Packet switching with satellites*

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INTRODUCTION

History

The first computer-communication networks put into operation were designed around the communications provided by the existing worldwide telephone network. Lucky has given a convincing rationale for that decision.[1]

> "The voice telephone network is perhaps the most remarkable information processing system yet constructed by man. In 1970 it served 100,000,000 telephones in the United States. The number of possible interconnections is clearly enormous. The worth of this plant is approximately 50 billion dollars. Over one million people are employed by AT&T alone in the care and feeding of this huge network. Virtually every statistic associated with the telephone network can be phrased in some extraordinary manner. Its ready accessibility and virtual ubiquity make it the obvious first contender for handling data traffic."

As the limitations of this system for data communications became apparent, a number of methods were introduced to overcome the limitations of dial-up telephone and leased line systems. Data concentrators are used to increase the utilization of expensive long distance lines. High speed, wideband facilities are used to handle those situations where the burst data rate requirement of the network is larger than can be transmitted in a single voice channel. A few large systems use leased line data channels in a network with multiple paths between nodes for increased reliability. All of the systems built before 1970 however based the organization of their data communication channels on the circuit switching methods developed for voice signals during the latter part of the 19th century.

As the need for more powerful and more flexible computer-communication networks, distributed over large geographical areas, increased the basic limitations imposed by the organization of circuit switched systems was questioned.[2,3,4] By 1970 the ARPA Network,[5] the first computer-communication system to employ packet switching techniques suited to the peculiar statistics of digital data had gone into operation. The network is described in Reference 6:

> "The ARPA Network is a new kind of digital communication system employing wideband leased lines and message switching, wherein a path is not established in advance and instead each message carries an address. Messages normally traverse several nodes in going from source to destination, and the network is a store-and-forward system wherein, at each node, a copy of the message is stored until it is safely received at the following node. At each node a small processor (an *Interface Message Processor*, or *IMP*) acts as a nodal switching unit and also interconnects the research computer centers, or *Hosts*, with the high bandwidth leased lines."

By January 1973 the use of packet switching techniques in the ARPA Network had made possible a resource sharing computer network among more than 30 large machines; these machines represent an investment of more than $80,000,000, span a geographical region from Hawaii to Massachusetts and the network is still expanding at a rapid rate. At this time packet switched techniques are under consideration for other computer-communication networks in the USA, Canada, Japan and Western Europe.[7,8] But no common carrier has yet announced plans for a packet switched data service for the general user of data communications.

Although the basic packet switched method of organizing communication channels in the ARPA Network represents a significant step forward from the circuit switched methods of the voice oriented common carriers the communications medium of the ARPA Network (with the exception of a special satellite link to the University of Hawaii) is still the point-to-point wire (or microwave) channel.

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The medium is the multiplexor

In June 1971 the first remote terminal in THE ALOHA SYSTEM, an experimental UHF radio, packet switched network was put into operation at the University of Hawaii.[9] THE ALOHA SYSTEM is a packet switched computer communication network using many of the design concepts of the ARPA Network. The design of THE ALOHA SYSTEM departs from that of the ARPA Network in two major respects however. The first is in the use of a new form of burst random access method of employing a data communication channel. That method is particularly attractive for use with a broadcast radio channel such as in THE ALOHA SYSTEM; the characteristics of the ALOHA burst random access communication method are described in the next section.

The other respect in which the design of THE ALOHA SYSTEM departs from that of the ARPA Network, and indeed from the design of all other computer networks, is in the form of multiplexing which occurs in THE ALOHA SYSTEM. The network uses two 24,000 bits/second channels for all remote units—one of these channels is used by all remote units for data into a central machine (an IBM 360/65) and the other channel is used for data out of the central machine. Since data packets from all remote users access the same 24,000 bits/second radio channel in 30 millisecond bursts, each user automatically multiplexes their data onto that single channel at the time it transmits its packet. Thus the multiplexing is accomplished between the transmitting antenna at each user station and the receiving antenna at the central station. Steven Crocker of ARPA has characterized this effect by noting that in THE ALOHA SYSTEM, "the medium is the multiplexor".

