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COM 400

SUBJECT

PACKET RADIO NETWORK

PRESENT

To my parents

To my brothers

To ali my family

To teacher Prof.Dr. Fahrettin M.SADIGOGL U

To my fr i ejrd s

To everybody tolled me

a Ie t t e r

ACKNOWLEDGEMENTS

I would like to acknowledge to my parents who supported me during my education period who have patiently encouraged me to be the best everywhere

I would like to thank my teacher Fahrettin M. SADIGOGLU who assisted me to get a full picture about, my p.r.oj ect and he has a very strong reason of understanding the topic of 'I'e lecommu nica ti ons.

I specially appreciate my friends who helped me in preparing outputting the project. I also thank my home mate who provided a healthy and quite environment during my preparing the project.

I continue to thank ali people who got a right upon me.

Halit Aydin

INTRODUCTION

After discover of computer world becomes smaller and smaller everyday scientist make inventions this inventions effect the telecommunications and new data communications technics developed.

in this thesis I introduce Packet radio network . This is very interesting subject it is shortly called wireless communication inother world called ALOHA. This communication are based radio waves with frequency band between 300-3000 MHz. Transmission data from removed station to host computer is realised some Frequency of Fl and opposite communication is performed by frequency F2.

EQUATIONS

1 $Pi(k)=i_{1d}\ e^{-O}\ e^{-O}$

2 S-Gıı"G

3 $S_{1}\ \text{ıı}G_{1}\ \ [/\ (1\text{-}oj)$ (j'1i)

4 $\sum_{i=1}^{N} ol=1$

5 $Sl \cdot Gl\ \ (t\text{-}ol)^{Nl}\ \ -1\ \ (t\ \text{-}02)^{H2}$

6 $S2=02\ \ (1\text{-}02)^{N2}\ \ .1\ \ (1\text{-}01)^{Hl}$

7 $Nl\ \ 01+N2\ \ 02\cdot 1$

8 $\frac{1}{01}\cdot R+\frac{L+1}{2}$

9 $fıı \cdot Pr\ \ (nml)\ \ Pr(\text{ıı}\text{ıı}0)+\&(n\text{-}0)\ \ Pr(\text{ıml})+$

10 throu@l?UV8NO: $(1-\hat{o}_{1}\ t\text{-}1$

PACKET RADİO NETWORKS

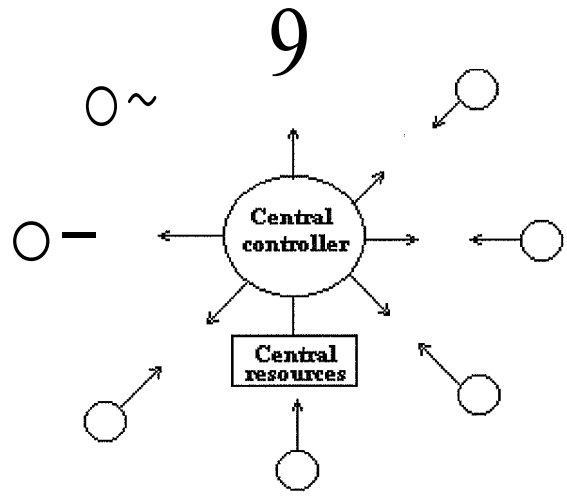
in this chap ter we begin our discussion of packet br o ad c ast in g n etwor ks . Recall that such n e tw o rk s sh ar e th e following ch ar ac ter is t ic s:

* Packet tr an srni s s i o n.
* No switching.
* Reception by many Of all stations.
* Common tr ansm is s io n medium.

This ch ap ter deals with packet r ad i o and satellite n etwo r k s, which exhibit a numb er of similarities. The ch ar a c ter is t ic s of local n e tw o rks ar e quite diff'er erıt, Fo r both packet r a d io and satellite netwo rks, we begin with a discussion of ar ch i te c tur al issues, and then look at medium access c o ntr o l pr o to co l s.

PACKET RADIO ARCHITECTURE

The ar ch it e ctur e of packet r a di o netw or ks can be classified as centr al is e d of d is tr ib u te d (Ei gur e 1) in a c entr al is e d ne tw o rk, th er e is on c entr al tr an s m itt e r/ r ece iv er attached to a c en tr al re s ourc e. All o th er nodes co mmun icat'e only with



(a)Cenirelized

(b)Dlıtributed

FIGURE-1 (Basıc Packet Radıo Archıtecture)

the central node. Node-to-node communication is a dir.ect, mediated by the central node. The earliest networks followed this model, and were designed primarily to provide terminal access to a central time sharing system. in a centralised system, two radio channels are required. Individual nodes send packets

to the central node on channel and the central node broadcasts packets on another. Since radio transmission is by directional, packets transmitted by the central node are heard by all the other nodes. Thus the configuration, is logically equivalent to a multi point line with a primary and a number of secondaries.

PACKET RADIO ARCHITECTURE

The centralised network is not appropriate or the more common situation today of a collection of microcomputers that wish to exchange data, messages, programs, and so forth. The distributed architecture takes full advantage of the omnidirectional property of radio. On channel is used for all transmissions and each transmission is heard by all other nodes. This configuration is logically equivalent to a local area network

Figure and the discussion above assume line-of-sight propagation, recall that the maximum distance between transmitter and receiver is slightly more than the line of sight, or a distance of 100 kilometers. Where h is the height of both antennas in meters, and K reflects a refraction effect. For example, with two antennas at a height of 10 m, and using a nominal value of K= 4/3, the maximum range is 26 km. This represent the maximum radius of a centralised system, and the maximum diameter ofa distributed system.

To overcome this geographic limitation, a store-and-forward repeater is used (Figure 2) A repeater performs much the same task as a node in a packet

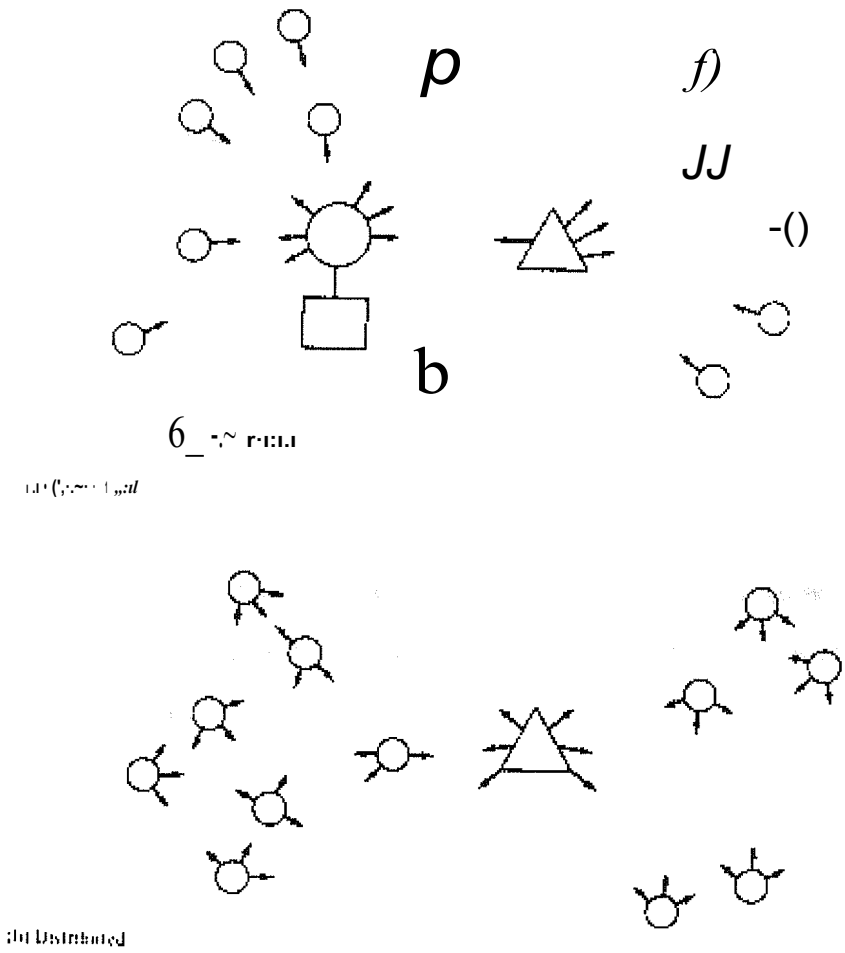


Figure 2 (Packet radio Network with repeaters)

Switched network except that it works with broadcast link rather than point to- point link. in a centralised s system, the repeater accepts packets from the central node and retransmits them to remote nodes. it also accepts packets from these rernote nodes and forwards them to the central node. in a distributed

system, the repeater acts as a switch between two sets of nodes, accepting packets form one set for re transmission to the other, an vıce versa.

We now turn to a more detailed description of these two configurations, using ALOHANET (ABRA 70), (BIND 75 A) as our example of a centralised system, and a standard known as AX.25 as our example ofa distributed system.

Centralised Networks: ALOHANET

The first packet radio network, ALOHANET, was developed by the University of Hawaii and became operational in 1970. Its principal objective was to allow user terminals in widely scattered locations to access the university computer system. Traffic was primarily terminal-to-host, but terminal-to-terminal traffic could be routed via the central node, called the menehune (Hawaiian for "imp"). Remote units were of two types. The terminal control unit (TCU) operated with a simple half-duplex terminal and included a buffer, control logic, and transceiver. The programmable control unit (PCU) was a microprocessor-based device for terminal concentration and/or a computing station.

As a centralised system, ALOHANET requires two channels. PCU- and TCU-to- menehune traffic are on channel f1 using a frequency of 407.35 Mhz traffic from the menehune carried on channel f2, at a frequency of 413.475 Mlız. Both

channels have a bandwidth of 100 kHz and, using PSK, a data rate of 9600 bps. Transmission on both channels uses packets with the following format:

* SYNC (100 bits) : A fairly lengthy synchronisation pattern was deemed advisable to minimise errors.

* Header (32 bits): The header includes the user address (8 bits) repeater address (6 bits) packet type (3 bits), packet length (8 bits), and various other control bits.

* CRC (16 bits): The header is protected with its own error-detecting code.

* Data (640 bits): A maximum of 80 characters can be trans mi tted.

* CRC (16 bits): The <lata are protected with another error-detecting code.

The f1 (user) channel uses a multi access contention protocol known as ALOHA Each station transmits a packet when it has <lata to send. it then expects to hear an acknowledgment (ACK) from the menehune. However, since each station transmits at will, it is possible that two transmissions will overlap. This is known as a collision; the result is that the menehune receives a garbled transmission. To account for transmission errors and collisions, a user node retransmits a packet if no ACK is received during a random time out interval. The random time interval avoids a second

collision between packets that had originally collided. The time is uniformly distributed in an interval with a minimum of 0.2 s, chosen to allow time for receipt of the ACK, and a maximum of 1.5 s. The lower bound is increased for nodes transmitting through repeaters, to account for the repeater delay in both directions.

The f2 channel is used primarily for two types of packets: acknowledgment packets an data packets prom the cerıtr.al resource. Because the timing of ACK's

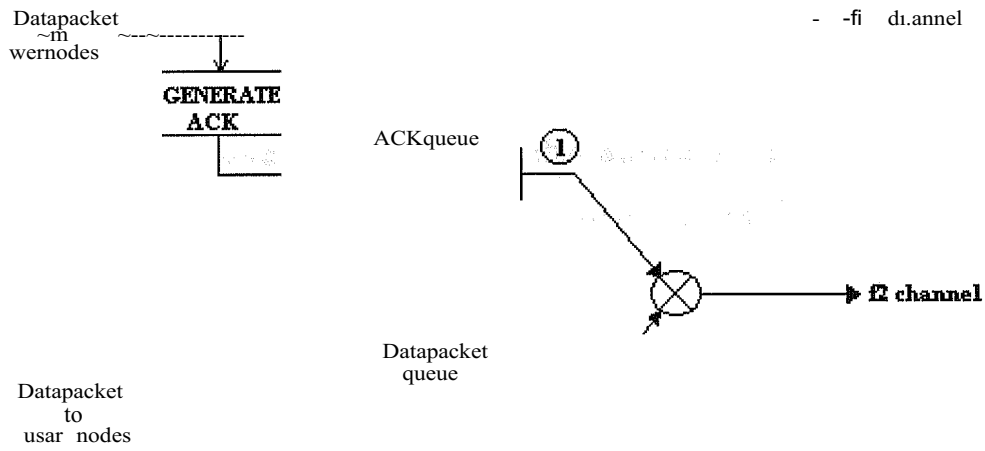


Figure 3 (ALOHANET Broadcast channel multiplexing)

ıs critical, acknowledgment packets have absolute priority. Tw.o queues of packets (Figure 3). As long as the ACK queue is. not empty, the next packet is transmitted from that queue.

In the original implementation, packets from the menehune were not acknowledged by the user nodes, for two reasons. First, since the f2 channel was non contention, there was a high probability of successful transmission. Second, ACKs would increase the congestion of the contention-based f1 channel. Later on, ACKs were added for selected applications such as file transfer.

