplitude fluctuates as a function of time. Fading channels are characterized by frequent signal dropouts that are long compared to packet duration; hence, substantial buffer space must be provided at both ends of the link.

In a typical mobile radio propagation environment, the received signal will show fading consisting of a very rapid fluctuations around the mean signal level superimposed on relatively slow variations of the mean level. The short term variations are caused by multipath propagation; it has been found that the amplitude distributions of the signal can be approximated very closely by the Rayleigh distribution. The medium term mean value variations are caused by shadow effects, and are usually found to be log-normally distributed [9]. In theoretical work, the mean value is normally assumed to be constant, that is, the distribution is assumed to be pure Rayleigh. This assumption simplifies the mathematical analysis considerably and is allowable for the theoretical system analysis. However, it will seriously impair the accuracy of any attempt to predict practical system performance.

The mobile packet radio channel can be characterized as follows:

- **A time-varying channel.**
- **Short-term characteristics**—Fading of the received signal envelope is due to multipath propagation. Statistics of the received signal envelope is Rayleigh distributed and phase of the received signal is uniformly distributed.
- **Long-term characteristics**—Shadowing of the received signal envelope is due to buildings, hills, trees, and so forth. Local mean of the received signal envelope obeys log-normal distribution.
- **Attenuation of the signal with distance**—Signal power varies inversely as the M^{th} power of distance ($3 < M < 4$).
- **Doppler effect is due to vehicle motion.**
- **Ignition and other vehicular noise.**

Atmospheric optical paths, tropospheric and ionospheric channels, and intra-urban mobile radio channels, all suffer from signal fading, a phenomenon produced by partial

reinforcement or cancellation among the signals that reach the receiver by different paths. Although the traditional remedy has been diversity transmission, a considerably more effective alternative exists. The receiver can monitor the instantaneous path gain and send back requests for the transmitter to stop sending when the signal is weak, and to resume when the signal is strong, in order to compensate for the fading process. This and other adaptive methods have been the objective of study for some years, and it has been established that they provide substantially better performance than diversity systems.

A Protocol for Packet Radio Network in Mobile Computer Communications

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. 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. Improved performance under mobile operations is needed for all traffic types, to reduce the load on the radio channel and improve overall network performance.

Earlier analysis of packet radio performance assumed that packet collisions were the major cause for loss of a packet and subsequent retransmission. 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 [2,10]. On the other hand, in a ground-based mobile packet radio network, performance degradation occurs due to transmission errors resulting from packet collisions, noise, fading, and shadowing. Therefore, we need to consider the effect of link errors due to noise and fading too. The analysis of mobile radio slotted ALOHA networks and some other interesting schemes have been presented in a recent publication of the IEEE [11]. Let us consider a protocol for the mobile radio channel environment.

- L = Message Length (bits)
- B = Packet Length (bits)
- b = Packet Overhead (bits)
- M = Number of packets in the message
- R = Packet transmission rate (bps)
- T = Packet Duration
- f_d = Doppler frequency shift
- $\rho = \frac{\text{Threshold Power Level}}{\text{RMS Power Level}}$
- V = Mobile vehicle speed

The protocol under study is derived from the "stop-and-wait" control procedures. In this protocol, 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. The acknowledgment message informs the sending unit of the first packet that was found in error, so that in the following cycle this packet and the following one 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.

In the analysis, the channel is modeled by a renewal process and it is assumed to be in one of the two possible states at anytime:

- The ON state represents the case when the received signal is above the threshold level.
- The OFF state represents the case when the signal is below the threshold level.

The packet is assumed to be received correctly if the whole packet was contained in a nonfade interval. This implies that the packet has at least one detected error if it overlaps to any extent with a fade slot. The nonfade interval is exponentially distributed and the envelope of the fade interval is Rayleigh distributed.

The analysis of this model is given in [12] and some results are stated below without proof.

- 1) The expected value of the retransmitted packets per cycle:

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

Where $\alpha = \exp(T/T_2)$ and the channel parameters T_1 , T_2 and T_3 are the average values of the fade, nonfade, and interfade intervals respectively.

- 2) The packet delay per message due to channel error:

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

- 3) The packet error rate, given by the probability that a packet transmitted over the channel will have at least one detected error is:

$$P_B = 1 - \exp [(-\rho + f_d \sqrt{2\pi\rho} T)]$$

- 4) 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:

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

- 5) For outbound channels, the major cause for loss of packets is due to fading. The channel throughput (S) defined as the average number of packets generated per transmission time, that is, the input rate normalized with respect to T is given by:

