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Dr. Kuo was a member (1966-1972) of the COSINE (Computer Sciences in Electrical Enginering) Committee of the National Academy of Engineering. He is Vice Chairman of the ACM Special Interest Group on Data Communications (SIGCOMM), a member of IFIP Working Group 6.1, International Network Working Group (INWG), and a member of the IEEE Communications Society, Computer Communication Technical Committee. He is listed in *Who's Who in America, American Men and Women of Science, Outstanding Educators of America*, and *Who's Who in Engineering.*

The Organization of Computer Resources into a Packet Radio Network

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***Abstract*—Packet radio communications provides an effective way to interconnect fixed and mobile computer resources. The ALOHA System at the University of Hawaii first introduced this capability in the context of a single-hop system using off-the-shelf RF equipment with all terminals within line of sight of the central station. The packet radio network described in this paper is 1) an extension of the basic Hawaii work to a geographically distributed system involving the use of repeaters to achieve area coverage beyond line of sight, and 2) provides added capabilities for authentication, antijam protection, and coexistence with other possibly different systems in the same band. An overview of the packet radio system concept is given in this paper.**

INTRODUCTION

IN this paper, we describe the use of packet radio communication for organizing computer resources into a computer communications network. A system to demonstrate the packet radio concept is being developed by the Advanced Research Projects Agency (ARPA). Initial testing in the San Francisco area began in 1975. The attributes of this system are presented and its application to mobile radio communications and computer architecture is briefly discussed.

The development of packet switching has made possible the economic sharing of computer resources [23], [24], [36] over a wide geographic area and, as a valuable byproduct, it has provided an effective alternative to circuit switching in providing error-free wide-band communication networks [27], [30]. The basic architecture of a resource sharing computer network includes Host computers connected to one or more packet switches which may be co-located or remote from the Hosts. The packet switches are interconnected by point-to-point data circuits according to a topological design which results in low-cost networks for a given target throughput, reliability, and delay [14], [29]. For a given packet switching technology, it is possible to increase network throughput greatly by assembling a higher performance switch out of a cluster of lower performance switches (see Fig. 1) and by providing many more circuits between clusters [22]. An alternate approach which uses multiple minicomputers to obtain a higher performance switch is described in [21].

The use of packet broadcasting techniques for interconnection becomes attractive when the number of minicomputers (or microprocessors!) is sufficiently large and the overall traffic flow is small. The use of wire "busses" for packet broadcasting appears certain to be an effective interconnection technique. However, packet radio provides another alternative that may be useful for organizing the communications among a large or even a small number of computer resources regardless of the physical setting; inside a box, within a room, or throughout a wide geographic area (see Fig. 2). In addition to its utility for mobile communications, packet radio may eventually result in the development of improved techniques for maintenance, breadboarding, and packaging of computer equipment.

For a geographically distributed network, economic studies have shown that the cost of local distribution for a large user population can be a significant part of the overall system cost [11]. For this reason alone, it would be desirable to identify more economic techniques for local data distribution than the use of telephone lines. Some progress in this direction has already taken place [28] and further development of cable systems is expected. However, even if the cost of telephone access lines were not a dominant factor, an effective means of obtaining mobile access would still be required. This has provided one incentive for the development of a local radio distribution system. The burst characteristics of computer communication [31] will surely be significantly different from the characteristics of mobile radio telephone. By using packet

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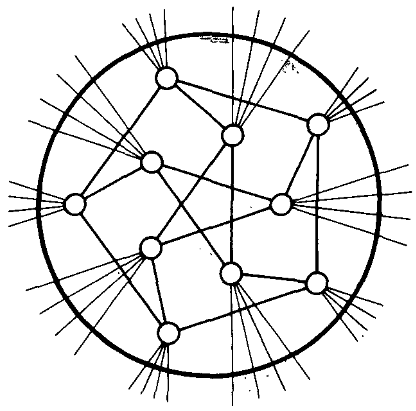

Fig. 1. Packet switch formed by clustering.

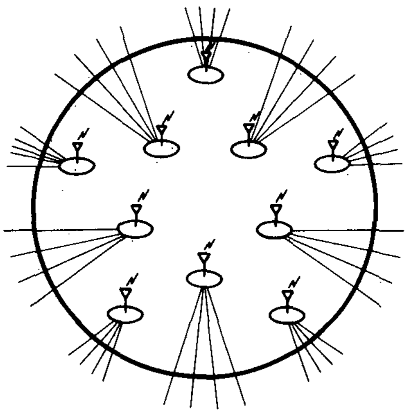

Fig. 2. Packet switch using radio transmission.

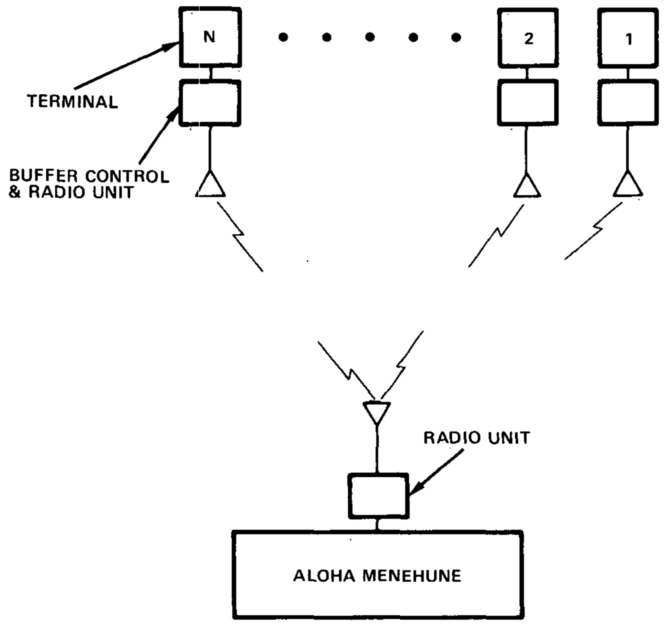

Fig. 3. Original ALOHA System.

switching over radio channels, one should be able to achieve more efficient utilization of the frequency spectrum for computer communications than with conventional fixed channel-allocation techniques.

