MEMORANDUM
RM-3097-PR
AUGUST 1964

ON DISTRIBUTED COMMUNICATIONS:
V. HISTORY, ALTERNATIVE APPROACHES, AND COMPARISONS

Paul Baran

PREPARED FOR:
UNITED STATES AIR FORCE PROJECT RAND

The RAND Corporation
SANTA MONICA • CALIFORNIA

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The RAND Corporation
1700 MAIN ST • SANTA MONICA • CALIFORNIA • 90406

PREFACE

This Memorandum is one in a series of eleven RAND Memoranda detailing the Distributed Adaptive Message Block Network, a proposed digital data communications system based on a distributed network concept, as presented in Vol. I in the series.* Various other items in the series deal with specific features of the concept, results of experimental modelings, engineering design considerations, and background and future implications.

The series, entitled On Distributed Communications, is a part of The RAND Corporation's continuing program of research under U.S. Air Force Project RAND, and is related to research in the field of command and control and in governmental and military planning and policy making.

The present Memorandum, the fifth in the series, is primarily a background paper acknowledging the efforts of people in many fields working toward the development of large communications systems where system reliability and survivability are mandatory. As these requirements become increasingly stringent, we are forced to consider new and more complicated systems than we might otherwise prefer.

In a very short period of time--within the past decade--the research effort devoted to these ends has developed from analyses of how a mechanical mouse might find his way out of a maze, to suggestions of the design of an all-electronic world-wide communications system.

Because this is a new field of study, its terminology has been borrowed from different specialities and lacks

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*A list of all items in the series is found on p. 49.

consistency. This Memorandum should be useful to one wishing to trace some of the related research efforts, focusing upon differences and their definitions. It should also be of interest to military planners in aiding them to understand the subtle differences between several systems, all called "distributed," but which exhibit completely different properties.

This Memorandum forms a bridge between the previous items in the series, concerned with the system concept and early modeling studies, and the remaining volumes, which detail the actual design and implementation of a network of the type proposed.

SUMMARY

This Memorandum describes some of the system design alternatives that delineate the proposed Distributed Adaptive Message Block Network from earlier distributed systems.

The discussion is restricted to systems using identical local switching policies at each switching node, and which do not rely on a single or a small hierarchy of critical routing control centers. A brief history of the development of some sample "distributed networks" is given with emphasis on the development of heuristic routing doctrines able to find "best" surviving paths in a heavily damaged network.

The term "distributed network" is often used as a generic term encompassing different systems. These systems, while appearing superficially identical, have markedly different properties, equipment, and survivability characteristics. Survivability is shown to depend upon the flexibility of switching with the limit of switching flexibility being defined as "perfect switching." These differences of flexibility of switching are often not fully appreciated. One cannot look at a communications network and necessarily predict survivability properties.

Several described example systems are categorized for comparison to aid in evaluating proposed systems and in synthesizing new ones.

CONTENTS

I. INTRODUCTION

The term "distributed networks" is commonly used as a broad generic term encompassing a number of communications systems with different properties. A brief history of the development of "distributed networks" is provided in the following sections, with emphasis on the development of "heuristic routing" doctrines that seek "perfect switching"; i.e., those able to find "best" surviving paths in a heavily damaged network. The discussion is restricted to those systems using "locally" implemented switching rules, and which do not need a single, highly critical, control center.

Such systems have different properties, require different equipment, and exhibit different survivability characteristics. But, they can be factored into categories for comparison.

The work of at least six separate disciplines is germane, but inasmuch as the members of these separate disciplines reside in different communities of interest, the all too common problem of a lack of communication between one another is quite noticeable. And, when there is an interchange of ideas, the words used take on different meanings to the representatives of the various fields of study. The term "distributed networks" is one of these very ambiguous entities. Sometimes it is simply a meaningless, "ok" word used to spice up hardware proposal brochures. To others, the meaning is exact, and narrow.

One writer has defined distributed switching as any switching medium noncollocated with the communications subscriber; another has implied that collocation is almost a necessary condition in a distributed system. Though these two definitions contain explicit delineations, they are at opposite ends of a spectrum. In our usage, collocation has no bearing whatsoever in determining whether or not a system is "distributed."

It might be helpful to enumerate the fields concerned in these studies. Distributed networks, of one sort or another, are of interest to:

1. Those concerned with "artificial intelligence";
2. Those concerned with communications within organisms and organizations;
3. Mathematicians working with optimization of flow in networks;
4. Mathematicians using dynamic programming to optimize incompletely understood and changing systems;
5. Those connected with civilian common carrier telephone plant switching;
6. Military systems planners, especially those dissatisfied with existing communications network techniques.

The present Memorandum is written primarily from the viewpoint of the latter group. And, while significant contributions have come forth from each and every one of the above listed disciplines, the present work has taken its examples principally from projects concerned with study of military systems.

Just as there are various definitions of "distributed networks," there are many ways to build such networks; in fact, there are probably as many ways of building them as there are designers. Therefore, several properties have been factored out, and our attention will be focused on distributed networks which possess these characteristics:

1) A certain degree of routing flexibility;
2) Capability for implementation by real-world hardware at a "reasonable" price;
3) Compatibility with existing input devices;
4) Survivability in an unfriendly environment;
5) Capacity for orderly system growth;
6) Operational routine of sufficient simplicity--that is, one that can be maintained by reasonably intelligent personnel.

Design of such systems tends to be quite complex, and the systems themselves are inherently intolerant of poor design, due to the practical difficulties encountered in preventing or minimizing propagation of system malfunctions. But, the potential promise of a high degree of survivability and the potential use of low-reliability elements makes the labor of a complex design worthwhile.

The switching criteria will receive considerable attention since survivability is a function of switching flexibility. The resulting detailed inspections of system proposals are necessary to accurately determine survivability properties.

The following section is devoted to a presentation of the distributed network concept and its characteristics, while Sections III and IV detail some of the history of distributed networks, both in theoretical studies and experiments and in hardware implementation proposals. To those interested in the evolution of modern systems and proposed systems, Appendix A contains several charts which summarize the stages of this development, using specific proposals as signposts along the evolutionary path.

II. THE DISTRIBUTED NETWORK CONCEPT

DEFINITION OF "DISTRIBUTED NETWORK"

In ODC-I* it is suggested that the term "distributed network" is best used to delineate those communications networks based on connecting each station to all adjacent stations, rather than to just a few switching points, as in a centralized network. It is difficult to limit the use of the term to describe a single network, since it is frequently used in this broader meaning--as delineating that portion of the spectrum of networks having a more decentralized configuration than those which exist as a single, inseparable entity.

Various modes of system connectivity--i.e., configurations--are depicted in Fig. 1. Figure 1-a shows a centralized communications network; Fig. 1-b, a decentralized network; and, Fig. 1c, a distributed network. Figure 1-d is a series of points along a continuum, representing more accurately how Figs. 1-a, 1-b, and 1-c delineate zones on a broad spectrum of possible system designs where the boundaries between zones are fuzzy.

To appreciate how fuzzy these boundaries can be, consider Fig. 2. One very large communications network in existence today is called the "spider web." When this network is viewed in a schematic, one obtains the illusion of Fig. 2-a. However, when only allowable paths between

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*ODC is an abbreviation for the series title, On Distributed Communications. The numeral refers to the specific volume in the series. A list of all items in the series is found on p. 49.

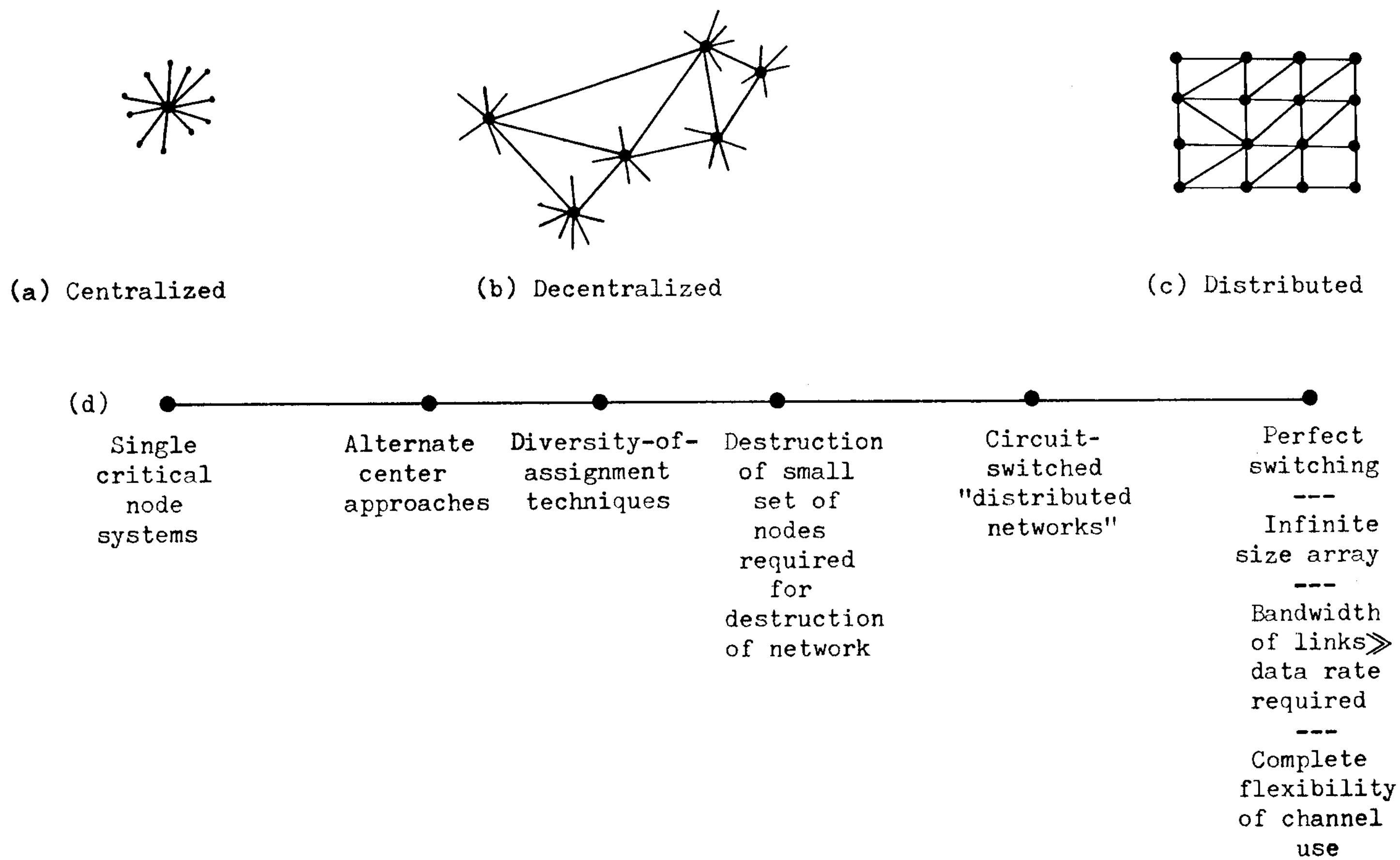


Fig. 1--The Spectrum of System Connectivity

(a)

(b)

(c)