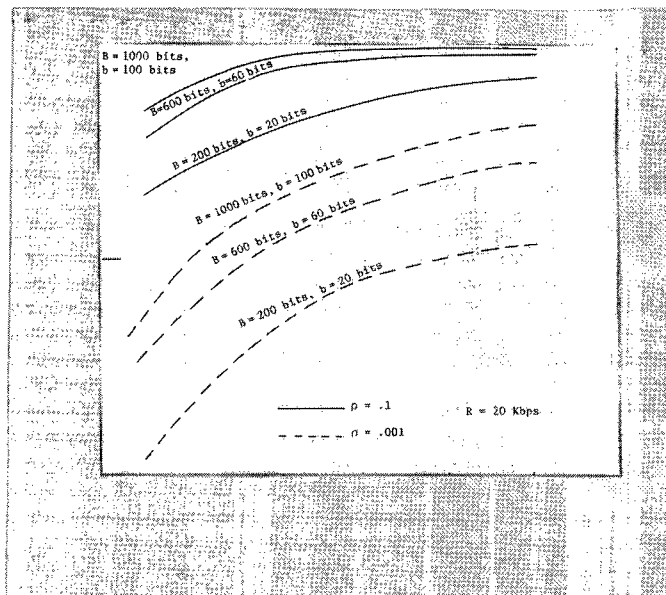
$$S = \left(\frac{N-\eta}{T_c} \right) T$$

To study the behavior of the performance parameters for this protocol, we chose a carrier frequency of 850 MHz. Figures 1-5 show the performance in terms of packet error rate, packet delay, throughput, and optimum number of packets transmitted per cycle that will minimize delay, as a function of packet size, packet transmission rate, signal-to-noise ratio, and vehicle speed. Notice that the performance degrades rapidly with vehicle speeds up to approximately 80 MPH. Above this speed, the degradation is slow for reasonably good SNR.

The expressions stated above assumed that only one terminal was using radio channel, and therefore the transmission error occurred due to packet loss by fading alone. For inbound channels, we need to take into account errors caused by the random access policy, as the loss of packets will occur due to collisions and fading.

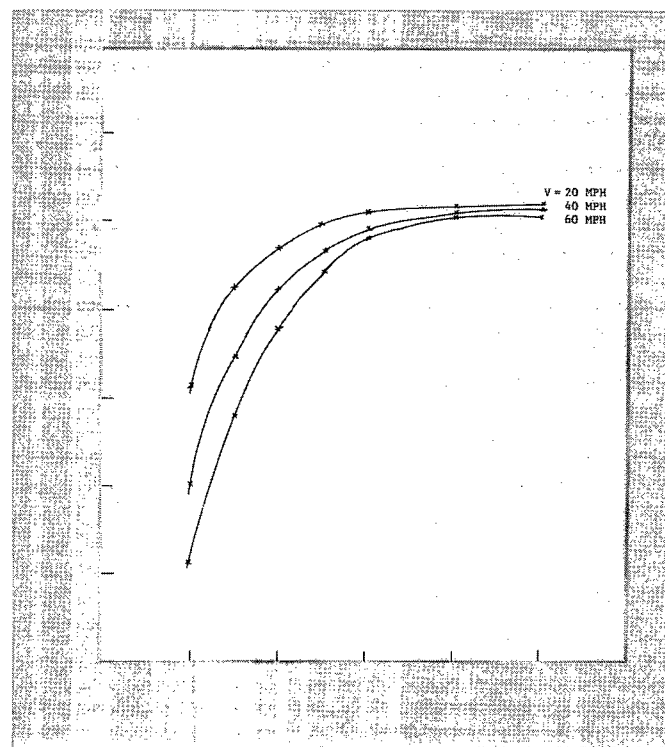
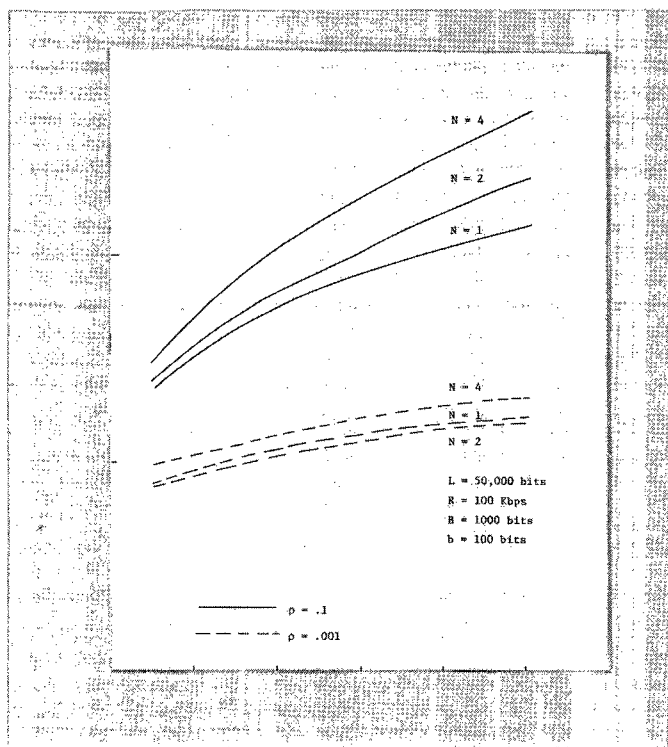
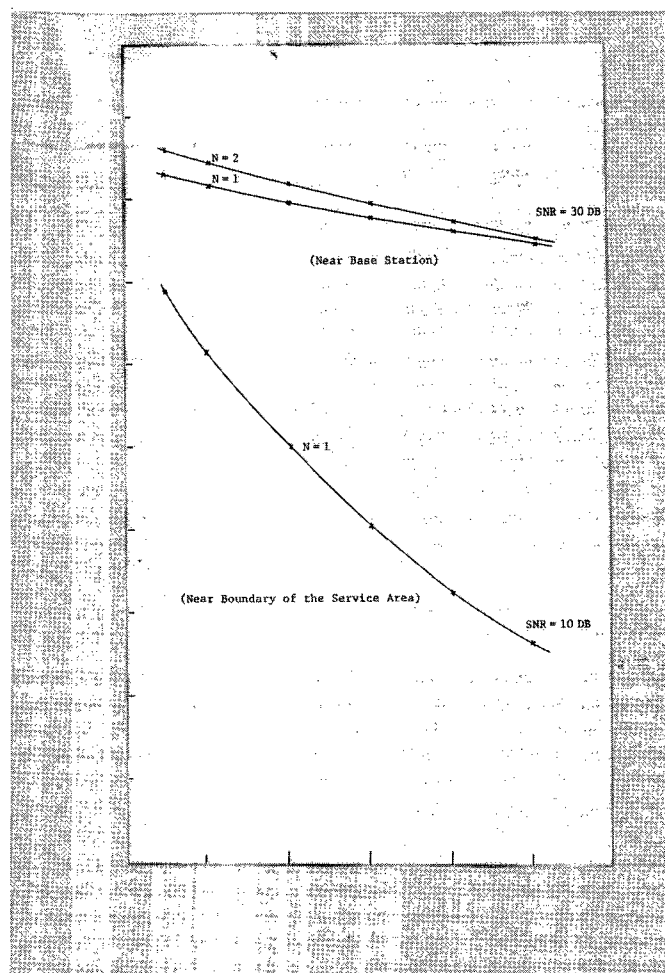
Carrier Sense Multiple Access for Mobile Packet Radio Channels