The progress in integrated circuit electronics, low power displays, and microprocessors makes it feasible to develop a personal terminal which may be conveniently carried about by an individual [3], [8]. This capability allows a user with access to a radio network to be continually in communication with people and computer resources or, selectively, to avoid any and all communications if desired. This latter capability becomes increasingly important as computers and communication capabilities are brought increasingly close to the individual.

The ALOHA System

Several years ago, researchers at the University of Hawaii, noting the unusually high error rates on the local telephone lines which adversely affected their ability to remotely utilize the university computer, proposed a research program to investigate the use of burst radio transmission in place of telephone lines for error-free line-of-sight communications to the computer center. This led to the development of the ALOHA System at the university, a set of terminals linked directly to the computer center by UHF packet radio [7]. A discussion (in retrospect) of the lessons learned in the ALOHA System experience is given in [6].

A simplified schematic diagram of the original ALOHA system is given in Fig. 3. In this system, all terminals were in line of sight of the antenna atop the computer center which served as the hub or station for all communications. Subsequently, a simple form of relay was developed to allow the range of the system to be extended over the mountains of Oahu and to the other islands.

For some applications, the ALOHA architecture as developed by Hawaii represents a good choice without modification. For other applications where it is desirable to obtain coexistence with possibly different systems in the same frequency band, antijam protection, authentication, or direct communication by a ground radio network between users over a wide area, the ALOHA System would have to be extended. In this paper, we discuss a packet radio system which is capable of meeting these added requirements and which is a network extension of the basic Hawaii work.

The main attributes of the packet radio system to be described in this paper which differ from the original ALOHANET are as follows.

1) Distributed control of the network management functions among multiple stations for reliability, and the use of a netted array of possibly redundant repeaters for area coverage as well as reliability.

2) The use of spread-spectrum signaling for coexistence with other possibly different systems in the same band and for antijam protection. Surface acoustic wave technology is a viable current choice for matched filtering in the receiver.

3) The provision of authentication and antispoof mechanisms.

4) The use of system protocols that include network mapping to locate and label repeaters, route determination and resource allocation, remote debugging, and other distributed network functions.

5) The use of various implementation techniques to provide efficient operational equipment such as repeater power shutdown except while processing packets.

The ALOHANET has served as a useful model of a system which has a single central station with many distributed terminals within line of sight. Considerable progress has been made in analyzing this model [25], [26], [32], [33]. In addition to random ALOHA and slotted ALOHA, the techniques analyzed have included carrier sense multiple access, busy tone multiple access, and split-channel reservation multiple access [5], [15].

The packet radio system described in this paper is predicated upon the existence of an array of low cost repeaters and the need for reliable backup of all the critical system functions. It has served from the beginning as a useful model of a multiple station repeatered network. Analysis of this model has proven to be considerably more difficult than the single station model with terminals within line of sight. Consequently, simulation techniques have been extensively used for the packet radio network design [2]. We shall refer to this multistation repeatered network as the RADIONET to distinguish it from the original ALOHANET at the University of Hawaii.

Frequency Management

Frequency management has become a topic of considerable importance for both commerical and military use. The spectrum is already heavily crowded and efforts are constantly being made to obtain more effective use of the spectrum [13]. For example, there would seem to be no valid reason why a RADIONET could not coexist in the same band as broadcast TV with virtually no adverse technical effect. Although laboratory tests of data under voice and data under video are known to have occurred, we are aware of no efforts to carry out coexistence tests in the broadcast TV band. It would not be surprising if both systems could coexist in the same band to mutual advantage.

New frequency allocations and assignments are becoming increasingly difficult to obtain due to the existence of prior assignments. This has resulted in a continual push, in the one direction, for frequency allocations at higher and higher frequencies. Nonessential use of the radio spectrum is likely to meet with pressure for movement to cable or other suitable channels. There is obviously a practical limit to the rate at which technological development can move the frequency frontiers and better techniques are needed for utilizing spectrum which is already handled by existing technology.

According to current doctrine, spectrum is assigned roughly in accordance with each users stated requirement, which are usually worst-case requirements. Once allocated to a given user, the frequency band is not usually available for use by others in the same area. Joint use is presumed to cause mutual interference and thus degrade at least one and possibly both systems. This would be an effective management technique if each assigned band were actually used most of the time. In Fig. 4(a), we show a set of N channels each allocated to a single user. For computer communications, the utilization of each channel would typically be on the order of a few percent or less. If each channel were used approximately p percent of the time on the average, the total utilization of the assigned band would also be about p percent and could not be increased without employing a different strategy. It appears that a factor of 10-100 more utilization can be obtained for burst type traffic with the use of mutiple-access techniques.

