PERFORMANCE EVALUATION OF PACKET RADIO SYSTEMS BY SIMULATION--A CASE STUDY●

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ABSTRACT

Packet-switching broadcast radio networks are receiving considerable attention as a feasible solution for applications involving fast network deployment requirements, inaccessible physical environments, and mobile communication devices. Such networks also offer economic alternatives to traditional multiplexing schemes for local distribution.

Since analytic performance evaluation of packet radio networks is intractable, a simulation program was developed which models quite accurately channel and device characteristics. In this paper, a variety of simulation studies which guided decision making during the research and development phase of a packet radio system are discussed. These studies addressed both hardware and software issues and resulted in the functional specification of the critical network components.

INTRODUCTION

The Packet Radio Network (PRNET) is a store-and-forward packet switching network in which communication devices are linked together by broadcast radio channels (see Figure 1). The main features which distinguish the PRNET from point-to-point packet-switching networks are:

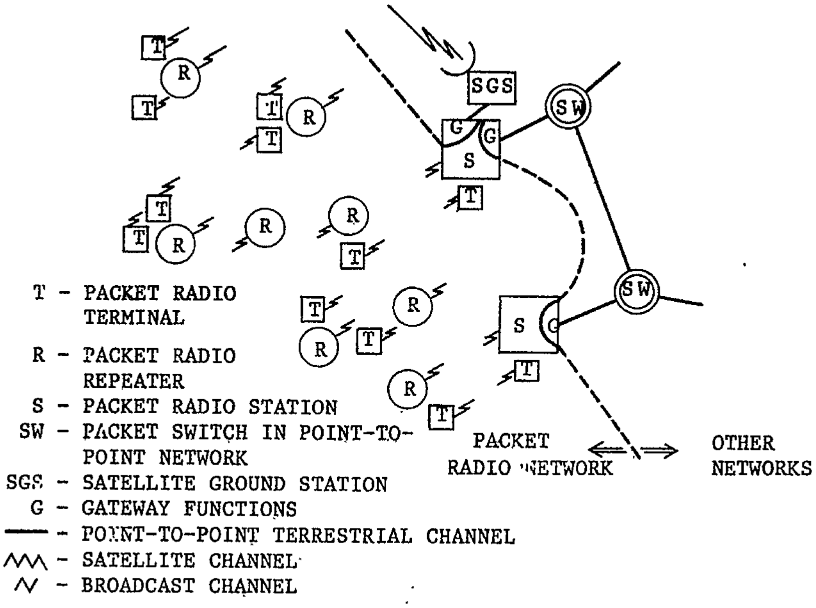
1. The communication channel is shared dynamically using a random transmission scheme, and
2. Devices use a broadcast mode of transmission so that packets can be transmitted to several devices simultaneously, and/or more than one packet can simultaneously arrive to a receiver because of several independent transmissions.

The hardware of the PRNET is based on the packet radio unit (PRU), which consists of a microprocessor with associated electronics and a radio transceiver [1]. The applications software consists of novel techniques for dynamic sharing of the communication channels, for efficient and reliable packet transportation, for network initialization and reconfiguration, and techniques for real time diagnosis and control of programs and parameters in the PRU's.

There are three basic functional components of the packet radio system: the packet radio terminal, the packet radio station, and the packet radio repeater. The terminal consists of a common type terminal or computer, interfacing to a PRU. The repeater is a stand alone PRU which operates as a relay switching node and provides radio connectivity to interconnect communication devices within the radio net and/or to connect to a gateway into another network. In applications in which terminals are mobile, the repeater is considered as an area coverage device [2]. The station consists of a minicomputer interfacing to a PRU. The station performs such functions as PRU initialization, connectivity monitoring, global stability control functions, accounting, buffering, and directory functions for radio communication devices. When the PRNET interfaces with other networks, the station performs the gateway functions [3].

Performance evaluation of packet radio networks by analysis is intractable. Analytical results of single-hop radio networks were reported in [5, 6, 7, 8, 9, 10] and of a two hop network in [11]. However, these analyses do not extend to multihop networks; furthermore, the assumptions used in the above models do not enable addressing "real" design alternatives as is done by simulation in this paper.

FIGURE 1



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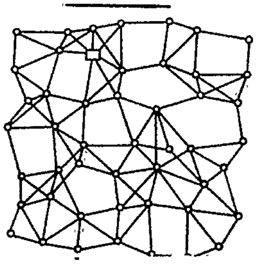
The objective of this paper is to evaluate specific hardware and software design alternatives for packet radio networks. The comparison is on the basis of relative performance; however, since the experimental packet radio network being developed by ARPA is quite accurately modeled by the program, it is anticipated that numerical values of performance will approximate those obtained by measurements.

A detailed description of the system simulated is given in [2]. The structure of the simulation program is presented in Section 2. The basic elements which define the systems studied in this paper are stated below:

- Common Channel Two Data Rates (CCTDR) or Common Channel Single Data Rate (CCSDR). In CCTDR a low data rate is used for communication between terminals and repeaters (or station), and a high data rate in the repeater - station network. A packet on the high data rate channel can interfere with one on the low data rate channel, and vice versa. In CCSDR a single data rate is used for communication between all devices.

- The topology consisted of 1 station and 48 repeaters. The connectivity of terminals, repeaters and stations are determined by parameters indicating the effective transmission range. The location of repeaters and stations and the radio connectivities used in the studies are shown in Figures 2 and 3. Terminals are introduced at random times and are placed in random locations in the plane "covered" by repeaters and stations. The rate at which terminals are introduced and the amount of communication depend on the traffic offered to the system and are controlled by parameters.

FIGURE 2



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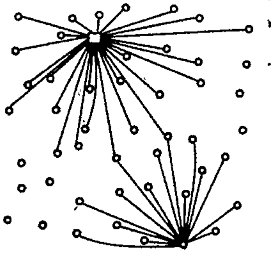


- The routing used in the studies is hierarchical with restricted alternate routing; the alternate routing enables only forward transmission of a packet, bypassing only one failed or busy repeater, before returning to the established path [4]. The radio links assigned for routing form a tree structure. Figures 4 and 5 show the structure of the networks studied.

- The channel access scheme is non-persistent, non-slotted, carrier sense [8]. Propagation time is simulated as a function of distances between devices.

- Other parameters used in these experiments are: A maximum of 3 end-to-end transmissions and a timeout of 60 slots (packet transmission time on low data rate) between end-to-end transmissions.

The following are the performance measures used for system evaluation and comparison:

- Ratio of system throughput to system input rate. The throughput is the rate of end-to-end acknowledged information packets.