A final point should be brought out about the lack of need for multiplexing equipment in THE ALOHA SYSTEM. The cost of communications for a network of terminals connected to a central time sharing system is often thought of as being composed of the line charges (lease cost or dial-up charges), the modem charges at either end of the link plus perhaps some portion of the cost of the communications processor. For long distance connections to a machine the line charges will usually dominate the cost of communications. Even for local connections however the real costs of simply connecting a terminal to a machine by common carrier communication facilities are hard to come by. A good portion of these costs can often be attributed to the front end communications processor and multiplexor. The need to sample telephone input lines on a frequent basis and to assemble characters, limits the number of input lines which can be handled by a single processor and the data rates at which these lines can operate. Some indication of the magnitude of the cost of performing these functions can be obtained from a survey of national time sharing services published in November, 1971.[10] The typical charge for connect time to one of these services (that is, the cost necessary for simply tying up communications resources, not CPU time) was about $10/hour.

Since multiplexing in THE ALOHA SYSTEM is accomplished automatically the channel now used in the system is capable of handling over 500 active terminals[9] each transmitting packets at a *burst* data rate of 24,000 bits/second. (Of course the *average* data rate of each user must be well below 24,000 bits/second.)

The ALOHA channel

Consider a number of widely separated users each wanting to transmit data packets over a single high speed communication channel. Assume that the rate at which the users generate packets is such that the average time between packets from a single user is much greater than the time needed to transmit a single packet. (In THE ALOHA SYSTEM the ratio of these times is about 2,000 to 1.)

Conventional time or frequency multiplexing methods or some kind of polling scheme could be employed to share the channel among the users. Some of the disadvantages of these methods are discussed by Roberts in a related paper in this session.[14] The method used by THE ALOHA SYSTEM is suggested by the statistical characteristics of the packets generated by remote users. Since each user will generate packets infrequently[11] and each packet can be transmitted in a time interval much less than the average time between packets the following scheme seems natural.

Each user station has a buffer which it uses to store one line of text. When the line is complete a header containing address, control and parity information for a cyclic error detecting code is appended to the text to form a packet and the packet is transmitted to the central station. Each user at a console transmits packets to the central station over the same high data rate channel in a completely unsynchronized (from one user to another) manner. If and only if a packet is received without error it is acknowledged by the central station. After transmitting a packet the transmitting station waits a given amount of time for an acknowledgment; if none is received the packet is automatically retransmitted. This process is repeated until a successful transmission and acknowledgment occurs or until some fixed number of unsuccessful transmissions has been attempted.

A transmitted packet can be received incorrectly because of two different types of errors; (1) random noise errors and (2) errors caused by interference with a packet transmitted by another console. The first type of error has not been a serious problem on the UHF channels employed. The second type of error, that caused by interference, will be of importance only when a large number of users are trying to use the channel at the same time. Interference errors will limit the number of users and the amount of data which can be transmitted over this ALOHA random access channel as more remote stations are added to THE ALOHA SYSTEM.

Capacity of ALOHA channels

In order to describe these limits we assume that the start times of message packets in our channel comprise a Poisson point process with parameter λ packets/second. If each packet lasts τ seconds we can define $S=\lambda\tau$, where

$$S = \text{normalized channel message rate} \qquad (1)$$

S is called the normalized channel message rate since a value of S equal to one would correspond to a channel with packets synchronized perfectly so that the start of one packet always coincided with the end of the previous packet. (Of course this will not occur because of our Poisson assumption.) Note that S takes into account only message packets, not retransmission packets.

In addition we assume that the start times of the message packets plus packet retransmissions comprise another Poisson point process. (This assumption will hold only if the packet retransmission delays are large. See Reference 9.) Then we can define a quantity G, analogous to the normalized channel message rate, which takes into account the message packets plus the retransmission packets.

$$G = \text{normalized channel traffic rate} \tag{2}$$

In general we know that

$$G \geq S \tag{3}$$

In Reference 9 we showed that

$$S = Ge^{-2G} \tag{4}$$

and this relationship is plotted in Figure 1.

Note from Figure 1 that the message rate reaches a maximum value of $1/2e = 0.184$. For this value of S the channel traffic is equal to 0.5. The traffic on the channel becomes unstable at $S = 1/2e$ and the average number of retransmissions becomes unbounded. Thus we may speak of this value of the message rate as the *capacity* of this random access data channel. Because of the random access feature the channel capacity is reduced to roughly one sixth of its value if we were able to fill the channel with a continuous stream of uninterrupted data.