On the other hand, if each of the N channels could be scheduled for transmission of one packet and then released, approximately N/p users could be served with equivalent service. Approximately the same service could also be achieved by pooling all the users into a single channel N times as wide [35]. In Fig. 4(b), we illustrate the spectral occupancy of a common band by a set of users who coexist with each other.

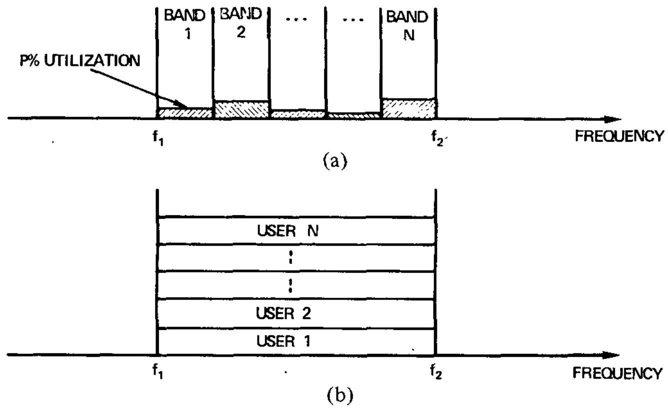

Fig. 4. (a) Fixed frequency allocations. (b) Utilization of a common frequency band.

In a spread-spectrum multiple-access system, additional bandwidth is used to provide protection against unwanted interference. However, the spread system can self-interfere in multiple-access mode as each signal of received power P contributes P/K noise power to the output of a spread-spectrum receiver, where K is the ratio of the spread bandwidth to the unspread band. Although it doesn't seem straightforward to increase the utilization by a factor of K without control of system timing to within a small fraction of 1/bandwidth, additional users may be simultaneously permitted to access the system without system wide control of timing, provided the self interference does not become too great. Thus, one pays a price for spreading the spectrum, but one also receives the advantages of a multiple-access antijam system. Multiple-access coding techniques may also be useful to increase the overall system efficiency [16]-[18].

TARGET SYSTEM REQUIREMENTS

In this section the overall system objectives and the basic requirements to be met by the RADIONET are discussed. The system consists of terminals and stations linked together by line-of-sight radio repeaters. The stations are minicomputers which provide system control; the terminals are hand-held devices, I/O consoles, computers, sensors, etc. We include Host computers in the general category of terminals. The repeaters are simple relay devices which provide network area coverage for terminals and for one or more stations.

One could also envision a substantially different kind of radio network where increased capability is resident in the repeater. The intent here, however, is to keep to a practical minimum all the functions that a repeater performs and to delegate the rest to the stations.

No attempt is made in this paper to compare the packet radio techniques with standard mobile radio techniques and assignment methods. The interested reader is referred to [37] for background information. Comparative studies of these systems will no doubt be a topic for discussion in the coming years.

Computer Communications

The system should be capable of meeting the requirements for mobile communication with computers including real-time speech communication to and from computers as well as handling data to or from portable digital terminals, various types of Host computers, etc. Since computer communication is characterized by a high ratio of peak to average traffic, a multiple-access radio system is appropriate since it provides shared use of a common radio channel and is therefore expected to be more efficient than a system which dedicates resources to users with low duty cycles. A peak user data rate of 100 kbits/s is desirable to meet the need for the rapid transfer of files and for real-time response.

The packet radio system should appear to a user as if a direct connection exists between the user and the destination. The operation of the RADIONET should otherwise be transparent to the end user. For initial testing purposes the coverage area should have a diameter of at least 100 mi. The design of the radio net should be capable of extension to handle increasingly larger geographic areas with attendant increases in cost, delay, and amount of equipment.

Coexistence

The system should be able to share a common frequency band with other (possibly different) systems. The advantages of shared frequency bands are the following. 1) That certain equipments for different systems can be made compatible at the digital level allowing internetting to be conveniently achieved, if desired. This capability could have striking economic impact in situations where separate radio nets with separate equipment and separate frequency bands are currently established. With common equipment types and a common band, the separation could be achieved via packet labels rather than by using different bands and incompatible equipment. 2) That shared operation can result in better utilization of the frequency spectrum. 3) That the system may be introduced into a band which is currently assigned to one or more other users without first requiring the other users to vacate the band and without mutual interference. 4) That the system shall inherently be capable of providing some degree of protection against unwanted interference. Spread-spectrum signaling can assist in achieving this objective and is desirable for antijam communications [19].

Mobile Communications

It is desirable that the packet radio technology to be able to serve users whether on land, at sea, or in the air. Relative speeds of several thousands of mi/hr may occur among high-speed aircraft. In the initial testing, the technology is only required to serve speeds such as might occur with ground vehicles or while walking. A target speed of one hundred miles per hour is sufficient to conduct tests with automobiles and is an appropriate initial choice. Doppler and system timing considerations are being studied to insure that higher speed vehicles can be incorporated at a later time, if desired.

No special demands should be placed on the user of the system in order that he be able to use the system while moving within its specified boundaries. In particular, the method of utilization should be the same for a user at rest and a user in motion and the performance of the system should be nominally the same regardless of the users location within the boundaries of the RADIONET. Further study is required to determine what, if any, degradation results from trying to achieve exactly equal performance (as opposed to nominally equal) within some widespread portion of the RADIONET.