The repeaters in ALOHANET also use channels f1 and 2a. Each repeater has a list of addresses of nodes with which it can communicate. Packets on f1 from a user node within the address range are repeated on f1 to the menehune or to the newt repeater in the case of c asçad e d repeaters. Packets on f2 addressed to user node within the address range are repeated on f2 in the opposite direction. The process is depicted in Figure 4 a which shows a repeater that communicates with a central controller (c) and a detail set of user nodes (A). Since radio transmission is omnidirectional. It is clear that the menehune and a repeater should not transmit on f2 at the same time. To avoid this, the menehune will pause after transmission of a packet to a repeater long enough for the packet to be forwarded.

Two more elements of ALOHANET that need to be described are the strategies for routing and flow control. Routing is required ifa packet-radio network has more than one repeater. In the case of ALOHANET, a fixed routing strategy is used. The system is set up so that the ranges of addresses for

the various repeaters do not overlap. in a system with many repeaters. A more complex routing strategy would be indicated.

Flow control on f2 requires that the menhune know the input characteristics of the user node. in essence, the menehune waits sufficient. time for a node to absorb a packet of <lata before sending another. Flow control on f1 is normally not a problem for lenghtly transfers fro m a PCU, ago-ahead packet mechanism is used. The PCU can only send a certain amount of <lata and then has to wait for the go-ahead packet.

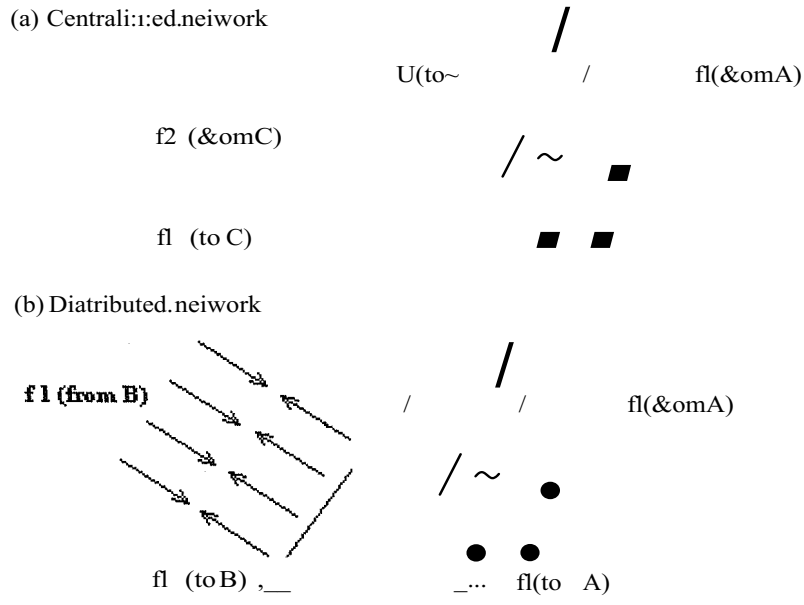


Figure 4 (Function of a radio packet repeater)

D is tri bu ted N etwork: The AX. 2 5 S tandard

An increasingly common application of distributed packet radio is to provide distributed networking among personal

computers, including access to centralised computing resources. In most cases these networks consist of amateur radio stations and are open to any user who conforms to the protocol used on a particular network. And are open to any user who conforms to the protocol used on a particular network.

Amateur packet radio networks exist in a number of areas throughout North America, and the number is growing/steadi1y. An effort to standardise these networks has been un.def Way since 1982, under the sponsorship of the American radi o Re18.y League (KARN85), (BRUN84), which has produced a standard for a link level protocol suitable for packet-radio networJ.<:s known as AX.25 (ARRL84)

An ARRL- type network is a drstr ibute network, organised into clusters of stations connected buy repeaters. All stations an repeaters share a single frequency for traı:isın.issiôı:i and deception. The AX.25 standard does not specify frequency to be used. Based on FCC-approved ch8.nı:iel availabili ty, the typical network uses the 220-Mhz bend, lıs1riğ FSK and with a bound width of 20 kHz or 100 Khz. A typid8.1 data rate is 4800 bps. As with ALOHANET, a fixed routing sc h crn e is used. ln this case, the route to be followed ıs specified by the source station, as explained below.

The link protocol is based on , and very close to, HDEC. The fr am e format is as follows.

* Flag (1 octet): as in HDLC, 01111110.

* Address (14 to 70octets): explained below.

PACKET RADIO ARCHITECTURE

* Corrtrol: as In HDLC.

* Protocol Identifier (1 octet): specifies what kind of network layer protocol, if any, is in use.

*Information :as in HDLC.

* Frame Check Sequence (2 octets): as in HDLC.

* lag (1 octet): as in HDLC

There are two differences between the AX. 25 frame format and that of HDLC: the protocol Identifier (PID) field and the address field. The PID field is used to designate the layer 3 protocol that is using the AX.25 link protocol. This would allow multiple users of the link layer protocol. For example, ARRL is in the process of specifying a network-layer protocol tailored to packet-radio networks. Another alternative is an İnternet protocol. Typically, the layer 3 protocol within systems on a network is unique and of no concern to the link layer. Thus, at present ,the utility of this field is doubtful.

The most important difference between AX.25 and HDLC is in the addressing technique. In HDLC, there are two possible configurations: a point-to-point link with two stations, and a multi droplink with one premary and multiple secondaries. In either case, a single address is sufficient for the operation of

the protocol. This is not true in a packet- radio network, for two reasons:

1- Since the network is a peer, distributed network, both the source and destination stations should be identified; neither is unique. For flow control, error control, and sequence nurnbering, both addresses are needed. To see this, consider a situation in which station A is sirnultaneously erıg aged a logical connections to two other stations, B and C. A is excharıgıng AH.25 frarnes with both B and C, using the HDLC rnechatlisın. is for flow control and error control. Thus, A rnust keep tr ac of the send and receive sequence nurnbers used for its separate connections to both A and B. To da this, each incorning frarne rnust identify the sender.

2. If repeaters are involved, these repeaters rnust be specified. In particular, it is the responsibility of the transrnitting station to specify the repeater or repeaters that rnust be used to get frorn source to do destination.

The AX. 25 address field is frorn 14 to 70 octets long, depending on whether and how many repeaters are used between a particular source-destination pair. If the sending and deceiving stations are in the sarne cluster (within range of each other),. then it is only necessary to specify the source and destination station addresses. Each is specified using 7 octets. Which contains a call sign of up to 7 characters. IF c frarne is to go through a repeater, an additional 7-otet address supplied is appended to the end of the address field. This field contains

the call sing of the repeater. It also contains two flag bits of interest: The H (has-been-repeated) bit and the address-extension bit. If a station wisher to send o frame to a station that con be reached only through a repeater, it includes not only its address and the destination address, but the repeater address as well. The h bit is set to zero. repeater ignore all frarnes that do not contain its address If its address present the repeater sets the H bit and retransmits the packet. A station receiving a frame with a repeater address whose H bit is set to zero will ignore it. This ds the problem of a station receiving duplicate packets, one from the source and one from the repeater. This is possible since line-of-sight transmission radii of necessity overlap. Figure 4b shows the use of a repe'arer to lirik two Sefir of uSer staliôriS.

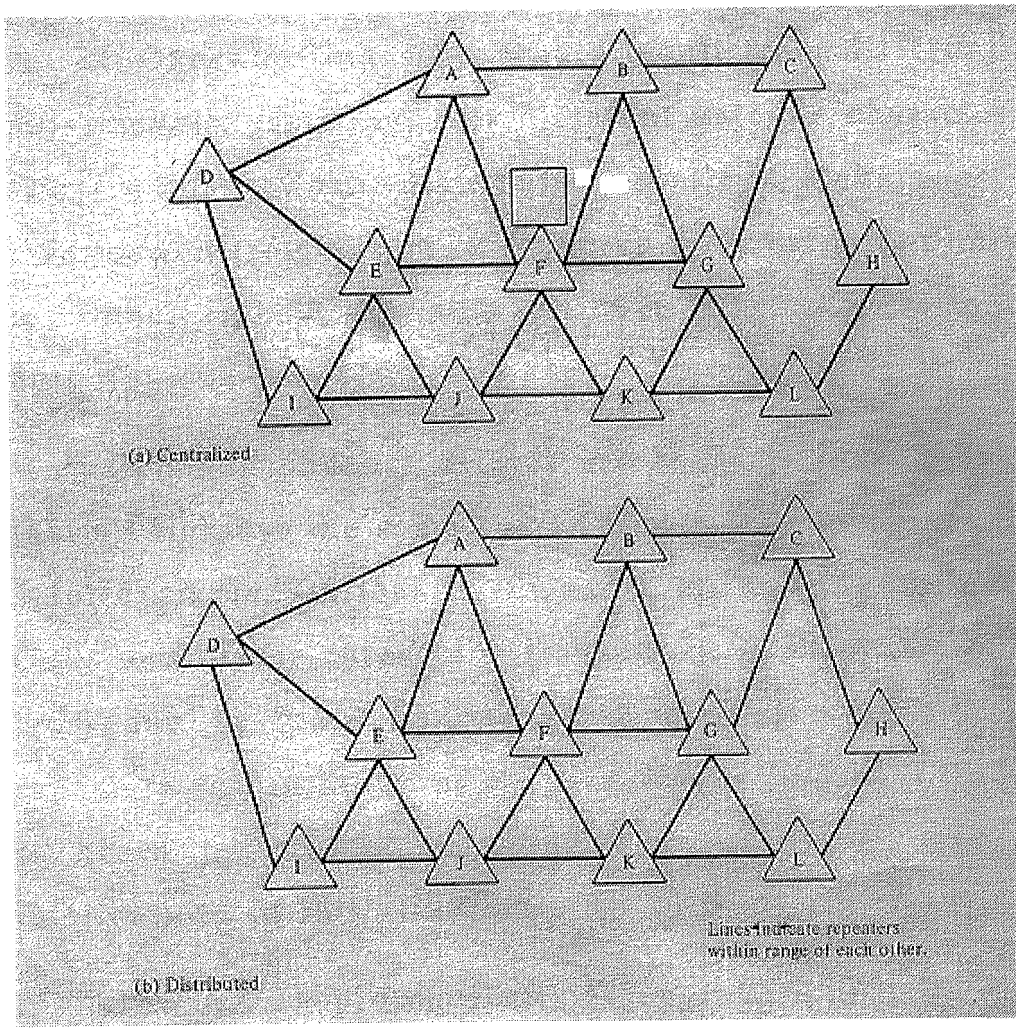


Figure 5 (Packet Radio Network with many repeaters)

* Variable data rate links: Data link error detection control techniques contribute to transmission overhead and reduce the effective data rate. Some radio designs allow these techniques, and thus the effective data rate, to significantly in response to link quality variations. This affect the selection of minimum delay routes.

* One-way link: This would result from different ambient noise levels, jamming, , or different antenna characteristics at two radios. Most distributed routing techniques requıre information from any node to which a packet might be sent, but it is unclear how a sender can even learn the existence of an outgoing one-way link.

Common channel effects are those produced by the facr that all link use the same shared transmission channel. In figure 5 for example, stations G. K, and L are in range of each ofhief. Only one of the three may trans mit at a time. A transmissiOn. from one is heard by the other two as well as any othet rep ea ters wi thin range of the trans mi tter (e. g. G'.s transmissiori. is heard buy K and L. And als o by, 13,.. G, implications of .thi.s si tuation are:

The AX.25 protocol allows operation thr ou more one repeater, creating a primitive routing mechanisnı. Up to eight repeaters may be used by extending the repeater- address sub field. Each address but the last will have the ad dress extension bit set to zero. The first repeater address designates the first repeater in the chain. As a frame progresses thr oüğb a chain of repeaters, each successive repeater will set the H bit ın its own address, indicting that the frame has successfully repeated through it.

Whether one or multiple repeaters are employed particular transmission, it is the responsibility of the source

station to design the route and specify the repeater addresses ın the frame.

The operation f theAX.25 protocol is essentially the same as that of HDLC. Functions such as flow control, error control, link establishment, and so forth are Ident ic.al. One additional requirement in a packet-radio environment .is the use <Of u medium access control technique, several which described below (ALOHA, P. ALOHA S- ALOHA)

Routing

In packet radio networks with a small number repeaters, a fix'ed roüt.ing scheme is adequate. As these of packet radi'o grcws, we are more likely to see networks with a large numb ert 10) of repeaters and with at l some of the stations being mobile. Military requirements clearly reflect this architecture. Figure 5 illustrates the types of configurati ons of multirepeater networks. In a centralised net works In a centralised network, the routing problem is to find a route between the central node F and all work, the routing probl em is to find a route between the central node F and all other nodes. In a distributed network, we have the apparently more difficult problem of finding a route between each pair of repeater s. Note also that in a distributed network, one would need some sort of two-level address for each station of the network, would need some sort of two-level address for each station of the form

(Repeater, station), where "repeater" identifies the cluster of stations local to a particular repeater. This section present an overview of the routing problem for such networks an is based primarily on (CAR8 l)

Each repeater is equivalent to a node, and the local cluster of each repeater is equivalent to multiple stat ions attached to a node. Because of the similarities, one might think that. the routing algorithms discussed previously would be applicable to multirepeater packet radio networks. However, there are differences, due to the transmission characteristics netwo rks. , and the fact that some packet radio nodes may be mobile. the two networks, and the fact that some packet radio nod may be mobile. We can group those differences between the types of networks that affect routing strategy into categories: Link reliability affect and common channel effects.