- Percentage of total loss. The loss includes packets of terminals which are blocked (terminals which did not identify a repeater or station after exhausting the number of transmissions upon entering the system and packets which are not delivered to the destination after the maximum number of end-to-end transmissions.

- Delays. The round trip delay averaged over all packets, independent of the number of hops from the station was used.

- Average buffer occupancy in the entire repeater network.

The time scale used is the transmission time of an information packet on the low data rate channel, or a slot. If it is assumed that the size of an information packet is 2,000 bits and the low data rate channel is 100 Kbps, a slot time would be 20 msec. The size of short packets (ETE ACK, and other control packets) used in the simulation is 10% of an information packet. Similarly, the traffic rates are in percentages of the low data rate channel; thus, a throughput of 30% means a throughput of 30 Kpbs of bits in information packets.

Before specific problems are introduced, it is noted that lack of space will prevent showing all the output curves of simulation runs in support of conclusions. Figures 6 and 7 are shown as sample outputs. The figures show the average offered traffic rate to the system, the average measured input rate, the throughput and the total number of occupied buffers in the system as a function of time. When the offered rate is larger than the input rate, the difference indicates the blocking in the system. The difference between the input rate and the throughput shows the loss. These figures are also used to determine whether the system is stable and can operate at steady state for the given offered rate - as in Figure 7, or whether the system is saturated -as in Figure 6. When the system is overloaded, the throughput steadily decreases as a function of time and the buffers never empty (Figure 6).

FIGURE 4

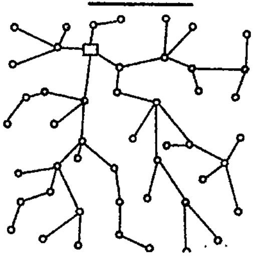
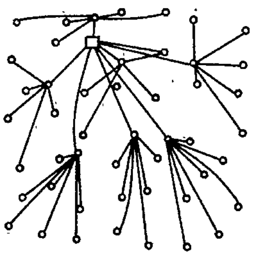


FIGURE 5



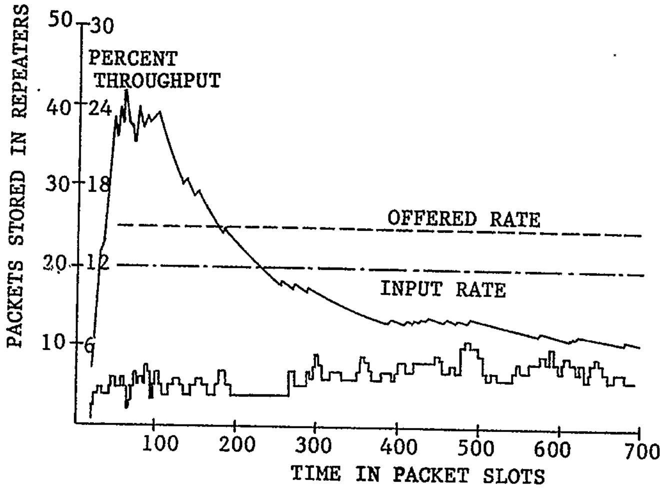


FIGURE 6

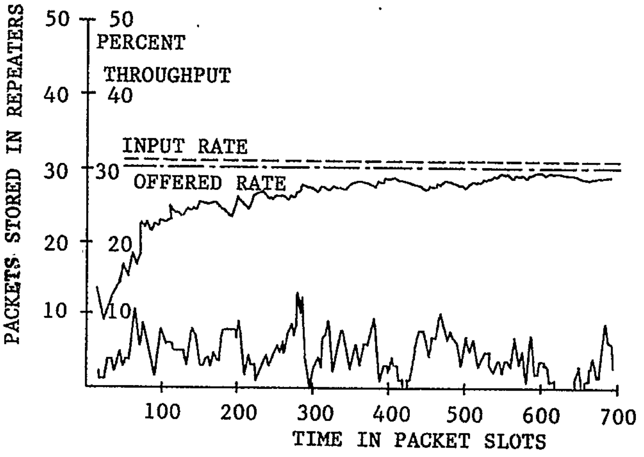


FIGURE 7

GENERAL STRUCTURE OF SIMULATOR

A separation between data structure and management functions on the one hand, and communication and device functions on the other hand characterizes the structure of the simulator. There are several advantages in doing so: First, one communication device does not have access to information available in other devices, and secondly, it is easier to identify and distinguish the communications part of the program for the purpose of modification or software transfer. We have developed efficient data structures which can be used for simulation programs of communication systems.

There is one main subroutine for each type of communication device. For example, one subroutine for all switching nodes of the same type. The differences between the devices (e.g., switching nodes) is recorded in a state vector associated with each device. The state vector includes information such as, the switching nodes to which this device is connected, the state of occupancy of storage buffers, the routing algorithm that this node is using, and others. In addition, there are buffers associated with each device in which the content of specific packets (e.g., packet type, priority) are stored.

There are distinguishable functions which are used by all devices (e.g., the PRU); these functions are coded in separate subroutines.

The global information for the Packet Radio Simulation Program is contained in five (5) data structures:

1. Event Structure,
2. Active Message Structure,
3. Active Packet Structure,
4. Repeater-Station Structure, and
5. Data Collection Tables.

Event Structure: The simulation program is event-driven. That is, periodically the Event Structure is consulted to determine the time of occurrence of the next event. The Event Structure also contains information telling the program what the event is. Examples of events are arrivals of messages to terminals, transmission of packets, arrival of packets at receivers, and arrival of messages to the stations. As events are executed, they are deleted from the structure, and periodically, newly-generated events are added to the structure. Since there are a large number of events, many more than the number of exogenous message arrivals, for example, the process of efficiently determining the next event is of vital importance. To this end, the event times are maintained in a "heap." Corresponding to each event "i" is its time "t_i", the device subroutine "d_i" to which it refers (e.g., station, terminal, repeater), the index "w_i" of the device in question, a number representing the point at which the routine is entered, and, finally, the packet number of the packet in question. In addition, there is the heap index vector itself. "j_j" points to the event which occupies the j^{th} position in the heap. A heap is a structure in which $t_{h_j} \leq \text{Max}\left\{t_{h_{2j}}, t_{h_{2j+1}}\right\}$. At all times t_{h_1} is the smallest t_i over all the events. This structure allows for quite rapid selection of the minimum t_i while using a minimal amount of storage, [14, 15, 16]. In order to efficiently eliminate old events and to reuse the space created by the elimination, a garbage stack of unused locations is maintained.

