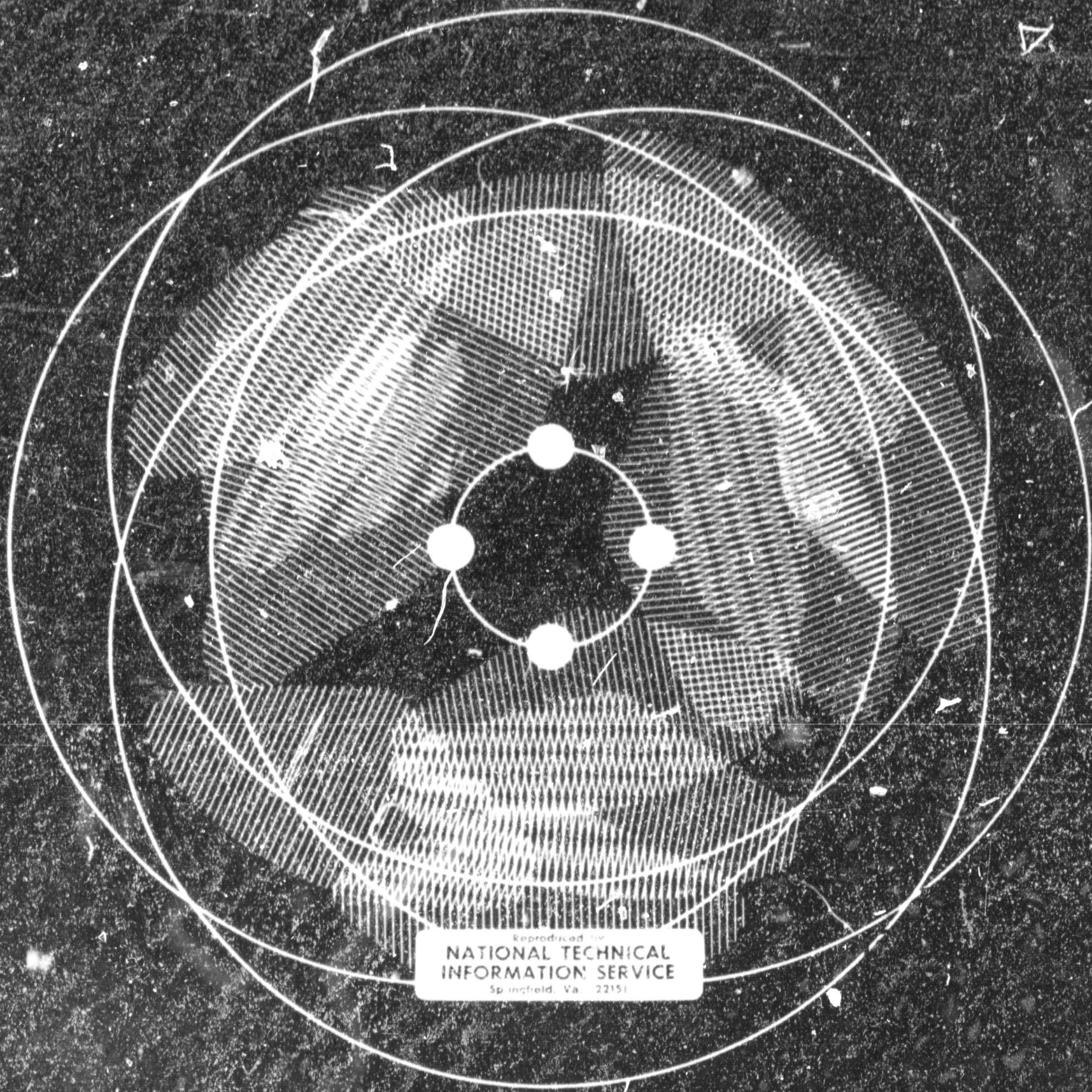


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13. ABSTRACT

This report provides a status report and description of THE ALOHA SYSTEM research project at the University of Hawaii. THE ALOHA SYSTEM involves the analysis and construction of advanced methods of random access communications in large computer-communication systems.

The existing ALOHA SYSTEM computer-communication network uses two 24,000 baud channels in the UHF band. The system employs message switching techniques similar to those of the ARPANET, in conjunction with a novel form of random access radio channel multiplexing. By means of these techniques the system has the capacity to accommodate several hundred active users of alphanumeric consoles on the two channels available. Each of these users can transmit and receive at a peak data rate of 24,000 baud although the average data rate of the users must of course be considerably less.

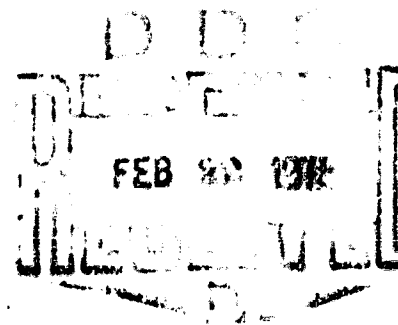
In June 1971, the central UHF station of THE ALOHA SYSTEM had been built and tested by the first radio linked remote terminal. By the end of 1971, four remote terminals had been connected to the 360 through THE ALOHA SYSTEM central station and the design and construction of new forms of UHF links for intelligent terminals, minicomputers and RJE stations was in progress. Present plans are to continue adding new forms of remote links and to continue a program of upgrading the capabilities of the existing central station through the summer of 1972. At that time the existing design will be frozen and a period of experimental operational use of a statewide radio linked computer-communication network will begin.

THE ALOHA SYSTEM

by

Norman Abramson
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Honolulu, Hawaii

January 1972



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Chapter 14. THE ALOHA SYSTEM

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Chapter 14

THE ALOHA SYSTEM *

Norman Abramson, University of Hawaii, Honolulu, Hawaii

INTRODUCTION

In September 1968, the University of Hawaii began work on a research program to investigate alternatives to the use of conventional wire communications for computer-computer and console-computer links. In this chapter we describe an experimental UHF radio computer-communication network - THE ALOHA SYSTEM - under development as part of that research program.

