PACKET BROADCASTING NETWORKS

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Abstract

Computer-communication networks employing packet broadcasting techniques can be implemented using satellite or ground radio channels, coaxial cables or optical fibers. We shall give an overview of packet broadcasting techniques and examine them within the evolution of resource allocation techniques for computer communications.

To be presented at the Workshop on Pattern Database Systems, Tokyo, December 14-16, 1977.

1. INTRODUCTION

The trend in the evolution of computer-communication networks has been towards a greater degree of resource sharing and more flexible resource sharing mechanisms. This may be attributed to the bursty nature of data traffic [1,2] and the diversity and uncertainty of the traffic environments of an enormous variety of potential network applications (e.g. inquiry-response distributed database, electronic mail). An effective approach to handling bursty unpredictable traffic is to statistically average the transmission requirements of a large population of users; this benefits from the variance reduction effect of the law of large numbers in probability theory.

In the early days of computer networks, techniques originally developed for voice traffic (e.g. point-to-point dial-up and leased lines) were directly adopted for computer communications. Later, store-and-forward networks were developed. These include data concentrators for local or regional distribution and collection as well as message and packet switching networks on a national scale (e.g. ARPANET [3]). The ALOHA System [4] was the first of a new breed of packet broadcasting networks and techniques.

In its purest form, packet broadcasting is a technique whereby data is sent from one node in a network to another by attaching address information to the data to form a packet. The packet is then broadcast over a communication channel which is shared by a large number of nodes in the network; as the packet is received by these nodes, the address is scanned and the packet is accepted by the proper addressee (or addressees) and ignored by the others. The physical communication channel employed by a packet broadcasting network can be a ground radio channel, a satellite channel or a system of cables. The key attributes here are the any-to-any connectivity (a consequence of broadcast) and the sharing of a single channel (multiaccess). This last implies that the channel operates at a high speed relative to the average data rate of individual users; each user must be capable of sending and receiving data at the channel burst rate. Various packet broadcasting techniques are distinguished by their approach to resolve simultaneous demands and to optimize channel utilization given certain traffic assumptions.

Conceptually, we can visualize the total communication resource R of a network as being available in frequency, time and space. One way to resolve simultaneous user demands is to divide R up into small dedicated pieces, e.g. frequency and time division multiplexing. Different terrestrial communication links as well as satellite spot beams are some examples of space division.

Consider now the fraction α of R that is available to an individual user in the network for attempted use. We witness the evolution of network resource allocation techniques towards a large measure of resource availability (α) for individual users, as illustrated in Figure 1.

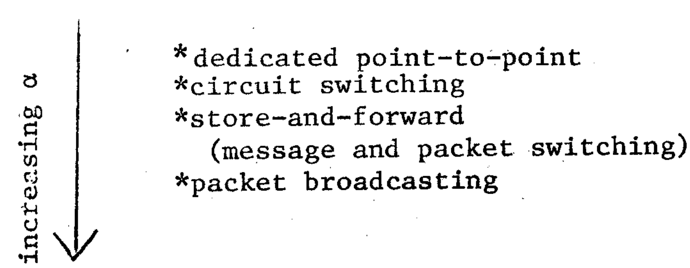

Fig. 1. Evolution of resource allocation techniques for computer communications.

Techniques with a large α afford more opportunity for sharing among a population of users and hence benefit more from the variance reduction effect of the law of large number. However, they also require more sophisticated strategies and additional overheads for conflict resolution and congestion control to prevent deadlocks, instability etc. Although some solutions are available for specific techniques [5,6,7] such problems have yet to be satisfactorily solved in general for packet switching networks and many of the packet broadcasting techniques to be discussed below.

A survey of packet broadcasting networks and techniques is next presented from a historical perspective.

2. THE BEGINNING

The ALOHA System as described by Abramson [4] marked the beginning of the class of packet broadcasting networks of interest to us.