The form of channel analyzed above corresponds to THE ALOHA SYSTEM channel now in operation.

It is possible to modify the completely unsynchronized use of the ALOHA channel described in order to increase the capacity of the channel. In the pure ALOHA channel each user simply transmits a packet when ready without any attempt to coordinate his transmission with those of other users. While this strategy has a certain elegance it does lead to somewhat inefficient channel utilization. If we can establish a time base and require each user to start his packets only at certain fixed instants it is possible to increase the channel capacity. In this kind of channel, called a *slotted ALOHA channel*, a central clock establishes a time base for a sequence of "slots" of the same duration as a packet transmission. Then when a user has a packet to transmit he synchronizes the start of his transmission to the start of a slot. In this fashion, if two messages conflict they will overlap completely, rather than partially.

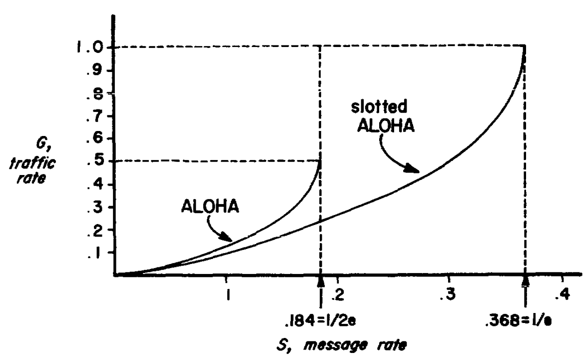

Figure 1—Traffic rate vs. message rate for a pure ALOHA channel and a slotted ALOHA channel

To analyze the slotted ALOHA channel define S_i as the probability that the i'th user will send a packet in some slot. Assume that each user operates independently of all other users and that whether a user sends a message in a given slot does not depend upon the state of any previous slot. If we have n users we can define $S = \sum_{i=1}^{n} S_i$, where

$$S = \text{normalized channel message rate} \tag{5}$$

As before we can also consider the rate at which a user sends message packets plus packet retransmissions. Define the probability that the i'th user will send a message packet or a packet retransmission as G_i. Then, for n identical users we define $G = \sum_{i=1}^{n} G_i$ where

$$G = \text{normalized channel traffic rate} \tag{6}$$

and, as in the pure ALOHA channel

$$G \geq S \tag{7}$$

We note here that although S, the sum of the S_i, is the probability that some user will send a message packet in a given slot, the analogous statement is not true for G. The sum of the G_i is not the probability that some user will send a message or repetition packet in a given slot. In fact even though G is the sum of the probabilities G_i, G is not itself a probability and G may be greater than 1.

For the slotted ALOHA channel with n independent users, the probability that a packet from the i'th user will not experience an interference from one of the other users is

$$\prod_{j=1, j\neq i}^{n} (1 - G_j)$$

Therefore we may write the following relationship between the message rate and the traffic rate of the i'th user.

$$S_i = G_i \prod_{j=1, j\neq i}^{n} (1 - G_j) \tag{8}$$

If all users are identical we have

$$S_i = \frac{S}{n} \tag{9}$$

and

$$G_i = \frac{G}{n} \tag{10}$$

so that (8) can be written

$$S = G\left(1 - \frac{G}{n}\right)^{n-1} \tag{11}$$

and in the limit as $n \rightarrow \infty$, we have

$$S = Ge^{-G} \tag{12}$$

Equation (12) is plotted in Figure 1 (curve labeled Slotted ALOHA). Note that the message rate of the Slotted ALOHA channel reaches a maximum value of $1/e = 0.37$, twice the capacity of the pure ALOHA channel.

This result for Slotted ALOHA channels was first derived by Roberts[12] using a different method.

PROPERTIES OF SATELLITE CHANNELS

The cable in the sky

In the worldwide telephone system satellites are used more or less interchangeably with cables for transmission of voice signals. Because of this desirable feature, it is not surprising that the common carriers and even satellite designers have tended not to emphasize the differences between cable and satellite channels.

A communications satellite however is not just a big cable in the sky. There are several significant differences between the communication channel properties of a cable or microwave link and the communication channel properties of a satellite transponder.