When the designer of a computer-communication system is freed from the constraints imposed by the use of common carrier communications, a number of new possibilities present themselves. The starting point in the design of THE ALOHA SYSTEM was the question, "Given the availability of a fixed amount of communications capacity, how does one employ this capacity to provide effective communication from remote users to a central machine?". Stated in these terms it became clear that the simple replacement of the wire communication channels of the common carriers by equivalent radio channels was not the answer. Indeed it would have been most surprising had the form of communication network evolved at the end of the nineteenth century for purposes of voice communication been the form of communication network chosen at the end of the twentieth century for communication in computer networks.

The University of Hawaii is composed of a main campus in Manoa Valley near Honolulu, a four-year college in Hilo, Hawaii, and five two-year

* THE ALOHA SYSTEM is a research project at the University of Hawaii, supported by the Advanced Research Projects Agency under NASA Contract No. NAS2-6700 and by the U.S. Air Force Office of ~~Aeronautics~~ *Scientific* Research under Contract No. F44620-69-C-0030.

community colleges on the islands of Oahu, Kauai, Maui and Hawaii. In addition, the University operates a number of research institutes with operating units distributed throughout the state within a radius of 200 miles from Honolulu. The computing center on the main campus operates an IBM 360/65 with 500K bytes of IBM core memory and 2M bytes of Ampex extended core memory. Several other University units operate smaller machines for research in computer science, for remote job entry and for monitoring of a variety of scientific experiments.

Remote terminals and remote job entry devices were introduced into the University of Hawaii system in 1969. By the end of 1971 approximately 50 terminals and RJE stations were connected using conventional dial-up and conventional leased line communications. The cost of this communications including telephone and leased line charges, modems and communication controllers had become a substantial portion of the University's computing budget. In June 1971 the central UHF station of THE ALOHA SYSTEM had been built and tested by the first radio linked remote terminal. By the end of 1971, four remote terminals had been connected to the 360 through THE ALOHA SYSTEM central station and the design and construction of new forms of UHF links for intelligent terminals, minicomputers and RJE stations was in progress. Present plans are to continue adding new forms of remote links and to continue a program of upgrading the capabilities of the existing central station through the summer of 1972. At that time the existing design will be frozen and a period of experimental operational use of a statewide radio linked computer-communication network will begin.

The existing ALOHA SYSTEM computer-communication network uses two 24,000 baud channels in the UHF band. The system employs message switching techniques similar to those of the ARPANET, in conjunction with a novel form

of random access radio channel multiplexing, explained in Section 14.2. By means of these techniques the system has the capacity to accommodate several hundred active users of alphanumeric consoles on the two channels available. Each of these users can transmit and receive at a peak data rate of 24,000 baud although the average data rate of the users must of course be considerably less.

14.1 WIRE COMMUNICATIONS FOR COMPUTER NETS

At the present time conventional methods of remote access to a large information processing system are limited to wire communications -- either leased lines or dial-up telephone connections. In some situations these alternatives provide adequate capabilities for the designer of a computer-communication system. In other situations however the limitations imposed by wire communications restrict the usefulness of remote access computing [1]. The goal of THE ALOHA SYSTEM is to provide another alternative for the system designer and to determine those situations where radio communications is preferable to conventional wire communications.

We should emphasize that some of the points we make in this section do not apply or apply only in part to unconventional methods of wire communications which have been proposed [2,3,16] or which are in the first stages of development (e.g., DATRAN, MCI [Chapter 9] and the ARPANET [Chapter 13]). These alternatives were in fact proposed in response to some of the difficulties of conventional wire systems mentioned in this section.

The reasons for widespread use of wire communications in present day computer-communication systems are not hard to see. Where dial-up telephones

and leased lines are available they can provide inexpensive and moderately reliable communications using an existing and well developed technology [4]. For short distances the expense of wire communications for most applications is not great.

Nevertheless there are a number of characteristics of wire communications which can serve as drawbacks in the transmission of binary data. The connect time for dial-up lines may be too long for some applications; data rates on such lines are fixed and limited. Leased lines may sometimes be obtained at a variety of data rates, but at a premium cost. For communication links over large distances (say 100 miles) the cost of communication for an interactive user on an alphanumeric console can easily exceed the cost of computation [5]. Finally we note that in many parts of the world a reliable high quality wire communication network is not available and the use of radio communications for data transmission is the only alternative.

There are of course some fundamental differences between the data transmitted in an interactive time-shared computer system and the voice signals for which the telephone system is designed [6]. First among these differences is the burst nature of the communication from a user console to the computer and back. The typical 110 baud console may be used at an average data rate of from 1 to 10 baud over a dial-up or leased line capable of transmitting at a rate of from 2400 to 9600 baud. Data transmitted in a time-shared computer system comes in a sequence of bursts with extremely long periods of silence between the bursts. If several interactive consoles can be placed in close proximity to each other, multiplexing and data concentration may alleviate this difficulty to some extent. When efficient

data concentration is not feasible however the user of an alphanumeric console connected by a leased line may find his major costs arising from communication rather than computation, while the communication system used is operated at less than 1% of its capacity.

Another fundamental difference between the requirements of data communications for time-shared systems and voice communications is the asymmetric nature of the communications required for the user of interactive alphanumeric consoles. Statistical analyses of existing systems indicate that the average amount of data transmitted from the central system to the user may be as much as an order of magnitude greater than the amount transmitted from the user to the central system [6]. For wire communications it is usually not possible to arrange for different capacity channels in the two directions so that this asymmetry is a further factor in the inefficient use of the wire communication channel.

