

WHY A RING?*

Jerome H. Saltzer and David D. Clark

Massachusetts Institute of Technology
Laboratory for Computer Science
Cambridge, Massachusetts

Kenneth T. Pogran

Bolt Beranek and Newman Inc.
Cambridge, Massachusetts

Abstract

In a world increasingly populated with Ethernets and Ethernet-like nets a few sites continue to experiment with rings of active repeaters for local data communication. This paper explores some of the engineering problems involved in designing a ring that has no central control, and then compared the M.I.T.-designed ring with the Ethernet on a variety of operational and subtle technical grounds, on each of which the ring may possess important or interesting advantages.

Introduction

The M.I.T. Laboratory for Computer Science has, for more than two years, been operating a prototype one Mbit/sec. distributed control ring network of eight nodes. The laboratory is engaged in checkout of an improved, simpler, ten Mbit/sec. ring design, intended to link groups of up to 250 desktop computers. Since there are already several competing local network designs that use contention-controlled broadcast on passive coaxial cable rather than a repeater ring, we are often asked why one should bother to develop an alternative approach--the contention-controlled broadcast technology is field proven, its properties are well understood and adequate for the application. In addition, there are at least three difficult engineering problems involved in the design of a distributed control ring network: reliability of the repeater string, distributed initialization and recovery, and closed-loop clock coordination. Of course the ring approach has also

*Authors' addresses: J.H. Saltzer and D.D. Clark, M.I.T. Laboratory for Computer Science, 545 Technology Square, Cambridge, Mass. 02139. K.T. Pogran, Bolt Beranek and Newman Inc., 50 Moulton Street, Cambridge, Mass. 02138. Please address correspondence to J. H. Saltzer, telephone (617) 253-6016.

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been field-proven[1,2,3], but in no case in a form that settles all the questions. Upon analysis, it appears that an apparent preference for contention-controlled broadcast networks in the United States but for ring networks in Europe has been more determined by accidental historical precedents than by persuasive technical arguments.

This paper examines briefly nine technical differences between the contention-controlled broadcast approach and the ring, and argues that it seems interesting to pursue the ring technology. It assumes that the reader is familiar with the basic concepts involved in local networks and in ring networks as described in published papers[4,5]. There are a wide variety of possible designs both for rings and for passive broadcast networks, and these design choices have both gross and subtle differences that affect comparisons. To be specific, the kind of ring network assumed in this discussion is a token-controlled system in which the originator removes his own message and in which there is no central control or monitor station. Both the one and ten Mbit/sec. rings at M.I.T. mentioned earlier are of this design. For contrast, the Ethernet local communication network developed by the Xerox Palo Alto Research Center will be used, with the understanding that it is typical of a contention-controlled passive coaxial cable broadcast design[6,7,8]. The Mitre Corporation MITREBUS[9], another contention-controlled broadcast design, is mentioned for comparison also.

These specific designs are chosen because they reflect two distinct and important design choices:

- access control by contention (Ethernet) versus token (ring), and
- communication by broadcast (Ethernet) versus point-to-point (ring).

As shall be seen, the nine technical differences discussed all flow directly from these two choices. This point should be kept in mind when applying the observations to other local network designs that use a different combination of design choices, for example, a token-controlled broadcast net or a contention-controlled ring.

Ring design problems

The three difficult ring engineering problems referred to above appear to have elegant and straightforward solutions, and one of the reasons for trying out ring technology in the field is to verify that these solutions work well in practice. Other papers[5,10,11,12] explore these three engineering problems and considerations in their solution in some depth, so they are only summarized here:

1. Reliability of the repeater string. The basic problem here is that a failure in any one repeater can disrupt the entire local network and, if one strings together one hundred or more active repeaters, one would expect to end up with a very fragile system. Further, locating the troublesome repeater could require perambulation of the entire network. Very reliable repeaters and careful system engineering seem to be needed at first glance. However, a simpler solution to these problems is to arrange the transmission links between successive nodes so that each internode link loops through a central point, a wire center. At the wire center, bypass relays that are energized remotely by the network stations can do a majority of the reconfiguration operations automatically. The resulting configuration, a star-shaped ring, creates a centralized location for maintenance and reconfiguration and at the same time provides reliability, without compromising the distributed nature of the ring control. Further, clusters of nodes can be connected by nearby wire centers that are in turn connected hierarchically through more distant wire centers. This approach reduces the wiring cost that one might anticipate in a star topology.
2. Distributed initialization and recovery. To avoid designating some one ring node as special (and thereby making ring operation depend on that node's continued good health) some algorithm is required whereby all active repeaters can quickly and simply agree upon the need for initialization and recovery, and not fall all over one another trying to accomplish it. A suitable strategy can be devised using two ideas developed for passive broadcast networks. First, when any node detects ring trouble, it jams (as in Ethernet) the ring net with a characteristic signal that insures agreement among all participants. Second, after jamming, a virtual token, whose time of arrival is based on the station's address (as in the Chaosnet[13],) determines which single station actually performs network reinitialization.
3. Closed-loop clock coordination. A subtle problem of distributed agreement on data transmission rate arises in a ring. The issue is that not only must the collection of repeaters agree on a common clock rate, but that clock rate must result in an integral number of bit times of delay when traversing

the closed ring. Fortunately, there appear to be at least three different, workable ways of achieving this agreement. The simplest of these ways is to open the ring when originating a message, and thereby allow all non-originating repeaters simply to track the originator. An intermediate approach based on inserting time wedges in the clock at repeaters that fall behind the fastest repeater was used in the prototype ring[5]. The most sophisticated approach is to have a phase-locked-loop in each repeater tracking its preceding neighbor, and design loop filters so that the resulting ring of PLL's is stable[12].

These three problems are, of course, problems only until they are solved. Since good solutions appear to be in hand, the following discussion assumes that the ring design being compared with the Ethernet includes the star topology, automatic decentralized reinitialization, and any one of the clock coordination techniques.

Nine points of comparison of rings with Ethernets

1. The contention-controlled broadcast net has a significant analog engineering component, while the ring net is almost entirely a digital design. This difference looks very interesting to explore, because of its possible ramifications in ability to exploit rapidly advancing progress in digital technology and VLSI. To understand this difference, consider that a broadcast net transmitter's signal must be receivable by all receivers on the cable. These receivers are at varying distances from the transmitter and therefore will experience different attenuations and echoes. Similarly each receiver must be able to hear every transmitter. In all, there are $N(N-1)$ such combinations that must work in an N -node network, and the transceiver system must be designed conservatively enough that the worst possible receiver-transmitter placement combination (in terms of echo buildup and attenuation) must deliver acceptable performance. The analog noise level contributed by idle transmitters grows with the number of nodes, though probably less than linearly. Finally, in order for a "listen-while-transmit" collision detection feature of an Ethernet to work, an active transceiver must be able to notice that it is not the only active one. Thus the receiver part must be capable of detecting the weakest other transmitter during its own transmissions and distinguishing that other transmitter from its own transmitter's echoes. This set of requirements is not impossible to meet, but very careful analog transmission system engineering is needed, and the resulting design has many analog components. In contrast, the analog part of a ring network repeater is more tractable. Any given transmitter sends a signal down a private line to only one receiver. The receiver has one echo environment and one received signal level to cope with. Thus, a relatively simple line driver/line receiver combination can suffice. For this reason, the passive broadcast technology is straining to reach a 10 Mbit/sec. signalling rate with a 200 node net, while the ring can operate at

that speed and scale with a fairly elementary analog system.