In the next three sections we shall explain some of these differences and how they can affect the operation of a packet switched system using a satellite. But first we should mention one property of a satellite channel which the common carriers have emphasized. A satellite transponder in geosynchronous orbit is stationed 36,000 kilometers above the equator. A signal transmitted using the satellite will therefore experience a delay of about a quarter second, corresponding to the round trip propagation time up to the satellite and down again. This delay can decrease the effective data rate of certain error control schemes requiring positive acknowledgments sent from the receiver back to the transmitter. Such schemes should not ordinarily be used over satellite channels.

There are three properties of communication satellites which we want to discuss here, in terms of their significance to packet switched communications. These are:

(a) data rates
(b) bilateral broadcasting
(c) perfect information feedback

Data rates

The first property of satellite channels is not a fundamental property of the satellite itself, but rather a property of how the satellite is used. A single voice channel on INTELSAT IV uses a bandwidth of 45 Khz. and provides the capability of transmitting data at 56 kilobits on a single voice channel. This mode of operation is in fact employed in the SPADE demand assignment system now used in the Atlantic satellite; it is employed in the single-channel-per-carrier digital voice link installed in the Paumalu earth station in Hawaii and the Jamesburg earth station in California. Since December 1972, THE ALOHA SYSTEM has been linked to the ARPANET using a single leased satellite voice channel to transmit data at 50 kilobits to NASA Ames Research Center in California.

Bilateral broadcasting

In the conventional use of communication channels the term "broadcasting" refers to the fact that many receivers may obtain the transmission from a single transmitter. Perhaps the most striking feature of a satellite channel is its broadcast nature as opposed to the point-to-point nature of wire channels. The reception of broadcast signals for satellite communication channels used with conventional circuit switched methods is a natural idea. But when a satellite channel is used in a packet switched mode it is possible to consider broadcasting use of the channel by transmitters as well as receivers. This capability we have called *bilateral broadcasting*.

Since a number of transmitting ground stations operating in a packet switched mode may all access the same channel in an unsynchronized (from ground station to ground station) fashion the analysis of an earlier section applies to bilateral broadcasting without any change. Each of the twenty or more ground stations accessing a given INTELSAT IV channel can transmit packets at will up to the ALOHA random access capacity of that single channel.

There is no technological reason why such a system could not be employed now to extend the capabilities of the existing worldwide satellite communication network in data communications. There is an existing regulatory restriction on such an unconventional use of INTELSAT IV however and discussions are under way with several agencies to remove these regulatory barriers in either the INTELSAT system or one of the several domestic satellite systems to be installed (or already installed in two countries).

Except for the not inconsiderable constraints imposed by regulatory considerations the same 50 kilobit leased satellite channel linking THE ALOHA SYSTEM to the ARPANET could be used to link machines in Alaska, Japan, Australia and any of the other sixteen earth stations which access the Pacific satellite. While these regulatory problems are being worked out however THE ALOHA SYSTEM has established a limited burst random access satellite network using the packet switching techniques described. In a joint experiment with NASA Ames Research Center in California and the University of Alaska we are operating such a link by means of the NASA ATS-1 satellite. The satellite transponder is operated as an unslotted ALOHA channel between earth stations in Hawaii, Alaska and California, and although usage of that channel is now restricted to two hours per day or less and the data rate of the channel is only 20,000 bits/second, the experiment is providing valuable information on this new communications technique.

Perfect information feedback

In the use of satellites for packet switching yet another property of little value in circuit switching assumes importance. In a packet switched system each ground station has the capability of transmitting packets up to the satellite addressed to any other ground station (or to all other ground stations). Each packet is then received by all ground stations, *including the ground station which transmitted the packet*, approximately one quarter second later. Therefore each ground station can initiate transmission of a packet at will as in THE ALOHA SYSTEM. However, whereas in THE ALOHA SYSTEM, it is necessary to provide information on packet interference to the sender in the form of positive acknowledgments, such information is not necessary in the system we are describing. Since each sender can listen to his own packet retransmitted from the satellite each sender can be considered to have the same information on packet interference available to the receiver earth station. (In information theory terms, these channels are modeled as channels with perfect information feedback.)

Unfortunately in the real world, nothing is perfect and there will undoubtedly be circumstances when the transmitter and the receiver do not detect the same bit string from the satellite. The fact remains however that positive acknowledgments to combat packet interference are not required, and the more efficient use of a negative acknowledgment scheme in conjunction with packet numbering is feasible for this system.