The reliability requirements of data communications constitute another difference between data communication for computers and voice communication. In addition to errors in binary data caused by random and burst noise, the dial-up channel can produce connection problems - e.g., busy signals, wrong numbers and disconnects. Meaningful statistics on both of these problems are difficult to obtain and vary from location to location, but there is little doubt that in many locations the reliability of wire communications is well below that of the remainder of the computer-communication system. Furthermore, since wire communications is usually obtained from the common carrier, this portion of the overall computer-communication system is the only portion not under direct control of the system designer.

14.2 THE ALOHA SYSTEM

The central computer of THE ALOHA SYSTEM (an IBM 360/65) is linked to the radio communication channel via a small interface computer (Fig. 14.1). Much of the design of this multiplexor is based on the design of the Interface Message Processors (IMP's) used in the ARPANET [7]. The result is a Hawaiian version of the IMP (taking into account the use of radio communications and other differences) which has been dubbed the MENEHUNE (a legendary Hawaiian elf). The HP 2115A computer has been selected for use as the MENEHUNE. It has a 16-bit word size, a cycle time of 2 microseconds and an 8K-word core storage capacity.

THE ALOHA SYSTEM has been assigned two 100KHZ channels, at 407.350MHZ and 413.475MHZ. One of these channels has been assigned for data from the MENEHUNE to the remote stations and the other for data from the stations to the MENEHUNE. Each of these channels operates at a rate of 24,000 baud. The communication channel from the MENEHUNE to the consoles provides no problems. Since the transmitter can be controlled and buffering performed by the MENEHUNE at the computer center, messages from the different stations can be ordered in a queue according to any given priority scheme and transmitted sequentially. At the present time a first-in, first-out priority scheme is used, but consideration will be given to other procedures as the capacity of the channel is approached.

Messages from the remote stations to the MENEHUNE are not capable of being multiplexed in such a direct manner. If standard orthogonal multiplexing techniques (such as frequency or time multiplexing) were employed we would have to divide the channel from the remote stations to the MENEHUNE

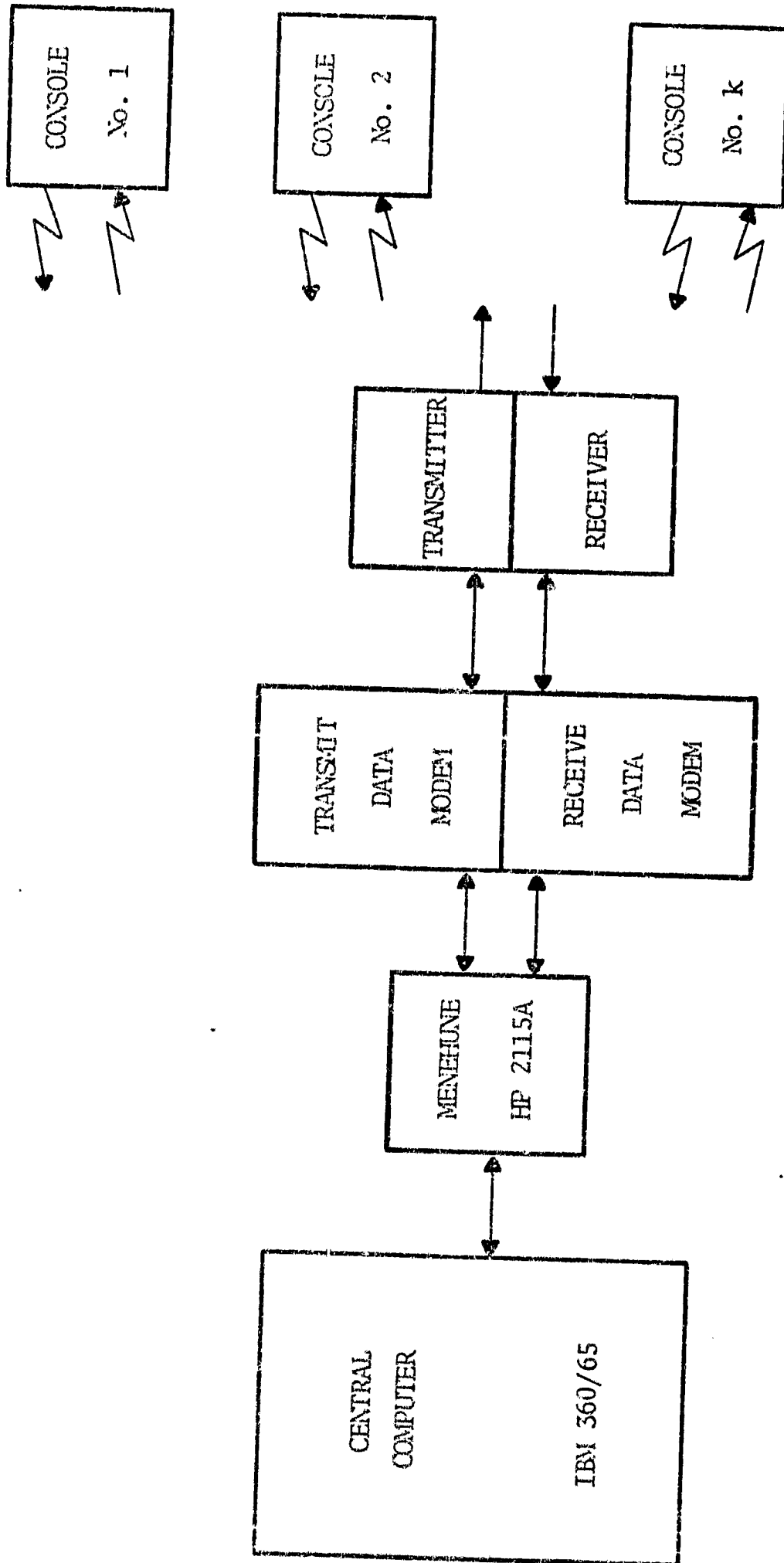


Figure 14.1 THE ALOHA SYSTEM

into a large number of low speed channels and assign one to each station, whether it is active or not. Because of the fact that at any given time only a fraction of the total number of stations in the system will be active and because of the burst nature of the data from each station such a scheme would lead to the same sort of inefficiencies found in a wire communication system. This problem may be partly alleviated by a system of central control and channel assignment (such as in a telephone switching net) or by a variety of polling techniques. Any of these methods will tend to make the communication equipment at the consoles more complex and will not solve the most important problem of the communication inefficiency caused by the burst nature of the data from an active remote station. Since we expect to have many such stations it is important to minimize the complexity of the communication equipment at each station.