Active Messages Structure: The external or exogoneous traffic consists of terminals and message arrivals. Messages are to be dinstinguished from packets. In general, there may be several packets in the network carrying segments of a message or copies of segments. Messages are added to the Active Message Structure when the event corresponding to their generation occurs. It stays on the list until the last packet associated with the message is dealt with. Associated with each message "i" is its arrival time "t_i"; its length "l_i;" "x_i" and "y_i," the coordinates of the terminal and other pieces of data. In order to elimiate old messages and add new ones efficiently, the messages are kept in a doubly-linked list structure. A list is kept for messages and one for unused message spaces.

Active Packet Structure: The active packets are kept in a list. Associated with the i^{th} packet is a pointer to its corresponding message and several words for use by the routing and packet processing algorithms. A garbage stack similar to the one used for events keep track of vacant spaces in the Packet Structure.

Repeater-Station Structure: The Repeater-Station Structure is basically a list of the repeaters and stations, their locations, their possible neighbors (repeaters and stations within range of their transmitters and receivers), and their state. Associated with the i^{th} station or repeater is a state vector which, among others, specifies items such as whether the repeater or station is busy, free, turned off, or failed.

Data Collection Tables: Sufficient statistics for the evaluation of the system performance measures are kept in the data collection tables.

An Outline of the Use of Data Structures

The global simulation structure is based on events of packets arriving at devices: stations, terminals, and repeaters. Figure 8 schematically illustrates the program flow. It is quite simplified, one simplification being especially important and needing emphasis. The events of retransmissions and acknowledgments resulting from a packet's arriving at a repeater, station, or terminal are not necessarily generated immediately, but may depend on the arrival of packets at the device subsequent to the packet which gives rise to the new events.

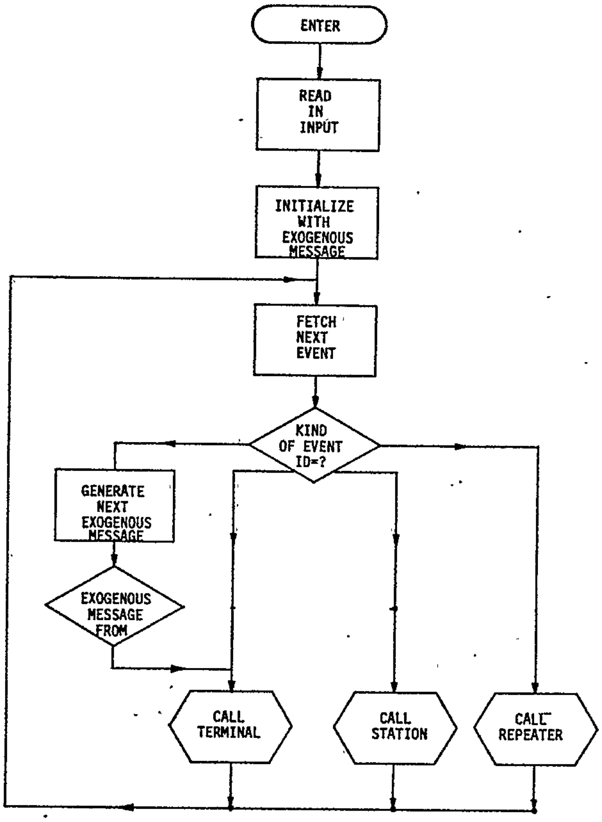


FIGURE 8

TRANSMISSION RANGE VS. NETWORK INTERFERENCE

A variety of situations are possible concerning the range and interference patterns of devices. For example with identical RF elements and similar antenna placements, Repeater to Repeater range is the same as Terminal to Repeater range. This need not always be the case since repeaters can often have higher antennas than terminals, (especially hand held terminals). Thus, if repeaters are allocated for area coverage of terminals, the repeater range will be higher than terminal range and higher network connectivity (and device interference) will result.

The problem which then arises is to determine the impact of this interference on system performance. Alternatively, one may seek to reduce repeater transmission power when transmitting in the repeater-station network. As an indication of the tradeoffs that occur, two systems with common channels and single date rates (CCSDR) were simulated, one with high interference CCSDR (HI), and the other with low interference CCSDR (LI). As a first step, the routing labels of the two systems were the same and are shown in Figure 4. The interference (for two devices) of the CCSDR (HI) systems is shown in Figure 3. A different label assignment for the high interference system is shown in Figure 5. These labels correspond to minimum number of hops from each repeater to the station, taking advantage of larger effective transmission range.

The results are shown in Figure 9 and Table 1. Figure 9 shows the throughput of the two systems as a function of time while Table 1 summarized other measures of performance. The third row of Table 1 summarizes performance of the high interference system under the improved set of repeater labels. It is clear that the high interference system has better performance than the low interference systems. The only better performance measure of the low interference system is terminal blocking which is a direct result of the low interference feature. In fact, CCSDR (LI) is saturated at the offered traffic rate. This can be seen from the fact that the throughput is decreasing as a function of time. The CCSDR (HI) with improved labels (Figure 5) compared in Table 1, has better performance than the other two systems. This indicates the importance of proper link assignment for routing - or labelling. The experiments of this section suggest that it is preferable to use high transmitter power to obtain long repeater range, despite the network interference that it results in.

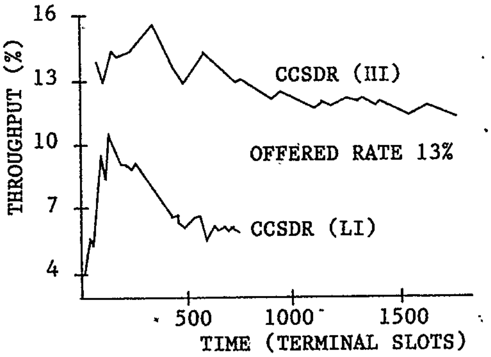


FIGURE 9

SINGLE VS. DUAL DATA RATE SYSTEMS

To prevent developing different hardware (r.f. and digital) for repeaters, terminals and stations, a basic design decision for the experimental system was adopted, to use the same hardware, called a Packet Radio Unit (PRU) for all three devices. However, in many applications the antennas of repeaters and stations can be placed in elevated areas, and therefore, the quality of the transmission links between devices within this category can be superior to the quality of the links between terminals and repeaters or terminals and stations. Consequently, an important problem is to determine whether repeaters and stations should use this extra capability to achieve longer range or higher data rates.

This section discusses some of the studies performed to investigate this tradeoff. The results indicate that a dual data rate approach can significantly improve system performance. Thus, the Packet Radio Unit has been implemented with this feature.