Traffic Handling

Experimental evidence [34] indicates that a maximum packet size of 1000 bits seems to be a satisfactory choice for the vast majority of computer communication requirements. For portable digital terminals (as with real-time computer speech input) packet sizes of a few hundred bits are more than ample, and character-by-character transmission is often needed. The use of special protocols [20] for handling character transmission will help in reducing the number of single-character packets. This reduction is achieved by allowing transmission to occur only when an appropriate character (such as a command terminator) occurs or when sufficient characters have been accumulated. The RADIONET should therefore be able to handle packet sizes from zero to 1000 bits and, for interactive response, an average delivery time of 0.1 seconds is desired for the longest packets within the 100-mi coverage area.

Rapid and Convenient Deployment

The individual elements of the packet radio system should be constructed so that they can be installed in the field with little delay. Technology has progressed to the stage where the individual elements that must be deployed can be made small enough and light enough to be carried by hand. There should be no requirement for careful alignment or other tailoring of the equipment during installation. Rather, it should be insensitive to the specific characteristic of the setting. Omnidirectional antennas can be used and the system can be made to learn of the presence or absence of individual components automatically so as to avoid the need for careful coordination among different sites in the deployment or installation process.

An omnidirectional radiation pattern is also desirable for area coverage of mobile terminals. In specific cases, however, directional antennas may be useful for very low power terminals or for an occasional long range shot to a predetermined location. It is expected that alignment will involve greater installation complexity and coordination and, in addition to taking somewhat longer to install, may rule out simple forms of deployment. Assuming no problems are encountered with the equipment as a result of the transportation, it should be possible for a small team of persons to completely install the field elements of a RADIONET (or remove them) in little more time than it takes to reach the appropriate deployment locations.

Unattended Operation and Reliability Considerations

Once in place, a packet radio network should not require the presence of any personnel for its normal operation. Furthermore, certain debugging and restart or shut-down operations should be possible to perform remotely. Power consumption should be kept to a minimum and reduced to almost zero during periods when no packets are being processed. This technique will lengthen the interval between maintenance visits which is expected to be principally determined by the powering requirements.

A hand-held terminal might be expected to provide several hours of service without recharging. A repeater unit should be able to provide service for many days, if not several weeks or months, between replenishments of the power supply. This time period will depend on the amount of traffic handled.

The probability that some part of the network is unable to communicate with the rest of the net should be less than 0.5 percent and the mean time between failures should be at least 1000 hr for any component in the field under normal conditions.

Error-Free Performance

The system should provide essentially error-free performance for computer communications. A target objective of no more than one undetected packet error per 10 exp (10) packets assuming 1000-bit packets, a 100-kbit/s data rate, and 100 percent occupancy. This is equivalent to a mean time between undetected packet errors in excess of 30 years.

Experiments in urban areas have shown [10] that noise impulses occur every few milliseconds in both the UHF and L bands, principally due to automobile ignition noise. A packet has a very high probability of encountering one or two impulses and therefore some form of error correction is required. In general the error correction choice should depend on the characteristics of the environment. A simple form of error correction should be provided and the system design should facilitate the addition of additional error correction capability, if necessitated by the environment.

Internetting

Internetwork communication is of particular importance in the computer communications field due to the expected proliferation of multiple nets and the high cost of user interfacing. Thus, it may be necessary for a user or a Host on the RADIONET to access a particular user or resource on some other packet switched network. This should be possible using a protocol designed for internetting so that differences in format, packet size, addressing and other conventions can be properly handled [9].

Resource Allocation

When traffic levels are sufficiently low, there is little need for regulating or otherwise controlling the use of the packet radio channel. As the potential demand for service rises, however, a point is reached where some form of system control of the channel is necessary for resource allocation. The packet radio system must be able to guarantee service to authorized individual subscribers so that their requirements are provided by the system even when certain users require or are privileged to obtain a larger allocation of resources than others.

Directories and Virtual Subnets

A user on the RADIONET should be able to communicate with other users or systems by name rather than strictly by numerical ID. Thus, a user named Smith could be reached using only Smith's alphanumeric name. The system performs the directory lookup and all necessary conversions from Smith to the appropriate internal addressing on behalf of the user who need never be aware of the address mapping. If more than one Smith were known to the system, the user would have to supply additional information to distinguish among them. Smith may also choose to refuse communications.

In addition, selected users on the net may wish to form logical subnets of their own within the RADIONET for handling specific functions or for otherwise organizing themselves. The net should provide a mechanism to allow the formation of these virtual subnets and allow authorized individual users to join or leave these subnets as needed. Initially, these subnets could be provided as a special service to the net by one or more Hosts on the network.

SYSTEM STRUCTURE

The communication system consists of a distributed array of packet radio repeaters (see Fig. 5) each of which is able to receive and then transmit a sequence of packets, thereby serving as a relay. The range of each repeater is determined by its geographic setting and its effective radiated power. A maximum spacing of 20–25 mi between repeaters is practical in the light of the target requirements in the previous sections. A denser packing of repeaters is desirable for communication with hand-held terminals and for reliability. In particular, certain repeaters could be placed in the field and remain inactive until needed for reliability.

The initial system concept utilizes a single radio channel shared by all the repeaters which operate as transceivers. Two repeaters may communicate with each other by "leapfrogging" over any other repeaters which may happen to lie in their path. A discussion of these choices is contained in a paper by Frank *et al.* [2]. Simulation results show that a higher data rate (e.g., 400 kbits/s) should be used for repeater-to-repeater communication than for terminal to repeater communication (100 kbits/s).