We have therefore designed a random access communication method particularly well suited to the transmission of data packets, allowing each remote station in THE ALOHA SYSTEM to use a common high speed data channel without the necessity of central control or synchronization. Information to and from the MENSHINE in THE ALOHA SYSTEM is transmitted in the form of "packets" or "half packets", corresponding to a single message in the system [8]. Each packet has a fixed maximum length of eighty 8-bit characters plus 32 bits identification and control bits and 32 parity bits; thus each packet consists of 704 bits and lasts for 29 milliseconds at a data rate of 24,000 bits/second. Half packets are identical in structure to packets except that they contain 40 rather than 80 characters, and thus take up only 16 milliseconds.

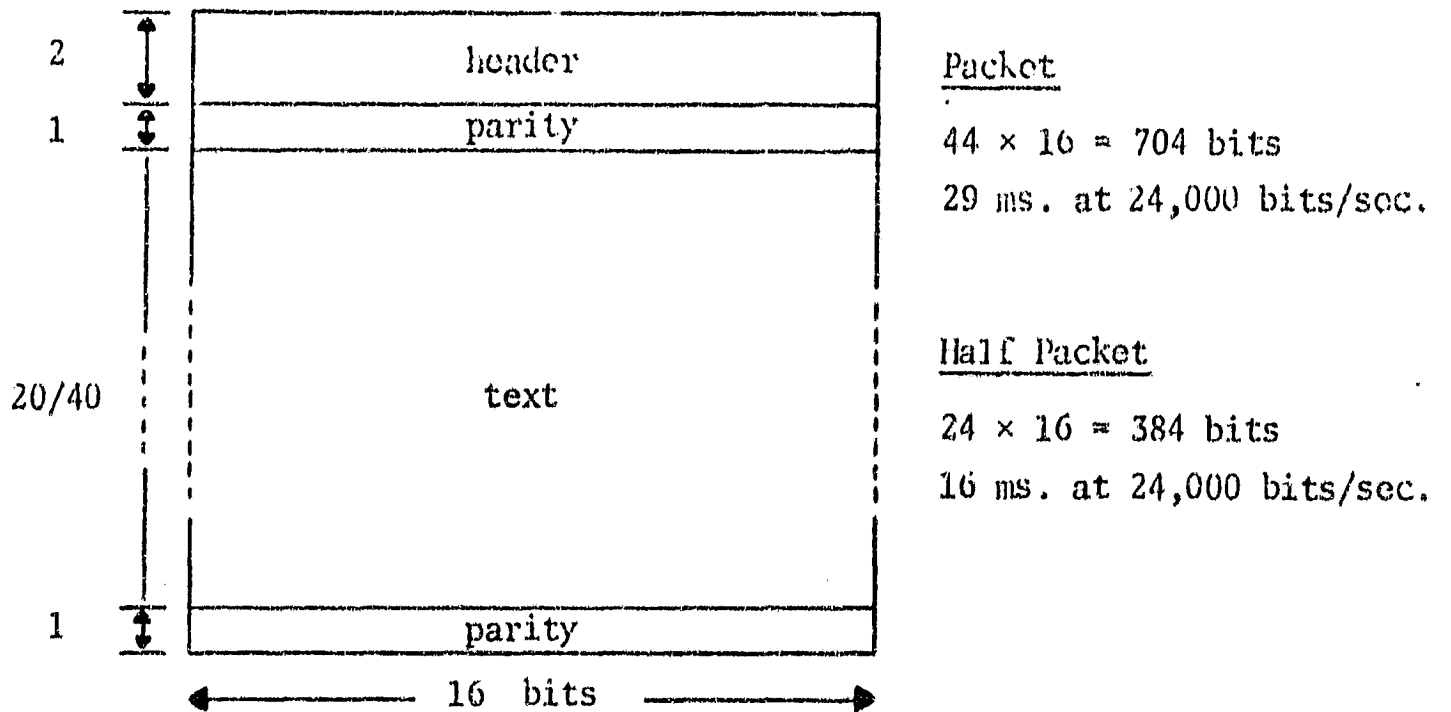


Figure 14.2 ALOHA SYSTEM message format

The parity bits in each packet are used for cyclic error detecting code [9]. Thus if we assume all error patterns are equally likely the probability that a given error pattern will not be detected by the code is [10].

$$2^{-32} \approx 10^{-9} .$$

Since error detection is a trivial operation to implement [10], the use of such a code is consistent with the requirement for simple communication equipment at the consoles. The possibility of using the same code for error

correction at the MENEHUNE will be considered for a later version of THE ALQIA SYSTEM.

Note that 16 parity bits are used to check only the identification and control bits in the 32 bit header, while the last 16 bits are used as a validity check on the entire packet. This configuration provides extra protection for the important identification and control information contained in the header; in addition it allows the MENEHUNE to discard invalid information after reception of only the first three words of the packet.

The random access method employed by THE ALQIA SYSTEM is based on the use of this error detecting code. Each user at a console transmits packets to the MENEHUNE 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 MENEHUNE. After transmitting a packet the transmitting station waits a given amount of time for an acknowledgement; if none is received the packet is automatically retransmitted. This process is repeated until a successful transmission and acknowledgement occurs or until three unsuccessful transmissions have 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 random access channel as more remote stations are added to THE ALOHA SYSTEM.