The systems studied were:

- The CCSDR (HI) system of the previous section with improved labels to take advantage of high range to improve the routing labels of repeaters and obtain fewer hierarchy levels which we denote by CCSDR. The routing labels used are shown in Figure 5 and the connectivity is shown in Figure 3.
- A CCTDR system with the routing labels as in Figure 4 and connectivity as in Figure 2. The ratio of data rates was 5 to 1.

In the CCTDR system, the terminal has a low data rate channel, the same rate as in the single data rate system, for communication with a repeater or station. Repeaters and station have two data rates. The high data rate is used for communication in the repeater-station network. The two data rates use the same carrier frequency so that only one can be used at a time.

The two systems were tested with offered rates of 13% and 25%. The throughputs as a function of time for the two runs are shown in Figures 10 and 11, respectively, and the summary of other measures is given in Table 2. The comparison demonstrates that the CCTRD system is superior to the CCSDR system, in terms of throughput, delay, and other measures. One can see that the CCSDR system is saturated at an offered rate of 25%.

Effect on Blocking Level: In Table 2, one can see that one reason for the relatively low throughput of the CCSDR system at an offered rate of 25%, is due to blocking. Furthermore, the fraction of time that the station is busy has decreased. This may suggest that the station may be able to handle more terminals providing they are able to enter the system. To examine this point, we ran the CCSDR system with offered rate of 25 percent, and relaxed the constraint for entering the system. This can be done, for example, by increasing the number of terminal transmissions for identifying a relay repeater. When we enabled more terminals to enter the system, the throughput increased insignificantly (by 3%) and the average packet delay increased significantly (by 89%). These experiments also suggest that one of the important design problems in the packet radio systems is the blocking level of terminals.

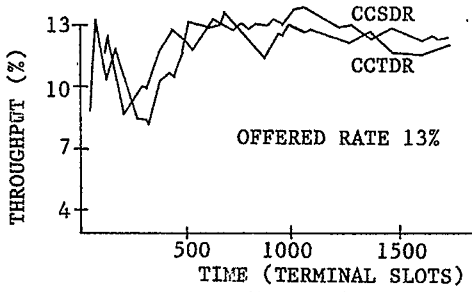


FIGURE 10

MAXIMUM NUMBER OF TRANSMISSIONS FOR REPEATERS AND STATIONS

In this section we report on a study for evaluating network performance as a function of the amount of resources assigned to a packet. A packet which traverses the network to its destination utilizes a certain amount of networks resources: channel storage, and processing. The parameters which control the amount of resources that a packet utilizes are the degree of alternate routing (number of hops relative to shortest path), the maximum number of packet transmissions before it is discarded, and the time interval between transmissions (storage). With hierarchical routing [4], the number of hops on the alternate path is the same as on the shortest or assigned path; hence, one of the major parameters that controls the channel and processing resources is the Maximum Number of Transmissions (MNT) per hop that a device uses before discarding the packet, in the absense of a hop acknowledgment. The appropriate value of these parameters are investigated in this section. It is of interest to note that an end-to-end time out and retransmission protocol is used in the packet radio network. Hence, it is not justifiable to enable a packet to remain indefinitely in the network, since a copy of same will be introduced by the source. Limiting the amount of resources to a packet is significant in radio networks due to the limited storage capabilities of repeaters and the broadcast nature of transmission.

The CCTDR system was used in the study with a 4 to 1 ratio of data rates (e.g., 100 and 400 Kbps which is implemented in the experimental packet radio system), a zero capture receiver (see next section), and a header checksum.

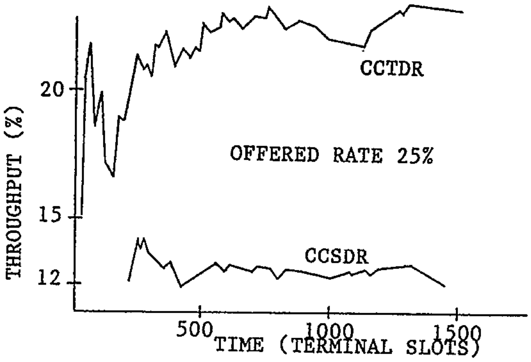


FIGURE 11

In the study, all system parameters were kept constant and the performance was studied as a function of MNT. The values of MNT used were: 3, 6, 9, 15, ∞ , and a variable number which was a function of the number of hops from the station. For the variable MNT, the formula used was: 10 - (Hierarchy Level). Thus, the station used an MNT of 9, repeaters one hop away from the station used the value of 8, etc. The reason for this variable MNT assignment are theoretical results showing that the average number of transmissions before success increases with the traffic level; and previous simulation results and anlysis which demonstrated that the traffic bottleneck is near the station and that the traffic level decreases with the distance (in hops) from the station. The value of infinity (∞) was used as a reference value because it simulates the case in which packets are not discarded until successfully forwarded.

For each value of MNT, the system was run with two values of offered rate: 15% and 30%. The number of terminals simulated for the various tests ranged from 50 to 100. The average number of hops of the terminals from the station (measured) was 4 to 4.5.

Table 3 summarizes the performance of all the simulation runs. One can see that all the systems, apart from that with MNT = ∞, perform well when the offered rate is 15%. The unsatisfactory performance of the system with MNT = ∞ can also be seen in Figure 6, where the throughput and buffer occupancy are shown as a function of time. Although one can observe the same qualitative differences, for the 15% offered rate as the ones for 30% offered rates, the absolute differences in performance seem to be too small to justify conclusions. Hence, the runs with 30% offered rate are used for comparison.

Figure 12 compares the various systems in terms of performance measures defined as a function of MNT. The comparison of the system for all values of MNT demonstrates that the variable MNT scheme shows much better performance in all measures used. There is a large difference in performance between the variable MNT and any of the fixed MNT cases. For example, the average round-trip delay for the variable MNT case is 17.04 slots; on the other hand, it is 34.12, 33.8, 39.0, 34.12 and 29.75, for MNT = 3, 6, 9, 15 and ∞, respectively.

The comparison of systems with MNT of 3 or 6 against systems with MNT of 9 or 15, shows that the former perform better. The only measure in which the system with MNT of 15 is better than that with MNT of 3 is the average round trip packet delay per hop (8.12 vs. 8.66); however, this is obtained for a lower throughput (22.91% vs. 27.75%, respectively). In all other measures drawn in Figure 12, the performance of MNT of 3 or 6 is better than that of MNT 9 or 15.