The 1710–1850 MHz fixed and mobile band has been selected for the initial experimentation. The system will be operated in a 20-MHz portion of the band. In addition to being wide enough to support the initial requirement of 20 MHz, it is capable of supporting possible requirements for multiple channel operation using a 100-MHz bandwidth. Alternate bands in the range between 100 MHz and 2 GHz were considered for possible selection, but were rejected for the initial tests due to their heavy usage. Operational use of the RADIONET at some lower frequency can be easily achieved by using a different amount of band shifting.

Although the characteristics of the lower frequency bands are somewhat better suited to radio propagation in adverse environments, the higher bands will afford a more conservative system test. The use of the lower frequencies is particularly important when all users are expected to receive directly the initially launched wave which may encounter built-up areas, mountains, etc. For a repeater system, it makes less difference if the waves pass around mountains since the end user would not normally be expected to receive the initial wave, but only a repeater version of it. Although it is slightly more efficient to generate power at the lower frequencies, this difference in

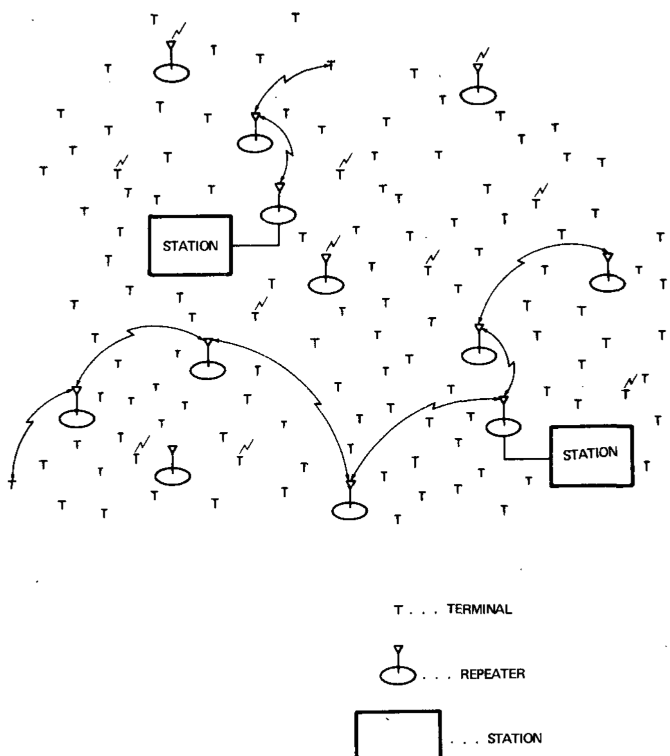

Fig. 5. User communication in a packet radio network.

the bands under consideration is no greater than a factor of two and is compensated for by the scaling down in size of components, particularly the antenna.

As there is a potential for confusion between the function of a repeater and the function of a terminal, we digress a moment to discuss terminology. A device which is capable of transmitting a radio packet or receiving a radio packet is called a packet radio. A repeater, in our context, is merely a particular kind of packet radio which is equipped to retransmit by radio some or all packets which it receives by radio.

A terminal on the RADIONET also requires the capability to transmit radio packets and to receive radio packets. Its role, though, is one in which it accepts no packets destined for other users and consequently it only transmits packets which are originated by its user. That is, it does not act as a repeater and it is not programmed to act as a repeater. A repeater is simply a packet radio which happens to be programmed to function in a repeater mode. If there is need for clarification, we shall refer to the packet radio at the terminal, or to the packet radio repeater (or simply repeater).

Practically speaking, there will be some difference in implementation between a repeater and a packet radio at the terminal, although they will both function in similar (if not identical) ways. For one, the repeater will be more heavily powered to last longer and may be a more rugged unit (particularly if it must be housed outdoors in all weather). A good description of the technology for packet radio is given in [1].

A packet radio which fits in one's pocket will obviously have different attributes. In addition, the user will require some means of inputting data to the packet radio and reading out received data. For example, this may take the form of voice or keyboard input, and display, print, or voice output.

The logical functions of packet processing in the RADIONET are handled by microprocessors. A user terminal may actually have two separate microprocessors, one for keyboard and display control and one for the radio processing, or it may have only one to provide both functions. A discussion of digital terminals for packet radio networks is given in [3].

The repeaters are designed to be relatively simple, and most of the system control functions are deliberately separated out for handling by one or more control stations. The control station consists of a minicomputer which is a repository of centralized information and control for the packet RADIONET It is connected to the rest of the system by its own packet radio. The packet radio at the station is logically equivalent to a packet radio at a terminal. However, the radio at the station may also serve as a repeater in the multistation case.

For reliability, a packet RADIONET will contain two or more stations. Two ways to allocate responsibilities between the stations are the following.

1) To have one station assume the active role of controller while the other stations are kept in readiness and advised of the network status in order that one of them may automatically become active should the currently active control station fail or need to be removed from service.

2) To dynamically apportion or partition the control task among the stations such that each station only serves its share of the users and/or network resources. Backup of each station by the others is also provided in this case and automatic switchover occurs if a station fails.

A goal in either case above is to quickly achieve a switchover with as little loss of data as possible (hopefully none). Both of these techniques are currently under study. A description of the station and its functions is given in [4].