14.3 ALOHA INTERFACE *

In order to connect a remote station into the ALOHA channel it is necessary to provide buffering up to a full packet of data together with automatic generation of certain identification, control and parity information. This information is generated in a hardware buffer/control interface unit from each user console to a modem. The buffer/control unit also provides for reception of messages and acknowledgements into its remote station, rejection of unwanted packets and automatic retransmission of packets not receiving an acknowledgement [8]. In the case of buffered terminals, intelligent terminals and minicomputers some of the buffer/control functions may be handled by software packages in the remote station.

A multiplexor program in the MENEHUNE provides the interface between the ALOHA radio channel and the IBM 360 computer [8,15]. In addition, up to 16 user terminals may be accommodated by hard wire connection or incoherent light channels to the IIP computer. Both the radio and the other users can utilize the 360 at the same time via the IIP multiplexor program and the TSO time-sharing system in the 360.

The multiplexor program utilizes the hardware interrupt structure of the IIP, and all processing is initiated by a hardware interrupt from user terminals or the 360. Data is received from the radio link in either 20 or 40 word bursts, each 16-bit word consisting of two data characters. Hardware circuits convert the serial bit stream from the radio link to

* Portions of this section were obtained from [15].

16-bit words, which are transferred in parallel to a 16-bit buffer register in the MENEHUNE. Upon receipt of each word an interrupt signal is also sent to the MENEHUNE, causing the word to be read in and stored by the program. When the last word of a burst has been read in, the program initiates transfer of the packet to the 360. Similarly, packets are received from the 360 on a word-by-word interrupt basis and then routed to the appropriate user.

To transmit a packet using the radio link, the MENEHUNE places each word of the message in an output buffer register located in the MENEHUNE and sends a flag signal to a hardware device connecting it to the radio transmit modem. The hardware device stores the word in a second buffer and converts it to a serial bit-stream which is then passed to the modem. Whenever a word is read from the MENEHUNE output buffer, an interrupt signal is sent to the MENEHUNE which causes the program to output the next word of the packet.

In addition to the message words, control words are transferred between the MENEHUNE and the radio link and between the MENEHUNE and the 360. Each packet in the radio link is preceded by two control words (the packet "header") and a header parity word, and each packet's text is followed by a text parity word (Fig. 14.2). At this time the hardware circuits between the radio modems and the MENEHUNE perform the tasks of both parity and syndrome generation. The parity words are inserted into the packet by the hardware prior to entering the transmit modem, and the syndrome words are inserted in place of the received parity words of the packet prior to being placed in the MENEHUNE input buffer register.

Consideration is being given to incorporating parity and syndrome generation in the MENEHUNE multiplexor program. A word with all bits set to 'one' is also sent to the MENEHUNE by the hardware units preceeding the start of each packet, providing synchronization for the MENEHUNE program.

A control word is sent between the MENEHUNE and the 360 prior to a packet transfer in either direction. This word contains the terminal ID number and a packet length indicator (now restricted to 20 or 40 words). The length information allows the block size to be specified so that direct-memory-access transfers can be made by both the 360 and the MENEHUNE.

The program is modular in design, allowing the processing functions for a particular user channel to be easily changed. Editing functions are localized within each user channel module, allowing the editing characters used by a particular terminal to be changed without affecting the other modules in the program. Fixed buffer areas are assigned for each system user in the program. Because of the relative data transmission rates of the user MENEHUNE and MENEHUNE-360 links, it is necessary to store only one packet for each user within the MENEHUNE at any particular time (although the most recent packet sent to a remote station will be kept in storage for user retransmission requests). This fact and the small number of users anticipated for the initial system led to the choice of fixed storage allocation in the current implementation, allowing a later implementation of dynamic storage allocation to be made on the basis of a more detailed study which can include actual operating characteristics of the system.

To facilitate coding, debugging and future modifications, the MENEHUNE program was written in a high-level language, XPL. A compiler was written for this purpose which produced HP machine code from an XPL source program.

The compiler runs on the IBM 360, providing that system's I/O facilities as an aid in debugging syntax errors and in producing program documentation.

The MINIEUSE compiler (HPCOM) was written for use on an IBM 360 to take in a program written in a subset of XPL (called HPL) and emit the proper machine language for a Hewlett-Packard 2115 computer. The compiler had two main design considerations, efficiency of the machine language, and versatility, so that most operations could be done in the higher level language.

Since the programs written in HPCOM are to be loaded into the HP 2115 via the IBM 360, the compiler has no input-output in the higher level language. However, many features and conventions have been implemented in the compiler such that it is easy for the programmer to write his own I/O routines exactly as he wants them, and to utilize the interrupt system of the Hewlett-Packard. To do this, the programmer needs a basic knowledge of the HP input-output system, and how to use some of the built-in functions of the compiler.

The output of the compiler is the raw machine code for the Hewlett-Packard ready to be loaded into the machine, a printed output of the source program, the machine code resulting from each statement with explanation in assembly code for readability, and error statements.

14.4 CAPACITY OF THE RANDOM ACCESS ALOHA CHANNEL

In Fig. 14.3, we indicate a sequence of packets as transmitted by k active consoles in the ALOHA random access communication system.