Link reliability effect are those due to the fact that r links are less reliable than guided-medium link. They subject to fading, multipath and noise interference and, in hotile environment, to jamming. Lower reliability suggests:

*More frequent monitoring of link status: This is required to assure reliable communication. If overhead packets for purpose are exchanged on a regular hasis, routing inform ation could be added. (Piggybacking).

*Variable data rate links: Data link error detection control techniques contribute to transmission overhead an

reduce the effective <lata rate. Some radio designs allow these techniques, and thus the effective <lata rate, to vary significantly in response to link quality variations. This affects the se.l e c ti on of minimum delay routes.

* One-Way link: These would result from-different ambient noıse levels, j amrn in g, or different antenna characteristics at two radios. Most distributed routing techniques require information from any node to which a packet might be sent, but it is unclear how a sender can even learn existence of an outgoing one-way link.

Common channel effects are those produced by. The that all link use the same shared transmis sion channel. In Figure 5, for example, stations G, K, arrd L are in range of each other. Two as well as any other repeaters wi thin range of the transmitter. (E.g. G's transmission is heard by K and also by B, C, and F). The implications of this situation are·

* Link delays are the same for all output link: With p each node has a queue of packets for each link and knows length of its queues. With broadcast lines, these local view packets waiting to use the common channel. This will affect routing strategies that use queuing delay as a parameter.

* Link are not independent: The amount of traffi c(and hence delay) between one pair of repeaters will affect the delay one other pair wise links. This is not taken into acco

most algorithms for globally generating all routes through the network.

* Routing overhead packets need be sent only once: Many dtstribute d routing strategies require that routing information be sent by a node to each of its neighbours. This would require only one radio broadcast.

It should be clear that the problem of routing in ra packet radio network is even more complex than in a conventional packet-switched network. As yet, there has been little experience or research in this area. As examples, we mention two a:pproaches.

Because of the problems of unreliable links and mobile nodes, it is clear that a highly roust routing algorithm ıs required. Flooding comes to mind, but is the most wasteful of bound width. However, from the point of view of the individual repeater, flooding is required! Even ifa packet transmitted by repeater includes a destination repeater address field. Th packet will be received by all other repeaters within range. On way to reduce waste with a flooding approach would be to to minimise the number of repeaters that actually do retran (LIU80) The procedure works as follows. When a repeater receıves a packet to broadcast, it waits a random length of before doing so. If it receives another copy of the packet before its own broadcast, only one of them will relay it. This reduces but does not eliminate packet duplication. In Figure 5, for example, if repeater H broad cast a packet, both C and

rece ive it. Since C and L are not within range of each other, both will rebroadcast it.

Another way to reduce duplicate packets is for each repeater to only forward a packet when it is closer to the destination than the repeater from which it receive d.

The packet (GITM 76). Suppose that each repeater knew ist hop-count distance from every other repeater Then process would work as follows. When a repeater receives a packet form a station for forwarding, it adds a distanc.e whose value is the number of hops to the destination rep eater, and then broadcasts the packet. When a repeater receives packet from another repeater, it does the.following:

* If the pack et is for a station local cluster, broadcast it.

* If the packet is to be forwarded, check the di stance field. If this repeater is closer to the destination than repeater, update the distance field an transmit.

in Figure 5b, for example, suppose that K broad cast a packet with a destination of D and a distance of 3. Rep eaters J,F,G and L rece ive the transmission, but only J and F have a hop count to D of less than 3. They both broadcast a packet with a distance of 2. Repeaters I, E, A, B, G, K, and J get one or two copies of the packet. Of these only I, E and A are closer to D and they all send a packet to D.

This seems to work fine. The question is how each repeater may determine its ho count to every other repeater. This could be done in several ways. Each station could maintain a distance table which is periodically exchanged with its neighbours, much like ONA and the original ARPANET algorithm. Another alternative is a backward learning algorithm. When a repeater receives a packet for .tlre first me that packet will have traversed the shortest route ftoı.n the original repeater. This information could be used to update the distance table in the destination repeater.

Pure ALOHA.andSlotte.d ALOHA

in the early 1970s. Nôrfüan Abramson (1970,1973a, 1973b, 1977) and his colleagues at the University of Hawaii devised a new and elegant method to solve this problem. Their work has been extended by many researchers since then (Binder et al., 197 5; Carleial and Hellman, 197 5; Ferguson, 1975b; Lam, 1974; and Roberts, 1973, to name just a few). Although Abramson's work, called the ALOHA system, used ground based radio packet broadcasting rather than satellite packet broadcasting, the basic idea is applicable to any system in which uncoordinated users are competing for the of a single shared channel. Nevertheless, there are some ımportant differences between ground radio packet broadcasting satellite packet radio broadcasting (notably the propagation delay). We will examine ground radio in general, and the

University of Hawaii ALOHA system in particular, later in this chapter.

'The basic idea of an ALOHA system is simple: Just let the users transmit whenever they have <lata to be sent. There will be collisions, of course, and the colliding packets will be destroyed. However, due to the perfect feedback property of packet broadcasting, the sender of a packet can always find out whether.

Or not his packet was destroyed by just listening downward rain of packets one round- trip time after sending the packet. If the packet was destroyed, the sender just waits a random amount of time and sends it again. The waiting time must be random or the same packets wi l collide over and over. in locked. Systems in which multiple users share a common channel in a way that can lead to conflicts are widely known as contention systems.

A sketch of packet generation in an ALOHA system is given in Fig.6. We have made the packets all the same length because it has been shown that the throughput of ALOHA systems is maximised by having a uniform packet size rather than allowing variable length packets (Abramson, 1977; ferguson, 1975a; Gaardar; 1972).

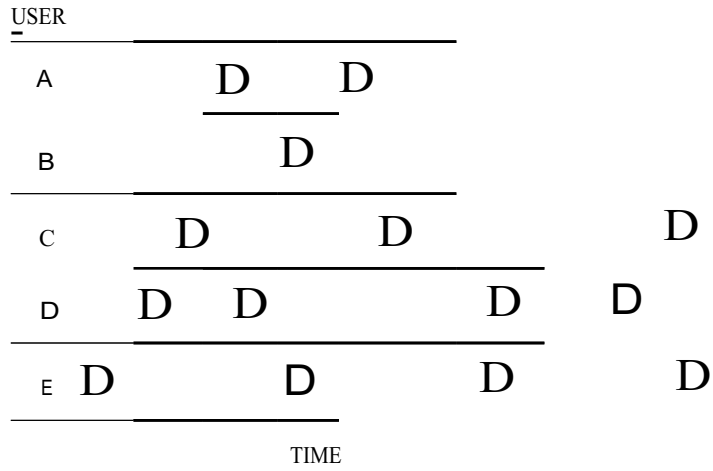


Figure 6 (in pure ALOHA Packets are trans mitted at completely arbitrary times)

Whenever two packets try to 0 ccüp'y channel at the same time there will be a collision and bot will b e garbled. You should realise that if the first bit ofa new packet ov erlaps with just the last bit of a packet almost finished, both p ackets will be totally destroyed, and both will have to be re transmitted later. The check sum cannot (and should not) disti nguish between a total loss and a near miss. Bad is bad.

A most interesting question is: What is the throu ghput of an ALOHA channel? Let us first consider an infinite co llection of interactive users sitting at their terminals. A user is always ın one of twostates: thinking or blocked. Initially, all u sers are in the thinking state. Whenever someone decides wh at to do next, he types a line of text followed by a carriage r eturn. At

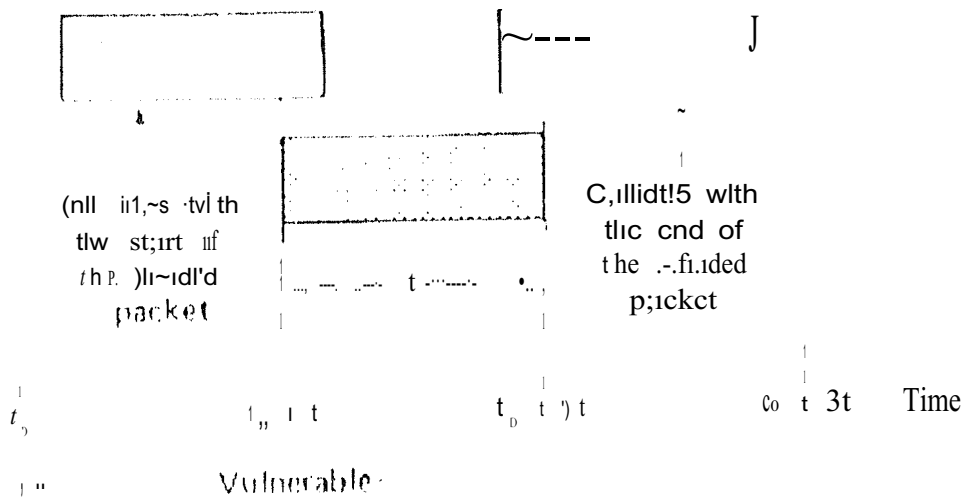
this point he is blocked and stops thinking. The microcomputer inside the terminal immediately locks the keyboard to prevent any more input. it then sends a packet containing the line to the satellite and waits R sec to see if it was successful. If so the user7s keyboard is unlocked. If not, the keyboard remains locked, and the packet is retransmitted over and over until it is successfully sent.

Let the "packet time" denote the amount of tim.e needed to transmit the standard, fixed- length packet (i.e., the packet length divided by the bit rate). At this point we assume that the infinite-population of users generates new packets accor ding to a poison distribution with mean S packets per packet time. infinite- population assumption is needed to ensure .th at S does not decrease as users become blocked.) If S 1, community is generating packets at a higher rate than channel can handle, and nearly every packet packets at a hi rate than the channel can handle, and nearly every packet suffer a collision. For reasonable throughput we would expe S 1.

in addition to the new packets, the users also generate transmissions of packets that previously suffered collis Let us further assume that the probability of k transmis attempts per packet time, old and new combined, ıs Poisson, with mean G per packet time. Clearly, G S. At load (i.e., S O), there will be few collisions, hene retransmissions, so G S. At high load there will be many

collisions, so G S. Undcr ali loads, the throughput is just the offered load, G times the probability of a transmission being successful that is, S= Oo where Po is the probability that a packet does not suffcr a collision.

A packet will not suffer a collision if no other packets are scnt within onc packet time of its start, as shown in Fig7. Under wliat conditions will the shaded packct arrive undamaged IOF any othcr uscr has generated a packet between tO andtO+l the end of that packct will collide with the beginning of shaded one, in fact, the shaded packct's fate was already se even bcfore thc first bit was sent. But due to the long propagation delay, it has no way of knowing that another packet was alrcady undcr way. similarly, any other packet started betwcen to+a and ao+2. t will bump into the of the shaded packct



Fif~. 7 Vulnerablc pcrind for tlıc 'ilıadcd packcı.

The probability that k packets are generated during a gıven packet time is given by the Poisson distribution:

So the probability of zero packets is just e . ln aninterval two packet times long, the mean number of packets generated is 2G The probability of no other traffic being ın itiated during the entire vulnerable period is thus given by

This result was first derived by Abromson (1970)

The throughput- offered traffic relation is shown in Fig. 6-3. The maximum throughput occurs at G= =.5, with S-1/(2e), which is about 0, 184. In other words, the best we can hope for is a channel utilisation of 18%. This result not very encouraging, but with everyone transmitting whenever he wants to, we could hardly have expected a 100% success rate.