In the initial tests, all data will flow from the user to the station and then from the station to the final destination! However, the protocols are such that it would be possible to support direct communications between source and destination for some or all of the network communication (with the station not in the path). However, changes in the repeater functions may also be necessary if the station is not directly involved, which might complicate the repeater design. These alternatives will be a subject for study during the test program to determine whether or not 1) it is desirable or necessary for the station to be in the path to guarantee allocation of resources or to provide critical services for certain users; 2) to determine the limits on system performance induced by the station in the path; and 3) to determine how the results of 1) and 2) above are affected if multiple stations are simultaneously in use within the same net. The station also serves as the gateway to other networks, and unless the destination user or Host resource is also on the packet RADIONET, all traffic must pass through a station anyway.

When the station is in the direct path, it provides flow control. Each packet is hop-by-hop acknowledged between repeaters for error control as it proceeds to the station and from the station, but is acknowledged from the station to the packet radio at the terminal and from the destination to the station for flow control. A Host is allowed to have multiple packets in transit within the net at any time. End-to-end acknowledgments are required every N packets according to the flow control doctrine, and do not depend on the proper sequential receipt of packets by the station. The RADIONET will allow occasional packets to be delivered out of order unless specifically required to provide sequencing for a given terminal or Host. It is assumed that the Host/Host protocol is prepared to handle sequencing.

A user's packet radio makes initial contact with the station by sending a search packet. All repeaters which hear the search packet forward it to the station which, in turn, selects one of the repeaters and transmits the address of the selected repeater to the users packet radio. As a user moves about within the the boundaries of the RADIONET, the station detects when a handoff from one repeater to another is desirable and performs the handoff by advising the user's packet radio to address a new repeater.

The repeaters do not determine routes. All the routing computations are performed by the station. The complete routing information for each packet is inserted in the packet by the source and is carried along with the packet as it moves through the RADIONET.

AUTHENTICATION AND PRIVACY

In principle, every packet radio is capable of being modified to receive packets not intended for it, and packets must be encrypted to provide privacy or security. The situation in the RADIONET is considerably different from that which occurs in a wireline network where access to internal network packets is restricted. Similarly, every receiver in a RADIONET is also a transmitter and capable, in principle, of being modified to masquerade as another packet radio. Some mechanism must therefore be introduced into the net to verify the authenticity of both the sender and the receiver in each stage of the communication process, and to avoid disruption of normal communications.

The same basic considerations apply whether we focus on a repeater or on a packet radio at the terminal. Consequently, in the following discussion, we shall only consider the case of authenticating repeaters within the net. Authentication and privacy mechanisms will not be incorporated into the initial packet radio system, but are planned for incorporation in a later phase.

Authentication

Let us assume that all data are suitably encrypted for privacy and that we are interested in verifying at repeater A that traffic leaving repeater A and addressed to repeater B is actually being received by intended repeater B. In addition, we are interested in verifying that traffic being received from a so-called repeater B is actually coming from an authentic repeater B.

One possible approach to this problem is outlined below. Each repeater is assumed to include an algorithm whose operation is unknown to the users and which may be changed dynamically. Identification of nonauthentic repeaters is primarily dependent upon the detection of a violation of protocol or by observing a repeater using the wrong algorithm. The algorithm is assumed to be packaged in a repeater in such a way that it cannot be read out if a repeater is captured. We recognize that this assumption, as well as the assumption that the algorithm can be kept private enough, may be subject to question. However, the packaging of the algorithm in an appropriate way is believed to be achievable and an approach of this form is believed to be necessary if mobile terminals and unattended operation of repeaters is to be achieved in the RADIONET.

Several methods of using the algorithm are currently under study. One possible method involves a three way handshake to communicate data. Let us assume that repeater A selects a number at random and communicates it to repeater B with an implicit request to forward a packet. Repeater B, acting suspiciously, uses the received number to generate a new number with the aid of the algorithm. Repeater A also generates the new number which it uses to select a spread-spectrum code pattern. Repeater B acknowledges the request using the spread-spectrum code. Repeater B then prepares to receive the data within several milliseconds after receiving the original request. The request thus serves as the preamble for signaling the arrival of a packet. It could also provide exact timing for the data, if desired.

The data are sent by repeater A using another portion of the spread-spectrum code. The acknowledgment from B to A serves to validate the receiver to A and the receipt of the data by B from A in the correct code serves to validate A to repeater B. Eventually the packet will be correctly received by B and, to avoid endless repetitions from A, B acknowledges the correct receipt back to A using yet another portion of the spread-spectrum code. One effect of this handshake procedure, however, is to reduce the capacity of the sytem and to increase the average delay in order to provide authentication and to protect the transmission from unwanted interference. Several techniques are available for insuring that some postulated level of interference can be overcome, through the use of spread spectrum for antijam protection and by random selection of preambles.

Privacy

Data are encrypted at the point of origination and decrypted only at the final destination. Although we do not discuss it further in this paper, it is assumed that a key distribution scheme is used to achieve the requisite protection. In Fig. 6 we illustrate a terminal, a station, and a Host on the RADIONET. The terminal is shown with two microprocessor units, one on either side of an encryption unit. One microprocessor is an integral part of the packet radio. The other microprocessor is used to support the keyboard display portion of the terminal.

Each packet is assumed to be encrypted independently of the others. Only one encryption unit is shown at the Host, but for multiple access, more than one might be desired. In this situation, the station only serves to provide functions such as flow control, resource allocation, and address mapping. It does not and cannot interpret the data which pass by in any meaningful way.