While engineering in the analog domain is substantially easier in the ring, in the digital domain the situation reverses. Note that two of the three difficult ring engineering problems discussed earlier (initialization and clock coordination) can be handled by techniques that are mostly digital. This difference in the character of the hard engineering problems of the two technologies offers an exploitation opportunity that may favor the ring network. The recent and projected waves of technology improvement have benefited the digital domain more than the analog, mostly because it is easy to see how to solve problems systematically by increasing digital component count; it often seems to be harder to take systematic advantage of increased numbers of components in the analog domain. A less compelling, but still interesting, argument is that because of the simple analog transmission system required by the ring, even the line drivers and receivers might be integrable into a future VLSI implementation; it is probably harder to do this integration for the more complex analog transceiver technology of the passive broadcast net.

2. A problem with the Ethernet that is closely related to its analog domain engineering emphasis lies in ground reference and power supply. It is important that a local network not impose a uniform ground reference on all attached hosts. If it did, the network risks carrying large ground currents or creating ground loops. In order to obtain maximum transceiver performance, all present Ethernet designs seem to require direct coupling of an active component (e.g., the base of a transistor) to the cable, with consequent need for a power supply whose ground reference is the cable shield. To avoid adding a central, shared component, a per-node, isolated power supply for the active part of the transceiver electronics seems to be a requirement of an Ethernet. The ring, on the other hand, can be designed to deliver enough energy that ground isolation can be achieved in the signal path ahead of the first active component of the receiver. (The prototype M.I.T. ring used optical isolators for this purpose; the ten Mbit/sec. ring uses pulse transformers.) Finally, because sensitive, active electronic components are directly attached to the Ethernet coaxial cable conductors, transient suppression (e.g., from lightning) requires that the coaxial cable ground shield system be grounded at no more than one point. To enforce this requirement and maintain the ability to divide a long cable into sections for trouble shooting, the Ethernet specification[8] requires that there be no ground for the cable. Such a floating conductive system becomes a severe personnel hazard in the case in which it accidentally becomes shorted to an electric power conductor.

3. Electromagnetic compatibility between the net and other physically adjacent electrical equipment is generally easier to engineer with a balanced transmission medium than with an unbalanced one. One of the attractions of the Ethernet is the ease

of attaching to it at any point, which ease relies on the use of clamp-on connectors with coaxial cable, an unbalanced medium. If one tried to use a balanced transmission medium for the Ethernet, it would probably become necessary to install ordinary connectors every time a new node is added, and the easy attachment virtue would be compromised. In addition, the Ethernet strategy of listening for collisions depends on the transmitter being off half the time. Collision detection with balanced lines would probably become more complex, since in the most obvious balanced waveform modulation schemes the transmitter runs continuously rather than for half of each bit time. In contrast, the ring network can use shielded twisted pair and balanced waveform modulation, thereby reducing both radiation to other equipment and susceptibility of the network to noise spikes and electrical interference originating elsewhere. At the same time, the passive star arrangement for a ring captures much of the easy attachment property.

4. An attraction of the passive broadcast net is the intrinsic high reliability that comes from having a minimum number of active components whose failure can disrupt the net. The most important shared component--the coaxial cable--is completely passive. In contrast, the primary objection to a ring network is the operational fragility of a series string of 100 or more repeaters. However, this fragility appears to be easy to overcome by the passive star arrangement of the ring network.

5. Another attraction of the passive broadcast net is that it is exceptionally easy to install--a single cable is routed through the building, near every office or other location in which a network node might be needed. Actual attachment of nodes can be deferred until the node is required, at which time attachment can be accomplished by clamp-on connectors; attachment does not disrupt network operation. However, hand-in-hand with this convenience goes an associated inconvenience, namely that trouble isolation and first-aid repair cannot easily be centralized. Some kinds of failures will require foot-by-foot inspection of the network and each node attachment, involving access to offices and other spaces throughout the building. The passive star configuration of the ring network appears to completely overcome this potential problem. With a passive star, addition of a new station involves running a cable from the office to a nearby wire center, so one might consider wiring a building in advance by running one such cable per office. Then, installation of a station is done by attaching a connector and plugging it in. No extra disruption is associated with this kind of installation. Further, many buildings are already designed with cable trays and wire ducts in place that emanate from a wire center, because both telephone and electric power wiring practice also call for wire centers. Field experience with both kinds of networks is really required to determine which is more effective on day-to-day operational issues such as this and the previous two. Such experience is being reported for the Ethernet[7,14]; corresponding experience with a ring is not yet so extensive.