The classic derivation of the Carrier Sense Multiple Access (CSMA) channel throughput and delay performance [10] assumes that only user packet collisions over the single packet



radio channel result in the failure of an acknowledgment to be returned. Also, the channel for acknowledgment was assumed to be separate from the message channel and both were assumed perfect. However, for the mobile packet radio channel, we need to modify the fundamental throughput-delay analysis, as the assumptions of nonfading, noiseless channel is not applicable. On a fading channel in mobile packet radio, the signal-to-noise ratio becomes a critical parameter.

We consider blocked data transmission over random channels and derive CSMA channel throughput and delay as a function of the probability of a packet error. The probability of an acknowledgment error, assuming that the packet and acknowledgment channels are separate and independent, is shown in the network link model of Fig. 6. We assume that individual user transmissions are independent of one another



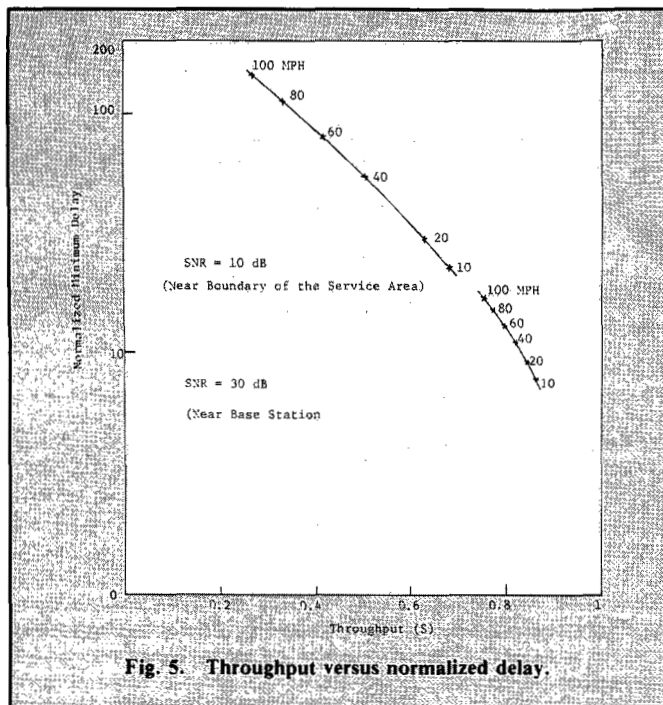


Fig. 5. Throughput versus normalized delay.

and that successive user packet transmissions are also independent.