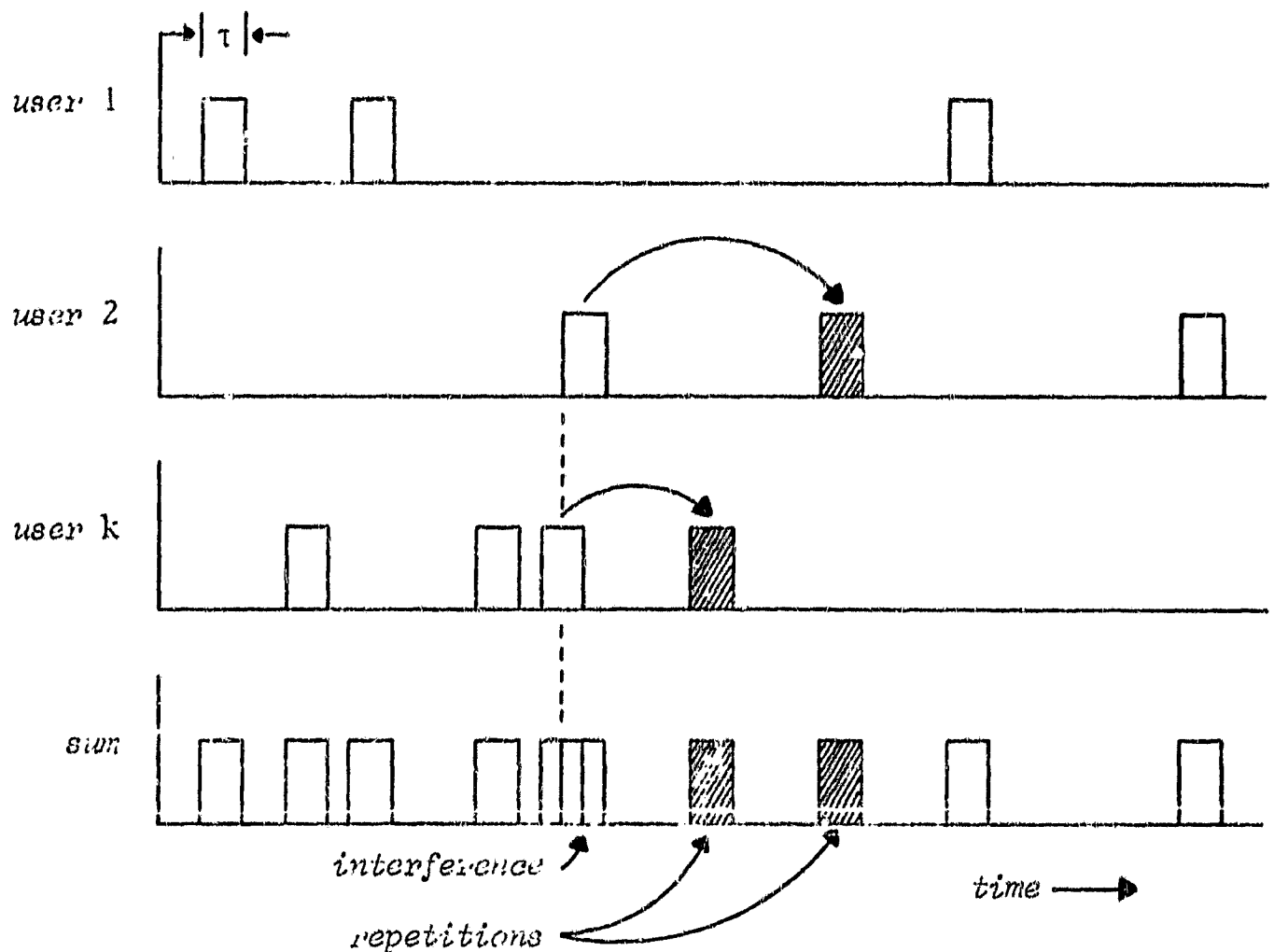


Figure 14.3 ALOHA communication multiplexing

We define τ as the duration of a packet. In THE ALOHA SYSTEM τ is equal to about 34 milliseconds; of this total 29 milliseconds are needed for transmission of the 704 bits and the remainder for receiver synchronization. Note the overlap of two packets from different stations in Fig. 14.3. For analysis purposes we make the pessimistic assumption that when an overlap occurs neither packet is received without error and both packets are therefore

retransmitted.* We also assume only full packets are transmitted. Clearly as the number of active stations increases the number of interferences and hence the number of retransmissions increases until the channel clogs up with repeated packets [11]. We must therefore compute the average number of active stations which may be supported by the ALOHA random access channel.

We may define a random point process for each of the k active users by focusing our attention on the starting times of the packets sent by each user. We shall find it useful to make a distinction between those packets transmitting a given message from a station for the first time and those packets transmitted as repetitions of a message. We shall refer to packets of the first type as message packets and to the second type as repetitions. Let λ be the average rate of occurrence of message packets from a single active user and assume this rate is identical from user to user. Then the random point process consisting of the starting times of message packets from all the active users has an average rate of occurrence of

$$r = k\lambda \quad (14.1)$$

where r is the average number of message packets per unit time from the k active users. Let τ be the duration of each packet. Then if we were able to pack the messages into the available channel space perfectly with absolutely no space between messages we would have

$$r\tau = 1 \quad (14.2)$$

* In order that the retransmitted packets not continue to interfere with each other we must make sure the retransmission delays in the two consoles are different.

Accordingly we refer to rt as the channel utilization. Note that the channel utilization is proportional to K , the number of active users. Our objective in this section is to determine the maximum value of the channel utilization, and thus the maximum value of K , which this random access data communication channel can support.

Define R as the average number of message packets plus retransmissions per unit time from the K active users. Then if there are any retransmissions we must have $R > r$. We define Rt as the channel traffic since this quantity represents the average number of message packets plus retransmissions per unit time multiplied by the duration of each packet or retransmission. In this section we calculate Rt as a function of the channel utilization, rt .

Now assume the interarrival times of the point process defined by the start times of all the message packets plus retransmissions are independent and exponential. This assumption, of course, is only an approximation to the true arrival time distribution. Indeed, because of the retransmissions, it is strictly speaking not even mathematically consistent.* If the retransmission delay is large compared to τ , however, and the number of retransmissions is not too large this assumption will be reasonably close to the true distribution. Moreover, computer simulations of this channel indicate that the final results are not sensitive to this distribution. Under the exponential assumption the probability that there will be no events (starts of message packets or retransmissions) in a time interval T is $\exp(-RT)$.

* Another approach at modelling a channel closely related to the ALOHA random access channel is provided in reference [12].