6. There is an intrinsic limitation in the contention-controlled broadcast net approach in its ability to make effective use of higher speed transmission media, such as optical fibers. In a contention network, at the beginning of each packet transmission there is a period when there is a risk of collision: this period is proportional to the length of the transmission medium, since the packet is exposed to collision until its first bit propagates to the farthest transceiver. The duration of this exposure is thus fixed by the physical configuration. As the transmission speed increases, the time required to transmit an average size packet decreases, until the packet transmission time becomes as short as the cable propagation time. At that point, most of the advantage of carrier sense is lost and the system becomes an ordinary Aloha channel, with an intrinsic data capacity limit of about 18% of the channel capacity[6,15]. For a 1 Km. coaxial cable, the end-to-end propagation time is typically 4500 nsec. This is comparable to the time required to transmit a 60-octet packet at 100 Mbit/sec. Thus an attempt to build a 100 Mbit/sec. passive broadcast net might result in an effective performance limit near 20 Mbit/sec. The ring, because it does not use a contention access scheme, does not have any corresponding limiting effect, and thus can be scaled up directly to a 100 Mbit/sec. configuration. (The importance of this limitation in contention-controlled nets depends critically on the distribution of packet sizes. If most packets are 6000, rather than 60, octets in length the limitation would be inconsequential at a 100 Mbit/sec. rate. One can make a good argument that any application that requires a 100 Mbit/sec. transmission rate for 100 nodes will not typically generate small packets because of per-packet software overhead, so there should be an opportunity to avoid the Aloha phenomenon. Until some more experience is gained with applications that really require this bandwidth, the questions will remain unanswered. Experience with the Hyperchannel[16] network, which is a contention-controlled net that runs at 50 Mbit/sec., may be useful in this regard.

7. A second limitation of the passive broadcast net approach that appears to require some considerable ingenuity to overcome is to take advantage of fiber optic technology. This technology offers the attraction of very high speed, excellent electromagnetic compatibility, avoidance of lightning and ground reference problems, and (predicted) low cost. However, the problems of turning optical fiber into a broadcast medium are formidable. One must invent a satisfactory technique for tapping an optical fiber and detecting a signal without diverting too much optical energy or else the system will not scale up very well in number of nodes. Yet the same tap must allow introducing a new signal without loss. (Some recent experiments with many-tailed star couplers are promising, but that approach gives up the single cable routed by every office that is one of the chief attractions of the Ethernet[17].) In contrast, since a ring network uses one-way, point-to-point transmission, replacing the wire links in a ring network with fiber optic links is

quite straightforward. The Cambridge ring has operated for some time with one fiber optic link[1].

8. Because it uses repeaters, a ring network can with ease span much greater physical distances than can the passive broadcast net. The passive broadcast net can also be augmented with repeaters, as in the new Ethernet standard and the Mitrebus. However, use of contention control, which makes the propagation time between the two most widely separated stations a critical, performance-limiting parameter, limits the distance that one can extend a broadcast net even with repeaters. Since in order to arrange a ring to span a longer distance at least parts of it must be "stretched out" rather than fully looped back in a passive star, one trades away some maintenance ease to gain a greater geographical span. Thus the contention-controlled broadcast net trades both performance and maintenance ease with increased geographical coverage, while the ring trades only maintenance ease. The distance spanning effect is quite substantial, for two reasons. First, when using comparably expensive driver, receiver, and cable technology, a single ring link, being point-to-point rather than broadcast, can be slightly longer than a single broadcast cable segment. Second, when successive ring links are placed in tandem the maximum geographical span is multiplied by half the number of stations--perhaps a factor of 100. Thus for an area such as a campus of a hundred buildings and building wings, a ring may have a considerable advantage over a passive broadcast network.