EXCESS CAPACITY OF AN ALOHA CHANNEL

The idea

The type of packet switched satellite data channel we have described so far (either pure ALOHA or slotted ALOHA) has a certain elegant simplicity to it. The user of the channel simply transmits a burst of data when he wants at a data rate equal to that of the entire channel. Nevertheless there is a price to be paid for this simplicity in terms of channel capacity and in terms of delay. The question of delay is dealt with by Kleinrock[13] and Roberts[14] in the other two papers of this session. Roberts also discusses an effective method of employing the channel at rates significantly higher than the 37 percent capacity indicated by Figure 1. In the next section we provide some results which show that a slotted ALOHA channel can be used at rates well above 37 percent of capacity, if all users of the channel do not have identical message rates.

The idea of excess capacity in an ALOHA channel was first suggested by Roberts who derived a result for the case of several small users and a single large user of a slotted ALOHA channel. Roberts' proof was published along with a number of other interesting analytic results by Kleinrock and Lam.[15] The approach we shall take was suggested by Rettberg,[16] who also treated the case of a single large user and was able to obtain numerical results for that case. In the next section we provide a complete analytic and numerical solution to the use of slotted ALOHA channels by any number of users, each operating at an arbitrary rate.

The theory

From equation (8) we have a set of n equations relating the message rates and traffic rates of the n users

$$S_i = G_i \prod_{j=1, j\neq i}^{n} (1-G_j) \qquad i=1,2,\ldots,n \tag{13}$$

Define

$$\alpha = \prod_{j=1}^{n} (1-G_j) \tag{14}$$

then (13) can be written

$$S_i = \frac{G_i}{1-G_i}\alpha \qquad i=1,2,\ldots,n \tag{15}$$

For any set of n acceptable traffic rates $G_1, G_2, \ldots, G_n$ these n equations define a set of message rates $S_1, S_2, \ldots, S_n$, or a region in an n-dimensional space whose coordinates are the S_i. In order to find the boundary of this region we calculate the Jacobian,

$$J\left(\frac{S_1, S_2, \ldots, S_n}{G_1, G_2, \ldots, G_n}\right).$$

Since

$$\frac{\partial S_j}{\partial G_k} = \begin{cases} \prod_{i\neq j} (1-G_i) & j=k \\ -G_j \prod_{i\neq j,k} (1-G_i) & j\neq k \end{cases} \tag{16}$$

after some algebra we may write the Jacobian as

$$J\left(\frac{S_1, S_2, \ldots, S_n}{G_1, G_2, \ldots, G_n}\right) = \alpha^{n-2} \begin{vmatrix} (1-G_1) & -G_1 & -G_1 & \\ -G_2 & (1-G_2) & -G_2 & \cdots \\ -G_3 & -G_3 & (1-G_3) & \\ & \vdots & & \end{vmatrix}$$

$$= \alpha^{n-2}[1-G_1-G_2-\ldots-G_n] \tag{17}$$

Thus the condition for maximum message rates is

$$\sum_i G_i = 1 \tag{18}$$

This condition can then be used to define a boundary to the n dimensional region of allowable message rates, $S_1, S_2, \ldots, S_n$.

The results

Consider the special case of two classes of users with n_1 users in class 1 and n_2 users in class 2.

$$n_1 + n_2 = n \tag{19}$$

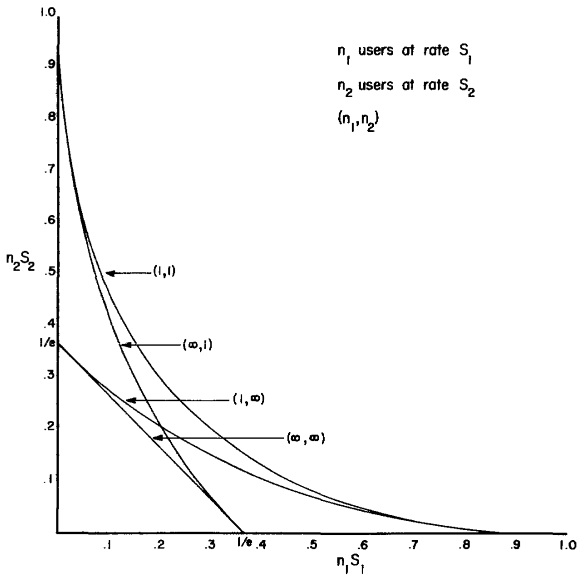

Figure 2—Allowable message rates

Let S_1 and G_1 be the message and traffic rates for users in class one, and S_2 and G_2 be the message and traffic rates for users in class 2. Then the n equations (13) can be written as the two equations