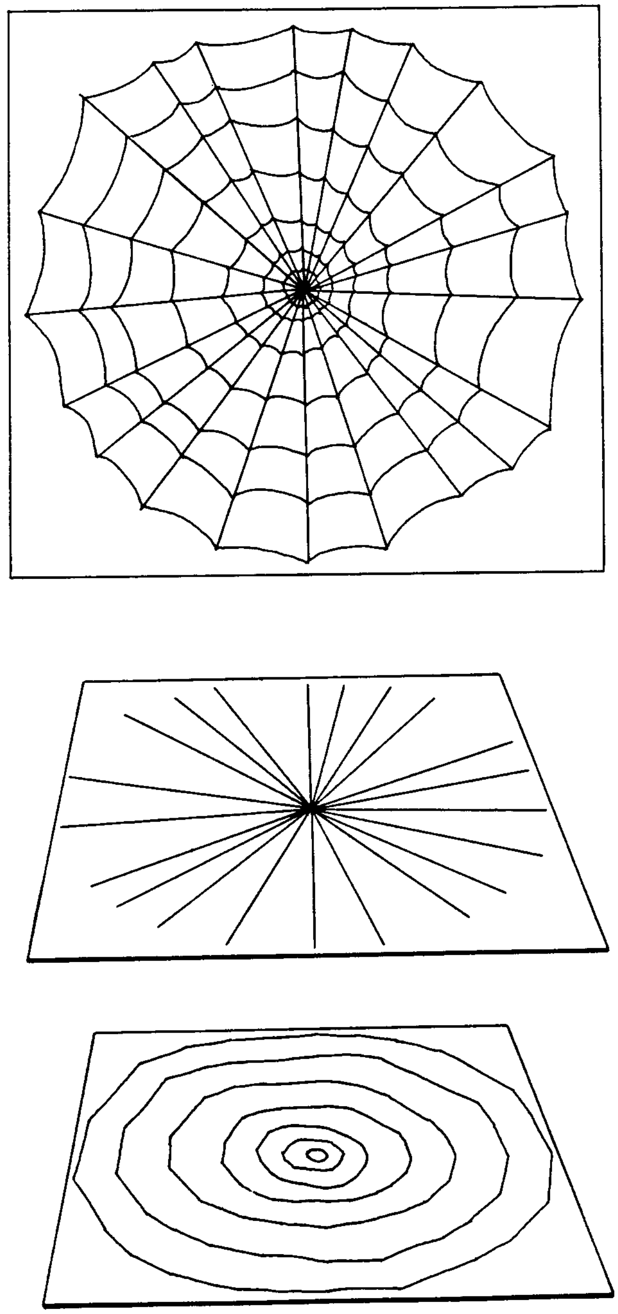


Fig. 2--The Spider Web Communications Network

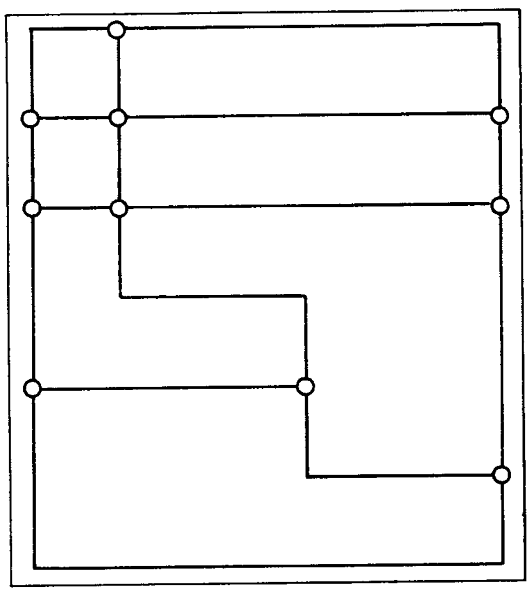
nodes are examined, one finds the number of such possible paths highly limited; so much so in fact, that it would appear that the network is formed by a superposition of the separate overlay networks of Fig. 2-b and Fig. 2-c. It can be seen that there is little, if any, connection of the warp and the woof of the spider web. While Fig. 2 is an exaggeration of such actual networks, Fig. 3 is a somewhat less strained example of this phenomenon; the separate non-switchable links are shown on maps, as in Fig. 3-b. Thus, one must be careful in examining a graph of a communications network in considering the limitations of signal paths at the nodes. To do otherwise would lead to confusing a network with nil survivability with a highly connected and more survivable one having full switching capability at all nodes.

In the systems being considered, networks in which a single point is entrusted with the entire task of transmission path selection, are also avoided. Such a central control node forms a single, very attractive target in the thermonuclear era.

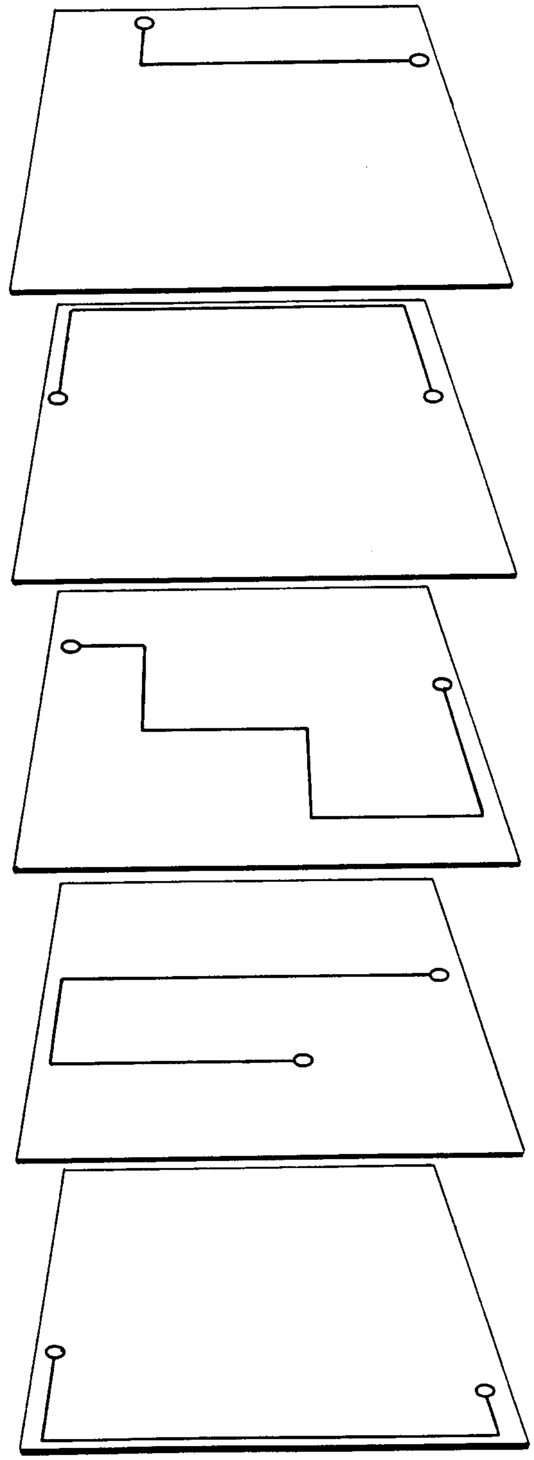
We are thus interested specifically in communication switching node doctrines that are able to produce "efficient" traffic routing using "local control only" and without need for a central control point. A second payoff for use of local control is that it avoids telling a possible enemy precisely which links are not destroyed, a probable occurrence should it be necessary to transfer network station and link information to a remote control point.

DEFINITION OF PERFECT SWITCHING

"Perfect switching" is defined as that form of



(a) Top view of a proposed "distributed" network.



(b) Side view of same network.

Fig. 3--The Spider Web Projected on a Rectilinear Grid

switching that permits a connection to be established between any two points in a network composed of short links that connect switching nodes. Each link terminates at two and only two switching nodes and any number of tandem links may be used to form the connection. The channel capacity of all links and nodes permits all such possible connections to exist simultaneously. This implies "no blocking"; i.e., establishment of any connection between two points shall not preclude connection between any two other points.

HEURISTIC LEARNING

The underlying concept of distributed networks is as old as man. Any interconnected grid of paths or roads may be considered as being a distributed network. When one drives to work over a distributed (or grid) road system and encounters a potential delay, it is possible to turn off, bypassing the traffic jam or obstruction. Thus, the actual route taken depends not only upon a predetermined route, but also upon the happenstance of encountering necessary detours which take us off the preferred shortest path. In spite of this uncertainty, and regardless of the number of detours, we almost always manage to get to work. On some mornings when we have a little extra time, we may chance to try a route that we have never taken before. If we find that this new route is quicker because of less traffic than our old route, we will probably take this newer route in the future. By this process, we learn in a relatively short time the quickest route between home and work. We may say that we have used a "heuristic" process to learn a "best" path in a network.

While this Memorandum examines different types of distributed communication networks, we shall emphasize the development of those networks that use heuristic route-learning.

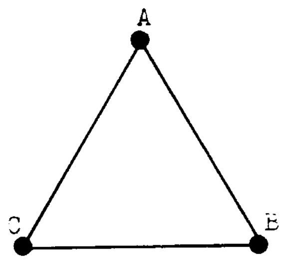
STORE-AND-FORWARD VERSUS CIRCUIT SWITCHING

Networks are described as being either of the store-and-forward type or the circuit-switched type. If the switches at the switching nodes of a network are semi-permanently engaged so that a "real-time" channel exists between the calling and called parties, circuit switching is being used. If messages are relayed from a source station via relay stations and stored at each relay station until a circuit is available to the next relay station (as in a telegraph system), store-and-forward switching is being utilized. The differentiation between the two categories, store-and-forward switching and circuit switching, is not always precise. For example, present-day telephone switching practice is called circuit switching, yet it makes use of a store-and-forward technique to relay dial pulses from switching center to switching center. When a call is placed from New York to Los Angeles, store-and-forward is used to establish the switching connection. After the connection is established, circuit switching commences. Thus, we must exercise caution in the interpretation of these differentiating terms.

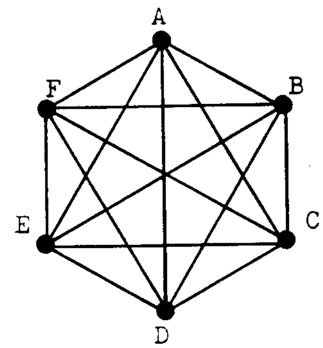
NEED FOR SWITCHING

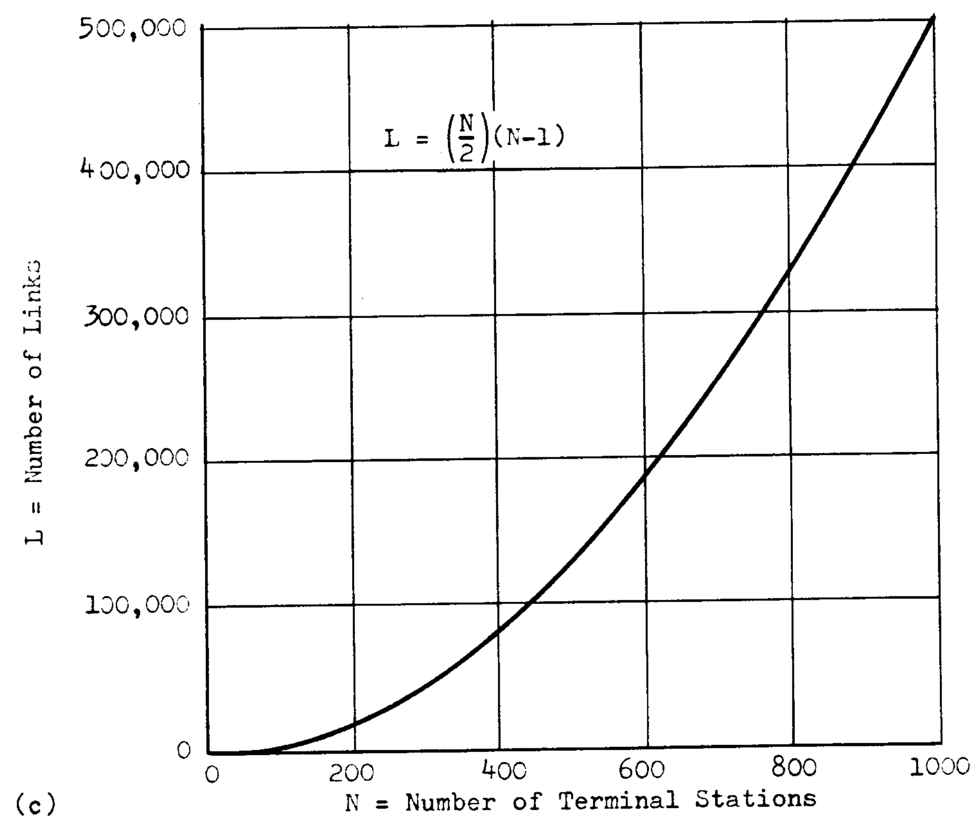
Figure 4-a shows three stations, A, B, and C, that are to communicate with one another. Three bi-directional links are required. In Fig. 4-b six stations, A, B, C, D,

(a)



(b)





(c)

Fig. 4--Number of Links as a Function of Number of Terminal Stations: The Necessity for Switching in a Communications Network

E, and F, are to communicate with one another. Fig. 4-c plots the number of links required as a function of the number of terminal stations in a network in which each station must be able to communicate with every other station in the network and where no switches are allowed. The number of links required by the network is $\frac{(N)(N-1)}{2}$, where N is the number of terminal stations. Thus, the number of links in this communication network will increase roughly as the square of the number of stations in the network. To keep the number of links in the network within reason as network size increases, we are forced to the expedient of Fig. 5. In Fig. 5-a we see three links connecting three communications stations; but, in Fig. 5-b we add a switching center, W, to connect A to B or to C, as needed. (If A is speaking to B, then there is no need for a channel between A and C, since A is already busy.) Figure 5-c shows six stations, each communicating with one another. If we imagine the links of Fig. 5-c as rubber bands, the links can be bundled in any manner without upsetting the basic topography of Fig. 5-c. We can visualize all the stations being connected to a single node as in Fig. 5-d or alternatively, we can connect the stations to the two separate switching nodes Y and Z.