9. A final, practical question to consider is whether or not there might be anything about a ring network that intrinsically requires either more or less complex logic than a contention-controlled broadcast network. Only examination of in-field designs can answer this question, but such examination is trickier than one might expect, because every local net designer seems to have chosen a different function packaging approach. Thus one design includes packet buffers, another doesn't but includes a direct memory access channel for some popular computer bus, the next assumes that part of the network control will be handled by software rather than hardware. To compare more carefully, implementations for the experimental Ethernet, the M.I.T. Artificial Intelligence Laboratory Chaosnet, and the ten Mbit/sec. ring network were compared by measuring the board area required to hold the implementation of the network control logic up to but not including speed-matching buffers. All three were found to require something less than 50 square inches of densely packed wire-wrap card. Casual observation of the implementation of a Mitrebus interface and a Prime Computer ring net controller suggested that these two network designs were similar in complexity to the others.

The conclusion is that there is no significant intrinsic difference in the complexity of implementation of the two approaches, and a straightforward TTL implementation of a ring network should require about the same amount of

hardware as an equivalent function contention-controlled broadcast net operating at the same speed. (This comparison of hardware complexity is distinct from that of point one, earlier, which raised some questions about the ease of VLSI implementation of the analog components of the broadcast network.)

Non-determinism

A sometimes-mentioned point of difference between token control as used in the ring and contention control as used in the Ethernet is the ability to predict the maximum time one must wait to obtain access. Superficially, it appears that a carefully-designed token control net could have an advantage here. If one limits the maximum message length, and insists that the token must be passed along after sending one message, then every network user has a guarantee that the token makes steady progress, and one can calculate with confidence the maximum length of time one might have to wait for access. In contrast, in the case of the Ethernet, since every attempt to transmit could in principle produce a collision, there is a worrisome possibility that one could go on engaging in collisions indefinitely. Such a possibility would be of concern, for example, in a distributed real-time process control application in which a deadline might be missed. This property is sometimes summarized by saying that the Ethernet is "non-deterministic".

That analysis is, however, superficial, because it omits a real-world consideration that intervenes to make the contention network and the token network much more similar than one might expect. In any network, no matter how access is controlled, there is a finite probability of transmission error. In a token-controlled ring, an error may destroy the token at the worst possible time, or when a station nearing a deadline finally receives the token the message it sends may be damaged by an error, and retransmission may be needed. Thus the prospective recipient of the message can find that the deadline has been missed; the token ring is non-deterministic, too. One must accept the fact that the real-world provides no guarantees, only a probability of success. Once that principle is clear, one can specify a required success probability and choose system parameters accordingly. However, this approach applies equally well to the token and contention networks. Given a required probability of successfully meeting a deadline, one can calculate immediately a loading level for an Ethernet that meets the deadline with more than the required probability in the face of contention. The rest of the system must, of course, be designed to insure that the intended Ethernet load is not exceeded, either absolutely or else with a probability consistent with the system success goal.

The numbers that result can be quite practical. For example, in a 50-node ring, one must plan to wait for as many as 50 maximum length messages to be sent until the token arrives. The probability that an Ethernet is busy for n or more successive message intervals when it is loaded to a

fraction of its capacity r ($r < 1$, exponential message arrivals, fixed message length) is approximately r^n . For $r = 0.5$ (a 50% loaded network) the probability that a wait of more than the 50 message intervals occurs is thus less than about 10^{-16} , probably 5 orders of magnitude smaller than the probability of a transmission error that calls for retry or reinitialization.