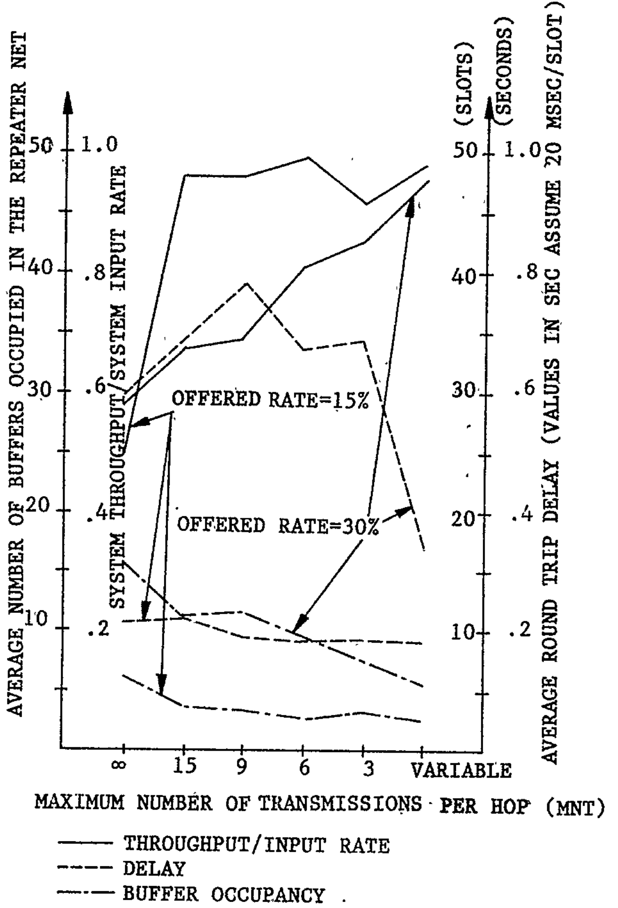
In comparing MNT of 3 and 6, neither case is uniformly better than the other. The system with MNT of 3 shows better performance in the ratio of throughput to input rate; whereas that with MNT of 6 shows better performance in delay.

The best performance obtained in this series of experiments with the variable MNT is 29.12% throughput at the relatively low average round trip delay of 17.04 slots (approximately 340 milliseconds at 100 kilobits per second and 2,000 bit packets). Other performance measures such as the total loss and the buffer occupancy are also very good, this can be seen in Table 3 and Figure 7. This implies that the capacity of a single station packet radio network can be increased above 30% when protocols are improved and the delay requirements are relaxed.

PERFORMANCE OF PACKET RADIO SYSTEMS WITH ZERO CAPTURE AND PERFECT CAPTURE RECEIVERS

This section reports on a simulation study for comparing the performance of the packet radio system with zero capture and perfect capture receivers. In the model of the zero capture receiver, it is assumed that if two or more packets overlap in time then all of the packets are received with error. For the perfect capture receiver model, it is assumed that the first packet detected by the device will be received correctly. That is, if several packets overlap in time, it is assumed that all the packets are received with error, apart from the first packet. It is recognized that the perfect capture model is not totally realistic (e.g., the power of the signals of overlapping packets is not taken into account). However, it is suggested that the qualitative performance of an improved time capture receiver will be similar to what has been observed for the perfect

FIGURE 12



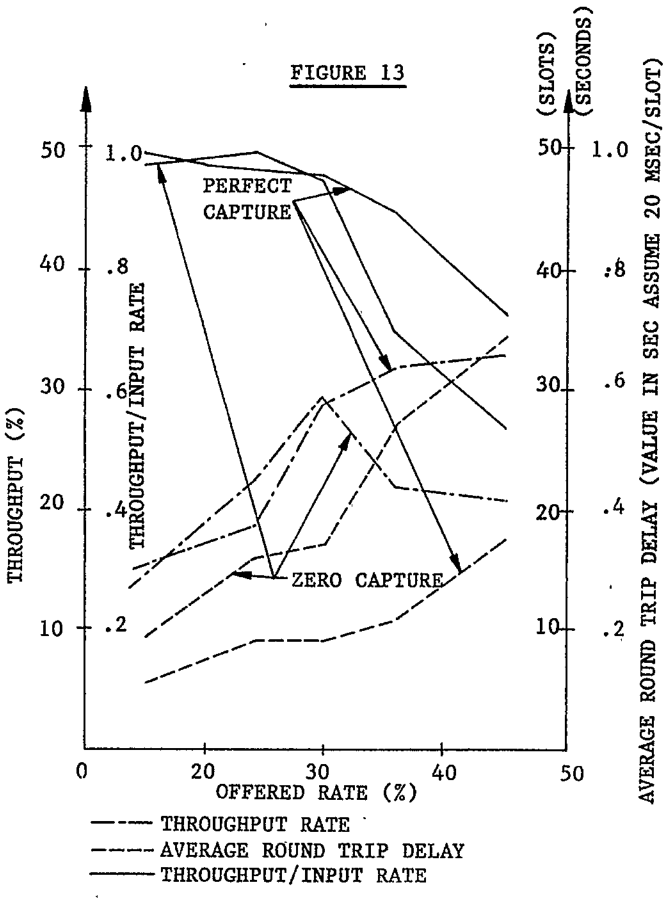
capture model, and the quantitative results may be considered as an upper bound on the improvements in performance that one may expect. The original packet radio receiver was designed to provide time capture; this, however, has not yet fully been realized in the experimental system. One incentive to continue research for improving reception properties is a quantitative demonstration of system performance improvement.

The system parameters, apart from the capture, were kept constant throughout the study. It is a CCTDR system with a header checksum, the variable MNT of the previous section, and a data rate ratio of 4 to 1.

The receiver of all devices— station, repeaters, and terminals—was assumed to be the same; namely, either zero or perfect. The zero and perfect capture systems were compared for the following offered rates: 15%, 24%, 30%, 36% and 45%. The number of terminals simulated for the various tests ranged from 40 to 100, and the number of end-to-end acknowledged information packets ranged from 90 to 300. The average number of hops of the terminals from the station (measured) was 3.9 to 4.5.

Table 4 summarizes the performance of the simulation runs used for comparison of the systems. Figure 13 compares the systems in terms of throughput, throughput to input rate ratio, and round trip delay as a function of the offered rate.

FIGURE 13



Observing the throughput curves, one can see two distinct regions. When the offered rate is less than approximately 30%, the two systems perform well, and each is capable of delivering the offered traffic rate. For example, when the offered rate was 30%, the zero capture system delivered 29.12%, and the perfect capture system delivered 28.48%. Considering the same offered rate interval for the delay curves shows that the performance of the perfect capture system is significantly better than that of the zero capture system. For the offered rate of 30%, the average round trip delay was 17.04 for the zero capture system versus 8.02 for the perfect capture system.