Figure 5-f shows 12 stations interconnected to one another. One can visualize the large number of possible groupings of these "rubber-band" links, such as in Figures 5-g and 5-h.

In the past much work has been done to pick that network topology that most economically connects stations or groups channels in such a manner by applying switching at

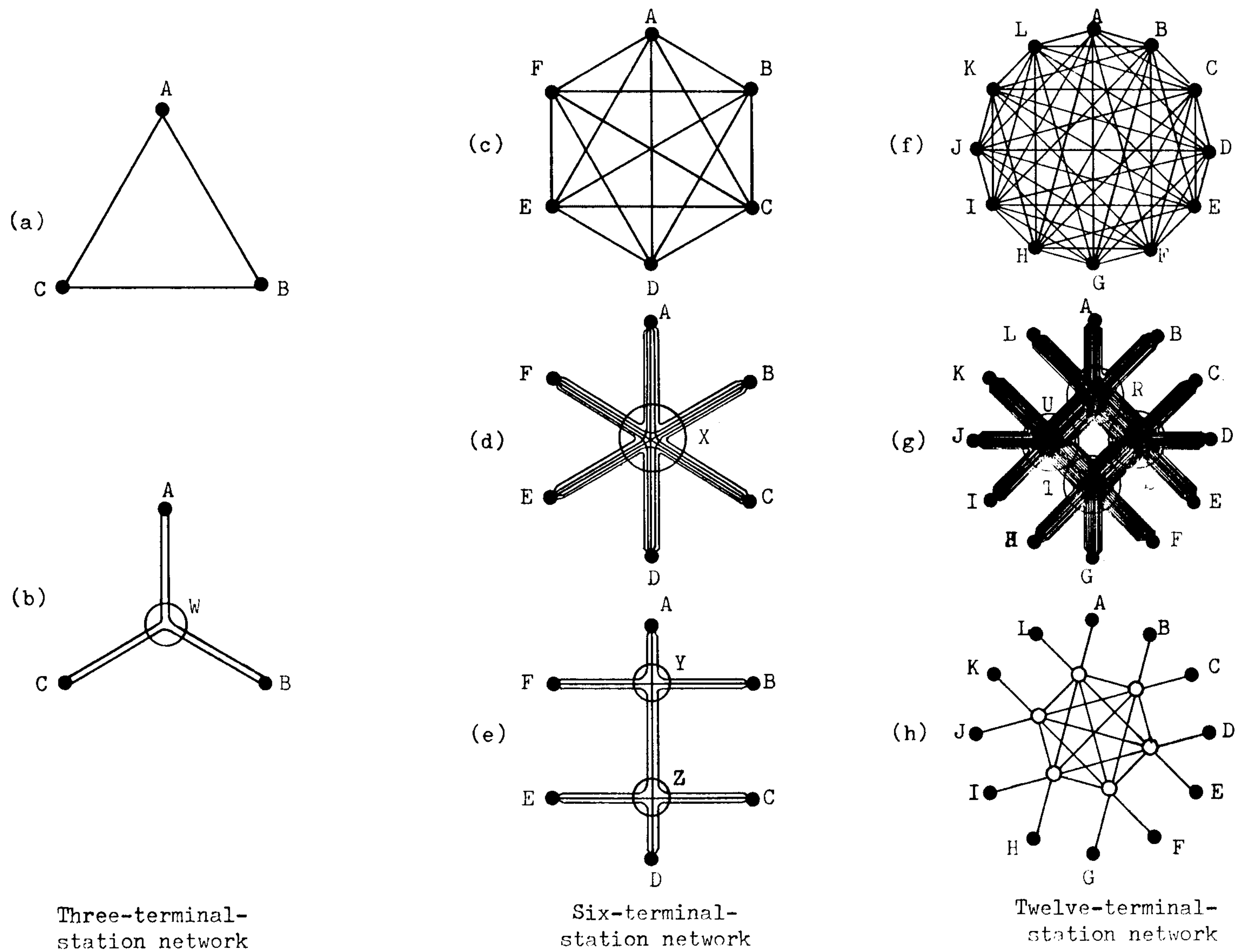


Fig. 5--Use of Intermediate Switching Stations

the nodes. It is not necessary to always have as many separate channels to connect switching stations R to S, for example, as there are link paths in Fig. 5-f. At any one time, very few of the subscribers in the network will be talking. If there were an overload between switching station R and S, for instance, then by proper design of the switching centers and transmission characteristics of the links, an alternate path might be found from R to U, to T, to S, and so on to the eventual end station. Whenever it is necessary to have a large number of stations communicate among a large number of potential addressees, it is a practical necessity to use some form of switching. There is always a very wide variety of potential groupings and possible network configurations. The shape and complexity of the resulting network is very much dependent upon the economies one wishes to make in circuit groupings. The choice of these groupings in turn depends upon the statistics of the expected traffic. If the traffic statistics are known very accurately, large savings in cost of selection of routes and assignment of channels can be realized. However, if it is necessary to build a military network whose configuration and demands are subject to drastic changes with little advance notice, then a network whose design is based on peace-time statistics may be expected to block, or overload, and prevent fulfillment of the original goal--i.e., permitting any subscriber to talk to any other subscriber.

III. EARLY HISTORY

MOUSE IN A MAZE

In 1952, Claude Shannon demonstrated* a machine which was a model of a mouse able to find its way out of a maze (see Figs. 6 and 7). Shannon showed that a relatively simple routing policy could be used to have the mouse examine the entire maze to find the piece of "cheese."

Shannon's mouse was not a distributed system, as his controls were centralized, but he did use a "heuristic" routing doctrine. There was no guarantee that his mouse would ever traverse the entire maze, but the probability that it would was near unity.

BARNSTABLE

In the Final Report** of MIT's Project Barnstable, another mouse-in-a-maze technique was suggested whereby a mouse could find its way out of a maze by marking each maze function point (node) traversed with a "chalk mark."

This technique appears to have the limitation that a message must store within itself the identity of all switching nodes traversed. Alternatively, each switching node would have to store a long history of recent traffic. In such a case, it would be necessary to compare each new message with previously encountered traffic to determine which paths have already been tried.

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*Eighth Conference of the Josiah Macy, Jr., Foundation, New York.

**Barnstable Summer Study, "A Study of Communications Theory Applied to Military Communications Systems," (U) MIT Research Laboratory for Electronics, Cambridge, Massachusetts, October 30, 1958 (Confidential).

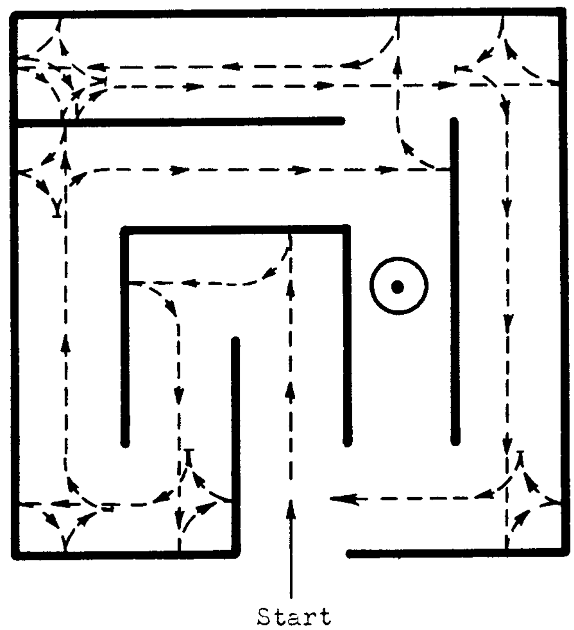


Fig. 6--Shannon's 1952 Maze

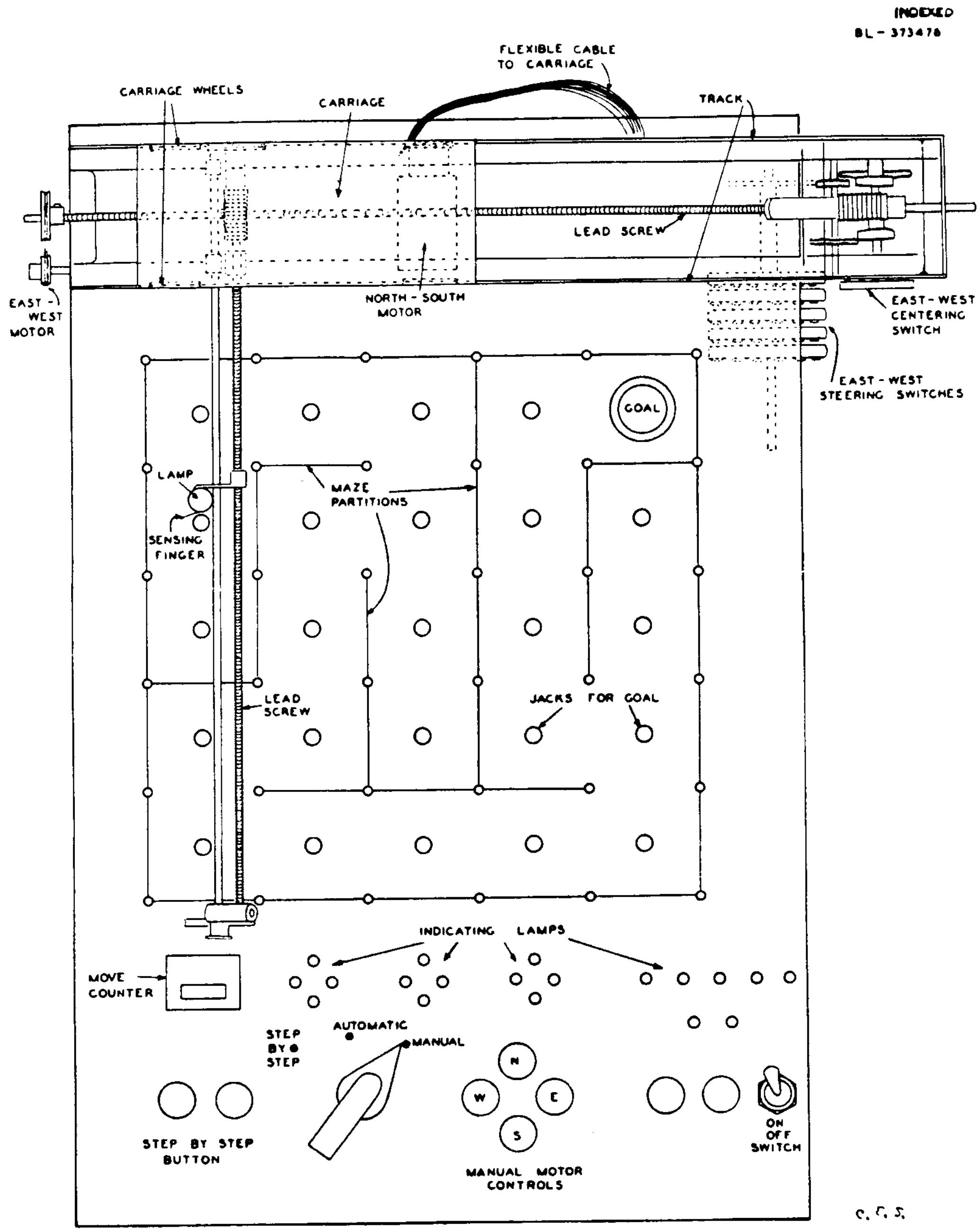


Fig. 7--Shannon's Electrical Mouse*

*Figure courtesy of Shannon, Claude, "Maze Solving Machines," in Cybernetics, Heinz von Foerster (ed.), Josiah Macy, Jr., Foundation, New York, 1952.