In practice there is one more level of subtlety to this line of argument. Suppose we have designed both an Ethernet and a ringnet for a time-critical application, and have determined the error rates on both nets and the maximum allowed load on the Ethernet so that the chance of missing the deadline is acceptably small. In the case of a token-controlled ring, if any host attempts to present an abnormal traffic load to the network, the token-control mechanism effectively throttles the runaway host, and other network participants still have their usual chance of meeting their deadlines. In the contention-controlled Ethernet, an abnormally active host can increase the probability of contention and perhaps thereby lower the chance of meeting deadlines. This difference represents a genuine advantage of the token ring. But if the system is correctly designed, this effect must be second order, when one considers that any single host is normally throttled internally by software overhead anyway. Although one might hypothesize a conspiracy of several runaway nodes, such a hypothesis takes us into the realm of predictably low-probability events. (One can also argue about whether incorrectly designed Ethernets fail more spectacularly than incorrectly designed token rings, but that somehow seems to be an uninteresting discussion.)

Thus it appears to us that the non-determinism of the contention system is an unimportant difference with the token approach.

Broadband

A related idea is that of using radio frequency broadcast signalling on coaxial cable ("Broadband") as, for example, the Mitre Corporation has done[9]. In these systems, both broadcast and contention control of access are used, so this scheme boils down to translating an Ethernet from baseband to some carrier frequency. It thus has most of the same attractions and disadvantages of the Ethernet, but with three extra appeals:

- a) The same coaxial cable can also carry other radio frequency signals with different purposes, for example cable television. Thus bringing the data network into an office would automatically bring the CATV system there, too.
- b) The coaxial cable is used in a frequency range where there is less dispersion (change of propagation velocity with frequency) so a greater bandwidth can be obtained.
- c) The cable television industry has developed a useful collection of modestly priced

components, including cable attachment hardware and radio frequency linear integrated circuits that one could exploit. In particular, high bandwidth, low delay analog repeaters are available at a modest price; this availability leads to more uniform, higher signal levels. Higher signal levels in turn allow simpler analog design and ground isolation techniques to be used.

The radio frequency signalling approach, however, ends up with the same kind of large analog engineering component as does the Ethernet-type broadcast net, this time in the form of wide-band linear amplifiers, voltage controlled oscillators, filters, modems, and phase-locked loops. Although there are available integrated circuits that help perform those functions, in real applications those circuits must be surrounded by additional analog components--capacitors, resistors, transformers, etc. In exploiting cable television industry developments, one misses the opportunity to exploit what may be even more potent (by reason of volume and potential total integration) economic forces in the digital logic area. Finally, if one tries to make use of the potential for higher bandwidth it turns out that one cannot so easily take advantage of the television industry chips. But if one uses discrete components, the cost climbs substantially.

Apart from these considerations, the broadband network is an example of a contention-controlled broadcast system, so the earlier technical comparisons with the token-controlled ring seem to apply to it also.

Conclusions

Considering these various technical arguments, it appears that one cannot make a clear case for either the contention-controlled broadcast net or the ring technologies. Both approaches have good arguments in their favor, and it is likely that operational issues such as ease of installation, maintenance, and administration will dominate the detailed technical issues. Thus practical experience with 100-node ring networks is really required to establish concrete comparisons of reliability and ease of maintenance and reconfiguration in the field. The answer to the question asked in the opening paragraph is that there seems to be substantial technical interest in continuing to develop ring technology.

A second conclusion concerns the interpretation of standards for local networks, such as the recently announced Ethernet standard of Xerox, Intel, and Digital Equipment Corporation[8]. With the current state of understanding and with substantial technical issues still to be resolved, such standards today can only provide guidance on how to implement a particular technology, not on choice of technology itself. A second standard may be required for ring technology, just as separate standards apply to phonograph records and magnetic tapes. It is possible that one could define a local network interconnection interface standard that is technology-independent although one may anticipate substantial technical arguments about

what functions are desirable or feasible in a compatibility interface. (The IEEE Data Link Media Access Committee seems to have started some of these arguments rolling[18].)

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