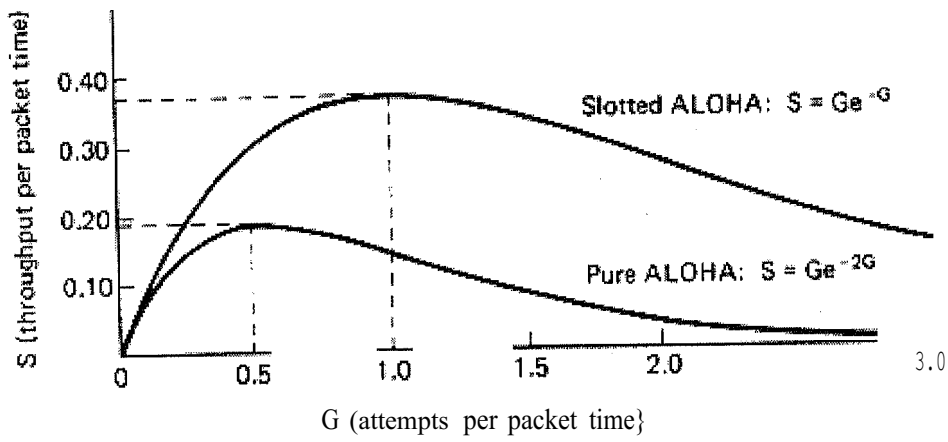


Figure 8 (Throughput versus offered traffic for ALOHA system)

in 1972, Roberts published a method for doubling the capacity of an ALOHA system. His proposal was to divitle time up into discrete intervals, each interval corresponding to one packet. üne way to achieve synchronisation among the users would be to ha ve the satelli te emi t a pip at the start of each interval, like a clock. Although the pips would arrive down at the earth 270 ms later, each user would receive the signal at abou t the same time. B y making the time slots slightly l arg er than the packet times, the variation in propagation time with position on th e earth could be compensated for.

in Roberts method, which has come to be known as slo AL OHA, in c o ntrast to Abr.arn s o n ' s pure AL OHA, a te rminal is not permitted to send .wlıemever a >.c arriage return is typed. Instead, it is required to wait for the beginning of the n ext slot Thus the continuous pure ALOHA is turned into a discre Since the Vulnerable period is now reduced in half, probability of no other traffic during the same slot as packet is e -G which leads to

$$S=Ge^{-G}$$

As you can se from Fig. 8, slotted ALOHA peaks with a throughput of S= 1/e or about 0,368, twice that of ALOHA. If the system is operating at G= 1, the prob ability of an empty slot is 0.368 (from Eg. 6-2). The best we can hope for using slotted ALOHA is 37% of the slots empty, 37% su ccesses, and 26% collisions. Operating at higher values of G re duces the number of empties but increases the number of collisions

exponentially. To see how this rapid growth of collisions with G comes about, consider the To see how this rapid growth of collisions with G comes about, consider the transmission ofca test packet. The probability that it will avoid a collision is e^{-G}. The probability of a transmission requiring exactly k attempt (i,e., k-1 collisions followed by one success)

$$P_k = e^{-G}(1-e^{-G})^{k-1}$$

The expected number of transmission per carriage return typed, E, is then

$$E = \Sigma\, kP_k = \Sigma\, ke^{-G}(1-e^{-G})^{k-1} = e^{G}$$

As a result of the exponential dependence of E upon smal increases in the channel load can drastically reduce its performance

Finite Population ALOHA

The above result is have been obtained usi assumption of an infinite number of users. Abramson (1973a) allows analysed Slotted ALOHA systems with a finite number of users. We now briefly summarise his results.

Let Si be the probability of a successful transmission generated by user i. Remember that at equilibrium the throughput rate must equal the rate at which new packet are generated. Let Gi be the total transmission probability (per slot) of user i, including both new packets and retransmissions

Cl e ar ly The probability that a given slot will contain a successful packet sent by user i is the probability that user i sends a packet, times the probability that none of the n-1 other users sends a packet:

Let us now specialise Eq.3 to the case of n identical users, each hang a through put of Si= S/N packets/slot aiid a total transmission rate of Gj= G/N packets/ slot, where $G=\Sigma G_i$. Substituting into Eq. (3), we get

Form Fi. 8 we see that the maximum throughput for an infinite population slotted ALOHA system occurs at G=1. Abramson (1973a) has shown that this intuitively reaso nable result also holds for systems with a finite number of users . The condition for m ax im'um thr oughput is

Now let us consider two classes of users, for ex ample file transfer users and interactive users. Let there be N_1 of first kind an N_2 of the second, with throughput S_1 and respectively (per user). Then Eq.(3) reduces to

$$S_1= 0.r\ 1- G_1)N_{1-1}\ (l-G_2)N_2$$

For maximum throughput we must obey the constraint Eg.(4), which becomes

We now have three equations in four unkno (S_1,S_2,G_1,G_2). By using Eq.(6), we can eliminate g2 from two class throughput equations Eq's(5) and (6) to yıe parametric equations for th e throughput, parameterised by G_1.

As a first example, consider N1=1 and N2=1 And N2 1. This leads to S1=G and are plotted in Fig.9(a). Notice that when gl is close to O, user 1 hardly ever attempts to send, and user 2 is free to use nearly every slot, so the total throughput is close to one packet per slot. The worst case is when both users attempt to send on everv slöt with a probability of 0.5. If that happens there is a 25% chance that user 1 will try and user 2 will refrain. Similarly, there is a 25% chance that user 2 will try and user 1 will refrain. The total throughput is therefore 0.5 packet per slot. The collusion to be drawn form this example is that an asymmetric situation yields a higher throughput than does a symmetric one.

Next let us specialise Eq's.(5) and (6) to the case and

. User 1 might be trying to transfer a large file, whereas the remaining users are doing interactive work. To keep total traffic finite, we must let in such a way remains finite. Letting we get

The condition for maximum total throughput is G1+G2=1 , which allows us to plot s1, s and the throughput, sl+s, asa function of G. This plot is given in Fig9.(b). When G is small, the interactive users are not doing much, and the single " large" user can continuously send packets without collusions, thus achieving

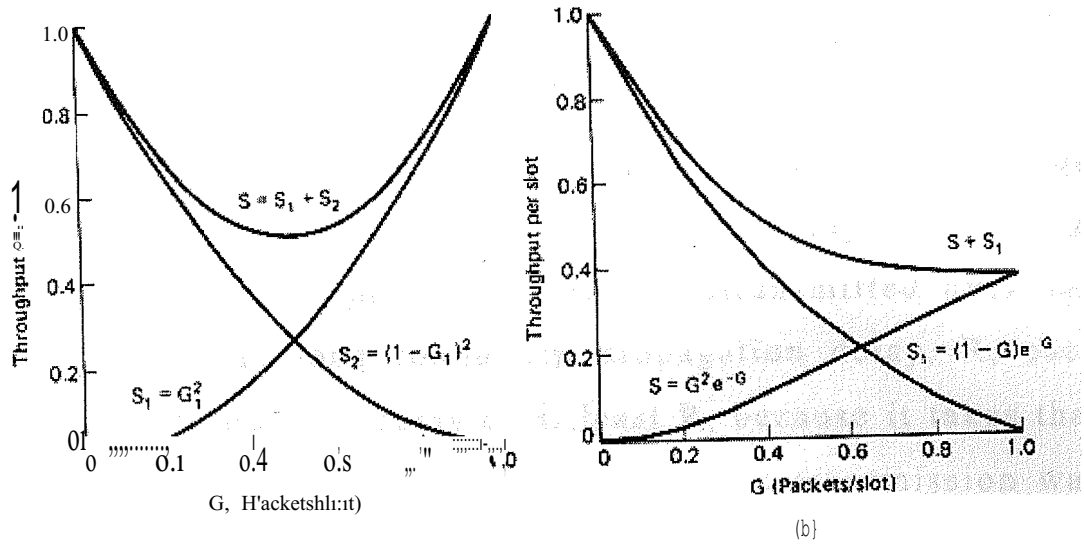


Figure 9 (a- Throughput of a two user ALOHA system.
b- Throughput of an ALOHA system with
one large and many small users.)

a very high total channel utilisation. As G increases, the interactive traffic claims a larger partition of the available bandwidth and the large user is forced to send less to maintain the total offered traffic at one packet per slot.

Delay and Throughput of Slotted ALOHA

The throughput is not the only parameter we are interested ın. The mean packet delay is also important, especially interactive users. Just as with store-and-forward network shall discover that high throughput and low delay are inherently

ın conflict. Good performance on one of them can be achieved only at the expense of other.

In store-and-forward networks, the delay comes from queuıng within the IMPs. In ALOHA, .the delay comes from collisions, forcing some packets to be retransmitted over and over. Due to the long round-trip prnpagattörı delay.. R,. each collision introduces a delay of at least because it takes that long to determine whether or not the packet transmission was successful. If a packet collides three times, the delay between first transmission and successful delivery will be at least 4R. Depending on how long the wait between a collision and the retransmission is, the delay may be considerably more.

To study the distribution of delay tim.es, we will adopt the following model . N identical users each generate new packets according to a poison distribution with a mean packets per slot when not blocked. Retransmissions are not counted i p. If the mean think time is T1 and the slot time is T2. Then Alternatively, p can be thought of as the probability of a given (unblocked) user generating a packet in a given slot. Since the total traffic, new packet in a given slot. In the total traffic, new packets plus retransmissions, must be one packet/slot for maximum throughput, he total rate at which new packets are introduced into the system must be less than 1 {)

When a user types a line, he is blocked and steps thinking, as in our previous model. We could allow the terminal to buffer several packets in order to allow the user to continue

imm e diat c ly, but this complicates the analysis. Furthermore, it affect the system stability adversely as we shall see later. Our goal is to compute the mean time between a user typing a carriage return and the packet being correctly received by the remote computer. We have used the model of people sitting at terminals (rather than having all nodes be computers) for its an thropomorphic val u e, but the analysis ıs ıuenrıcaı tor computer to computer communication, of course. However, for th e sake of generality, we will use the neutral term "st ations" from now on.

A key parameter in the model is how the station randomises its wai tin g times before attempting retransmission. In slotted ALOHA the waiting time consists an integral number of slots to be skipped before trying again. the mean number of slots skipped is short, the chance for same collision occurring again is large. For example, if stations collide and each waits either zero or one slot w equal probability, the chance for an identical collision second time is uO. 5. On the other hand, if the retransmiss ore spread out uniformly over the next 100 slots, the chanc the same packets colliding again is 0.001. Of course, the mean delay in the latter case will be much greater than in the fo rmer. This is the heart of the throughput- delay trade-off for ALOHA systems.

A reasonable algorithm to use deciding how many slots to skip is to redistribute packets uniformly into the next L slots.

Allowing for a round-trip propagation delay of r slots, the number of slots between the first and second transmission may be R+l,R+2, , R+L, each with probability 1/L.

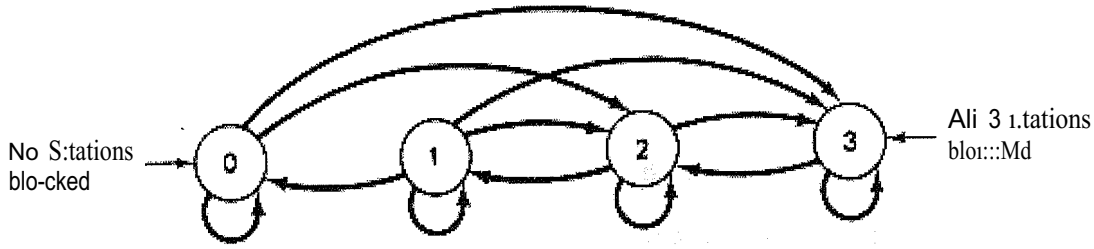
Unfortunately, this randomisation strategy is difficult to model, largely on account of the satellite propagati011 delay. lnstead, we will adopt a probabilistic model which previously collided packet (called a "b logged" packet hence worth) is retransmitted with probability in all slots following the original transmission unit it is sent. in this model the mean delay before retransmition si geometrically distributed, with the probability of a k slot delay given by The mean delay before retransmission is.

Notice that are inclllldirig the retransmission slot itself in the delay. Also Yeni.ernber that this delay the time the station is blocked, because a packet may have to be retransmitted many times and this delay corresponds only to the interval between consecutive retransmissions; it does ıot take into account how many such inter calls are needed.

Using simulation, lam (1974) has shown that the final result is sensitive to the assumed mean delay between retransmission attempts but not to the shape of the curve. By equating the mean delay in the probabilistic model to the mean delay in reality,we can use the probabilistic model, determine the optimal value for, and later deduce the appropriate value of L to use in reality.

The state of the ALOHA system can be completely described by telling how many stations are blocked. In sate k, there are k packets backlogged. Each of the backlogged stations may decide to retransmit its one and only backlogged packet, with the probability of transmission being and the probability of skipping the current slot being 1- . In addition to the mean retransmission traffic of k packets N- k unblocked stations are busy generating new packets at a collective rate of (N-k) packets per slot.

The sate of the system varies from slot to slot as new packets become backlogged and as backlogged packets are finally transmitted successfully. Unlike our earlier derivation of the M/M/1 queuing system, this is not a birth- death process, because state changes are not always to adjacent states. For example, three new packets could become backlogged during one slot. Figure 10 shows the allowed transiti ons for a three station system. Although the state may increase by more than one during a given slot, decreases are always in units of one, since the backlog can be reduced by at mots one during a single slot. Interestingly enough, the transition from 0 to 1 is impossible, because if there is no backlog and exactly one station decides to transmit, the transmission will always be successful.



An ALOHA system that moves around among 'a finite number of discrete. States in discrete fitne steps canibe môdeTled using a Markov process (Carleial an Hellm'an, 1975).

To analyse the behaviour of a Markov process, we need to calculate the probability, Pij , that a system in state i moves to state j in the next time slot. For convenience, we introduce the notation that n represents total number of *new* packets generated by the *N-i* unblocked stations during the current slot, whit *o::;n:s;N..i.* Sim'iIarly, r represents the number of retransmissions attempted by the i backlogged stations during the same time interval, with o::;r:s;i, Thus Pr [n=O] is the probability that no new packets are generated during the current slot, and Pr [r z 1] is the probability that one or more of the backlogged stations attempt a retransmission during current slot. With this notation, the transition probabilities can be written as in Fig. (a). The event probabilities are give Fig. (b) both for case of finite N and p and for the limit

N → ∞ p 7 0 , Np 7 S.

As an example, consider a slotted ALOHA syst three users, p=O. l, and a =0.2. The transition probabilities are given in Fig. (a). Notice that each row sums to 1.000 because

the probability that the system moves from its current state to *some* state is unity.