VOICE RELAY

In 1955, Frank Collbohm of RAND suggested that traffic could be relayed from broadcast station to broadcast station to provide an emergency means for transmitting extremely urgent messages. The routing was to be handled by human judgment.

IV. SPECIFIC HARDWARE PROPOSALS

The following specific system descriptions are not intended to imply an exhaustive survey of distributed systems; only enough cases are given to provide an introduction to the general subject.

TIME-OF-ARIVAL

In 1957, Frank Yates of the Hughes Aircraft Company described in engineering detail a non-synchronous time-of-arrival procedure to connect a group of stations together into a circuit-switched tree structure. Each node is connected via relay points to the origination station via the shortest possible path.

In Fig. 8 origination station A is connected via links K, E, and H. In Yates' method, shown in Fig. 9, a repetitively available time slot is reserved for each station allowed to transmit new traffic. During the initiation of each time slot all stations in the network listen over all their input lines to their neighbors. The leading edge of the first signal to arrive at each node via the several input lines throws local switches to disconnect all <u>other</u> input lines. Figure 9 shows four digital signals racing to arrive via lines 1, 2, 3, and 4. The message arriving first came over line 3. Thus, the switching node ignores later inputs from all stations other than from line 3. The signal from line 3 is amplified and sent outward on all connected outgoing lines. This procedure is shown to produce Yates' goal of transmitting messages which flood the network and try all possible paths, yet avoids the

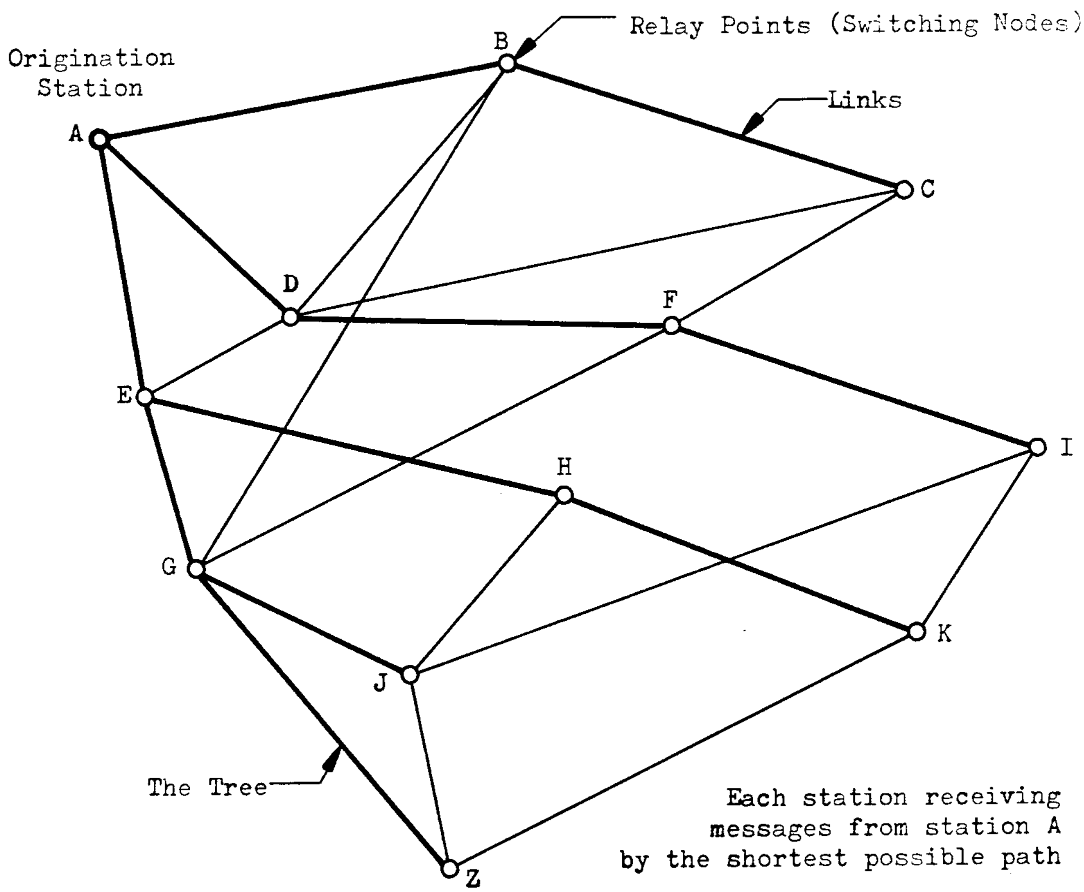
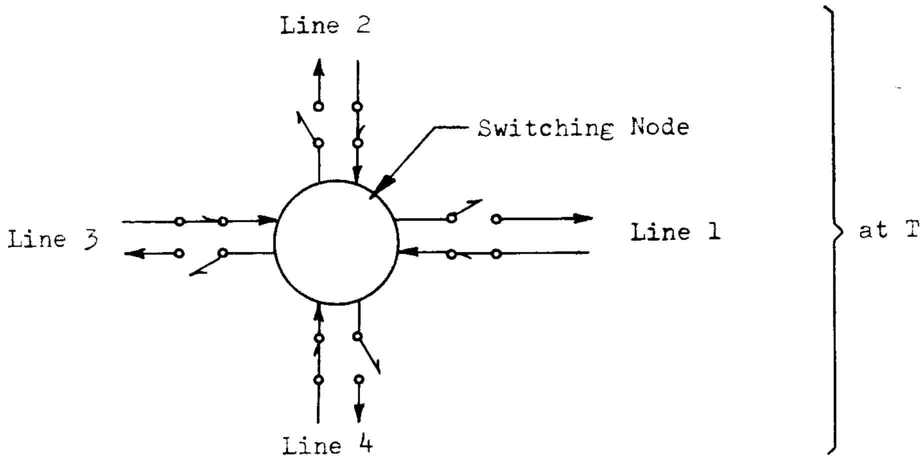
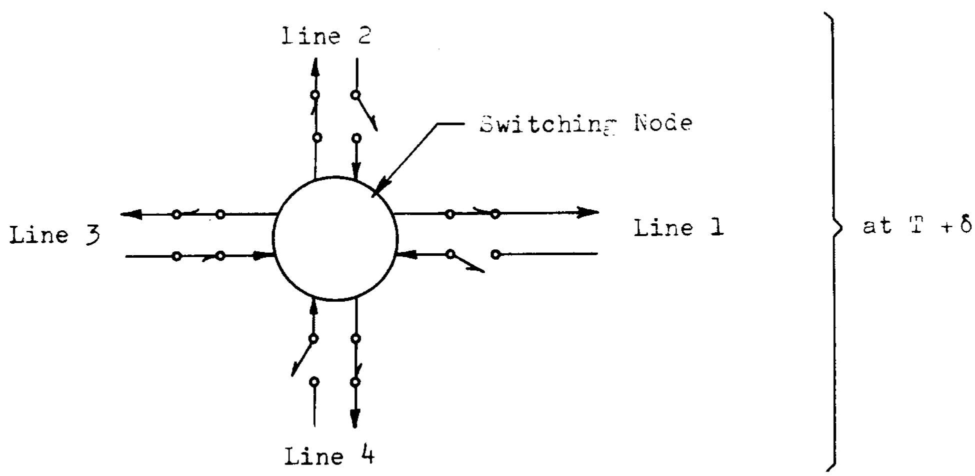


Fig. 8--Yates' 1957 Time-of-Arrival, Non-Synchronous Flooding (Message Flow Diagram)

In the READY MODE:



Transmits the first received signal



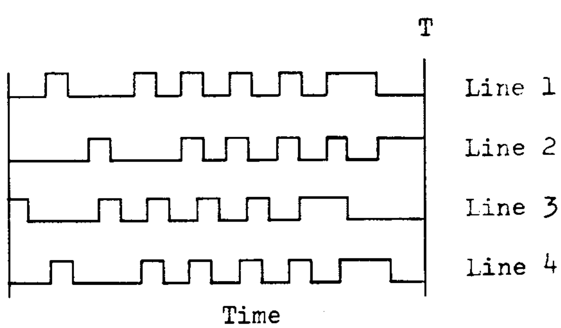


Fig. 9--Yates' 1957 Time-of-Arrival, Non-Synchronous Flooding (Timing Diagram)

"ring-around-the-rosy" effect (i.e., a defective route selection doctrine which allows tandem points which form a closed loop to be tried; the result is identical to falling into "a closed loop" in an improper computer program--useful work ceases until the loop is broken).

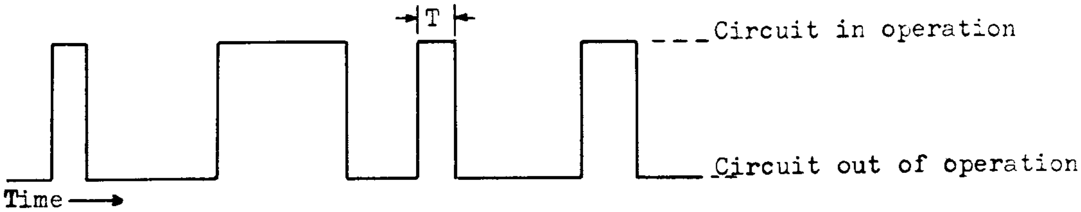
In Yates' approach, time slots must be assigned to every potential user. If the potential user has nothing to transmit during his time slot, this time is generally wasted. Each transmitting station floods the entire network, and so the system lends itself to simultaneous user-to-user communication between pairs of end users.

RANDOM REPEATED RELAY

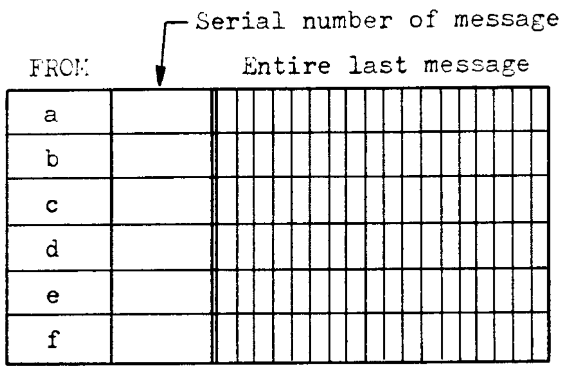
In early 1958, Jack Carne of The RAND Corporation suggested a random relay scheme designed for transmitting a small volume of critical data over a meteor-burst network (see Fig. 10). Carne's notions have not been described in any published document, but Carne examined his scheme using pencil-and-paper Monte Carlo simulation to provide an indication of whether it would work or not.