$$S_1 = G_1(1-G_1)^{n_1-1}(1-G_2)^{n_2} \tag{20a}$$

$$S_2 = G_2(1-G_2)^{n_2-1}(1-G_1)^{n_1} \tag{20b}$$

For any pair of acceptable traffic rates G_1 and G_2 these two equations define a pair of message rates, S_1 and S_2, or a region in the S_1, S_2 plane.

From (18) we know that the boundary of this region is defined by the condition

$$n_1G_1 + n_2G_2 = 1 \tag{21}$$

We can use (21) to substitute for G_1 in equation (20) and obtain two equations for S_1 and S_2 in terms of a single parameter G_2. Then as G_2 varies from 0 to 1 the resulting S_1, S_2 pairs define the boundary of the region we seek. A FORTRAN program to calculate the boundary was written and used to calculate several curves of the allowable region for different values of (n_1, n_2) (Figures 2, 3).

The important point to notice from Figures 2 and 3 is that in a lightly loaded Slotted ALOHA channel, a single large user can transmit data at a significant percentage of the total channel data rate, thus allowing use of the channel at rates well above the limit of 37 percent obtained when all users have the same message rate. This capability is important for a computer network consisting of many interactive terminal users and a small number of users who send large but infrequent files over the channel. Operation of the channel in a lightly loaded condition of course may not be desirable in a bandwidth limited channel. For a communications satellite where the average power in the satellite transponder limits the channel however[19] operation is a lightly loaded condition in a packet switched mode is an attractive alternative. Since the satellite will transmit power only when it is relaying a packet, the duty cycle in the transponder will be small and the average power used will be low.

Finally we note it is possible to deal with certain limiting cases in more detail, to obtain equations for the boundary of the allowable S_1, S_2 region.

(a) for $n_1 = n_2 = 1$
Upon using (21) in (20) we obtain

$$S_1 = G_1^2 \tag{22a}$$

$$S_2 = (1-G_1)^2 \tag{22b}$$

(b) for $n_2 \to \infty$

$$S_1 = G_1(1-G_1)^{n_1-1} \cdot \exp[-(1-n_1G_1)] \tag{23a}$$

$$S_2 = (1-n_1G_1)(1-G_1)^{n_1-1} \cdot \exp[-(1-n_1G_1)] \tag{23b}$$

(c) for $n_1 = n_2 \to \infty$

$$S_1 = \frac{G_1}{e}$$

$$S_2 = \frac{1-G_1}{e}$$

Additional details dealing with excess capacity and the delay experienced with this kind of use of a slotted ALOHA channel may be found in References 17 and 18.

PACKET SWITCHING IN DOMSAT

Background

The 50 kilobit INTELSAT channel now being used to link THE ALOHA SYSTEM to the ARPA Network could em-

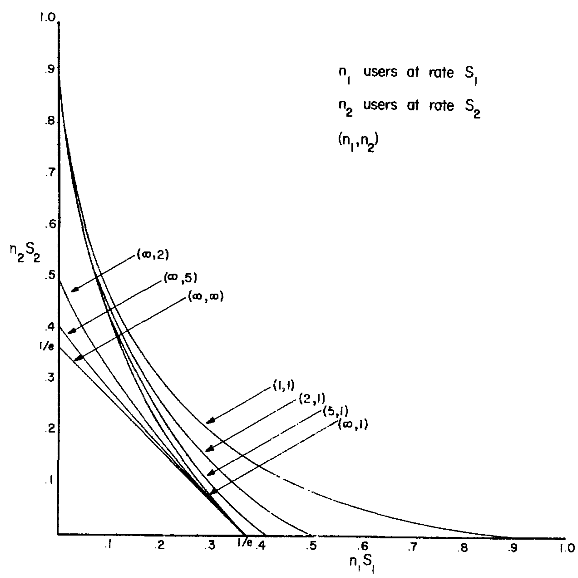

Figure 3—Allowable message rates

ploy the techniques we have described to link additional nodes in the ARPANET at each of the 16 earth stations with access to the Pacific satellite. These same techniques could also be employed by a common carrier to offer packet switched data communications of a quality to which we would all like to become accustomed.