The modified throughput and delay analysis to include the effects of a fading additive white Gaussian noise (AWGN) channel is given in [13] for the nonpersistent CSMA scheme. The analysis will be equally good for the other variations of the CSMA schemes. Furthermore, we assumed that the communication system employs a digital modulation/demodulation scheme that produces independent bit errors. The probability of block error is derived for the noncoherent modulation technique for both, the packet channel and the acknowledgment channel. The resulting expressions are stated below for the noncoherent frequency shift keying scheme without proof.

6) The channel throughput:

$$S = \frac{G \exp(-aG - \frac{22.5621}{\bar{\rho}})}{G(1+2a) + e^{-aG}}$$

7) The average packet delay:

$$D = R + 1 + (R + \frac{K+1}{2}) \left[\frac{G(1+2a) + e^{-aG}}{\exp(-aG - \frac{22.5621}{\bar{\rho}})} - 1 \right]$$

TABLE I
CAPACITY C FOR THE NONPERSISTENT CSMA PROTOCOL FOR
MOBILE PACKET RADIO CHANNEL ($\alpha = 0.01$)

Average SNR $\bar{\rho}$ (dB)	Offered Channel Traffic (G)	Channel Capacity (C)
10	9.4	0.085
15	9.4	0.399
20	9.4	0.650
25	9.4	0.759
30	9.4	0.797
35	9.4	0.809
40	9.4	0.813
45	9.4	0.814
50	9.4	0.815

where:

G = offered channel traffic
a = normalized propagation delay
 $\bar{\rho}$ = average signal-to-noise ratio

It is assumed that the two-way propagation delay equals R packet lengths, and that the packet retransmission times are selected from a uniform distribution of delays ranging from 1 to K packet lengths.

Table I shows the channel capacity (C) and the corresponding offered channel traffic rate (G) at different values of the average SNR ($\bar{\rho}$). It is interesting to note that at about 50 dB average SNR, the capacity of nonfading channel is achieved.

Figures 7 and 8 show the performance curves for the throughput (S) versus offered channel traffic (G), and average packet delay (D) versus throughput (S). These curves show strong dependence of the performance on the signal-to-noise ratio.

Carrier Sense Multiple Access with Collision Detection for Mobile Packet Radio Channels

The Carrier Sense Multiple Access (CSMA) is known to be highly efficient in environments with propagation delays, that are short compared to packet transmission time. It works very well as long as all the users contending for the channel have mutual RF connectivity, so they can sense each other's transmission. However, mutual RF connectivity cannot always be guaranteed and therefore, CSMA alone does not adequately reduce collisions. Therefore, these protocols were extended to environments in which the collision detection capability is available. In CSMA-CD protocols [14], in addition to sensing carrier, it is possible to detect interference among several