When the offered rate is greater than 30%, one can see (Figure 13) that the throughput of the zero capture system decreases, whereas that of the perfect capture system increases (although at a lower rate). Hence, the performance of the system with perfect capture receivers is superior to that with zero capture receivers both in throughput and delay for "high" offered rates. The difference in delays between the two systems increases as a function of the offered rate. The ratio of throughput to input rate as a function of the offered rate is also shown in Figure 13. This measure can be used to demonstrate the rate of performance degradation. It can be seen that the perfect capture system degrades "gracefully" whereas in the zero capture system there is a relatively fast degradation above the offered rate at which its maximum throughput is obtained. This essentially implies that a system with zero capture receivers must have more sophisticated stability control procedures and that it should be designed to operate below its maximum throughput.

As a final comparison note, the self regulation of the input rate is considered. From Table 4, one can see that when the offered rate is above 30%, the difference between the offered rate and the input rate for the zero capture system increases, whereas for the perfect capture system there is no significant trend. This seems to indicate that the zero capture system has an inherent control over the input rate and would tend to block terminals when the system is locally overloaded.

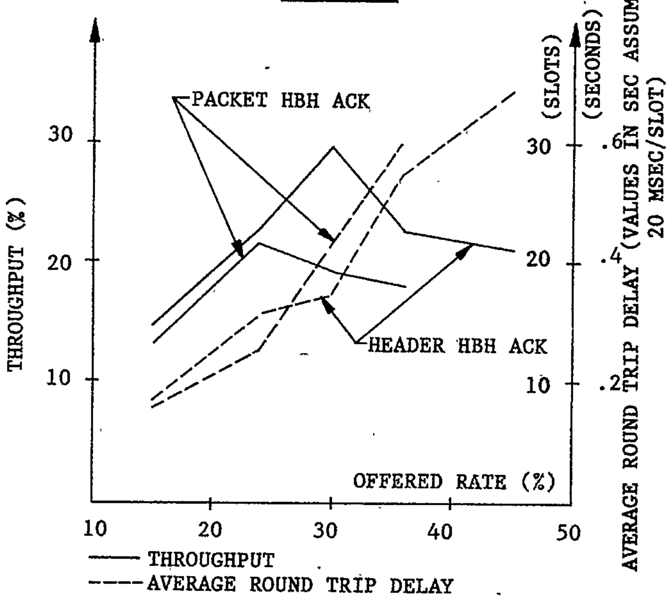
COMPARISON OF PACKET RADIO SYSTEMS WITH HOP-BY-HOP ACK'S BASED ON HEADER AND PACKET CHECKSUMS

The modelling by simulation of the two alternative schemes for Hop-by-Hop Acknowledgments (HBH Acks) concerns the time at which the receiving device (station, repeater, terminal) examines the Header content, and hence decides whether a HBH Ack has been received. A packet format with two separate checksums, one for the header and one for the entire packet, was stipulated in the early stages of the packet radio project. This was in part to conform with a similar implementation done in the ALOHA System [5]. The ALOHA System is a single hop system and the objective of the header checksum was to enable the identification of the terminal which sent a packet in case the complete packet was received in error. In the packet radio system, the header checksum is utilized for a different purpose, namely to determine the HBH Ack. In the Packet Radio Network, there is no need to generate or transmit Acks by intermediate nodes and the HBH Ack is obtained with minimum overhead. The Repeaters share a single radio channel and use omni-directional antennas. When a Repeater, K hops away from the destination, transmits a packet to a Repeater (K-1) hops from the destination, it times out to enable the latter to transmit the packet to a Repeater (K-2) hops from the destination. When the transmission (of the same packet) from the latter is received by the Repeater K hops away from the destination, it is considered an HBH Ack to the packet stored.

Apart from the checksum the systems were identical as defined, namely CCTDR with zero capture receivers and the variable MNT scheme. The systems were compared for offered rates of 15%, 24%, 30% and 36%. Table 5 summarizes the performance measures for the two systems, and Figures 14 and 15 compare the systems in terms of throughput, delay, throughput to input rate ratio, and buffer occupancy, all as a function of the offered rate.

It is evident from the figures, as anticipated, that the system with the header checksum performs better than without it. The difference in performance, however, is larger than we have anticipated. From Figure 14, one can see that the capacity (maximum throughput) of the system without a header checksum is approximately 22% whereas that of the system with a header checksum is approximately 30%. The difference in the average round trip delay is less significant. However, one should note that the delays are for different values of throughput.

FIGURE 14

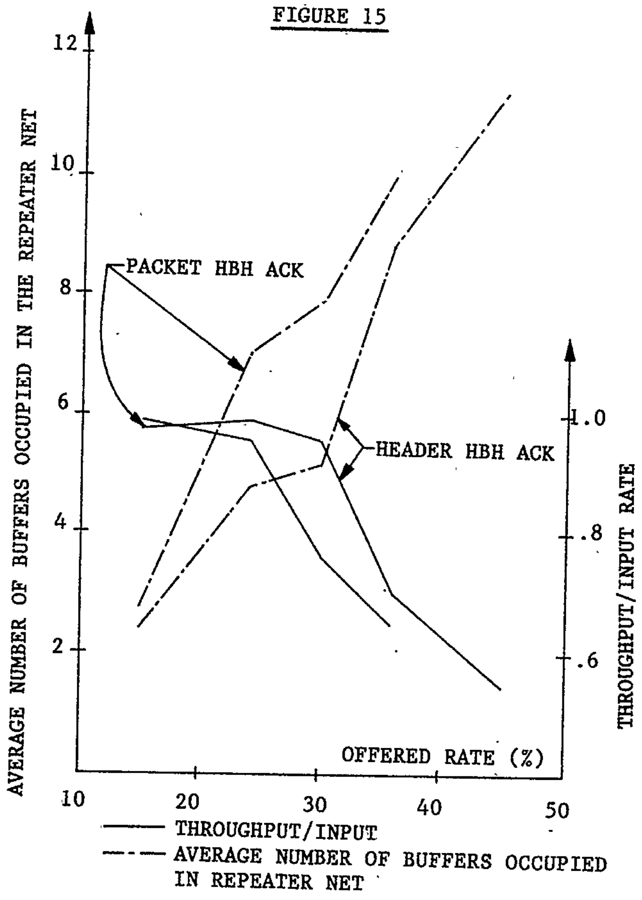


It is important to note that the improvement is gained only for packets which include text. Hence the difference in performance depends on two parameters: the relative header size in an average packet and the fraction of packets which contain text. In the simulation program there are two packet sizes; a short packet which includes a header only, and a long packet of which the header is 10% of the packet size. The fraction of header size packets in the packet radio system is not yet known. It would depend on the end-to-end protocol and upon the initialization and control schemes which will be implemented.