Using this assumption we can calculate the probability that a given message packet or retransmission will need to be retransmitted because of interference with another message packet or retransmission. The first packet will overlap with another packet if there exists at least one other start point τ or less seconds before or τ or less seconds after the start of the given packet. Hence the probability that a given message packet or retransmission will be repeated is

$$[1 - \exp(-2R\tau)] \quad (14.3)$$

Finally we use (14.3) to relate R , the average number of message packets plus retransmissions per unit time to r , the average number of message packets per unit time. Using (14.3) the average number of retransmissions per unit time is given by

$$R[1 - \exp(-2R\tau)] \quad (14.4)$$

so that we have

$$R = r + R[1 - \exp(-2R\tau)] \quad (14.5)$$

or

$$\boxed{r\tau = R\tau e^{-2R\tau}} \quad (14.6)$$

Equation (14.6) is the relationship we seek between the channel utilization r_t and the channel traffic R_t . In Fig. 14.4 we plot R_t versus r_t .

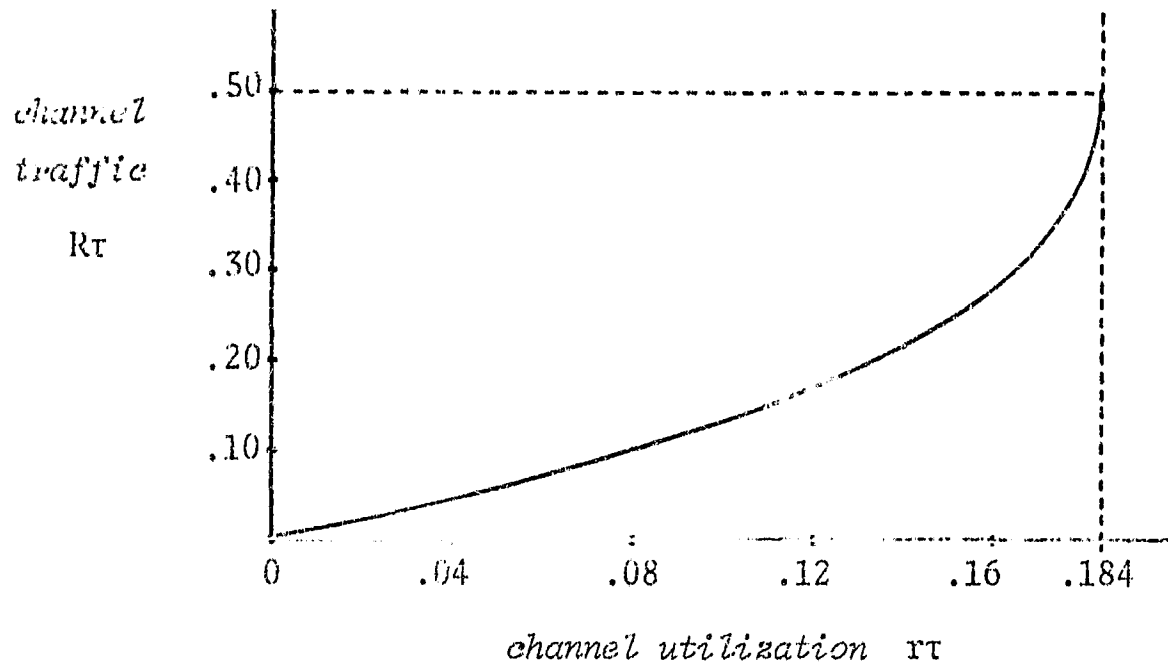


Figure 14.4 Channel utilization vs channel traffic

Note from Fig. 14.4 that the channel utilization reaches a maximum value of $\frac{1}{2e} = 0.184$. For this value of r_t the channel traffic is equal to 0.5. The traffic on the channel becomes unstable at $r_t = \frac{1}{2e}$ and the average number of retransmissions becomes unbounded. Thus we may speak of this value

of the channel utilization 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.

For THE ALOHA SYSTEM we may use this result to calculate the maximum number of interactive users the system can support.

Setting

$$r\tau = k\lambda\tau = \frac{1}{2e} \quad (14.7)$$

we solve for the maximum number of active users

$$k_{\max} = (2e\lambda\tau)^{-1} \quad (14.8)$$

A conservative estimate of λ would be $\frac{1}{60}$ (seconds)⁻¹, corresponding to each active user sending a message packet at an average rate of one every 60 seconds. With τ equal to 34 milliseconds we get

$$k_{\max} = 324 \quad (14.9)$$

Note that this value includes only the number of active users who can use the communication channel simultaneously. In contrast to usual frequency or time multiplexing methods while a user is not active he consumes no channel capacity so that the total number of users of the system can be considerably greater than indicated by (14.9)

The analysis of the operation of THE ALOHA SYSTEM random access scheme provided above has been checked by two separate simulations of the system [13,14]. Agreement with the analysis is excellent for values of the channel utilization less than 0.15. For larger values the system tends to become unstable as one would expect from Fig. 14.4.

14.5 OPERATION OF THE ALOHA RANDOM ACCESS CHANNEL

The calculations of the previous section show we may expect the ALOHA 24,000 baud channel to support over 300 simultaneous active users. In fact the real world operation of THE ALOHA SYSTEM is expected to differ from the model analyzed in several important respects.

First we note it is clearly wasteful of channel capacity to insist that each packet transmitted on the channel use eighty 8 bit characters. Especially for the case of interactive users of an alphanumeric console most lines transmitted will contain much less than 80 characters of information. In the present version of THE ALOHA SYSTEM we have provided the capability of transmitting either a "full packet" of 80 characters or a "half packet" of 40 characters. The header of each packet now employs a single bit as an indicator and the received message is decoded accordingly. A half packet transmitted with the same number of header and parity bits will consist of a total of 384 rather than 704 bits. Using this figure to obtain a value of τ for (14.8) we obtain a larger value for the maximum number of active users supported by the channel

$$k_{\max} = 594 \quad (14.10)$$

Consideration is now being given to allowing a greater set of packet lengths ranging down to a single character and up to multiples of 80 characters.