Data from the terminal are packetized by their microprocessor prior to encryption where they may also be echoed

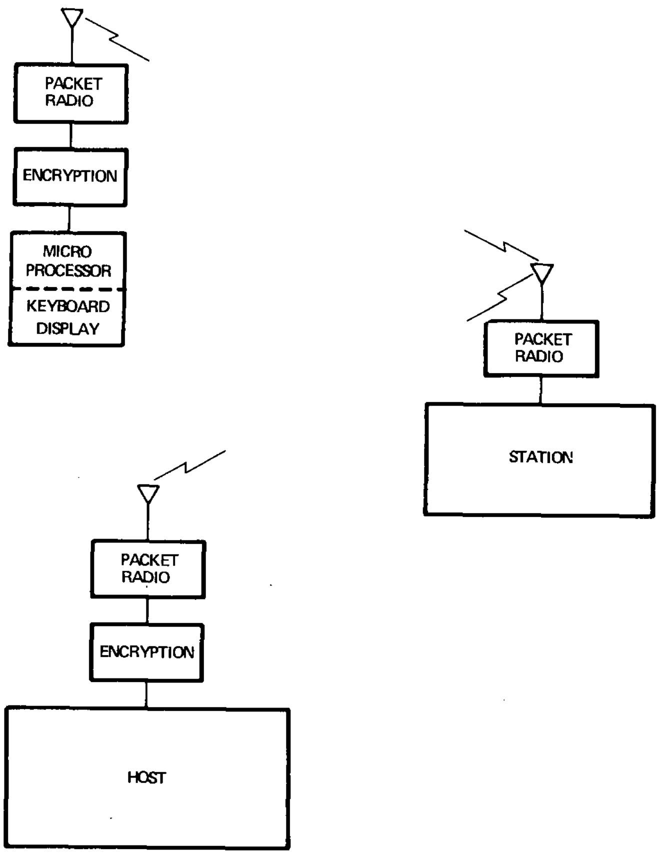

Fig. 6. Microprocessors and encryption.

according to a TELNET protocol [20]. We assume the address of the desired destination Host is resident at the station, it having been notified prior to setup of the connection either by the terminal or the key distribution system. The encrypted packet is stored in the packet radio microprocessor until acknowledged by the next repeater. The station may sequence packets from the terminal, but is not assumed to be able to ask for retransmissions. Such requests are assumed to come as part of the end to end protocol with the Host or other user. Communication from the Host to the terminal is typically sequenced by the station to simplify the reassembly task at the terminal. There is no such requirement in general for sequencing of packets headed to the Host. In certain cases, such as with speech, there may be no advantage to reordering packets headed to the terminal either.

In internetwork connections between the RADIONET and another net, the station serves as a gateway. However, the encrypted packets are forwarded as before to the destination Host without any meaningful interpretation at the station, and none is possible.

SWITCHING AND SORTING APPLICATIONS

The use of packet radio in switch design was briefly discussed at the beginning of the first section. Its use in the implementation of an $m \times n$ crossbar switch with $m + n$ radio units is also clear. In fact, if the output lines from the switch coincide with the input lines, then only m radio units are needed. Another example of the use of packet radio in bucket sorting is discussed below.

A bucket sort is one way of processing data items for rapid storage and retrieval from a small table. Let us assume that M data items are to be stored in K buckets. A unique name must be supplied to retrieve a data item. Each data item (and the unique name) is assigned to one of the buckets based on a simple test (e.g., its low order n bits).

In a typical implementation of a bucket sort, all the bucket items are stored in a single processor. Entries within a bucket are chained together serially. To store an item, its bucket is first identified and the item is appended to the end of the chain either by searching for the end or with the aid of a pointer to the end. To retrieve the item, a search of the chain is required. On the average, this takes $M/2K$ tries.

Now consider the implementation of a bucket sort on a set of microprocessors all in communication with each other via packet radio. The buckets are now conceptual entities each of which is distributed among the microprocessors. For simplicity, each processor is assumed to store only one entry from any single bucket, but may also store entries from other buckets. If bucket i contains k entries, they would be stored in k distinct microprocessors. Repsonsibility for storing the next item in a bucket is passed around round robin among the processors so that, at any time, only one microprocessor is designated to store the next item for a given bucket. Once that item is stored, some other microprocessor is designated to store the succeeding item. The storage contents of a set of microprocessors is shown schematically in Fig. 7. The items in bucket 2 are shown in boldface on the figure.

In order to retrieve an item in bucket j, a microprocessor broadcasts the unique name. Each microprocessor hears the request, determines the bucket and performs a match with the contents of the jth entry in its table. If the contents match the unique name, it broadcasts back the requested data item and the unique name. A data item may therefore be retrieved in exactly one try. If the number of microprocessors does not exceed the number of entries per bucket, the number of tries will be greater than one, but still much less than $M/2K$.

Many other applications of packet radio can be envisioned including remote monitoring and detection networks, satellite networks, factory automation, linguistics, and command and control. However, no attempt is made to discuss these or other applications in this paper.

CONCLUSIONS

The packet radio technology utilizes a distributed set of microprocessors to provide computer control of a multiple access radio communication system. It is capable of supporting switched wide-band communications over very short distances (inches) and over wide geographic areas (hundreds of miles). Within limits, the system allows coexistence with other, possibly different, systems which may reside in the same frequency band.