Initially, the system starts in state 0, with all stations unblocked . As time goes on, it approaches equilibrium. This does not mean that it is always in the same state', only that the probability of firidirıg the systerrı ın does not depend time (as it does in the early history) To solve for the equilibrium probability , *ek,* of firiding the system in state *k*, we must solve the simultaneous linear equations

$$e_k = \sum_{i=0}^{N} e_i P_{ik} \quad (k = 0, \ldots N)$$

subj ect to the constraint that $\sum e_k = 1$. Consider of the equations for N=3:

$$e_0 = e_0 P_{00} + e_1 P_{10} + e_2 P_{20} + e_3 P_{30}$$

Each term on the right-hand side corresponds to th probability of making the transition to state 0 from one of the states (including 0). The N+l equations are not independent, which why the additional constraint of requiring the ptobabilities to sum to unity is needed.

The equilibrium state probabilities can also be calculated in another way. If we take the matrix P_{ij} and multiply it by self, we get a new matrix, $P_{ij}^{(2)}$ which represents the two-step transition probabilities. For example, $p_{03}^{(2)}$ is the probability that an ALOHA system that is in state 0 during a certain slot

will be in state 3 two slots later. By multiplying Pij by it self rep_eatedly, we can get the n-step transition probabilities, each matrix multiplication adding one new step. For a well behaved Markov process such as ours, successively higher powers of the transition matrix .. rapi'dly approach Pij("") which gives the probability of being in state j given that the system was in state 1 long ago. (Figure 11 at -last .page) ObviO-u.sly thi s 1s independent of i, so all the elements in a column of I'ij (oo) are identical. in other words, all the rows are the, same, one gives the equilibrium state probabilities.

Given the equilibrium state probabilities, we can now the mean backlog (i.e., the expected number of stations blo waiting for retratı.smission):

$$\text{mean backlog} = \sum_{k=0}^{K} k e_k$$

To find the mean through put of the system, we need find the throughput for each of the possible states of the system, and then weight them by the equilibrium state probabilities. The throughput in state k is just the probability that a packet is successfully sent given that k stations are blocked and N-k

Origirıal state \ Nevıı state	0	1	2	3
0	0,972	0.000	0.027	0,001
1	0,162	0.792	0.036	0.010
2	0.000	0.286	0.676	0.036
3	0.000	0.000	0.384	0.616

(a)

At ec:ıuilibrium

0	1	2	3
0.760	0.131	0.095	0.014

ihroughput

0	1	2	3
0.243	0.306	U.~52	0.3841

{b)

Fig.12. { A three user slot ALOHA system with $p=0.1$ oc=0.2 (a) State transition probabilities. (b) Equilibrium values of state occupancy and throughput .)

are unblocked. A successful tran sm iss ion can happen ın one of two ways:

1. One unb lo cked station sends a new pack et; no retransmi s si 011s.

2.No new packets; exactly one retransmission attemp

The probability of this occurring is just

$$f_k = \Pr[n=1]\ \Pr[r=O] + \Pr[n=O]\ \Pr[r=1]$$

The mean throughput can now be found:

$$\text{mean throughput} = \sum_{k=0}^{N} e_k f_k$$

The equilibrium state probabilities and through puts for our three station example are shown in Fig.12 (b)

We now have enough information to find the mean delay as well . it is just the mean backlog divided by the mean throughpu t 1. e

$$\frac{\sum_{k=0}^{N} k e_k}{\sum_{k=0}^{N} f_k e_k}$$

This is essentially Little's result in disguise. Suppose, example, that the mean backlog is eight packets and the 111ean throughput is 0.25 packet/slot. If the stations queued up nicely, it would take 32 slots for a newly blocked station to work its way to the front of the queue. Nevertheless, the system can be seen as a single-server queue. Nevertheless, the syislem. can be seen as a single-server queue in which the qüeu.inğ cfisciplihe is not first come, first served. Instead, a random cüstôı:n.er is plucked from the middle of the queue each time and serveti:

F}gure 13 shows the throughput as a function of G, the del ay as a function of G, and finally the throughput-delay trade-off, using the Markov model, What is important to note is that delay is small as long as G is small. However, as soon as the system begins operating at too high a G value, the delay skyrockets due to collisions, and the throughput falls back. Notice the resemblance of Fig. 13 (a) to the infinite-population model of Fig 13, as well as the resemblance of Fig. 13 (b) to our earlier result E=eo (also for inf'in it e population).

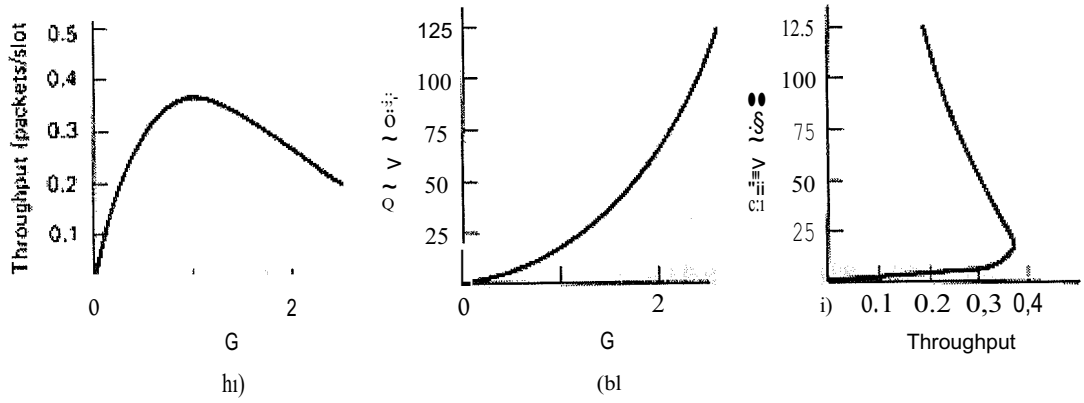


Fig .13. (Throughput and del ay cômputed Markov model with N=25 and oc =0.1.)

Stability of Slotted ALOHA

Some ALOHA system are inherently stable atid others inherently unstable. Due to random statistic fluctuations once in a while an unusually large number of unblocked stations will attempt to send during the same slot. Thete will be a collision and all the packets will become backfogged. Due to the large number of backlogged packets, thefe <Will be many collisions in the succeeding slots and the thröughput will be less than normal. As new packets are generated, most of them also become backlogged . Eventually, all N stations become backlogged, and from Eq. (9) we get

throughput =Noc(l-oc)N-l

Equation (9) suggests that by making oc small, we can achieve non negligible throughput even when the system is badly backlogged. This observation is true , but the price we must pay is long delay times. By Eq. (8) a small value of oc corresponds to a large value of L. In other words, the random time waited between retransmission rises quickly with decreasing oc If 1000 backlogged stations spread their retransmissions out over a million slots, the eh ofa collision will be negligible, but the price paid is terrible response.

To investigate the stability of slotted ALOHA, we n relation between mean backlog and mean thr.oμghpμt. Typically p is a given quantity i.e. the slot time divided he mean think time eg the user population . Using Eq, (9) it is straightforward to calculate the throughput as a function of the backlog has reached 60 packets, at oc=O.1 we are attempting to retransmit 6.0 packets/slot, not to mention any new packets. Thus it is not surprising that the throughput is low. For backlogged stations and oc=0.22, the retransmitted pac represent a load of only 1.2 packets/slot, which is only slightly higher than the optimal value of G.

As more stations become backlogged, the rate of packet generation drops linearly. With k stations backlogged, the input rate is (N-k) p. The input rate as a function of backlog is shown in Fig. 14 (b) for the case of p=0.002 N= 100. Such a plot is referred to as a load line (Kleinrock

Lam, 1,975). The slope of the load line is-p; its x intercept is

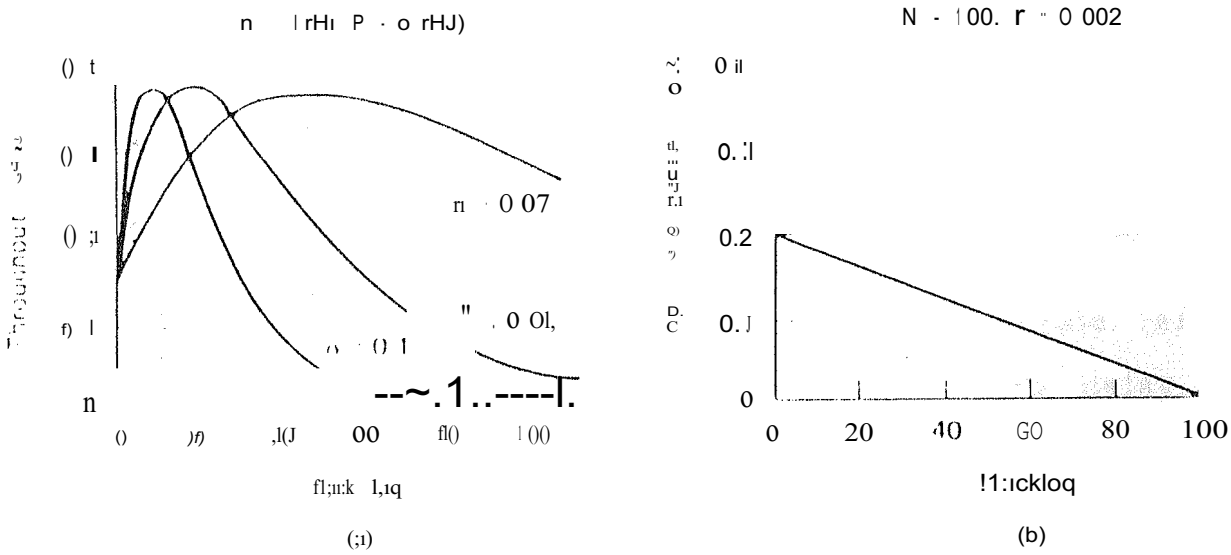


Fig. 14 ((a) Throughput as a function of backlog. (b) Input as a function of backlog.)

At equilibrium, the throughput rate 'mu equal the input rate. By drawing the throughput curve and the lo on the same graph, we can find their intersections, as shown in Fig 15 . For 'cases are depicted in Fig 15. in the first case, N is small the system is lightly loaded, and equilibrium is achieved whit a low backlog. So little traffic is offered that packets nearly always get through the first time and no backlog builds up.

Nevertheless, it is important to realise what happens if sudden fluctuation in input moves the system to a high backlog, as shown by the dotted vertical

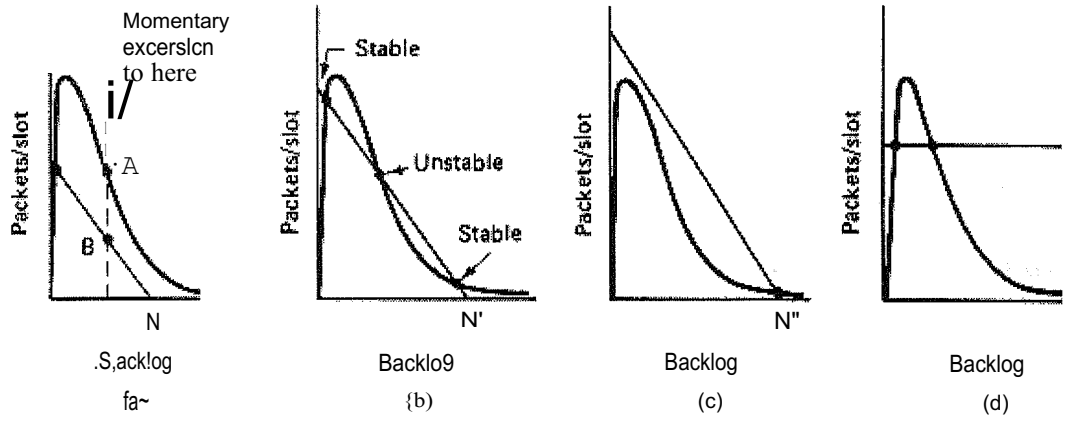


Fig. 15 (At equili brium, in put rate equals throughput Stable low delay (b) Bistable. (c) Stable, high delay. (d)Unstable.)

line . The throughput is rrow at poinf A and the input is at point B. Since A is hfg̃het than B, then throughpufe:x.ceeds the input area, which drives the backlog down 10 the eqifiifibrfurn po int. Any excursion above equilibrium produced a throughput higher than the rate at which new packets are generated. Similarly, an excursion to the left drops the throughput so sharply that the backlog builds up again. No matter what the backlog is, there are forces driving the system inexorably back to the equilibrium point. If the load line crosses the throughput curve in exactly one place, the system is globally stable and will always return to the equilibrium point after any excursion, no matter how big it may be. Lam (1974) has shown that the values of backlog and throughput at the equilibrium point are excellent approximations to the true mean backlog and mean

throughput calculated by forming a weighted sum over all possible system states.

Now let us be greedy and increase the number of users, so that the load line moves up to the position of Fig. 15 (b). The load line intersects the throughput curve in three places. At all three points the input rate equals the throughput rate, so each one represents a possible equilibrium point. Two of them are stable. First consider the low backlog equilibrium point. For small excursions either way, the situation of Fig. 15 (a) prevails and the system is stable. At the middle equilibrium point, the situation is exactly reversed. If the backlog increases momentarily, the throughput drops faster than the input rate, so the backlog becomes even larger. The situation feeds upon itself until the system reaches the high backlog equilibrium points correspond to nearly no one backlogged and nearly everyone backlogged, respectively.