As this is being written, there are in operation two domestic satellite systems (Molniya in the USSR and Anik in Canada) in addition to the worldwide INTELSAT system. Seven US domestic systems (DOMSAT) are under consideration and one has entered the construction phase with a first launch planned for 1974. Japan has announced plans for its domestic communications satellite and several other national systems are expected in the late 1970's. Most of the DOMSAT proposals plan a system of less expensive and therefore more numerous earth stations than the standard 97 foot ~~earth station antennas now used in the INTELSAT system.~~ Thus the advantage of using a lightly loaded packet switched channel in a power limited situation[19] assumes added importance.

A proposal

Consider the use of a single transponder in a US domestic satellite system to provide a public packet switched data communication service. INTELSAT IV employs 12 transponders each with 36 Mhz. bandwidth. Only one of these transponders devoted completely to a public packet switched service in a US domestic satellite system could easily provide data at a rate of 10 million bits/second into a small earth station. The public packet switched service in the US could provide burst data rates between small communication controllers at each earth station of 10 megabits. Assuming 100 earth stations over the US, and assuming the system is operated at a message rate $S=0.15$, the average data rate into and out of each station would be about 15 kilobits although the variance about this average (both from earth station to earth station and at different times at the same earth station) would be large. A packet switched system would function without difficulty in the face of large variations of this type.

The capacity of such a system measured in terms of interactive users of alphanumeric terminals would be about 100,000 such active users at any one time on the system. Of course the system would be used by other devices generating larger amounts of traffic than a single terminal and the number of active users would have to be decreased accordingly. The point is that in a public packet switched service using a US domestic satellite the user of data communications could be charged by the packet, since the user would consume resources in the system proportional to the number of packets sent and received.

The preceding three sections and the accompanying papers by Kleinrock and Roberts explain many of the technological advantages of such a system. We need only add some short observations concerning the operational advantages of a public packet switched service. The system would possess a flexibility of operation simply not attainable with circuit switched systems. Although the *average* data rate into each of 100 earth stations would be 15 kilobits, the *burst* data rate into any given terminal could be close to 10 megabits. This capability for remote job entry and file transfer leads to the same potential for resource sharing shown to be so valuable in the ARPANET.

Another kind of flexibility is the flexibility in being able to start such a system with a small number of communication controllers at a few earth stations. The system would become operational with only two stations and would yield data on packet interference patterns and delay with only three stations. Since the computer-communication network brought into being by such a service is completely connected (topologically) there is no need for routing algorithms at each earth station (such as used in the ARPANET IMPS and TIPS) and to add a new earth station into the network it is ~~only necessary to activate the identification number of that~~ station. Peak load averaging of such a system would operate to increase its total capacity since the system is peak load limited only at the satellite and not at the separate ground stations. (This particular advantage could be especially important for a Pacific packet switched service where the international dateline would serve to average peak loads over different days as well as different hours.)

Finally we note that the economics of such a system are consistent with the economics of existing computer communication systems. The ARPANET in its present configuration provides a factor of ten or more in cost advantage over conventional circuit switched systems.[5] During the month of January 1973, approximately 45,000,000 packets were transmitted by the ARPANET. The capacity of the ARPANET based on an eight hour day was about 300 million packets per month at that time. A public packet switching service using a single transponder of a domestic satellite system, operating at a normalized message rate of 0.15 would have a capacity of about 1,500 million packets per month, again based on an eight hour day. Furthermore, at such a low message rate the system would easily accommodate intermittent users with large files at a megabit data rate and still draw average power from the satellite corresponding to a transponder duty cycle of less than 16 percent. The 50 kilobit lines now used in the ARPANET cost about $1,200,000 per year in January 1973 and this figure was growing rapidly. The ARPANET is but one possible customer of a public packet switched service. The projected average annual revenue of a single transponder in the several proposed US domestic satellite systems ranges from less than $1,000,000 to about $3,000,000 per year.[20]

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