The ALOHANET uses two radio channels (100 KHz. each in the UHF band operating at 9.6 KBPS [4,8]) for communication between geographically scattered remote users and a central computing bacility. One channel is used by the central node for broadcasting data packets to remote users. The header of each packet contains information identifying its destination so that only the intended receiver(s) will accept it. The second channel is shared by the remote users for accessing the central node using a multiplexing technique that has come to be known as <u>pure ALOHA</u>. Under a pure ALOHA node of operation, packets are sent by the remote users to the central node in a completely unsynchronized manner. If two remote users transmit packets at the same time, a "collision" occurs and both packets are destroyed. Thus, two distinct sources of error exist in the channel: (i) the usual random noise and (ii) errors due to packet collisions. In the ALOHANET, error detection is accomplished through the use of cyclic polynomial parity bits in each data packet, which are checked by the central node upon receipt of a packet. A positive acknowledgement protocol is used such that whenever the central node receives a data packet correctly, he returns a positive acknowledgement packet to the sender. Whenever a remote user sends a packet, if an acknowledgement for it is not received within a time-out interval, the user automatically retransmits the packet after a randomized delay. A randomization procedure is needed in order to minimize the probability of repeated collisions by the same users and was found to be crucial to the performance of all random access channels [5,6].

Collisions limit the useful throughput of a pure ALOHA channel. An analysis under the assumption of a large population of "small users" shows that the maximum throughput of such a channel is equal to $\frac{1}{2e} = 0.184$ of the channel speed.

Line of sight radio transmission is used in the ALOHANET. The original system had a star topology [4]. Later, the addition of radio repeaters to extend the range of coverage generalized the network topology [8].

Both techniques of broadcast and random access introduced by the ALOHANET are most suitable for data traffic sources which have been characterized to be extremely bursty i.e. the interarrival times between messages are much greater than the message delay constraints desired [2]. We further elaborate upon the desirability of broadcast and random access as follows.

1. A broadcast channel may be shared by a large population of geographically distributed users. It also permits allocation of the total

transmission capacity in a very dynamic fashion for statistical load averaging. One possible disadvantage is that each user must be capable of transmitting and receiving at the broadcast channel speed which is typically much greater than the average data rate of individual users. This requirement has implications on the cost of the individual nodes e.g. satellite earth stations.

2. In a centralized network, polling by the central node is the most common technique for sharing a communication channel. In such a system the central node does most of the talking while remote users can talk only when spoken to. It is not difficult to realize from the intermittent nature of the transmission requirements of bursty users that polling incurs a tremendous amount of overhead since most polling messages are met by a negative response i.e. the remote user has nothing to send. It is thus natural and conceivably more efficient for bursty users to take the initiative as is the case in random access techniques, such as pure ALOHA, and demand assignment techniques to be discussed below.

The ALOHANET is a centralized network for remote access to a central facility. Hence traffic flows in the inbound and outbound directions are highly asymmetric. Two separate channels are provided in the ALOHANET for inbound and outbound traffic flows. In what follows, we shall consider mostly distributed networks in which any node may want to communicate with any other node. Hence, a single channel is assumed unless otherwise stated. Finally, we note that in terms of the measure of resource availability α introduced earlier, a pure ALOHA system lies at the extreme bottom part of the spectrum ($\alpha=1$) in Figure 1.

3. SATELLITES

A satellite acts as a radio repeater. It receives signals at an uplink frequency and beams whatever it receives back to earth at a separate downlink frequency. (For the purposes of this paper, on-board intelligence is not assumed.) A satellite can receive signals from any earth station (multiaccess) and transmit signals to all earth stations (broadcast) within its antenna pattern. These are the same attractive features found in ALOHANET's radio channels and form the basis of a new class of techniques for dynamic allocation of the satellite transmission capacity to achieve load averaging at the satellite. There is one major difference between satellite and ground radio systems, namely, the relatively large channel propagation delay of 0.27 second for a geostationary satellite. As a result, various techniques which depend upon carrier-sensing suitable for ground radio and cable systems with a short propagation delay (relative to the transmission time of a packet) are not applicable to satellite systems. (See below.) On the other hand, in a satellite system each user can monitor the downlink broadcast and determine for himself if a packet previously transmitted by him had encountered a collision.