Begin even more greedy, as in Fig. 15 (c), is like killing the goose that laid the golden egg. The channel is now completely overloaded. The only equilibrium point is when the input rate and throughput are both very close to zero. When there are an infinite number of users, the input rate does not drop as the backlog state, the input rate will continue to exceed the throughput rate and the backlog will grow without bound.

Carleial and Hellman (1975) have expressed the stability problem in a slightly different form. They pointed out that the mean drift of the system in state i is.

$$\sum_{j=0}^{N} (j-i)P_{ij}$$

States with drift of 0 are equilibrium points. If the slope of the drift curve at the equilibrium point is negative, 'the equi ibr'iuni is stable, because increases in the backl'oğ tend to ma.ke the system drift dowtrwafd, arıd viCe \l'ersa.

An interesting question about the bistable sitUation öf Fig. 15 (b) is: What is the chance of the system gettin g itse l f into the high backlog stable state? Inductively , the farther down the "hill" the low backlog stable equilibrium point is, the less likely it is that a momentary burst of activity will push the system past the point of no return.

To calculate the probability of an initially eıi:ıpty)sysfem being near the unstable equilibrium point after a give11 numb er of slots, proceed as follows, Take the state-transition matrix and make state k absorbing by setting Pkk=l and all the other elements of row k to 0. With this new matrix if the system ever gears to state k, it will stay there. This model ıs an approximation, because the chance of spontaneously escaping from the unstable region, however small is not zero. By computing successive powers of the transition matrix, we get the multi step transition probabilities. The element P_{0k} gives the probability of the system having reached state k starting from an empty sys te m. By plotting Pok against the power of the transition matrix, we get the probability of reaching the unstable state with the corresponding time interval.

Figure 16 (a) shows the throughput rate, input rate afrd load line for 25 stations and p=0.01 . The corresponding multi step transition probabilities, PoN are show in Fig.16 (b). With = 0.25 there is a 50% chance that the backlog will grow to 2 within 10.000 slots. With oc = 0.40 the 50% point has dropped to 1000 slots. Wifh theie pa.r~hıeters, the system will collapse within seconds of begin sJatt.e(1 .ıtp\. Ry adjusting ∝ it is possible to trade off stability against delay. sınce the mean delay is closely approxiınated by the backlog divided by the throughput at the equilibrium point, from Fig. 16 it is easy to see that Ihe stability is more sensitive to oc than the del Conscquently, systeın designers have some latitude in choos i.ng a value o(oc that is sınall enoııgh to pr.ovide good stability, without extracti ng too heavy a price in terrns of excessive delay.

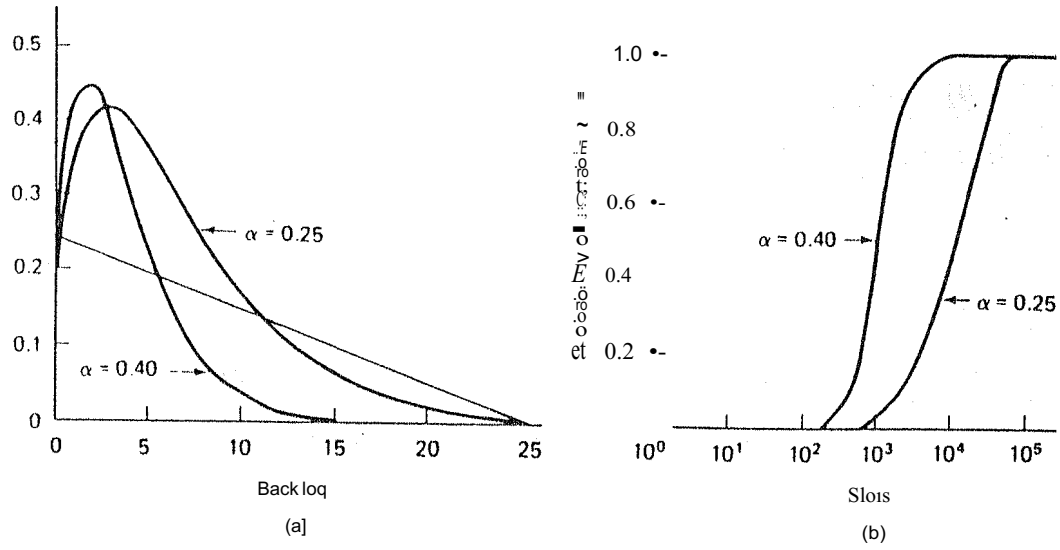


Figure 16 (a- Input throughput for N=25 and P=O.O l b- Probability of the system having reached state 25 within the specified number of slots.)

Controlled ALOHA

The o nl'y way t o' guaı'an.lee a stable syslem with a.fixed oc ıs to restrict the number of users to su eh low value that load line crosses the throughput curve in only orre place. Doing so is often uneconomical, because it gears the system t'o wôtst.. case behaviour. Put in other words, setting the parameters sb<as to guarantee stable operation under all circumstances, no m atter how unlikely , re str ict s the numb'er of us ers 'to a value so small that the sys te m may cost too much to be econoıni9allyjıstified. however, as we can see from Fig. 14 (a), oc has an iınportant influence on the shape of the throughput curve , and hence .o n the stability . If we could somehow decrease oc when the system got into trouble, we could raise the throughput curve above when the backlog is small (to get rid of packets quickly and achieve a short delay time), and small when the backlog is large (to drive the backlog down).

Several methods have been proposed (Lam and Kleinrock, 1975) for controlling oc dynamically in order to achieve short delays when the system is lightly loaded and stable behaviour when it is not. üne method is simply to have each station keep track of how many retransmissions the packet currently in the

output buffer has to its credit. When a packet is first generatedt the counter is set to zero . Upon each collision, it is increased by one . The value of the counter can be used as crude measure of the channel load. The station could have a series of (fixed) retransmission probabiliities, cci (i.e., randomisation intervals, Lj) subject to =: +1 ~ =r- As the channel load increases, every station attempting to trarismit wil]: autoıatically wait longer and longer between successive retransmissions This method has the advantage that it relies only on information directly available to the station (i.e. it does not require the station to monitor the channel other than to see if its own packets have collided). It has the disadvantage, however, that each packet must learn about the channel load all over again.

Lam and Kleinrock (1975) have studied ano.ther controlled ALOHA method that does retain some history, so that new packets can profit from their predecessors experience. In his scheme, there are only two values for oc.a large one that is used when the system is operating properly, and a small one that is used when the system gets into trouble . Whenever the collision rate exceeds a certain threshold value, all stations switch to the lower value and continue to use it until things are back to normal.

A more direct approach to the control problem is based on Abramson's observation that the throughput is maximised at G= 1. The goal of this method is to have each station estimate G

and adjust its own value of oc upward if G<l and downward if G>l.

To estimate G, we can use Eq. (1). The probability of an empty slot, P_0,is G_0e-o/0! which is just e·o. Taking logarithms, we have G=-In P_0. P_0 can be easily estiriiated by noting the fraction of slots th at" wete en1pty diir'in'g the recerit past. This requires a shift register with 1 bit per slot. The observation period should be longer than the round-trip time, to prevent instabilities.

When the channel is lightly loaded, we would like oc as large as possible subject to the constraint of Eq. When the channel is heavily loaded we want oc form G, for example oc=e·o/(R+l). This function ensures that we do not atrernpt to reduce L bellow 1, even when the channel is idle. The function is also easy to compute, because e -G is just the fraction of the shift register positions containing 0 (no collision).

Gerla and Kleinrock (1977a) have proposed another method based on estimating G. Their method is designed to handle the case of stations that do not block when a packet is generated, but just keep on going . As a result , two queues may build up in each stations: virgin packets that have not been sent yet and packets that are waiting for retransmission. Different probabilities are used for these queues. They propose that each packet header contain the probabilities currently in use at the sender' s station. In this way each station can set its parameters to be equal to the sender's station. In this way each station can

set its parameters to be equal to the mean of everyone else's, plus a correction term of the form (1-G)Dı, where D is an experimentally determined constant. When G> 1, the collection term is negative, decreasing the appropriate oc, when G<l, cc increased. The feedback inherent this proposal ensures that the probabilities only change slowly and, furthermore, that no station gets too far out of step with the others.

Reservation ALOHA

Even the most clever dynamically adjusted control scheme will never get the throughput of a slotted ALOHA channel above /e (except for small N) However, at high channel loads, there are other methods for makirıg good use of a sirigle shared channel, in particular, time-division multiplexing. Several researchers have proposed control schemes that act like .rıorrna.l or nearly normal slotted ALOHA at low channel utilisation, and move gradually over to some kind of TDM as the channel load grows.

All these methods have one feature in common: some slots are reserved for specific stations. Stations are required to refrain from attempting to use a slot reserved for somebody else. The methods differ in the way reservations to use a slot reserved for somebody else. The methods differ in the way reservations are made and released. For comparison, remember

that in TDM the slots are organised into frames of N slots, each slot permanently reserved for a specific stations.

Binder (1975) proposed a method that starts out with the basic TDM model and adapts to slotted ALOHA for low channel utilisation. As in. TDM, N consecutive slots are grouped together into a frame,\witht eachcstationiF'oWning" one frame position. If .the.re are more. .s.lots than /statio.ns, the. extra slots are not assigned to antenna. If the owner of a slot does not want it during the current frame he does nothing. an empty slot is a signal to everyone else that the owner gas no traffic . During the next frame, the slot becomes available to anyone who wants it, on a connection basis. If the owner wants to retrieve "his" slot, he transmits a packet, thus forcing a collision (if there was other traffic). After a collision everyone except the owner must desist from using the slot. Thus the owner can always begin transmitting within two frame times in the worst case. At low channel utilisation the system does not perform as well as normal slotted ALOHA , since after each collision, the collides must abstain for one frame to see if the owner wants the slot back. Figure 17 (a) shows a frame with eight slots, seven of which are owned.

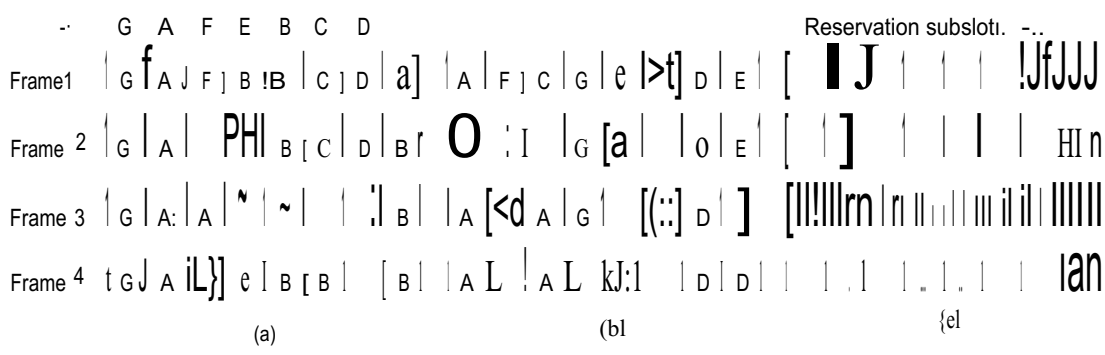


Figure 17 (Reservation scheme (a)Binder (b)Crowther c)Roberts)

One slight inefficiency with this method is that whenever the owner of a slot is through with it, the position must go idle during the next frame to announce that its owner is done. To eliminate. this wasred slot, an extra bit .coüld be<added to the header of all packets to anno'unce that the owrıer thaf the owner did or did not have any more data for the next fr ame.

A much more serious problem, however, is that the number of users must be know in advance, or at least bpunded from aboce. If this is not the case, several users could be assigned to the same slot, in the hope that it will not occur too often that both of them claim th'e slot s irmi It'ane ou s l y. To arbitrate w'h e n this does happen, each user c oul d be given a static priority, with lowerpriorty usersdeferring to higher ones in the case of conflict.

Crowther et al. (1973) have proposed a different reservation method that is applicable even when the number of station ıs unknow and varying dynamically. In their method,slots do not have permanent owners, as in Binder's but instead, whenever a transmission is successful, the station making th e succesful transmission is entitled to that slot in the next frame as well. Thus aslong as a station has data to send, it can continue doing so indefinitely (subject to some "Please-do-not-be-apig" rules). Since it is unlikely that all stations will have long runs of data send simultaneously, this method works

well even when the number of slots devoted to each varying with demand. Figure 17 (b) shows a frame with eight slots. Initially, E is using the last slot, but after two frames, it no longer needs it.It lies idle for one frame, and then D picks it up and keeps it until he is done.

A third scheme, due to Roberts (1973), requires stations to make advance request before transmistt irig: Each frame contains one special slot (the last one in Fig. 17 (c)), which is divided into V smaller subslots used to make reservations. When a station wants to send data, it broadcasts a short request packet during one of the reservation subslots. If the reservation is succesful. (i.e., no collision), then the next regulat slot (or slots) is reserved. At all times everyone must keep track of the queue length, so that when any station makes a succesfull reservation it will know how many <lata when any station makes a successful reservation it will know how manu <lata slots to skip before transmitting. Stations need not keep track of who is queued up; they merely need to konw how long the queue ıs. When the queue length drops to zero, all slots revert to reservation subslots, to speed up the reservation process.