The scheme uses memory at each node of the network to implement a store-and-forward relay operation. Long-range meteor-burst transmission radio propagation occurs when a meteor trail is in a favorable point in space to cause reflection of a transmitted station radio beam to a ground station. These links are fundamentally unreliable, since favorably located meteor trails occur only on a random basis. Carne's propagation rules were:

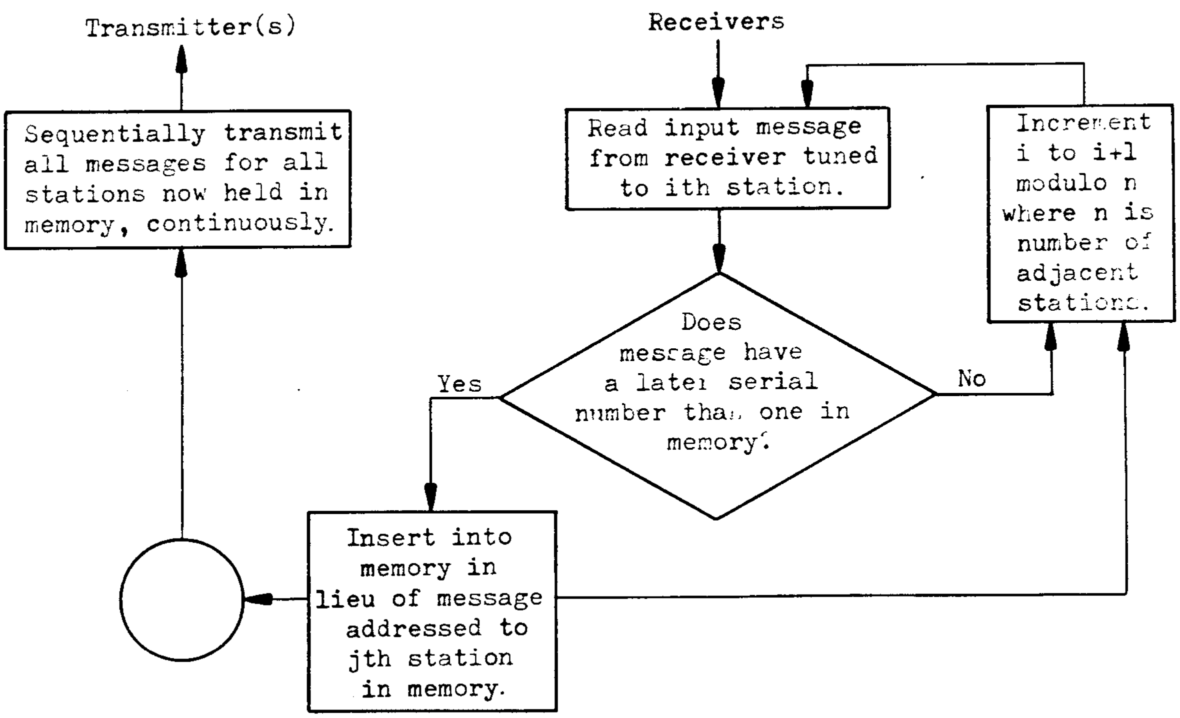
1) Each node has sufficient storage to simultaneously store messages from all potential transmitting stations;



(a) Assumed characteristics of meteor-burst relay.
Message length ≪ T



(b) Storage table at each switching node.



(c) Block diagram.

Fig. 10--Carne's 1958 Meteor-Burst Relay

2) Each message from each origination station carries a time-stamp or a serial number tag;

3) Each station serially transmits the latest message it has received from each possible transmitting station;

4) Each station receives data from several stations and sends to several stations;

5) New traffic serves to flush out old traffic;

6) A serial number appended to each standard-length message block provides a means for selecting newer traffic in preference to older traffic.

The original application envisioned for this doctrine had a low data rate requirement, where the efficiency of network utilization was not important.[*]

DIRECTIONAL RELAY

In 1959, Lt. Colonel Todd Williams of the Rome Air Development Center proposed a circuit-switched system comprising a linear grid array of microwave stations transmitting voice-bandwidth frequency-division channels. Any array of stations in which each node is connected to its neighbors by four or fewer links (planar networks) can be drawn in the form of a rectangular grid for ease of analysis or description.

Williams recently graciously supplied the writer with a detailed description of his network switching doctrine and Sharla Boehm of RAND performed a simulation of this

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[*]The equipment necessary to implement a meteor-burst system using this routing doctrine was examined in an unpublished study written by the consulting engineering firm of Janskey and Bailey, Washington, for The RAND Corporation.

network which compared it against distributed networks that were able to use "perfect switching"; i.e., those that test <u>all</u> possible paths.

Williams' routing doctrine avoided the ring-around-the-rosy problem by the following procedures:

1) All stations in the grid array are assigned a coordinate address comprising a column and a row number (see Fig. 11-a).

2) The coordinates of the addressee station are subtracted from those of the calling station to determine the quadrant of the addressee station relative to the calling station (see Fig. 11-b).

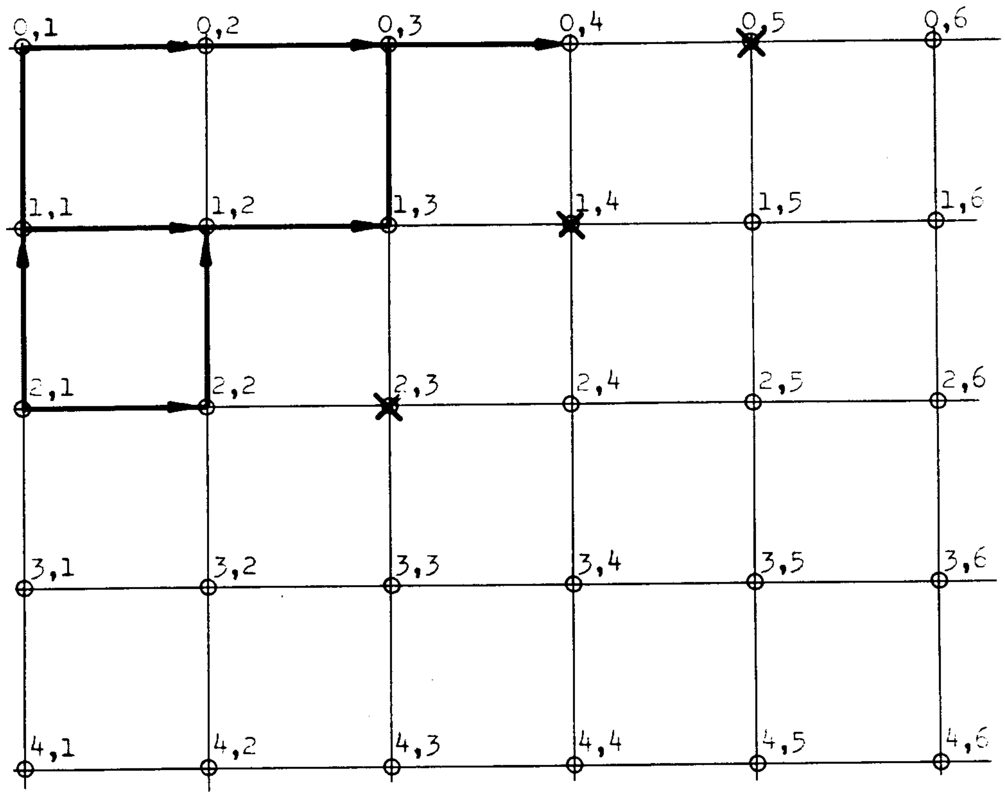
3) If addressee station is in quadrant I, one can go east or north to reach the end destination; if addressee station is in quadrant II, one can go west or north to reach the end destination; if addressee station is in quadrant III, one can go west or south to reach the end destination; if addressee is in quadrant IV, one can go east or south to reach the end destination.

4) The operation of each tandem mode is tested before the switch connection is locked up, thereby avoiding defective links.

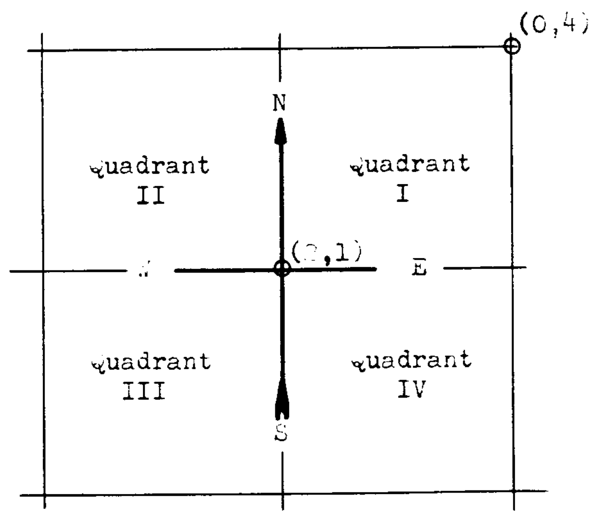
5) Backing out upon encountering a dead end is allowed, provided one remains in the same quadrant.

6) After path is found, then and only then, are the circuit relays locked up.

Several assumptions were made in the RAND simulation of the Williams' network in order to compare it against the goal of perfect switching:



(a) Designation of stations



(b) Determination of quadrant

Fig. 11--Williams' 1959 Directional Relay

1) A network array of 324 stations consisting of an 18 x 18 grid was used;

2) The network had a uniform connectivity of redundancy level 2;

3) There was infinite channel capacity for each switching point and link;

4) An infinite number of drops to baseband was permitted;

5) Only nodes were destroyed.

Because all surviving stations in a large group of adjacent surviving stations cannot always communicate with one another, except in the case of perfect switching, several different survivability criteria were used for comparison (see Fig. 12):

Criterion I (Perfect Switching)--Curve I is the number of stations contained within the largest single group of surviving stations, under the assumption of perfect switching. This curve is included as a comparison reference.

Criterion II (Williams' Switching)--Curve II is the *largest* number of stations in the *largest* single group of surviving stations with which any single station was able to communicate.

Criterion III (Williams' Switching)--Curve III is the *average* number of stations in the *largest* single group of surviving stations with which any single station was able to communicate. This demonstrates that although a station is a member of the largest single group, it cannot communicate with all of the stations in the group (see ODC-I).

Criterion IV (Williams' Switching)--Curve IV is the *average* number of stations with which the *average station*, surviving or not, was able to communicate.

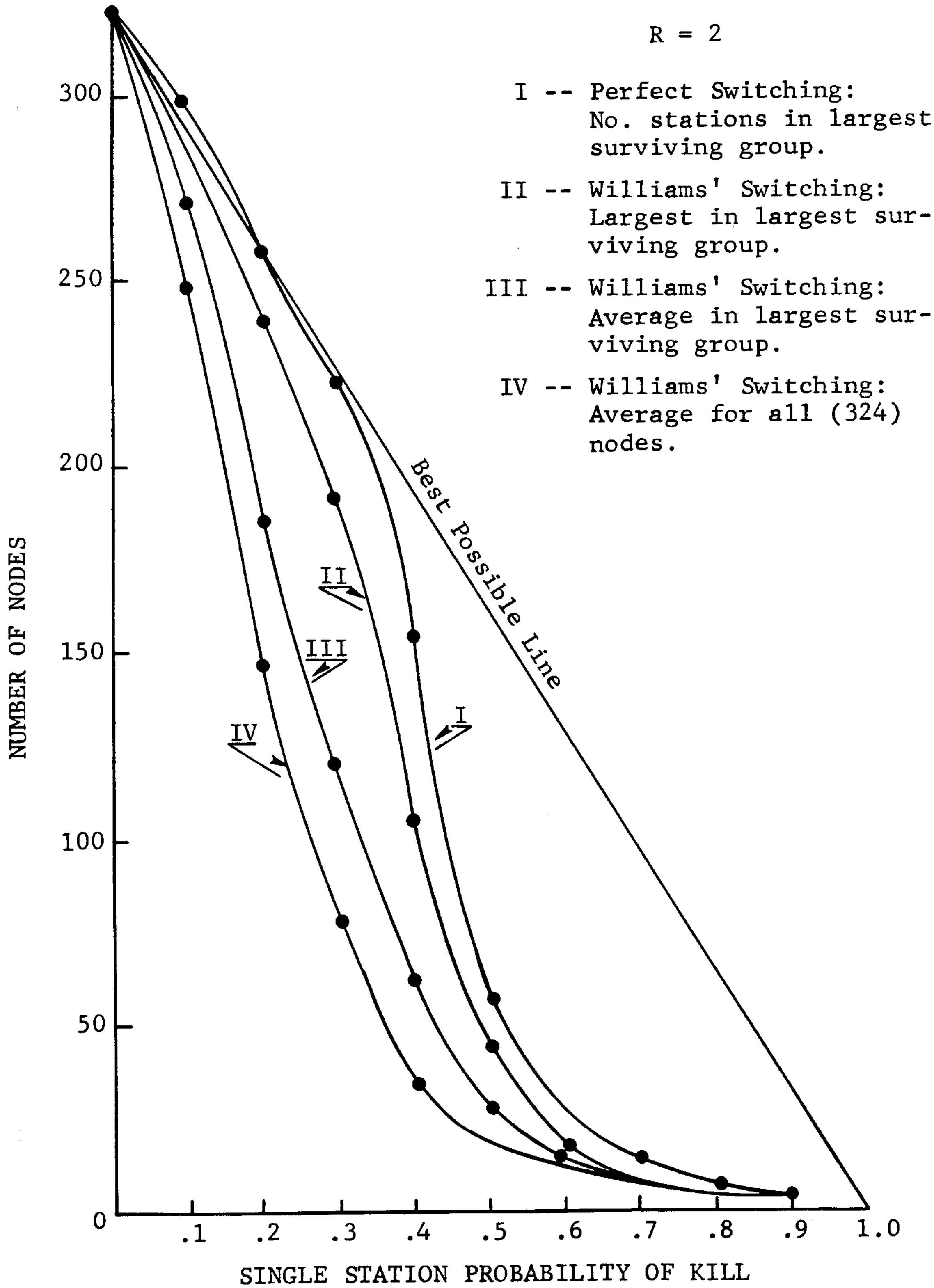


Fig. 12--Survivability of Williams' Switching Compared to Perfect Switching

There is a premium for being able to try all the path combinations possible under perfect switching--particularly in the event of heavy damage. For example, if in Fig. 11-a stations (0,5), (1,4), and (2,3) are destroyed, it would be impossible to communicate with (0,6), (1,5), (1,6), (2,4), (2,5), and (2,6), because of the quadrant-crossing limitation used to prevent the ring-around-the-rosy effect.