Satellite systems have traditionally been designed for voice traffic. Commercial satellite channels (either TDMA or FDMA) are usually employed as point-to-point links between earth stations just as if these earth stations were linked by a direct cable connection. However, we must realize that a satellite is more than just a bundle of cables in the sky! [9]. The multiaccess broadcast capabilities afford a level of flexibility that can be utilized to great advantage in a network. Even for point-to-point voice traffic, demand assignment techniques exist that permit the sharing of circuits among different earth stations. Circuits are dynamically allocated to voice conversations for periods of seconds and minutes. Similarly, for data traffic, the satellite transmission capacity can be dynamically allocated to packet or message transmissions originated anywhere within the satellite coverage for durations of microseconds and milliseconds.

Consider the sharing of a single satellite channel consisting of an uplink and a downlink by a population of data traffic sources. Just as in the ALOHANET, the downlink broadcast channel presents no contention problem since it is used by a single transmitter (the satellite). By attaching a destination address (or addresses) to each packet, it will be accepted by the proper addressee(s) and discarded by others. Various packet broadcasting techniques are distinguished by their method for sharing the uplink multiaccess channel among the population of users. Note that even in the limiting case of a dedicated TDMA channel for each traffic source [10], the broadcast capability can be utilized to permit packet transmissions addressed to any destination(s). Complete connectivity of N users is achieved with N broadcast channels compared to N(N-1) point-to-point links.

Under the sponsorship of the Defense Advanced Research Projects Agency (ARPA), the class of satellite packet broadcasting techniques has been actively pursued during the period from late 1972 to the present.

Slotted AHOHA

The slotted ALOHA technique was first proposed and studied by Roberts [11] and later by Kleinrock and Lam [12] and Abramson [13]. The protocols of slotted ALOHA are just like pure ALOHA with the exception that channel users are required to synchronize their packet transmissions into fixed length channel time slots. Time slotting can be accomplished in the same manner as in TDMA systems. With slotting, packet collisions due to partial overlaps are avoided. Under the same assumption of a large population of small users as before, the maximum throughput of a slotted ALOHA channel is equal to $1/e = 0.368$, twice that of the unslotted case.

Reservation-ALOHA

The traffic environment suitable for pure and slotted ALOHA is that of a large population of low rate bursty users and short messages (single packets). The Reservation-ALOHA scheme was proposed by Crowther et al. [14] for less bursty users. In addition to time slotting, the slots are organized into frames. Those slots in the previous frame that were unused (empty or containing a collision) are available in the current frame for random access by all users just as in slotted ALOHA. A slot which had a successful transmission by a user in the previous frame is reserved for the same user in the current frame. This scheme can achieve very good channel throughput for either bursty users with long messages or users with steady arrival streams.

An analysis [15] showed that Reservation-ALOHA adapts itself to the nature of the input traffic; its performance ranges from that of slotted ALOHA to fixed TDMA depending upon the specific traffic environment.

Packet Reservation Schemes

In packet reservation schemes [15-17], the transmission capacity of a single high-speed satellite channel is demand assigned to individual packets or groups of packets (i.e. messages). Because of demand assignment, a disadvantage of such schemes is that the average message delay is at least twice the satellite propagation delay (0.54 second). The key elements of a packet reservation scheme are its mechanisms for making reservations and management of the global queue.

In the packet reservation scheme proposed by Roberts [16], the satellite channel is divided into time slots. Certain time slots are subdivided into minislots. These minislots are for reservation request packets as well as possibly positive acknowledgement and small data packets to be used on a contention basis with the slotted ALOHA technique. A single global queue consisting of messages holding reservations is maintained via a distributed queue management method. It makes use of the satellite broadcast capability such that a reservation request packet successfully transmitted with no interference can be received by all users. Each user maintains his own copy of the global queue status.

An alternative to the use of contention-based demand assignment (i.e. slotted ALOHA for the minislots) is to superimpose a frame structure over the slots and fix assign a minislot to each user in every frame. This approach however incurs a large reservation overhead when the population of users is large. On the other hand, the reservation overhead of using slotted ALOHA is independent of the user population size [15].

Recent Development

Currently an experimental satellite packet broadcasting network (SATNET) is being developed under the sponsorship of ARPA [18]. The focus is on a rather elaborate packet reservation scheme with a contention-based demand assignment mechanism such as described above. The protocol (CPODA) is designed to handle both packetized data and voice traffic. A sophisticated traffic environment is assumed including multiple priority and delay classes, variable message length and an arbitrary load distribution among the earth stations. The receiving (speed) capability of earth station can also differ. Four satellite IMP's will be used for experimental activities using a SPADE channel on an INTELSAT IV-A satellite in the Atlantic region [18,19].