To see if satellite packet broadcasting worked as well ın practice as it does in theory, starting in 197 5, DARP A (nee ARPA) began supporting an experiental packet broadcasting system using a 64 kbps Intelsat IV satellite channel (Chu et al., 1979; Jacobs et al., 1978; Jacobs et al., 1979; Kalın, 1979). The paper by Kalın is especially interesting; it describes the legal

hurdles faccd by DARPA, cvcn though the project was clearly a research experiment, and was sponsored by the U.S.government.

Thc satcllitc nctwork, onw as SETNET, uscs large ground stations in Eta m, Wcst Virginia; Goonhilly, England; and Tanum, Swcden; and a smallcd ground station in Clarksburg, Marylan. Thc protoe'o'l üsed, called PODA '(Pr'i ör ity Oriented Dcmand Assignnıcnt), has two art snrs, FPODA (Ei'x ed PODA), which is csscntial TDM, and CPODA (Contentioh POIJa), which ısa sopliisticatcd vcrsion of Robcrts rcscrvation schemc.

Each Iramc is divided into a data part and a control part for rcservations. The relati.ve sizcs of the two parts are dynamically adjustcd dcpcndin g on .the load. A p.ortion the data part is reservcd for FPODA, providing guaranteed bandwidth for thosc processes nccding it. The rest of the data par t is used by CPODA. An intcrcsting f'catura of CPODA is thc ab ility to piggyback rcscrvation rcquests onto data packcts, whit the cons cqıcıcc that hcavy ıscrs of thc chan ncl do n.ot ha Ve to kecp fighting fo r rcscrvation slots. Thc rcscrvation information is used in lhe schcduling of the channel rather than simply using first come, first servcd. A sophisticatcd scheduling of the channcl rathcr than simply using first come, first served. A sophisticatcd schcduling algorithm is nceded since packet specch is transmitted, as well as <lata.

PACI(ET RADIO

Gr ound raclio packct broaclcasting differs from satellite packct broadcasting in scvcral ways. in particular, stations have limited rangc, introducing ıhe necd for radio rcpeatcrs, which in turn afects thc routing and acknowledgement schemes. Also, the propagation dclay is much less than for satellite broadcasting. ln the Follo.wing sections we will look at some of the ways in which ground r.adio diff'crs from satellite packet broadcasting. More details are providcd in (Gitman et al., 1976; Kahn, 1977, Kahıı et al., 1978; ancl Tobagi, 1980b, 1980c).

The Universty of Hawaii ALOHA systeın

T'hc first computcr system to cmploy radio instead of point-to-point wircs for its communication facilty was the ALOHA systcm at the Urıiversty of H'aw.a.ii The .systern first went on ıhe air in 1971, and has beerı evolving. ever since. Siıcc this systcm is thc ancestor of all packet broaelcasting systcm, wc clcscribc it bclow in some dctail. For a more complcıc dcscription, see (Abramson 1970, 1973b; and Binder et al., 1975).

Thc ALOHA systern was bcgun to allow peoplc at the Univcrsity of llawaii, who wcre spercad out over seven campuscs on four island, to access the main computcr center on Oahu without using telephone lines, which were expensive and unreliablc. Comnıunication is providecl by equipping each station witlı a small FM radio transmitter/receiver with suffi cient ıange (30km) to talk to thc computer center's

transmitter/receiver. La ter, a powerful repeater was introduced, increasing the theoretical range to 500 km.

All communication is either from a station to the computer center or from th e computer center to a station . There is no station-to-station communication. When a packet is received at the compüter ceriter, it is process'ed there. It is not retransmitted for all other stations to hear. This arrangement is fundamentally different from the satellite bro.adcasfin gom.o.de1, in which the satellite is merely a big repeater in the sky. Since incoming packets are not rebroadcast, a station has by the central site. As a result, explicit acknowledgements are needed, just as in point-to-point connections.

After overcoming some initial skepticism about the unusual coomunication mechanism, the project was assigned two bands in the UHF part of the spectrum. üne frequency band, at 407 .350 Mhz. is used for inbound traffic, from stations to th e central site. The other frequency band, at 413,475 Mhz, ıs use d for ou tb ound tr affic , from the central site to stations. Transmission is at 9600 bps. The of distinct vhannels for inbound and outbound traffic has important imp licati o ns for the whole system organization. After several years öf experience, the research group concluded that a single channel probably would have been a better idea.

The original rationale for haing two distinct channels was the fundamental difference in the inbound and outbound traggic. Inbound, many uncoordinated ysers are competing for

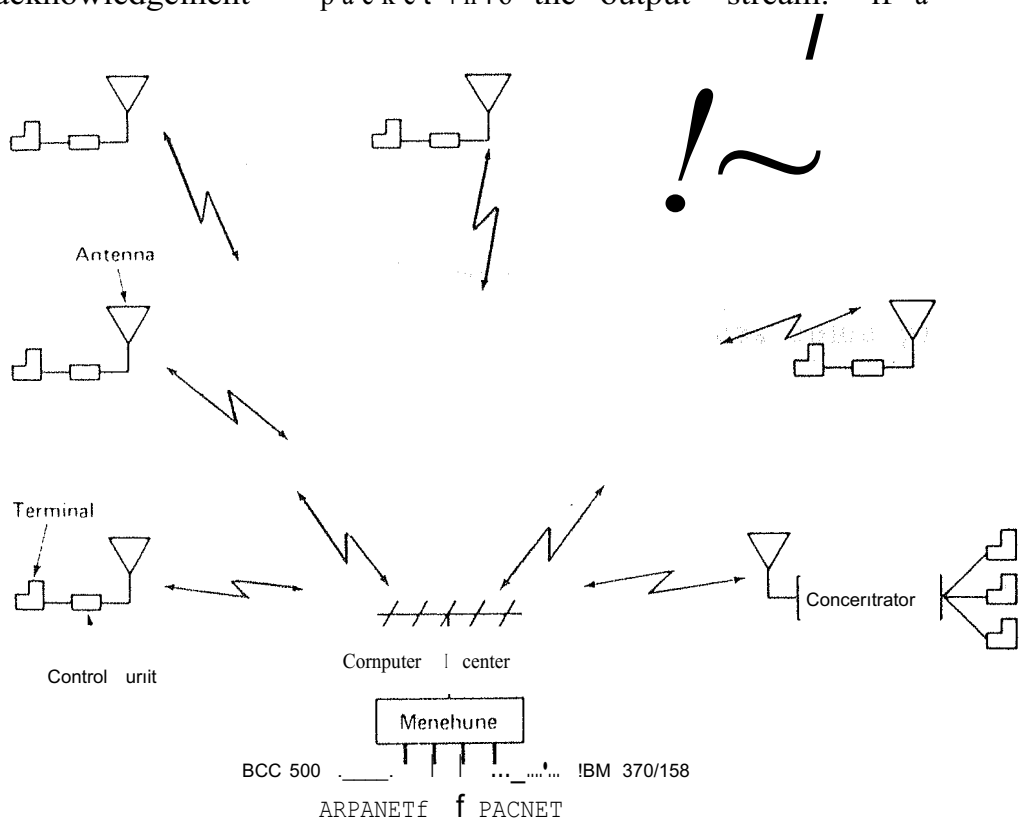
access to access to a shared resource. Outbound, a single site is in complete control of the channel, so there is no contention and no collisions. The basic idea is to use the inbound channel on a random access (what is now called pure ALOHA) hasis, and the outbound channel on a straight broadcasting hasis, with each station extracting those packets directed to it form the output stream.

Figure 18 shows the essential elements of the ALOHA system. At the central site is a 32 K HP 2100 minicomputer, called the Menehune (the Hawaiian word for "imp") that is connected to the antenna. All data in or out of the central site passes through it. The Menehune, in turn, is connected go two large computers, an IBM 370 and the BCC 500, as well as to two other networks, ARPANET and PACNET. Each station has a control unit that were hardwired, but later Intel 8080s were used to provide more flexibility. Some stations are connected to concentrators to reduce transmitter/receiver costs.

Packets consist of four parts. First comes a 32-bit headre, containing, among other things, the user identification and the packet length. To provide good reliability, the header ıs followed by a 16-bit checksum. Next comes the data, up to 80 bytes (640 bits), followed by another checksum. The maximum packet is 32+16+640+16=740 bits. At 9600 bps, the transmission time for the longest packet is 73 msec.

When a station has <lata to send, it just goes ahead and send. This way ogf operating is ALOHA at its purest. When the

Mencliunc correcıl y rcccıvas a packct, it inserts an acknowlcdgcıncnt packet ınıo thc output strcam. lf a



slalıon docs not rcccivc an acknowledgcment within a preset time, it assumes that the packct suffered a collision, and rctransmits it. 'Th e rctransmission intcrvals are distributed between 200 and 1500 mscc, with various distributions having becn tried (e.g., uniform, thrce shorts and thcn a long, ete.).

Although control of the outbound channel might at first seem trivial, thcrc are sonıc important design issues here too. For one thing, transnmitting packcts on a first come, first servcd hasis is not a good idea, bccause ifan acknowledgement packct is dclaycd ıoo long, ıh e station will assumc that a

collision has occurred and send the packet again. Under conditions of heavy load, many unnecessary retransmissions will occur, making the situation even worse. Consequently, the Menehune maintains a separate queue for acknowledgement packets and gives this queue priority over the <lata queue.

The use of store-and-forward repeters (to amplify signals and thus .increase .ıheir raııge) intrcduees some prcbiems. The repeaters use the same frequency for output as for input. This means that a rapeater connot start the retransmission until the input has been completely received and stored; otherwise, they would overlap and be unintelligible. If the Menehune broadcasted a new packet while a repearter was still forwarding an old one, stations within range of both while a repearter and the Menehune would receive the superposition of the two packets, which is meaningless. Furthermore, while forwarding a packet, the repeater is not able to accept new packets. Consequently, the Menehune must be careful about the order in which it send packetsi and must the the repearter geometry into accounty when making schedulling decisions.

Another problem unique to ALOHa is the way in which errors are handled. Because packets are not rebroadcast for all to hear, the Menehune must send acknowledgement packets back to the stations. Doing so is straightforward and causes no problems. What does cause problems is the Menehune's lack of knowledge about whether or not its transmissions are being correctly received. in an urban area, such as around Honululu,

there are many electrical devices that can cause static on an FM radio.

The obvious solution is to have the stations acknowledge reception of computer <lata, as well as vice versa. The trouble is, these acknowledgements must be sent in the random access channel, where it' s dog eat dog. The ptobabilty of an acknowledgementbeing delayed fora sub stanci af period of time due to collisions and timeouts is much greater than on a point-to-point line. If the acknowledgement is delayed too long, the Menehune times out and tries again, wasting valuable bandwidth.

The worst part of it is, the station has no way of konowing whether or not its acknowledgement has gottenn through. üne solution would be to have the acknowledgement themselves be acknowledged. This solution is not used. Instead, output packets are numbered. The Menehune simply refrains from sending a new output packet untill the previous orre has been acknowledged. When a station receives a new output packet, it knows that its last acknowledgement has arrived.

Yet another peculiar property of packet broadcasting that was first noticed in the ALOHA system is the need to decouple the transmission speed from the station speed. in a conventional time-sharing system, the computer knows the speed of all the stations and sends <lata to them at the correct speed. it does not try to force feed 300 bps hardcopy matrix

printers at 9600 bps, There is also no need to, because each station had a dedicated line connecting it to the computer.

in ALOHA, the situation is different. The Menehune could keep track of the printing speed of the recipient of each packet and adjust its bit rate accordingly, but sending a page of output at 300 bps would be a tremendous waste of bandwidth and would adversely affect all other users, even those with fast CRTs. The solution used is to have the Menehune always broadcast at 9600 bps with local buffering provided at the station. Nevertheless, the Menehuns must keep track of the actual printing speed, to avoid sending more data before the old data have a chance to be printed.

An a alternative solution would be to have the station refrain from sending its acknowledgement until it had finished printing. The trouble with this is that if the acknowledgement were delayed substantially due to collisions, the printer would lie idle, even when there was plenty of work for it. By sending the acknowledgement as quickly as possible (i.e., as soon as the data are received), the printer can be kept busy all the expense of some complexity in the Menehune.

Dcsiıg Issucs for Packet Rad io Networks

in ıhc prcccding section wc lookcd at the original ALOHa sysrcm as an cxamplc of a ground radio packet broadcasting systcm. lıı this scction wc will cxaminc some additional design problcms oltcn prcscnt in thcsc systems. The introduction ofa largc ıuıımbcr of repcatcrs, in particular (to increase the geographic covcragc of ıhe system), brings with it a number of complications because repeaters store incoming packets and then rebroadcası tlıcm on thc same frcquency . Siınultaneous rcception and ıransmission is lhcrcforc impossible.