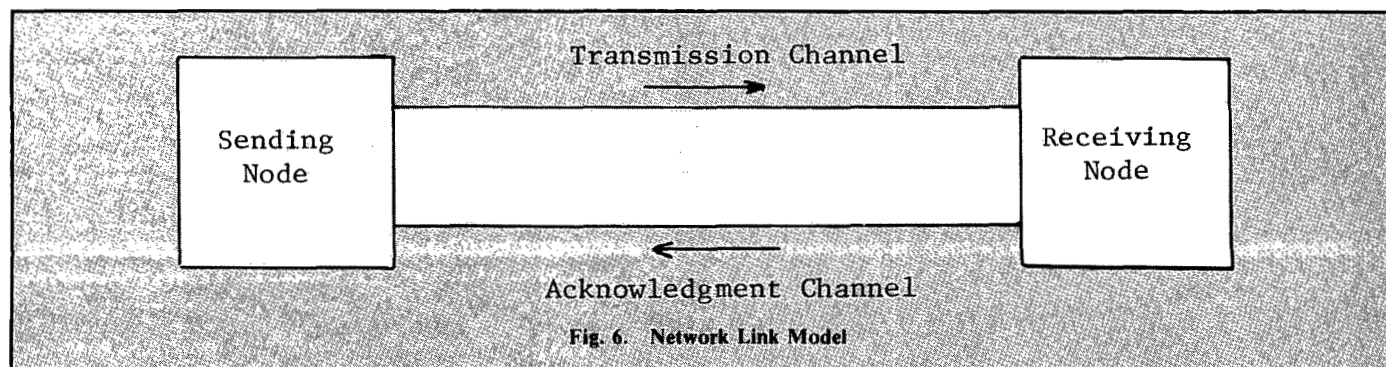
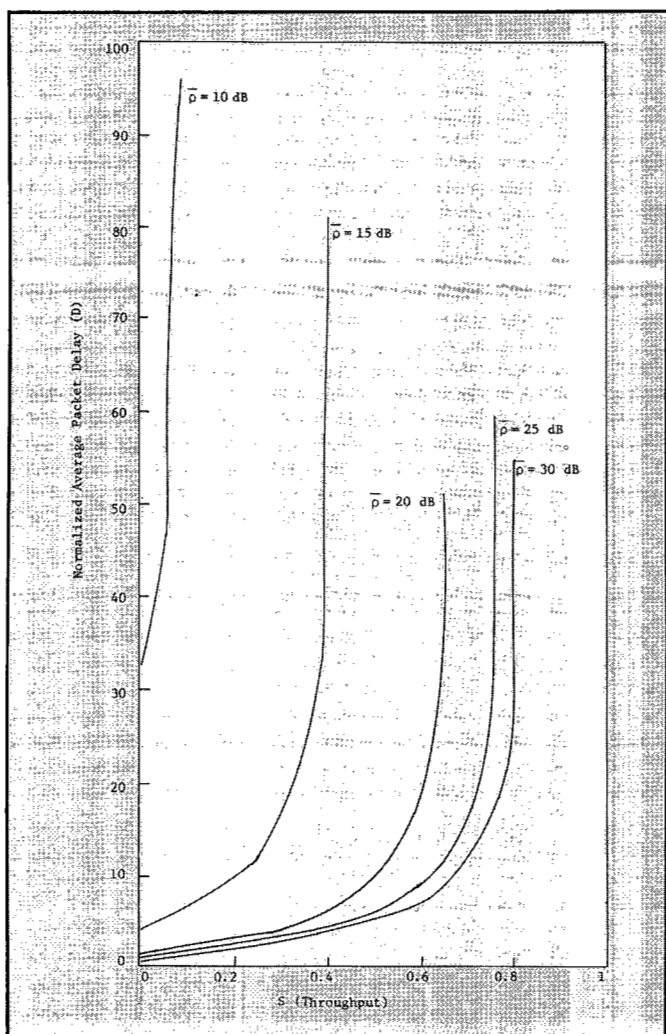
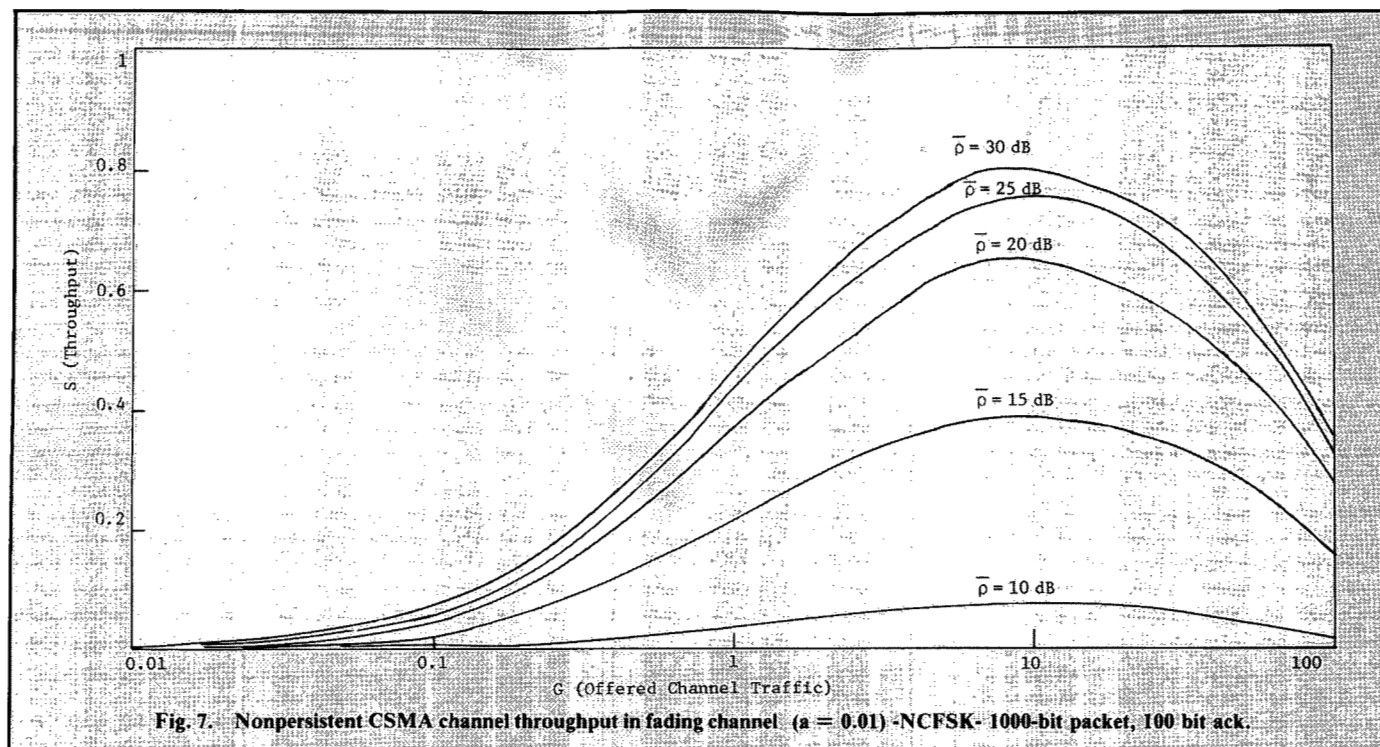