Williams' directional relay method has one very strong factor to recommend it: it is a relatively simple circuit-switched system able to handle voice. This simplicity must be weighed against a less than full realization of what perfect switching offers in survivability. As in any circuit-switched system, there will also be additional losses due to finite channel capacity of the links and number of tandem links that can be used.

SYNCHRONOUS FLOODING

In 1959, the writer, while employed at the Hughes Aircraft Company, described a switching scheme in a proposal submitted to Boeing. The peculiar requirement of the application called for a very-low-data-rate system, requiring the path-seeking ability of the Yates' system, coupled with freedom from the possibility of the network being seized by either equipment failure or by intentional acts.

The system uses what might be called a "synchronous-flooding" routing doctrine. Distances and bit rates are such that it is possible to synchronize each station in the network to operate in step. Each relay station receives messages from all adjacent stations simultaneously. The number of simultaneous messages received is as great as the number of links connecting each station. All messages transmitted by a single message origination station are simultaneously examined at each node. A decision is reached as to whether a correct message has been received and the single assumed correct message is sent out on all lines. Logical apparatus for reaching this decision is contained at each node and operates as follows:

1) A number, called a "hand-over number," is affixed to each originated message. This hand-over number tag provides a measure of the path length traversed by each message. The hand-over number tag is incremented every time a message is relayed.

2) The hand-over numbers of all messages transmitted by each origination station are examined simultaneously. Those messages with the lowest hand-over number are assumed to be the most recent messages and are propagated, while all other messages are dropped.

3) Two messages arriving simultaneously and bearing the same hand-over number but differing in message content are rejected to eliminate distorted messages. Also rejected are those messages which have been sent by two separate stations, both claiming to be the same station. If two messages arrive by different directions and have the same path length, they must match. If they are different, something is wrong, and "wrong" messages are not propagated. However, no valid messages will be lost, because a verified valid message will arrive later by an alternative path.

4) Messages bearing a hand-over number less than the predetermined minimum possible hand-over number are rejected and a trouble indication message sent. For example, if two stations are a minimum of five links apart, then it is clearly impossible for messages to be transmitted from one to the other with a hand-over number of less than five.

5) Messages having a hand-over number greater than a predetermined maximum value are assumed to be undesirably old and are rejected.

Under these selection criteria, one and only one received message survives. This latest assumed valid message is stored and held in storage until the proper transmission time frame occurs. A sequential time frame is reserved for the consecutive transmission of a standard-length message from each possible orgination station.

The relay scheme is really a broadcasting system, since each message is transmitted to all stations. Hence, it is called a "flooding" technique. Its chief merit is that in the event of fraudulent signal intervention, only a few stations in the network will receive the fraudulent message. Undesired signals are generally suppressed at most nodal points in the network. The system automatically uses its connnection redundancy to provide automatic error correction. If an independent error occurs in the text portion of the message, it will be propagated only until the node is reached where comparison of messages bearing the same hand-over number takes place. Such messages will then be rejected.

The limitations of this method of propagation include:

1) Inability to rapidly relocate the positions of stations in the network because of the minimum-fixed-distance-between-nodes test;
2) Suitability only for very low data rates;
3) Requirement for local storage and relatively long time delays necessitated by reception of messages from several different directions.

Although synchronous flooding is perhaps somewhat more secure than other networks described, it also makes least efficient use of the communications resource.

Figure 13 is a detailed example of message propagation in this network. Signals originate at Station 22 and are transmitted simulteneously to the north, east, south, and west. Messages arriving at Station 32, for example, will bear a hand-over number of 0. The hand-over number is incremented and passed on to the next station, No. 42. Messages at Station 33 arrive from two different directions: from Station 23 bearing a hand-over number of 1; and from Station 32 also bearing a hand-over number 1. These two simultaneously arriving messages are compared. If identical, the common message is transmitted out in all four directions.

All stations other than those in the diagonally-shaded area (Fig. 13), will, simultaneously (i.e., with the same hand-over number), receive messages from two or more links. These messages must exactly match; otherwise, these messages will not be relayed. If a fraudulent Station X were to insert messages, it could, theoretically, pretend it was Station 22 to those stations on the right-hand side of the network. However, if a rule that a known minimum distance exists between any two stations is included, then this counterfeiting would be credible only within the smaller dot-shaded area. If the number of co-operating friendly stations is much greater than the number of fraudulent stations, then even these few fraudulent stations can be located or cut out of the network with little impairment of residual network performance.

SATURATION SIGNALING

In 1959, Gunnar Svala of the North Electric Company described a circuit-switching arrangement which he calls

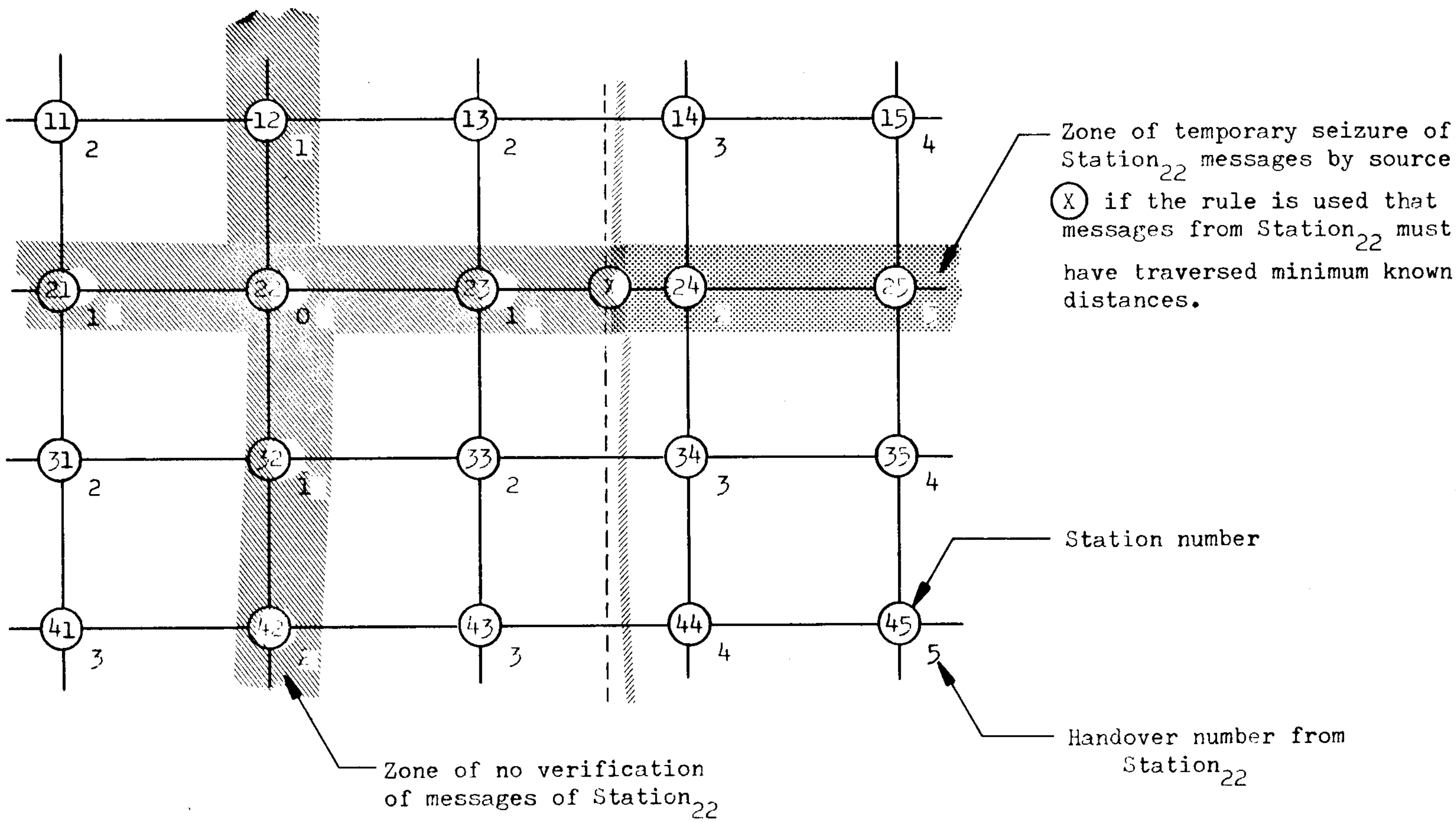


Fig. 13--Message Propagation

"saturation signaling." In this system, high-speed signaling information is broadcast throughout the entire network. When the end-party responds, a circuit is established between the called end-party and the calling party and all the tentative searching connections are closed off. In saturated signaling, each node or switching center may be connected to adjacent neighbors in the canonical manner of the distributed network. Each switching center is essentially a conventional switched toll-telephone exchange, but with the addition of a rapid-access memory and a sequential line-scanning device.

The rapid-access memory keeps a record of the telephone numbers of all local subscribers currently connected to the local switching center. The rapid-scanning device sequentially examines all circuits (trunks and lines) connected to the switching center.

Basically, the system uses a flooding technique in which the called number is transmitted throughout the network in a manner somewhat similar to Yates' method. Ring-around-the-rosy is prevented by each switching center asking the question, "Have I just received this called number?" The rapid-access memory at each node traversed is scanned until the called number is found. At this time, revertive signals are sent which lock up the circuit connection.

Figure 14 illustrates the propagation of signals in Svala's system. Switching center A transmits the telephone number of the party being called to several adjacently connected stations, B, C, and E. Each of these centers examines its own local memory to see if the called station is a local one. If not, the called number is relayed to other switching centers.