PERFORMANCE OF PACKET RADIO SYSTEMS AS A FUNCTION OF DATA RATES

One of the major issues in the development of the packet radio system involves the determination of the data rates for the low and high data rate channels. Theoretical considerations suggest that the rate of improvement in system performance (e.g., maximum throughput) should decrease as a function of the high data rate, given that the low data rate is kept constant. For example, when the high data rate is increased beyond a certain value, it is anticipated that the system bottleneck will become the low data rate channel. Hence, additional increase in the high data rate may not be economically justifiable. Furthermore, the performance of the carrier-sense multiple access schemes [8] are sensitive to the ratio of the propagation time between devices to the packet transmission time. Thus, assuming a fixed topology, an increase in the data rate results in an increase in the above ratio which tends to reduce the efficiency of the channel. This parameter will be reflected in the simulation, which simulates physical propagation times between devices as a function of distance.

FIGURE 15



In this section we study experimentally (by simulation) the performance of the packet radio system as a function of the ratio of the high data rate to the low data rate channels. It is the CCTDR system with zero capture receivers, a variable MNT scheme and a HBH Ack based on the checksum at the end of the packet.

Four different systems defined by the ratios of 2 to 1, 4 to 1, 8 to 1 and 12 to 1, were considered. The systems were tested for offered rates ranging from 15% to 60%. The significant performance measures of throughput, average round trip delay, and average buffer occupancy, for all the runs are summarized in Table 6. Figures 16 to 18 compare the performance of the systems in terms of the above measures and the ratio of throughput to input rate, all as a function of the offered rate.

FIGURE 16

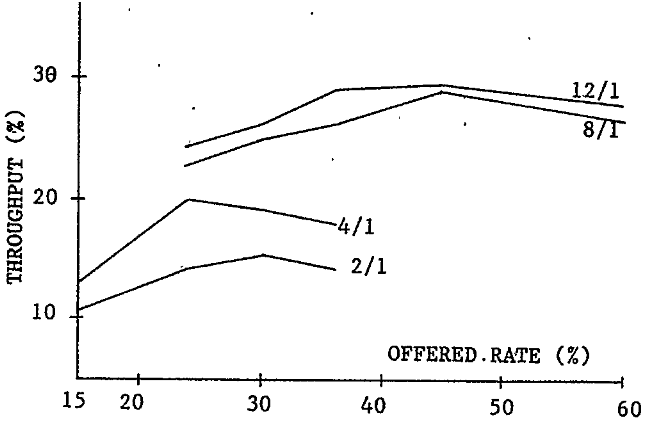


FIGURE 17

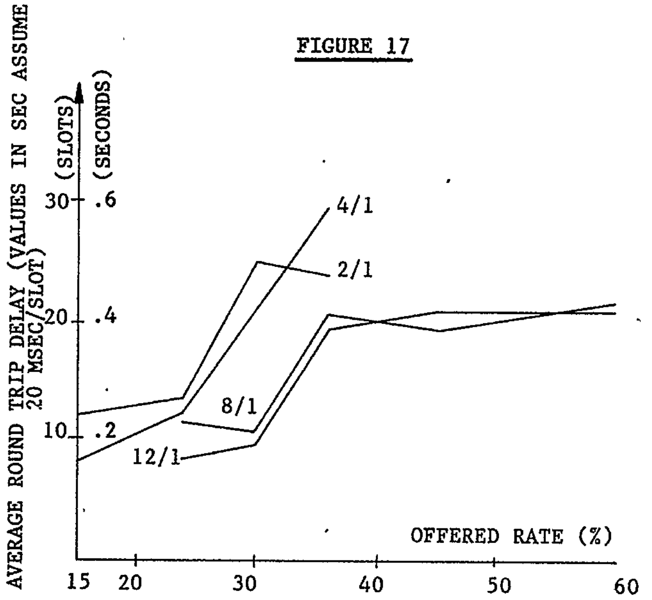
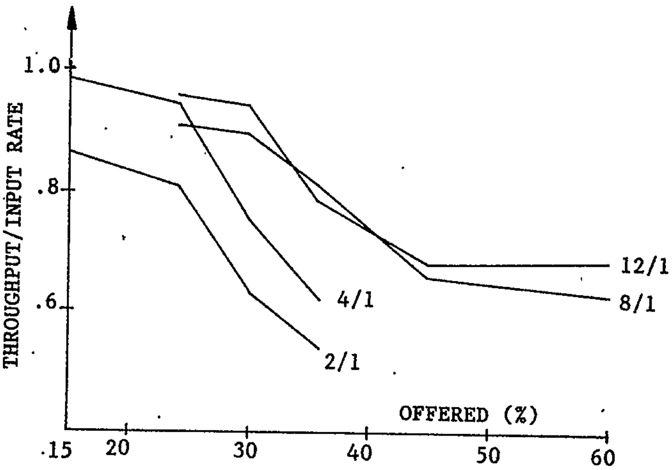


FIGURE 18



Apart from the buffer occupancy which does not show a definite trend to justify conclusions, all other measures of performance clearly demonstrate the following. An increase in the ratio from 2/1 to 4/1 significantly improves system performance. Similarly, an increase of the ratio from 4/1 to 8/1 also demonstrates a significant improvement in performance. On the other hand the performance of the system with the ratio 12/1 is almost the same as that with the ratio 8/1; hence, no significant improvement is observed in this range. For example, for an offered rate of 30%, the measured throughputs are 15.69%, 18.86%, 25.15% and 26.29%, for the systems with ratios 2/1, 4/1, 8/1 and 12/1, respectively.

Assuming that the low data rate channel is 100 KB/s, this study deomonstrates that the best choice for the high data rate channel will be between 400 Kb/s and 800 Kb/s. No significant gain is obtained when the data rate is increased beyond 800 Kb/s as is clearly demonstrated in Figures 16 through 18.

CONCLUSIONS

Several specific packet radio design alternatives were studied using a simulation approach. The alternative packet radio systems which result for a given design problem were compared on the basis of relative performance. The major conclusions of the study were:

1. A system with a large transmission range is preferable to a small transmission range, despite the interference that it results.
2. Using a higher data rate for repeater to repeater (station) communication than for terminal to repeater communication is preferable to using the same rate.
3. The maximum number of packet transmissions, MNT, before discarding the packet should be software modifiable. A variable MNT as a function of the hierarchy level demonstrated the best

performance. When a fixed MNT is used, a small value of MNT between 3 and 6 is preferable to large values.