Fig. 6. Network Link Model

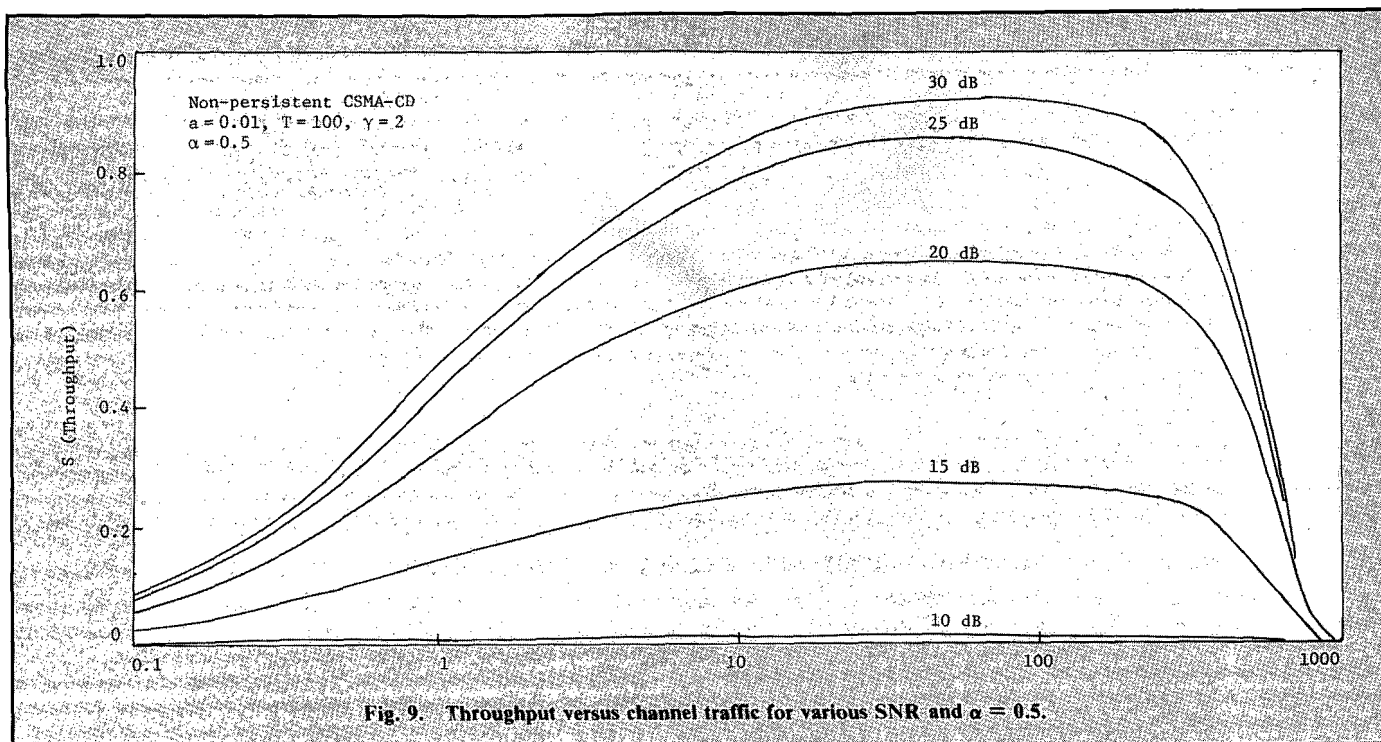


transmissions (including their own) and abort transmissions of their colliding packets. This protocol has been extensively studied for the Ethernet type networks and provides an improvement over CSMA, both in terms of channel capacity and throughput-delay performance.

To analyze the performance of CSMA-CD for mobile packet radio channels consider a spread spectrum scheme. The application of spread spectrum to packet radio system is motivated largely by the desire to achieve good performance in the fading multipath channels resulting from mobile users, antijamming capabilities in tactical applications, coexistence with other systems, security, and other network aspects. Spread Spectrum Multiple Access (SSMA) allows a packet to be captured at the receiver, while CSMA allows a user to capture the channel. Therefore, by using CSMA in conjunction with SSMA we achieve the benefit of keeping away all users within hearing distance of the transmitter and thus help keep the "capture effect" (defined as the ability of the receiver to "lock on" one packet while all other overlapping packets appear as noise), and antijamming capability of the system at the desired level. By accommodating the collision detection capability in the CSMA scheme and applying it to Frequency Hopping (FH)/Frequency Shift Keying (FSK) mobile packet radio, the overall improvement in performance is accomplished by exploiting the channel capturing capability of CSMA and packet capturing capability of the Spread Spectrum technique.