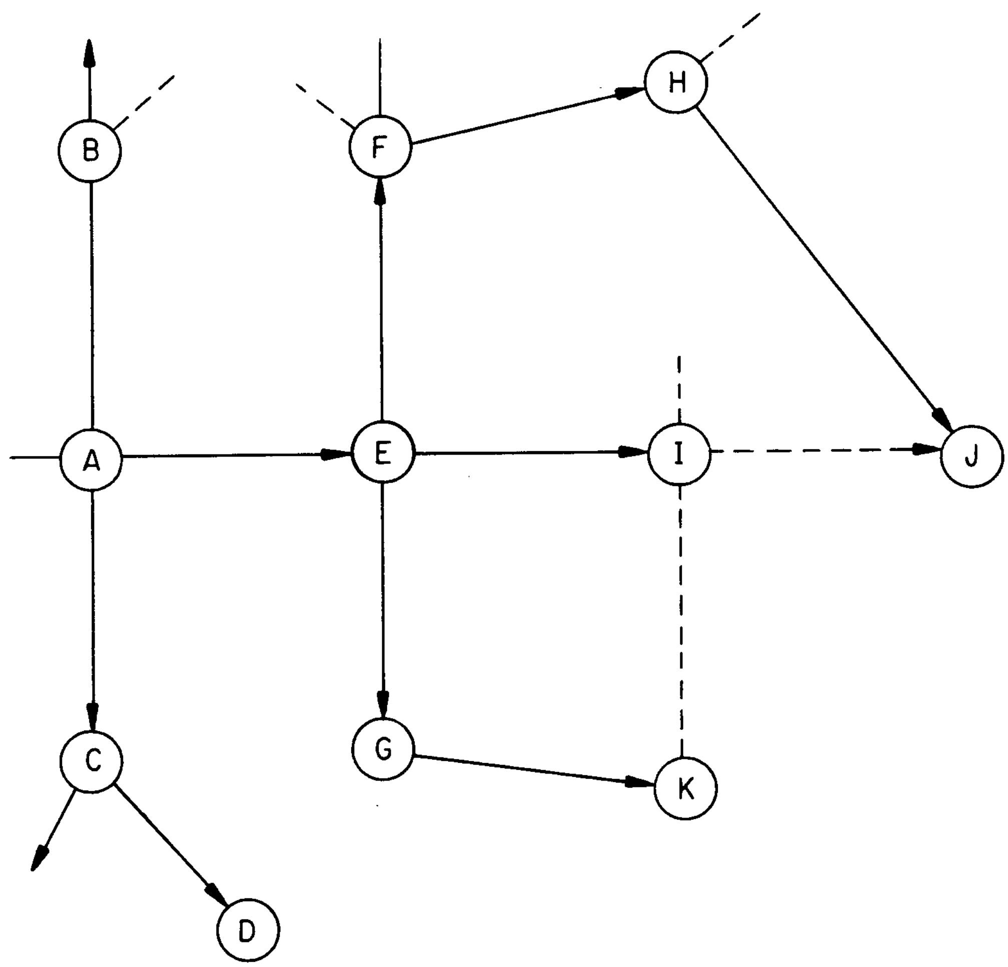


Fig. 14--Propagation of Signals in Svala's Saturated Signaling

The saturated signaling system appears to be a form of perfect switching with the resulting high survivability expected from such systems. There is, of course, an inevitable set of problems found in any complex system of this sort. What happens if many of the stations are destroyed? Will there be blocking because the signaling is overloaded while waiting to time out? How much time is spent in signaling relative to active circuit usage? These questions are most readily answered by a simulation, and such simulation is being conducted by the North Electric Company under a feasibility study contract with the U.S. Army Research and Development Laboratories.

A key feature of this network is that it allows a user to move across the country and take his telephone number with him. He has only to inform his last connected central office and his new one of the change of address.

TWO-PHASE ROUTING

In 1960, John Bower, in a patent disclosure entitled, "Logic for an Interconnected Net," described (in operational form only) a communication system which would essentially operate in two sequential time phases. During time phase A, information at the nodes on the status of traffic loads at each station in the network is transmitted to all other nodes. Each node contains memory to record the status, thereby enabling it to determine the optimum direction for routing traffic to any given end station. During a much longer time phase B, useful traffic is sent, based upon a flow pattern that corresponds to the most recent network status and loading measurements.

HOT-POTATO ROUTING

In 1960, the writer suggested the use of a "hot-potato" routing doctrine upon which to build a common-user, all-digital communications network; this system is described in detail in the other papers of this series. All traffic is converted to digital signals and blocked into standardized-format packets of data. Each packet of data, or "message block," is rubber-stamped with all the signaling information needed by other stations to determine optimum routing of the message block.

The system has a set of properties that are markedly different than present-day networks. Some are advantageous and others disadvantageous. These are described in detail in ODC-XI. Briefly, some of the features include:

1) Very efficient usage of time-shared digital links;

2) A high upper limit on allowable data rates;

3) Relative immunity to the effects of illicit intervention;

4) Application of a future all-digital network communication requirement;

5) Allows a reliable system to be built using low-cost and unreliable links.

The disadvantages of the hot-potato system include:

1) It is fundamentally an all-digital system;

2) It requires a more complex routing logic at the nodes than has ever been previously attempted.

In summary, one pays the price of logical switching complexity but buys a set of unusual network properties;

e.g., the network can handle digital data on an extremely short-term store-and-forward basis, and the system appears to be able to handle "real-time" digital voice.

TESSELLATED NETWORK

In 1961, Jack Craig of The RAND Corporation proposed a "Tessellated Network."* This network was designed to meet the communications requirements of a specific task--the air defense problem. In this network, each station transmits information to a small ring of adjacent stations. The inherent broadband capability of a microwave link is utilized together with conventional frequency division multiplexing to provide a large number of separate voice bandwidth channels. These channels are then so assigned that separate channels emanate from each station to adjacent stations. Switching per se, is not used. Craig and Reed suggest that a modest amount of manual patching at each node can be used to restore communications between essentially adjacent stations after attack. While this network makes inefficient use of a broadband channel by conventional communication practices (since but few of the potential channels in the microwave link are in active use), it should be pointed out that all distributed networks designed to withstand heavy attack are fundamentally inefficient. After attack, the last surviving link of the redundant network might have to carry the entire network traffic. Therefore, one must start with a built-in excess

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*Craig, L. J., and I. S. Reed, Overlapping Tessellated Communications Networks, The RAND Corporation, P-2359, July 5, 1961.

capacity. To build a network with merely enough capacity to handle the normal pre-attack load, is to be certain of not having enough capacity after an attack. While the tessellated network, conceptually, is the simplest of the networks proposed, it appears to be of primary use in those cases where a station usually needs only to speak to adjacent stations or stations only a few spans away. If the tessellation is extended to too many remote stations, the bandwidth (number of channels required) builds up tremendously, and survivability decreases markedly due to the requirement for a greater number of tandem serial connections.

The survivability of a network using tessellation is highly dependent upon the span distance required, given finite bandwidth link capacities. If the span distances are short, with connection made only to adjacent stations, the survivability of the network is excellent--resembling perfect switching. But, if the span distances between connected nodes are very great, then the survivability will be closer to that of diversity of assignment--leaving much to be desired. The efficacy of diversity of assignment drops off markedly with increasing span length (see ODC-I).

V. CONCLUSIONS

There is no single "distributed network." Many highly different systems can all be correctly called distributed, and some of these can be categorized as using perfect switching. Sufficient simulation has been run to predict the effects of overt destruction upon those using perfect switching and those using only diversity-of-assignment techniques. Generally, the more "perfect" the switching, the greater the survivability.

While those systems that use only diversity of assignment over large spanning distances are more vulnerable than those that use perfect switching, the essentially simple diversity-of-assignment technique appears satisfactory when only short spanning distances need to be considered.

The survivability of other switched networks that fall somewhere between these two known points of system performance cannot be determined without a specific examination being made. After many more such specific intermediate systems are examined in detail, we will have more known points upon which to interpolate performance characteristics of other proposed systems under overt attack.

It will always be necessary, though, to examine each switched system separately to determine its ability to withstand sophisticated tampering.

Appendix A

SUMMARY CHARTS

Table I

BIBLIOGRAPHY OF SEVERAL DISTRIBUTED NETWORK ROUTING DOCTRINES

	Date	Designation	Principal Investigator	Published Reference
1	1952	Mouse in a Maze	C. Shannon	C. Shannon in Cybernetics, H. von Foerster, Editor, Transactions of Eighth Conference, Josiah Macy, Jr., Foundation, New York, 1952, p. 173.
2	1958	Barnstable	D. A. Huffman C. E. Shannon E. N. Gilbert H. P. Galliher E. Reilly	Final Report, Barnstable Summer Study, "A Study of Communications Theory Applied to Military Communications Systems (U)," Confidential, MIT Research Laboratory for Electronics, Cambridge, Massachusetts, October 30, 1958, p. 117.
3	1955	Voice Relay	F. R. Collbohm	F. R. Eldridge, J. B. Carne, H. A. Shapiro, B. Holfer, "Vulnerability of Landline Communications for SAC and ADC (U)," The RAND Corporation, RM-1774, October 1, 1956, p. 67.
4	1957	Time-of-Arrival	F. Yates	Paul Baran and Frank Yates, "A Non-Synchronous Digital Data Link Transmission System Using Randomly Surviving Relay Points," The RAND Corporation, May 25, 1960.
5	1958	Random Repeated Relay	J. Carne	None
6	1959	Directional Relay	T. G. Williams	William G. Todd, "A National Survival Communications System," Rome Air Development Center, Technical Memorandum RCU-TM-59-1, February 1959.
7	1959	Synchronous Flooding	P. Baran	Paul Baran and Robert Hammerly, "A Verified Point of Origin Synchronous Digital Data Link Transmission System Using Randomly Surviving Relay Points," The RAND Corporation, May 25, 1960.
8	1959	Saturation Signaling	G. Svala	Gunnar Svala, "Saturation Signalling and Switching System," North Electric Company, Galion, Ohio, 1959.
9	1960	Two-Phase	J. Bower	Patent disclosure.
10	1960	Hot-Potato Routing	P. Baran	Current series.
11	1961	Tessellated Network	L. J. Craig	L. J. Craig and I. S. Reed, "Overlapping Tessellated Communications Networks," The RAND Corporation, P-2359, June 13, 1961.

Table II

COMPARISON OF PROPERTIES OF DIFFERENT DISTRIBUTED NETWORK PROPOSALS

	SWITCHING DOCTRINE					CHANNEL ASSIGNMENT FLEXIBILITY	SERVICE OFFERED					
	Type of Switching	Switching Route Selection	Number of Possible Routes Tested	Is Flooding Used?	Method Used to Purge Signaling Data		Analog Voice	Analog Fax.	Digital Voice	Digital Fax.	Digital TTY	Digital Data
Barnstable	S&F	Remember Path Taken	All	No	Path cannot pass same point more than twice	Fair					X[b]	X
Time-of-Arrival	CS	T-of-A	All	Yes	New traffic flushes out old	Poor-Fair					X[b]	X
Random Repeated Relay	S&F	Traffic Age	Very Many	Yes	Later serial number flushes out old traffic	Fair					X[b]	X
Directional Relay	CS	Determine Quadrant	Limited Number	No	No problems: number of paths tested is limited	Good	X	X	X	X	X	X
Synchronous Flooding	S&F	Handover Number	All	Yes	Lower handover number traffic flushes out old traffic	Poor						X
Saturated Signaling	CS	T-of-A	All	(a)	Maximum time to make connection; revertive signal knocks down undesired connections	Good	X	X	X	X	X	X
Two-Phase Routing	S&F	Traffic Statistics Broadcast	Many	No	Network status information sent periodically	Fair-Good					X[b]	X
Hot-Potato Routing	S&F	Handover Number	Almost All	No	Maximum allowable handover number	Good			X	X	X	X
Tessellated Network	CS	None; Manual Patch	Limited Number	No	No-write signaling used	Fair	X	X	X	X	X	X

S&F--Store-and-Forward CS--Circuit Switching T-of-A--Time of Arrival

[a] Signaling: Yes; Established Circuit: No.

[b] If buffering is used.