Lct us lirst look at thc conceptual model ofa packet radio systeın. Thcre are (at least) thec situations in which packet radio is aıtractive as a method of loca! distribution froın a central site ıo rcmotc stations,

1-The stations are locatccl in arcas where the telephone systcın is poorly dcvcloped or nonexistent; nearly ali rural areas, and most of thc T'hird World falls into this category. Automated wcathcr and scismic data collection stations arc oftcn parachuted into junglcs, dcserts, and hostilc ınountain terrain, which frcqucntly lack the amcnities of civilisation, such as ıclephone polcs.

2-The stalions are mobile. A flcet of ships is a good cxamplc of a group of users that is inhcrently mobile. Policc cars, ambulancos, fire cngincs and taxis are other cxamples.

3-Thc stations have a high peak-to-avcrage traffic ratio, or a low data raıc. in both cases, the cost ofa dedicated linc

may make the application uneconomic. Packet radio offers the possibility of sharing a single channel instead of having a large number of channels with fixed (and mostly wasted) capacity.

Although portable FM radio transmitters are usually equipped with a simple whip antenna, which makes them omnidirectional, repeaters may be equipped with omnidirectional or directional antennas, as needed. Repeaters may also be able to adjust their range. If a substantial number of repeaters ate battery powered, the system design must be sufficiently redun band to cope with repeaters whose batteries have gonedeaf, since this will be a regular occurrence.

When a packet radio system contains multiple repeaters, routing becomes an issue again, just as in point-to-point-an-forward networks. The most naive routing strategy, just having each repeater act as a transponder, storing and forwarding all incoming packets, does not work at all. Every packet would just bounce back and forth between adjacent repeaters forever, clogging up the channel.

When a repeater receives a packet, it must make a decision. To forward, or not to forward, that is the question. The choice of forwarding or discarding is analogous to an IMP's choice of output line in a point-to-point network. The goals of the routing procedure are the same as in all networks, of course; to achieve a high probability of delivering packets to the ultimate destination and to consume the minimum resources in the process.

Gitman et al. (1976) have suggested three possible routing strategies. The first algorithm is a modified version of flooding. Each repeater just forwards all incoming packets, subject to two restraints. The first restraint is a hop counter, which is included in the header of each packet. Each time the packet is forwarded the hop counter is decremented by one. When this counter gets to zero, the packet is discarded. This rule by itself is sufficient to guarantee that no packet lives forever.

The choice of the initial value of the counter is an important design parameter. lf it is too small, packets destined for outlying areas may never arrıve. lf it is too large vast numbers of useless duplicates may be generated, wasting precıous bandwidth. The problem is complicated by the fact that the central site may only have an approximate idea of the topology, if that much. in Fig. 19(a). the shortest patlı from the station to the central site is two hops, but if the battery in repeater A has become sufficiently drained, it may not have enough power to reach the central site. in that case a hop limit of two in the packet would prevent the packet from ever arrıvıng . With a hop limit of four, the packet could take the other route. The problem of choosing the hop count is closely connected with the problem of ensuring that a point-to-point network has k node disjoint paths between each pair of nodes. As the hop count is allowed to increase , more and more alternate paths become feasible, there by making the network

less and Iess vulnerable to repeater failures. If each station has a reasonable idea of how many hops it is form the central site, it can choose a hop limit appropriate to its distance rather than having all stations use the worst-case value.

A second restraint that is need to make flooding a practical algorithm is for repeaters to be available to recognise returns of packets that they have recently forwarded. Consider the example of fig. 19 (b). Suppose that the maximum number of hops for the station shown is set a four.

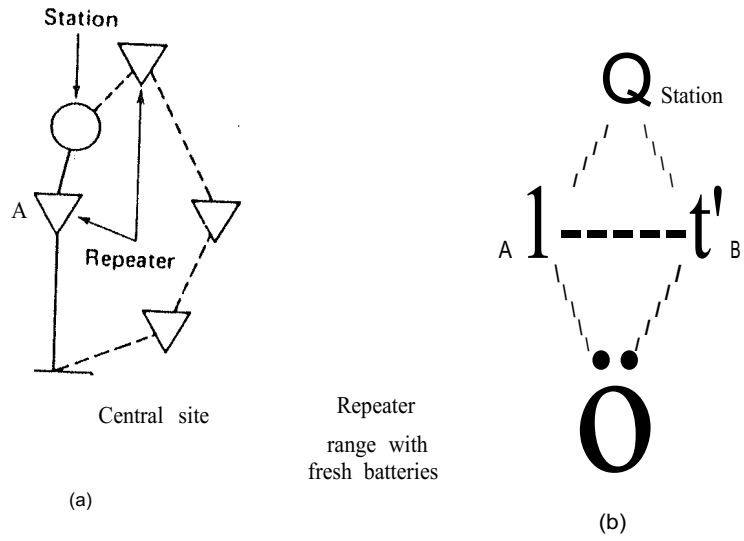


Figure 19 (a-T'h o shortest route fro m the station to the central site is shown as a solid Iine, b-An other repeater topology)

when the packet ıs answer packet due to another repeater, it appends its identification to the packet. Form the returned answers, the central site can easily determine the shortest patlı to each repeater. Upon learning the new topology, the central

site then informs each repeater of its new label. A label is just a patlı description, as shown in Fig. 20.

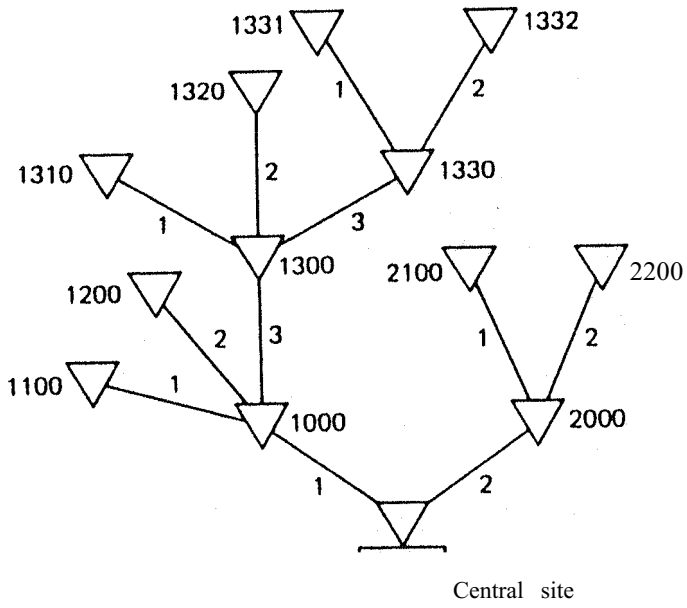


Figure 20 (A repeater tree and its labeling)

ünce the repeater tree has been formed, each data packet sent by the central site can contain the label of the repeater to which station has been assigned. The packet ınust also contain a pointer telling which field in the label is the curr erıt one. When a packet arri ve s at a repea ter, the rep ea ter checks to see if it is naıned in thc current field. If so, it advances the pointer by one field an forwards the packet. Of not, it just discards the packet.

To see why this ıncchanism is needed, consider a packet directed to repeater 1310 in Fig. 20. The central site initialises the pointer to the first 1 and broadcasts it. Repeater 1000

knows that it must forward it, and any other repeaters that hear the packet do not forward it. By the time repeater 1300 forwards the packet, the pointer is now pointing at the second 1. Were it not for the pointer, repeater 1000 might detect the packet, see that it was on the patlı, and forward it again.

If repeater along the required patlı has failed, all is not lost. The repeater, failing to get an acknowledgem.ent, could set a bit in the header telling all repeaters to adopt the flooding algorithm for the packet. It could also announce the failure to the central site (assuming that it was still connected), requesting the central site to conduct another probe and relabel the tree.

The broadcast nature of packet radio makes a completely different strategy also possible: the repeater could simply advance the pointer one field, turn up its power, blast away, and hope to skip over the failed repeater. This strategy implies a conservative deign, in which repeaters normally operate at less than full power. üne problem, however, is that although the correct repeater may receive the packet, it may be too weak to get the acknowledgement all the way back.

In the third routing algorithm, a repeater only forwards a packet it is closer to the destination than the last repeater that forwarded the packet. Each repeater is assumed to know its distance in hops from every other repeater. This information can be acquired by having each repeater broadcasts its distance table periodically. Each <lata packet contains the identification

of the destination and the sender's distance from that destination. At each hop there is a new sender, and hence a new distance. When a packet arrives at a repeater, the program checks to see if it is closer to the sender. If so, the packeı ıs heading the right way and is forwarded. If not, the packet ıs heading the wrong way and is discarded.

As an example, consider Fig. 21 When the central site sends a packet to A, it indicates that the distance is three hops. Both J arıd K receive the initiaJ transmission. J knows that it is only two hops from a, so it forwards the as far away as the sender, so it discards the packet. The packet sent by J is received by F, G, H and k. Of them, F and G are the only ones closer than rwo hops, so they alone forward the packet, each one changing the distance in the header to 1. A wil] eventually get two copies of the packet. This algorithm always uses the shortest patlı, but it is more robust thau the previous orıe, because it concurrently tries all alternate paths whose length are equal to the minimum length. It also consumes more bandwidth. This algorithm is also minimum length. It also consıımes more bandwidth. This algorithm is also applicable to station- station traffic rather !han just station-central site traffic. A lası point in its favor is its ability to easily adapt to mobile repeaters. The ARPANET algorithm adapts to new topologies.

An important design ıssue that must be resolved no matter which routing algorithm is chosen is the way packets are

ackonwledged. There is a basic distinction between hop-by-hop acknowledgeınent and end-to-end acknowledgeınent. When the error rate is low, the end-to-end scheıne ınay be sufficient, but when the error rate is high, as it is likely to be in a packet bro adc as ting en vironınen t, hop-by-hop should be used in order to detect lost packets as quickly as possible. üne property a network of packet repeaters has in coınınon with satellite broadcasting is the ability of a repeater to tell whether or not its neighbour received the packet correctly by just listening to the retransınission, In ınany cases this ınay eliıninate the need for an explicit acknowledgeınent. However, soıne kind of acknowledgeınent is still needed at the end of the patlı, because neither the station nor the central site retransınits its input.

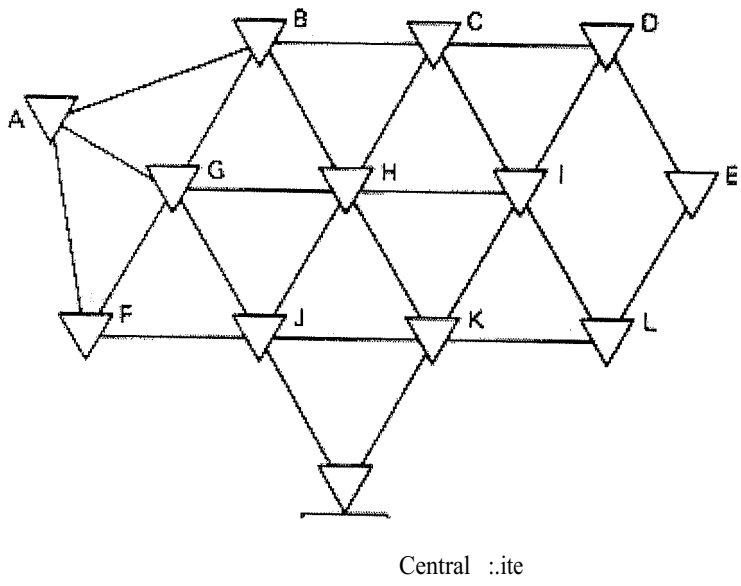


Figure 21 (A repeater Network)

Up until now we have made the assumption that when two packet collide, both will be lost. in fact, these is overly pessimistic. Since many FM receivers are able to extract the stronger of two overlapping packets without error. This phenomenon is known as the capture effect. To see how this influences the system performance, imagine that there are two classes of stations, one broadcasting at high power, and one at low power, (or one group close by and one group far away, both hat the same power). Of two overlapping packets both originate from the same group, the receiver cannot disentangle them, and both are lost. lf, however, they originate from different groups, the stronger one will be accepted. in half the cases, what was previously counted as a collision is now a success! An interesting property of the capture effect is that under conditions of heavy load, stations close to the central site may generate so much traffic that stations farther out are locked out completely. This occurs because when a close in and a far out station collide, the close in station has a stronger signal and always wins. Metzner (1976) has analysed the capture effect quantitatively.

CONCLUSION

Communication satellites are fundamentally different from terrestrial store and-forward networks in that they offer a single channel that must be allocated among the users. When

there are many bursty users, FDM and TDM are inefficient ways to use the channel, which leads to the ALOHA approach.

ALOHA systems, stations broadcast at will, detect the presence or absence of collisions them selves and retransmit if necessary. The key difference between ALOHA and other protocols for controlling a single channel is that in ALOHA there is no centralised channel allocator.

Slotted ALOHA can be modelled as a Markov process. Form this Markov model, we can find the equilibrium state occupancies, the mean throughput, an the mean delay -, as well as analysing the stability. To prevent bistable ALOHA systems from moving into the low throughput state, the retransmission probability can be dynamically adjusted. By using various reservation techniques, the throughput can be increased well above the 1/e limit of slotted ALOHA.

Packet radio is similar to satellite broadcasting, with the problem of the long propagation delay replaced by the problem the repeater topology. Routing becomes an issue again, just as in point- to-point networks, and some of the same techniques can be applied to deal with it. ..

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