The assumptions and network link model used to analyze the CSMA scheme are reused for the analysis of FH/FSK CSMA-CD mobile packet radio channel. The nonpersistent CSMA-CD channel throughput is derived in [15] for FH/FSK scheme in the presence of partial-band noise interference. A partial-band interference channel [16] is characterized by AWGN over only a fraction of the potential transmission bandwidth, but with the same average noise density. If the total hopped bandwidth is W Hz, the bandwidth of the partial-band interference is αW Hz, where $0 \leq \alpha \leq 1$.

← Fig. 8. Average Packet Delay versus channel throughput, S in fading channel. ($\alpha = 0.01$) -NCFSK- 1000-bit packet, 100 bit ack.



8) The modified throughput expression is stated below (without proof):

$$S = \left(\frac{TaG}{TaGe^{-aG} + (1 - e^{-aG} - aGe^{-aG})\gamma + 1} \right) \exp\left(-aG - \frac{39.552}{\bar{\rho}}\right)$$

where:

T = transmission time (in slots) of a packet
 γ = Collision recovery time (the time until all users stop transmission given that a collision has occurred).

Figure 9 shows the (S, G) relationship for CSMA-CD in FH/FSK mobile packet radio. Improvement in channel capacity and stability is gained by CSMA-CD over the CSMA scheme. Notice that higher throughput can be obtained for larger values of SNR and at about 40 dB, the conventional

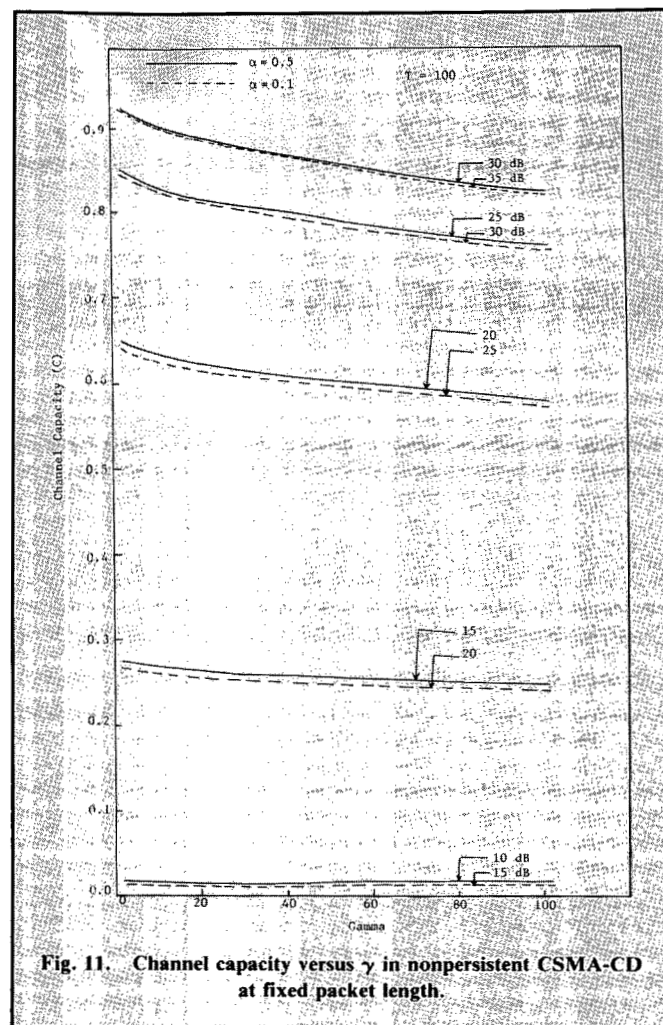
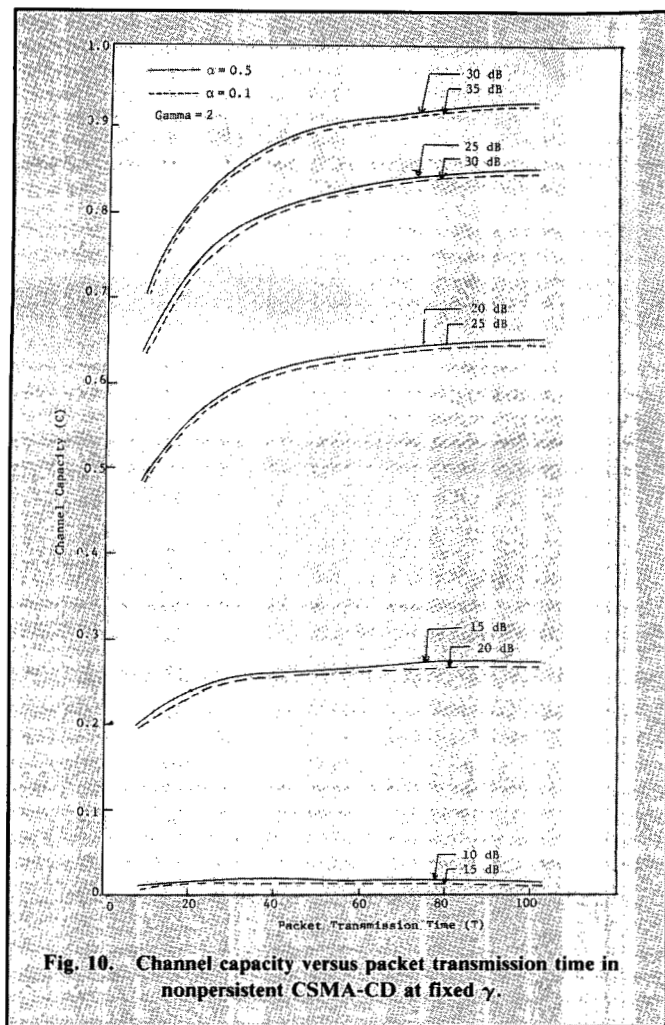
value of 0.96 is achieved (see Table II). Figures 10 and 11 show the sensitivity of the channel capacity improvement to the packet length T and the collision detect time γ respectively. Tables II and III summarize the channel capacity behavior for a fixed collision detect time, and for a fixed packet length respectively. It is noticed that throughput is sensitive to the SNR at the receiving node. The throughput degradation is severe at lower SNR values. To obtain a satisfactory performance of FH/FSK MPRNET and gain all the advantages of the nonpersistent CSMA-CD scheme, it is desirable to have a SNR of at least 30 dB or so.