4. A perfect capture receiver significantly improves system performance in two aspects. It increases the system capacity (maximum throughput) for a given value of delay, and it results in a system which is less sensitive to overload fluctuations by demonstrating gradual ("graceful") degradation as compared to the system with zero capture receivers.

5. A system which uses a header checksum, utilized for HBH Ack, performs better than one which uses only a checksum at the end of the packet. The difference in performance depends upon the relative header and packet sizes as well as the fraction of short (header size) packets in the network.

6. For a given 100 Kb/s low data rate channel, it is demonstrated that the "optimum" value for the high data rate channel will be between 400 Kb/s and 800 Kb/s. No significant gain in system performance is obtained when the high data rate channel is increased beyond 800 Kb/s.

It is noted that all the studies of the paper were done for a single station packet radio network. It is not anticipated that any of the conclusions of the studies presented will change for multistation packet radio systems. However, it is noted that other design issues which are specific to multistation networks need to be studies.

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TABLE 1: SUMMARY OF PERFORMANCE MEASURES FOR THE STUDY OF TRANSMISSION RANGE VS. NETWORK INTERFERENCE

	Offered Rate [%]	Through-put [%]	Delay of IP* to Station (Terminal Slots)	% of IP* Blocked	Total % of IP* Loss
CCSDR (LI)	13	5.95	40.11	2.98	32.83
CCSDR (HI)	13	10.55	23.93	9.83	9.83
CCSDR (HI) (Improved Labels)	13	12.14	16.61	10.63	11.41

TABLE 2: SUMMARY OF PERFORMANCE MEASURES FOR THE STUDY OF SINGLE VS. DUAL CHANNEL DATA RATES

	Offered Rate[%]	Through-put [%]	Delay of IP* to Station (Terminal Slots)	Prob Station Busy	% of IP* Blocked	Total % of IP* Loss
CCSDR	13	12.14	16.61	.50	10.63	11.41
	25	12.20	34.97	.48	29.50	32.95
CCTDR	13	12.39	4.91	.26	1.59	1.59
	25	23.33	11.51	.31	3.31	3.31

TABLE 3: SUMMARY OF PERFORMANCE MEASURES FOR THE MAXIMUM NUMBER OF TRANSMISSIONS STUDY

Maximum Number of Transmissions [MNT]	Input Rate [%]	Throughput [%]	Total Loss [%]	Round Trip Delay Average [Slots]	Round Trip Delay Average/Hop [Slots]	Average Buffer Occupancy [Packets]
3	15.83	14.32	0	8.86	2.06	3.20
6	13.59	13.41	0	8.81	2.17	2.57
9	18.75	18.04	0	9.50	2.16	3.41
15	16.83	16.18	10.89	11.13	2.65	3.80
Variable MNT	15.17	14.75	0	8.18	1.98	2.40
∞	12.24	6.34	27.87	10.83	2.55	6.59
3	32.83	27.75	6.34	34.12	8.66	7.34
6	27.34	21.79	12.24	33.38	7.15	9.40
9	30.37	30.85	16.49	39.00	9.22	11.65
15	34.03	22.91	14.18	34.12	8.12	11.08
Variable MNT	30.96	29.12	2.40	17.04	3.93	5.16
∞	23.00	12.98	6.58	29.75	7.07	15.45

* Information Packet

TABLE 4: SUMMARY OF PERFORMANCE MEASURES FOR THE STUDY COMPARING ZERO VS. PERFECT CAPTURE RECEIVERS

	Offered Rate [%]	Input Rate [%]	Throughput [%]	Total Loss [%]	Round Trip Delay Average [Slots]	Round Trip Delay Average/Hop [Slots]	Average Buffe Occupancy [Packets]
Zero Capture	15	15.17	14.75	0	8.18	1.98	2.40
	24	22.97	22.46	.33	15.21	3.47	4.63
	30	30.96	29.12	2.40	17.04	3.93	5.16
	36	32.31	22.37	18.81	26.80	6.52	8.75
	45	38.92	21.05	16.98	33.96	7.63	11.50
Perfect Capture	15	15.70	15.44	0	6.15	1.50	2.95
	24	19.68	18.80	0	8.13	2.07	3.42
	30	30.07	28.48	2.22	8.02	1.88	4.82
	36	35.26	31.66	7.87	10.52	2.59	6.74
	45	45.18	32.66	1.65	17.84	4.15	10.56

TABLE 5: SUMMARY OF PERFORMANCE MEASURES FOR THE STUDY OF HEADER AND PACKET CHECKSUM VS. PACKET CHECKSUM ONLY

	Offered Rate [%]	Input Rate [%]	Throughput [%]	Total Loss [%]	Round Trip Delay Average [Slots]	Round Trip Delay Average/Hop [Slots]	Average Buffer Occupancy [Packets]
HBH ACK Based on Header Checksum	15	15.17	14.75	0	8.18	1.98	2.40
	24	22.97	22.46	.33	15.21	3.47	4.63
	30	30.96	29.12	2.40	17.04	3.93	5.16
	36	32.31	22.37	18.81	26.80	6.52	8.75
	45	38.92	21.05	16.98	33.96	7.63	11.50
HBH ACK Based on Packet Checksum	15	13.32	13.09	0	7.91	1.92	2.75
	24	21.06	19.97	0	12.49	2.96	6.89
	30	24.99	18.86	0	21.37	5.51	7.77
	36	28.23	17.91	4.00	29.76	7.10	10.02

TABLE 6: SUMMARY OF PERFORMANCE MEASURES FOR THE STUDY OF RATIO OF CHANNEL DATA RATES

Offered Rate [%]	Throughput [%] Ratio of Data Rates				Average Round Trip Delay [Slots] Ratio of Data Rates				Average Buffer Occupancy [Packets] Ratio of Data Rates			
	2/1	4/1	8/1	12/1	2/1	4/1	8/1	12/1	2/1	4/1	8/1	12/1
15	10.15	13.09			12.03	7.91			5.18	2.75		
24	14.65	19.97	22.86	24.19	13.69	12.49	11.94	8.68	6.13	6.89	5.84	4.56
30	15.69	18.86	25.15	26.29	24.99	21.37	10.39	9.77	8.24	7.77	6.55	5.10
36	13.96	17.91	26.44	28.22	23.85	29.76	21.12	19.63	7.70	10.02	7.86	9.83
45			28.70	29.31			19.68	21.28			10.00	9.60
60			26.58	28.11			22.21	21.56			9.15	9.60