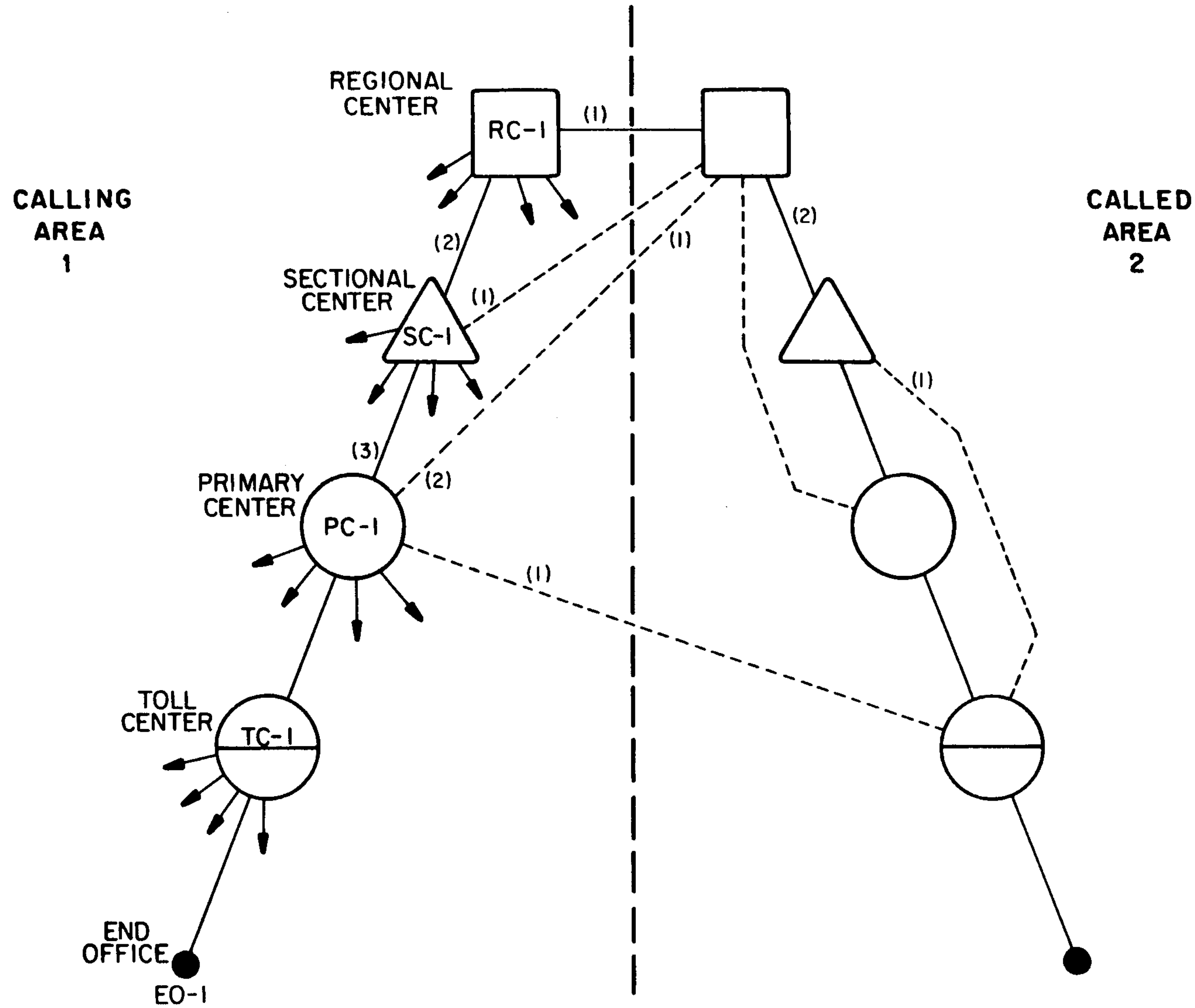
Appendix B

THE DDD SYSTEM

In the Bell System Direct Distance Dialing (DDD) network (Fig. 15), telephone number dial pulses are relayed to a Toll Center; if there are no lines available to the desired end destination, the call is routed to the next higher hierarchical level, the Primary Center. If again there are no free circuits to the end destination, the call is relayed via a Sectional Center, and thence to a Regional Center. (All Regional Centers in the United States are connected to each other.)

Thus, a telephone call starting from any place in the country will work its way up the hierarchical network, seeking an end link to the called telephone via a Toll, Primary, Sectional, or Regional Center, then back down the chain to the end telephone. Destruction of a small number of the upper echelon targets is magnified in the remainder of the communication network. The hierarchical procedure increases the target value of upper echelons of the switching network.

An ever increasing number of calls in the Direct Distance Dialing System are being transmitted from one Toll Center to an end Toll Center by direct trunk lines without requiring transmission through the upper echelons. In telephone language, these direct paths are called "high usage groups." The feasibility of being able to use such point-to-point non-switched high-usage circuit groups increases as the number of subscribers using the long distance telephone plant increases.



NOTES:
1. Numbers in ( ) indicate order of choice of route at each center.
2. Arrows from a center indicate trunk groups to other lower rank centers that home on it. (Omitted in right-hand chain)

Fig. 15--Direct Distance Dialing Hierarchy

Each of the links shown in Fig. 16 is made up of channels following separate paths, or using "diversity of assignment" (see ODC-I).

While determination of the vulnerability of switching will depend upon the actual numbers of options tested at each switching center, it is found in practice that very few of the large set of all possible connections existing are ever tried, as alternate routing is designed primarily to effect more economical handling of traffic.*

Figure 16 shows that in practice most connections are established by the use of only a few tandemly connected links. Therefore, it appears reasonable to assume that the survivability curves for diversity of assignment may be indicative of network performance.

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*Truitt, C. J., "Traffic Engineering Techniques for Determining Trunk Requirements In Alternate Routing Trunk Networks," The Bell System Technical Journal, Vol. 33, March 1954, pp. 277-304.

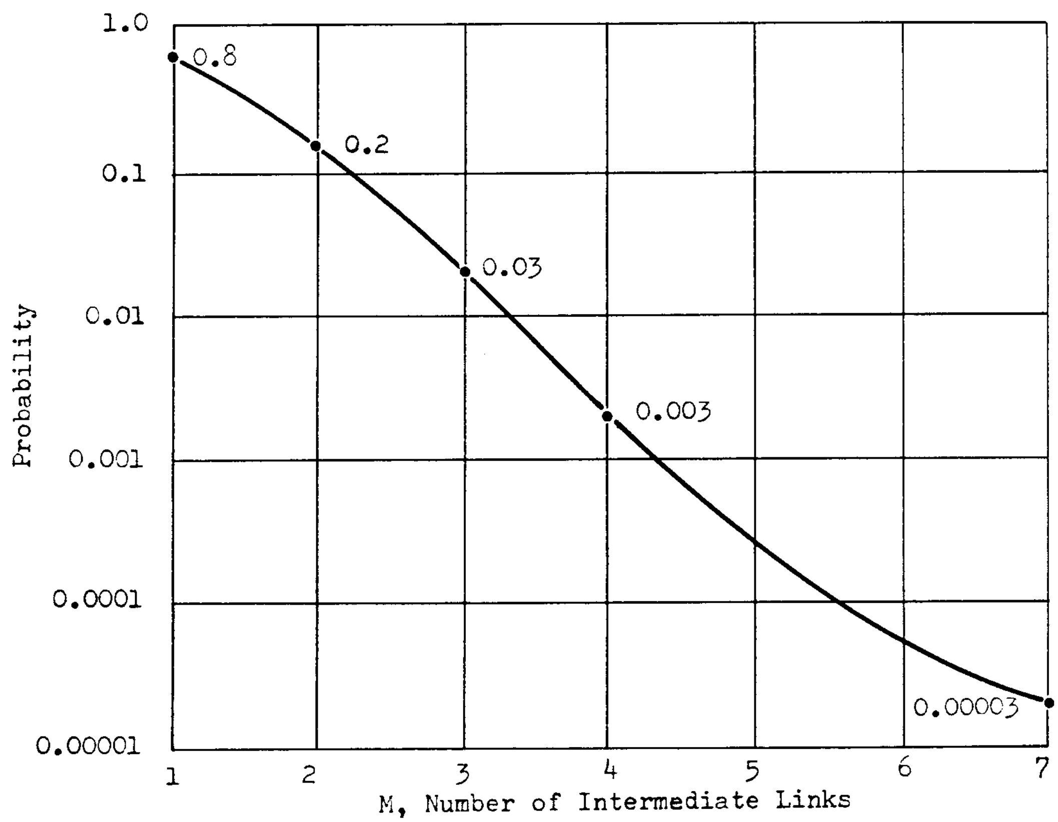

Fig. 16--Probability that M or More Links will be Required to Complete a Toll Call*

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*Courtesy Transmission Systems, 2d ed., Bell Telephone Laboratories, New York, 1958.

ON DISTRIBUTED COMMUNICATIONS:

List of Publications in the Series

I. Introduction to Distributed Communications Networks, Paul Baran, RM-3420-PR.

Introduces the system concept and outlines the requirements for and design considerations of the distributed digital data communications network. Considers especially the use of redundancy as a means of withstanding heavy enemy attacks. A general understanding of the proposal may be obtained by reading this volume and Vol. XI.

II. Digital Simulation of Hot-Potato Routing in a Broadband Distributed Communications Network, Sharla P. Boehm and Paul Baran, RM-3103-PR.

Describes a computer simulation of the message routing scheme proposed. The basic routing doctrine permitted a network to suffer a large number of breaks, then reconstitute itself by rapidly relearning to make best use of the surviving links.

III. Determination of Path-Lengths in a Distributed Network, J. W. Smith, RM-3578-PR.

Continues model simulation reported in Vol. II. The program was rewritten in a more powerful computer language allowing examination of larger networks. Modification of the routing doctrine by intermittently reducing the input data rate of local traffic reduced to a low level the number of message blocks taking excessively long paths. The level was so low that a deterministic equation was required in lieu of Monte Carlo to examine the now rare event of a long message block path. The results of both the simulation and the equation agreed in the area of overlapping validity.

IV. Priority, Precedence, and Overload, Paul Baran, RM-3638-PR.

The creation of dynamic or flexible priority and precedence structures within a communication system handling a mixture of traffic with different data rate, urgency, and importance levels is discussed. The goal chosen is optimum utilization of the communications resource within a seriously degraded and overloaded network.

V. History, Alternative Approaches, and Comparisons, Paul Baran, RM-3097-PR.

A background paper acknowledging the efforts of people in many fields working toward the development of large communications systems where system reliability and survivability are mandatory. A consideration of terminology is designed to acquaint the reader with the diverse, sometimes conflicting, definitions used. The evolution of the distributed network is traced, and a number of earlier hardware proposals are outlined.

VI. Mini-Cost Microwave, Paul Baran, RM-3762-PR.

The technical feasibility of constructing an extremely low-cost, all-digital, X- or K_u-band microwave relay system, operating at a multi-megabit per second data rate, is examined. The use of newly developed varactor multipliers permits the design of a miniature, all-solid-state microwave repeater powered by a thermoelectric converter burning L-P fuel.

VII. Tentative Engineering Specifications and Preliminary Design for a High-Data-Rate Distributed Network Switching Node, Paul Baran, RM-3763-PR.

High-speed, or "hot-potato," store-and-forward message block relaying forms the heart of the proposed information transmission system. The Switching Nodes are the units in which the complex processing takes place. The node is described in sufficient engineering detail to estimate the components required. Timing calculations, together with a projected implementation scheme, provide a strong foundation for the belief that the construction and use of the node is practical.

VIII. The Multiplexing Station, Paul Baran, RM-3764-PR.

A description of the Multiplexing Stations which connect subscribers to the Switching Nodes. The presentation is in engineering detail, demonstrating how the network will simultaneously process traffic from up to 1024 separate users sending a mixture of start-stop teletypewriter, digital voice, and other synchronous signals at various rates.

IX. Security, Secrecy, and Tamper-Free Considerations, Paul Baran, RM-3765-PR.

Considers the security aspects of a system of the type proposed, in which secrecy is of paramount importance. Describes the safeguards to be built into the network, and evaluates the premise that the existence of "spies" within the supposedly secure system must be anticipated. Security provisions are based on the belief that protection is best obtained by raising the "price" of espied information to a level which becomes excessive. The treatment of the subject is itself unclassified.

X. Cost Estimate, Paul Baran, RM-3766-PR.

A detailed cost estimate for the entire proposed system, based on an arbitrary network configuration of 400 Switching Nodes, servicing 100,000 simultaneous users via 200 Multiplexing Stations. Assuming a usable life of ten years, all costs, including operating costs, are estimated at about $60,000,000 per year.

XI. Summary Overview, Paul Baran, RM-3767-PR.

Summarizes the system proposal, highlighting the more important features. Considers the particular advantages of the distributed network, and comments on disadvantages. An outline is given of the manner in which future research aimed at an actual implementation of the network might be conducted. Together with the introductory volume, it provides a general description of the entire system concept.