Conclusions

The characterization of mobile radio channel and its impact on packet radio networks is well-established. The study of the analysis and performance evaluation of the protocols presented in this paper showed that signal-to-noise ratio, attenuation, and distance between the communicating nodes, all become critical

TABLE II
CHANNEL CAPACITY VARIATIONS WITH SNR AND PACKET LENGTH T FOR A FIXED γ

SNR $\bar{\rho}$ (dB)	Channel Capacity $\gamma = 2$											
	T = 10		T = 20		T = 40		T = 60		T = 80		T = 100	
	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$
10	.014	—	.016	—	.018	—	.018	—	.018	—	.018	—
15	.208	.011	.241	.012	.262	.013	.269	.014	.273	.014	.276	.014
20	.489	.191	.566	.221	.615	.240	.633	.247	.643	.251	.649	.253
25	.641	.476	.742	.551	.806	.599	.830	.617	.843	.626	.850	.632
30	.698	.635	.809	.736	.878	.800	.904	.823	.918	.836	.926	.843
35	.717	.696	.831	.806	.902	.876	.929	.902	.943	.915	.952	.924
40	.723	.716	.838	.830	.910	.902	.937	.928	.951	.942	.960	.951
45	.725	.723	.840	.838	.913	.910	.940	.937	.954	.951	.962	.960
50	.726	.725	.841	.840	.913	.913	.940	.940	.955	.954	.963	.962



parameters in determining the throughput-traffic or throughput-delay performance of MPRNET. Also, to achieve performance of a stationary PRNET, a SNR of about 40 dB is required, and at SNR of 10 dB, the performance falls below that obtained with the ALOHA schemes. The area of mobile packet radio networks is wide open and seems to hold a promising future. In particular, the analysis and performance study of distributed channel access protocols for a packet radio

network with mobile nodes poses one of the challenging problems to the researchers in the field. Let us hope to see an optimum and robust protocol scheme for mobile computer communication networks in the near future! The current developments in the areas of packet switching, mobile radio, and cellular technologies are sure to lead us to the entirely new field of packet switched cellular mobile computer networks in this decade!

TABLE III
CHANNEL CAPACITY VARIATIONS WITH SNR AND GAMMA FOR A FIXED PACKET LENGTH

SNR $\bar{\rho}$ (dB)	Channel Capacity (C) T = 100													
	$\gamma = 2$		$\gamma = 10$		$\gamma = 20$		$\gamma = 40$		$\gamma = 60$		$\gamma = 80$		$\gamma = 100$	
	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$	$\alpha = 0.5$	$\alpha = 0.1$
10	.018	—	.018	—	.018	—	.017	—	.017	—	.017	—	.016	—
15	.276	.014	.270	.014	.266	.014	.259	.013	.254	.013	.250	.013	.246	.013
20	.649	.253	.635	.248	.624	.244	.610	.238	.598	.234	.587	.229	.579	.226
25	.850	.632	.832	.618	.818	.608	.799	.594	.784	.582	.770	.572	.759	.564
30	.926	.843	.907	.825	.891	.811	.871	.793	.854	.778	.838	.763	.827	.753
35	.952	.924	.931	.904	.916	.889	.895	.868	.878	.852	.861	.836	.850	.825
40	.960	.951	.939	.931	.924	.915	.902	.894	.885	.877	.869	.861	.857	.849
45	.962	.960	.942	.939	.926	.924	.905	.902	.888	.885	.871	.868	.859	.857
50	.963	.962	.943	.942	.927	.926	.906	.905	.889	.887	.872	.871	.860	.859

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