An overview of the initial packet radio system was presented in this paper. Several of its design objectives are expected to be upgraded in a latter phase of the system development. These include higher data rates, smaller repeater size, expanded station functions, and improved coding and reception techniques for fading, interference, and multiaccess channels. Authentication and privacy mechanisms will be incorporated at that time.

Among the wide variety of uses to which packet radio may be put are the following.

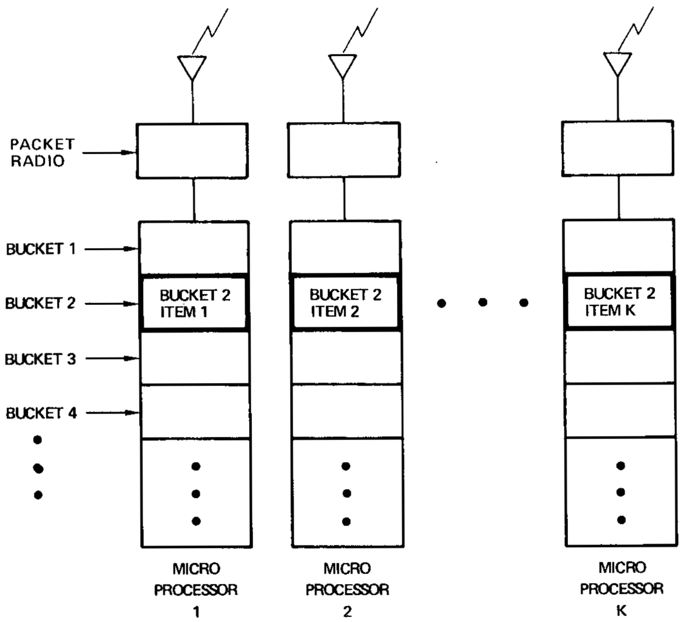

Fig. 7. Bucket sorting by packet radio.

1) Personal radio terminals: Each user has his or her personal radio terminal which he or she can use to communicate over the radio system with other subscribers and resources. Although keyboard entry and display devices are envisioned for the initial experimental terminals, low rate, high quality speech input/output devices will soon be available as viable means of computer interaction, and could augment the initial terminals.

2) Cable TV: The basic concept of packet radio may be applied to two-way cable TV systems for use within buildings and in urban areas. In principle, the radio signal (prior to RF conversion) could be sent over one or more cable TV channels.

3) Computer architecture: Low-power, low-cost packet radio devices in small enough size would allow the assemply of wireless combinations of computer resources such as memory, processors, and I/O devices. Such structures could provide for effective organization of large-scale computational procedures. We believe that packet broadcasting may become a natural way for system architects to interconnect large number of microprocessors in the future.

4) Rapid deployment: It is often desirable to introduce communications to a temporary work site in a very short time period. Packet radio is ideally suited to this requirement. In fact, the technology may herald an era of discardable electronics if the technology can be made low enough in cost and size.

5) Frequency management: Spectrum management techniques are sorely needed to assure that the present and expected requirements for use of the frequency bands can be effectively satisfied. Computer control of the spectrum along with coexistence techniques will allow graceful transitions from inefficiently used single-user systems to more efficiently used multiple-access systems.

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Book Reviews

Editor's Note: Seven books have been chosen for review in this special issue. Three are textbooks, ranging from the theoretical to the practical, with Kleinrock's *Queueing Systems, Volume II: Computer Applications* being the most theoretical, Martin's *Systems Analysis for Data Transmission* being the most practical, and Davis and Barber's *Communication Networks For Computers* being in between. Three are paper collections. Articles in Abramson and Kuo's *Computer-Communication Networks* were specifically written for the book. Many of the articles in Green and Lucky's *Computer Communications* were written specifically for the November 1972 issue of the PROCEEDINGS OF THE IEEE, a special issue on computer communications. Articles in Chu's *Advances in Computer Communications* were selected from all journals and conference proceedings that are relevant to the subject. No one can analyze data networks without a background of queueing theory. Thus, the seventh book is a pure queueing theory book. Kleinrock's *Queueing Systems, Volume I: Theory* was chosen because it is the companion book for another one that had been chosen for review. All the reviews in their original versions were more comprehensive than presented here. Because of the limitation of the number of pages, almost all the reviews subsequently have been shortened.

W. CHOU
Guest Associate Editor

Queueing Systems, Volume I: Theory—Leonard Kleinrock (New York: Wiley, 1975, 417 pp., $19.95).

G. ROBERT REDINBO, *Reviewer*

As new communication networks have come into existence, the prominence of queueing analysis techniques employed as major design tools has emerged. This is the case for computer-communications networks such as ARPANET, TELENET, and AUTODIN II, and it is likely that many more large and small computer and transactional-type networks will be built. Even a casual reader of the literature can sense this increased interest in queueing theory.

The reviewer is with the Department of Electrical and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY 12181.

How does a practicing communications engineer with an adequate background in probability learn or sharpen these new tools? The first volume of Professor Kleinrock's new book certainly offers a viable way to learn and understand a large area of queueing theory. His book is directed at a broad audience which extends from computer scientists to classical switch designers.

The author uses a crisp and exciting writing style which conveys a motivational enthusiasm to the reader. He not only knows his subject thoroughly, but he truly enjoys it. Professor Kleinrock is one of the leading researchers in many aspects of queueing theory and its applications. His depth of knowledge also makes his explanation of difficult topics seem effortless and sometimes deceptively easy. The author continually provides an overview of new material before it is presented;