Still another factor which will tend to make the real capacity of the ALOHA channel greater than the calculated capacity is the assumption made that a packet overlap will result in errors in both packets. In fact, because of the use of FM to transmit data in the ALOHA channel, if two packets are involved in an overlap, the packet with the stronger of the two signal strengths will capture the MENEHUNE receiver and may be received without error. Furthermore this phenomenon can be put to use to provide a simple form of priority scheme on the remote stations of THE ALOHA SYSTEM. By adjusting the received power from different remote stations at the MENEHUNE receiver we may cause a station with higher power to override a station with lower power in the MENEHUNE.

The radio nature of the ALOHA channel suggest the use of a broadcast feature to send messages to all users or to a selected subset of users with a single packet. By use of special identification bits the central station can broadcast system status information or special instructions to all users.

Most important of all considerations in trying to anticipate the real world performance of the ALOHA channel as opposed to the model we have analyzed is that the model is formulated only in terms of a large number of interactive users of alphanumeric terminals. THE ALOHA SYSTEM will be composed of large numbers of such terminals; we also plan to incorporate high data rate graphics terminals, remote job entry systems, minicomputers and terminal clusters

transmitting into the ALOHA channel by means of a simple form of random access radio channel multiplexor now under design. Reliable statistics on the number of packets generated by such remote stations is not available, but it seems clear that the average data rate from these stations will be higher than the average data rate from a console of the sort used in our model. The average number of active users of the ALOHA channel will therefore not be as large as the calculations based upon only interactive alphanumeric consoles would indicate. According to (14.7), the 24,000 baud channel into the MENHUNE is capable of transmitting at an average rate of 24,000 divided by 2e, or about 4,000 bits per seconds. (The burst data rate of course is still 24,000 bits per second.) The average data rate of the channel will always be greater than the sum of the average data rates of all stations feeding into the channel. Therefore the data communication resources of the total system are most effectively employed by users having a high ratio of peak data rate to average data rate.

It is of considerable interest to determine how user characteristics will be influenced by the resource allocation properties of the ALOHA channel. Each user draws resources from such a channel in direct proportion to the number of bits he transmits over the channel. This is in marked contrast to the usual case of wire communications where a user ordinarily must assume a fixed cost corresponding to the minimum communication channel available (e.g. a single teletype on a dial-up connection) or a fixed cost corresponding to a required burst data rate (e.g. remote graphics with communications limited response). In THE ALOHA SYSTEM it will be possible to allocate charges for channel use in proportion to the number of bits transmitted. Such

a pricing algorithm can be expected to encourage use of the channel by users having the high ratio of peak to average data rate mentioned above. In addition to the interactive users of alphanumeric consoles covered in our analysis such a policy would make the system attractive to remotely tele-metered experiments and to minicomputers requiring intermittent use of peripheral equipment.

As an example of the latter use we mention that one project now in progress in THE ALOHA SYSTEM plans to link an HP 2114 minicomputer into the ALOHA channel via a simplified communications module consisting of a small interface, a modem and transceiver. The hardware buffer/control unit will be almost completely absorbed by a software module within the HP 2114 remote station. Once this connection is established it will be possible to load programs into the 2114 from the ALOHA channel rather than from a teletype paper tape reader -- the only present alternative. Thus, assemblers and other programs for the 2114 will be stored on a disk at the central computing center and will be called and loaded into the 2114 by a single command on the 2114's teletype input. This should reduce the time necessary to load the 2114 from 20 minutes to less than 10 seconds. It will also be possible to write HPL programs on the 2114 teletype, transmit these programs to the central computer for compilation and transmit HP machine code back to the remote HP 2114.

In general it is difficult to predict user characteristics of a channel with the properties of the ALOHA channel. Studies of user characteristics up to now [6] have started with existing wire communication facilities and provided profiles of users on these channels. Our analysis has shown

that the ALOHA channel can be of value for users with those characteristics but we cannot now tell what new characteristics will develop when users are charged by the bit transmitted for the use of communication facilities.

THE ALOHA SYSTEM Communications Module is used as the sole piece of equipment necessary to connect any console or RJE device into the ALOHA channel. As such it takes the place of two modems, a dial-up connection and related switching equipment or leased lines usually used for computer networks. The module is composed of a UHF antenna, transceiver, modem and buffer control unit. Both the transceivers and modems employed so far have been modified versions of standard equipment designed for purposes different from the rather unconventional use to which they are put in THE ALOHA SYSTEM. This has been done in order to provide an operating system in a minimum amount of time and to provide us with valuable experience in this new form of data communications. The buffer control unit however was designed and fabricated completely in THE ALOHA SYSTEM laboratories, since no equivalent equipment was available. New versions of the ALOHA transceiver and modem matched to the characteristics of the UHF random access channel have now been designed and will be in operation during 1972.

The development of the first version of the communication module in the present ALOHA SYSTEM Project was accomplished at an equipment cost of around \$8,000 per console. This is the total one time equipment cost necessary to connect a single user into the system. As with conventional wire communication systems this figure can be reduced by data concentration at the remote station. This cost is achieved in spite of the use of standard transceivers and modems ill-suited to the special unconventional tasks in

which they are employed in THE ALOHA SYSTEM. The improvements already achieved in the design of the second version of THE ALOHA SYSTEM buffer control unit have shown that the cost of the ALOHA communication module can be reduced drastically. A communication module cost of \$3,000 by 1973 is projected. Furthermore, the size and power requirements of the module can be decreased considerably with further development work to the point where the communications module becomes a mobile unit allowing portable and instant access to a central computer system. It is not easy to project how far this miniaturization and cost reduction can proceed. But the vision of a user holding a portable terminal with a built-in communication module and a small protruding antenna is a tempting prospect.

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Appendix I

COMPUTER - COMMUNICATION NETWORKS

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