Stability and Control Issues

It has been recognized that all random access schemes suffer from potential instability behavior and may require some form of adaptive control [5,8,18]. For a slotted ALOHA channel accessed by a large population of small users, the instability phenomenon has been studied and characterized by Kleinrock and Lam [5]. A comprehensive theoretical treatment of adaptive control using a Markov decision model is given by the same authors in [6] while various heuristic control schemes and their performance are presented in [20,21]. Pure ALOHA, Reservation-ALOHA as well as contention-based packet reservation schemes exhibit similar instability behavior and require some form of adaptive control in their random access protocols.

4. GROUND RADIO

The ALOHANET provides a novel solution to the local distribution/collection problem between a central station and a population of users. Roberts noted that the use of radio communications permits mobile terminals and discussed the feasibility of a pocket-size personal terminal [22]. Mobile terminals are now a reality in a broadcast radio network sponsored by ARPA called the Packet Radio Network which is currently in its final testing phase [23]. It differs from the original ALOHANET in a number of ways; in particular, it uses a netted array of radio repeaters to achieve reliability as well as area coverage beyond line of sight. It also uses a spread spectrum signalling technique for co-existence with other systems in the same frequency band as well as for antijam protection.

The first application of the Packet Radio Network is likely to be in the military sector. The network is portable: it can conceivably be set up in one area, operated, broken down and moved to another area in a matter of hours.

The packet radio network concept will have enormous implications on the personal computing movement today as a means of communication between individuals and access to computing resources, as well as to nation-wide computer networks and databases.

The maximum propagation delay between any two users in a ground radio network is typically much smaller than the transmission time of a packet. As a result, the users who share a broadcast radio channel can attempt to aviod collisions by sensing the carrier for other users' transmissions. Based upon this information about the state of the channel, various actions can be taken by the user under consideration. Several such carrier sense multiple access (CSMA) protocols were studied by Kleinrock and Tobagi [24]. It was found that with carrier sensing, the number of packet collisions can be significantly reduced compared to pure random access such as ALOHA. For example, if the propagation delay is $\frac{1}{100}$ of the packet transmission time, the maximum throughput of a CSMA channel exceeds 0.8 (compared to 0.18 for pure ALOHA).

Packet reservation schemes such as those described above for satellites are also possible. In one proposed scheme, the central station serves as the central controller and two separate channels are used for reservation requests and other control messages between the central station and remote users [25]. When the population of users is not too large, efficient conflict-free packet reservation techniques with decentralized control are possible [26].

5. CABLES

The local distribution/collection problem also exists for terminals and computers within large office complexes, manufactoring plants etc. A system of cables (or optical fibers in the near future) can be used to provide a multiaccess communication facility very similar to that of the ground radio environment described above [27,28]. A piece of cable constitutes a broadcast medium for those users connected to it. Its "area of coverage" can be extended by branching (with the help of possibly a repeater at the branching point). Conceptually, this is almost identical to the Packet Radio Network structure! Since very short propagation times are involved, packet broadcasting protocols described earlier for ground radio systems can be adopted here.

The Ethernet developed at the Xerox Palo Alto Research Center uses coaxial cables with baseband transceivers and off the shelf CATV taps and connectors. Packet repeaters are used at branching points and a carrier sensing random access protocol is implemented [28].

6. CONCLUDING REMARKS

We have introduced in this paper the class of packet broadcasting protocols and described a number of packet broadcasting networks using satellite, ground radio or cables as the broadcast medium. The bursty nature of data traffic is such that a very high transmission capacity is required by individual users but only intermittently. We witnessed the evolution of resource allocation techniques for computer communications progressing from the dedicated point-to-point approach, to circuit switching, store-and-forward packet switching, and then to packet broadcasting. The trend is towards a greater degree of sharing and increased system flexibility. In particular, two new concepts stand out as being characteristics of packet broadcasting networks. First, a broadcast medium is uniquely capable of being shared by an entire population of geographically distributed users so that their total demands can be statistically averaged. Second, the use of random access and demand assignment are more attuned to the intermittent nature of user demands than previous methods (i.e. polling techniques) for multiaccess.

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